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***Abstract*— Detailed knowledge of both the sedimentological and ecological characteristics of the seafloor is essential when undertaking bottom-disturbing activities, but can be a challenge to obtain. Through backscatter data at different frequencies, collected with a multi-spectral multi-beam sonar, information on the structure of both the sediment surface and subsurface, and potentially also on the presence and distribution of benthic organisms, can be derived. We conducted two surveys at sea in summer 2021, in which we used an R2Sonic 2026 multi-spectral multi-beam sonar in the southern North Sea. Boxcore samples were taken to gather information on macrobenthos densities and sediment characteristics. The two studied areas were found to differ in seafloor morphology and correspondingly in the composition of the sediment composition and benthos distribution. Backscatter strength was used to classify the seafloor via the Bayesian method and via hierarchical clustering of angular variation. Relationships between the classification results for three frequencies and sediment and ecological variables were studied through redundancy analysis (RDA), for which hierarchical clustering of the angular variation in backscatter strength showed a higher model fit than Bayesian classification. We found that the density of the sand mason worm *Lanice conchilega* and percentages of dead shells, gravel and sand contributed most to the backscatter-based classification, with lower contributions of the percentages of mud and living bivalves. Our results suggest that acoustic backscatter can be used to delineate distinct seafloor regions, corresponding with concurrent gradients in ecological and sedimentological variables.**

Keywords—multi-beam, multi-spectral, backscatter, benthos, sediment characteristics

I. Introduction

When performing economic activities that affect the structural integrity of the seafloor, it is of great importance to fully understand the ecological context in and around the impacted areas. Habitat mapping should incorporate the physical nature of the sediment, but also biological variables in order to accurately describe the seafloor [1], [2]. Benthic habitats are determined by their physical environment, such as the type of sediment or the current speed, and by the presence of so-called "ecosystem engineers", that either create habitat by their presence (e.g. reefs of oysters or tube worms) or activity (e.g. burrowing animals) [3]. Soft-sediment seafloors, such as those encountered in the southern North Sea, consist of a multitude of different environments and therefore habitats. Currents create a topography of sandbanks and sand waves, which are characterized by gradients in environmental conditions [4]. Sandbank troughs are more sheltered from strong hydrodynamic activity than crests, offering more optimal conditions for a higher diversity of species [5], [6]. Likewise, a higher habitat heterogeneity, and resulting higher biodiversity, ensues from hard structures present within these soft-sediment environments [7].

Various environmental regulations demand a thorough understanding of the seafloor before undertaking bottom-disturbing activities, in order to safeguard protected habitats and species (e.g. the European Union's Marine Strategy Framework Directive). However, detailed knowledge of benthic communities is often lacking, due in part to a low spatial resolution and high cost of monitoring programs and techniques that result in a consistent undersampling of the community [8], [9]. A methodology for high-resolution monitoring is therefore desirable. With the added benefits of being relatively more affordable and less time-consuming than point sampling with grabs or box corers, multi-beam echo-sounding may well be a promising solution. Acoustic backscatter can be used to distinguish between seafloors of differing composition [10], [11], which could potentially be broadened to the detection of important habitat-building species. Different species are known to affect acoustic parameters such as sediment sound speed and attenuation in distinct manners and distinctly from uninhabited sediments [12], [13], raising the possibility that acoustic sediment classification methods can distinguish between important benthic communities, such as shell beds or tube worm reefs.

We performed a study in two distinct areas in the southern North Sea, collecting acoustic data that were used to classify the seafloor by means of two different classification techniques.

Through ground-truthing, ecological data were collected to provide additional, detailed information on the biological and physical nature of the seafloor. By combining both types of data, we aimed at establishing a backscatter classification that explains the distribution of distinct sediment types and communities of important habitat-building species.

II. Methods

A. Multi-beam data collection

Bathymetry and backscatter data were collected in July and August 2021 in two areas in the southern North Sea, north of the islands of Ameland and Schiermonnikoog, respectively (Fig. 1). Both areas are located in a region with large sand waves, the latter being within a region with more hard substrate known as the Borkum Reef Ground. An R2Sonic 2026 (R2Sonic, Austin, Texas) multi-spectral multi-beam echo sounder (MBES) was used on board *RV Zirfaea* of Rijkswaterstaat (Dutch Ministry for Infrastructure and Water Management), with frequencies of 90, 200, 300 and 450 kHz and beam opening angles of 2.3°, 1.1°, 0.7° and 0.5°, respectively, covering a total swath of 130°. In both areas, 20 tracks with a 20% overlap between adjacent tracks, and 9 cross-tracks were sailed. MBES data were processed in Qimera (QPS, Zeist, the Netherlands) for bathymetric cleaning. Backscatter strength (dB per m^2 at 1 m) was obtained for every frequency through processing raw backscatter data in MATLAB R2020b.

B. Bottom sampling

In each of the two areas, 13 bottom samples were taken with a 0.078 m^2 boxcore. At each sampling station, one replicate was taken for sediment analysis and two for macrofauna. For the sediment analysis, dry weight fractions were sieved over 62, 125, 250, 500, 1000, 2000 and 4000 µm and used to calculate median grain size and weight percentages of mud, gravel and sand. In addition, volume percentages of living bivalves, dead shells and stones (> 4 mm) were measured. The macrofauna was sieved on board over a 1 mm mesh size and stored in a 4% formaldehyde solution until analysis in the lab. Mollusks, tube-building worms and echinoderms were identified down to species level, all other animals to order or class level.

C. Distinction between seafloor sediment types

Two methods were used to classify seafloor types based on backscatter strength, both extensively described in [14]. We omitted the 200 kHz data for both methods, as the results did not differ substantially from the 300 kHz data. Firstly, we used the Bayesian method established and described by [15]. For a given frequency and incident angle, this method considers the beam-averaged backscatter strength a random variable dependent on seafloor properties, following a Gaussian distribution according to the central limit theorem. As each different seafloor type will produce a separate distribution, the histogram of the backscatter strength can be modelled as a sum of Gaussians. A χ^2 goodness-of-fit criterion can be applied to determine the optimal number of seafloor types.

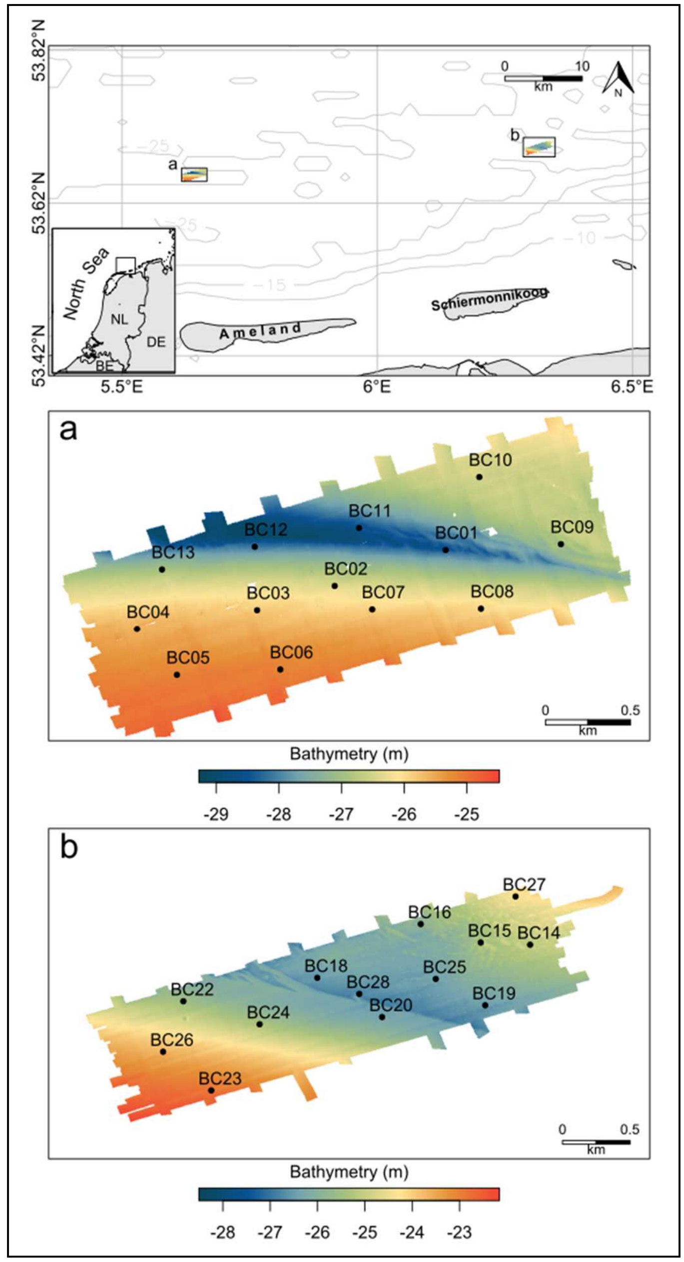

Fig. 1. Location and bathymetric maps of the two surveyed areas. Boxcore sampling locations are indicated with points.

In a second method, a discrete set of seafloor types was identified based on the angular variation of backscatter strength. Within three angular ranges for half a swath on port or starboard side (near-range, 0° - 25°; far-range, 25° - 55°; and outer-range, 55° - 65°), the mean backscatter strength was calculated and averaged over 10 pings to reduce noise. In order to reduce the dimensionality of the data, a Principal Component Analysis (PCA) was then performed on the covariance matrix of the mean backscatter in the three angular ranges. Covering more than 90% of the total variation in the data, the first PC was then used for hierarchical clustering with Euclidean distance similarity metric and complete linkage algorithm. The optimal number of clusters

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was chosen to align as well as possible with the results of the Bayesian method.

D. Linking backscatter to bottom sampling data

In order to identify potential relationships between the variables measured from the bottom samples and the acoustic seafloor sediment classification, we performed redundancy analyses (RDA). For every sampling station, biotic and abiotic ecological variables were regressed on either the Bayesian or hierarchical clustering classes at the three frequencies (90 kHz, 300 kHz and 450 kHz). From the total set of ecological variables used (median grain size, weight percentages of gravel, sand and mud, volume percentages of stones, living bivalves and dead shells, densities of mollusks, echinoderms and the tube-building sand mason worm *Lanice conchilega*), four were withdrawn (median grain size, percentage of stones, densities of mollusks and echinoderms) after accounting for collinearity by means of a variable inflation factor (VIF), with a cut-off level of 5. Significance of the model and its axes was tested through permutation tests. The RDA and associated analyses was performed by means of the package *vegan* [16] in the open-source statistical software R [17].

III. Results

A. Bathymetric characterization and backscatter seafloor classification

The seafloor of the two surveyed areas was located within a similar depth range, from 22.1 to 29.5 m. The first area, north of the island of Ameland, was characterized by a relatively smooth seafloor with a large central trough, running southeast to northwest and widening along its course. The seafloor in the second area, north of Schiermonnikoog, started similarly smooth in the west but with halfway a sudden bathymetric drop of roughly 0.5 m. East of that drop, the seafloor topography became markedly more heterogeneous, with patchy elevation differences (Fig. 1).

As described in [14], backscatter classification into seafloor sediment types by means of the Bayesian method produced 6, 4, and 4 classes, while hierarchical clustering of angular range data produced 7, 5, and 6 classes, respectively for 90 kHz, 300 kHz and 450 kHz. The classes broadly followed bathymetric patterns, with higher classes (and therefore higher backscatter strengths) mostly in deeper parts of both areas. The most notable backscatter feature without clear relation to the bathymetry was a band of increased backscatter south of the trough in the area north of Ameland. Classification patterns were similar between the different frequencies, although with clear differences (Fig. 2, 3). Likewise, between the two different classification methods differences existed but broad patterns were similar. In the area north of Ameland, rough weather conditions during the survey may have introduced artefacts that are especially noticeable on the 90 kHz maps.

B. Seafloor ecology in bottom samples

The two surveyed areas differed not only in their seafloor topography, but also in the abiotic and biotic composition of the bottom samples. Median grain size varied from 0.15 to 0.78 mm

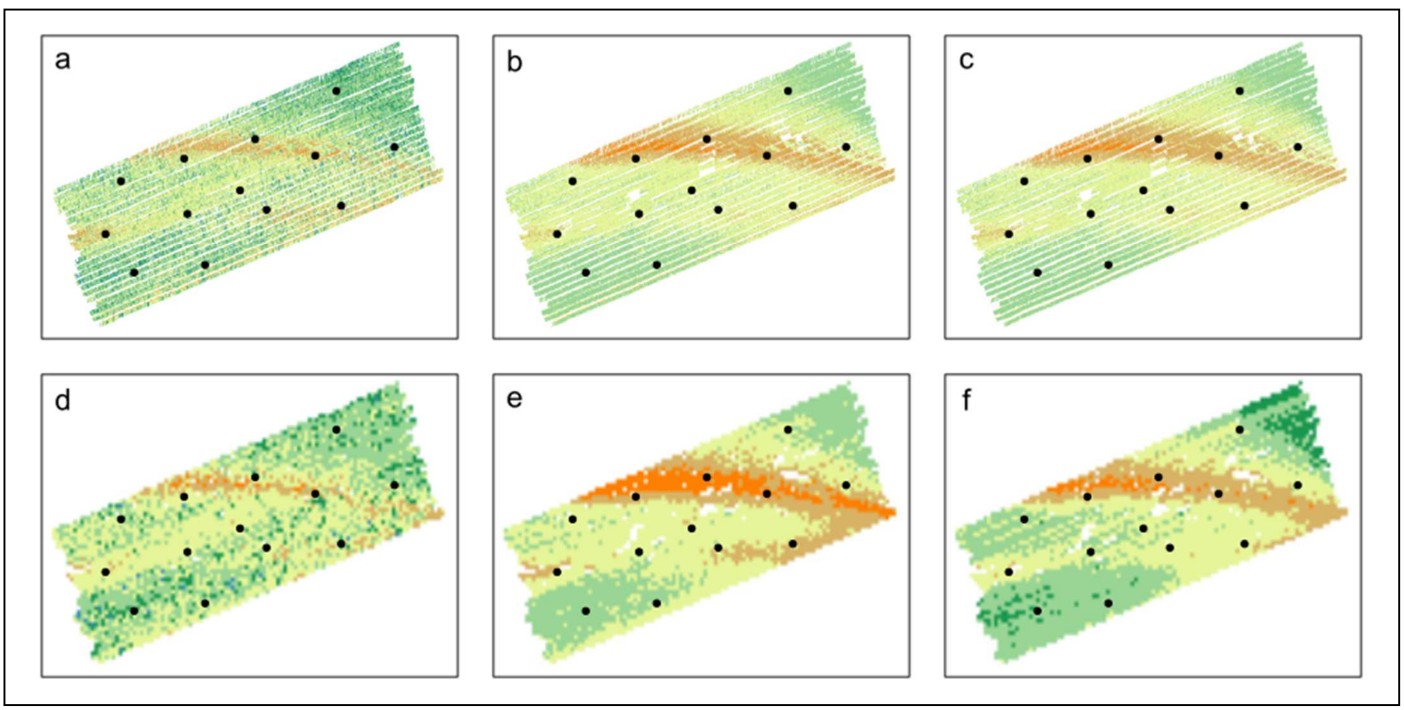

Fig. 2. Backscatter-based classification maps of the Ameland area, using the Bayesian method (a-c) and hierarchical clustering of the angular variation of backscatter strength (d-f), for 90 kHz (a, d), 300 kHz (b, e) and 450 kHz (c, f).

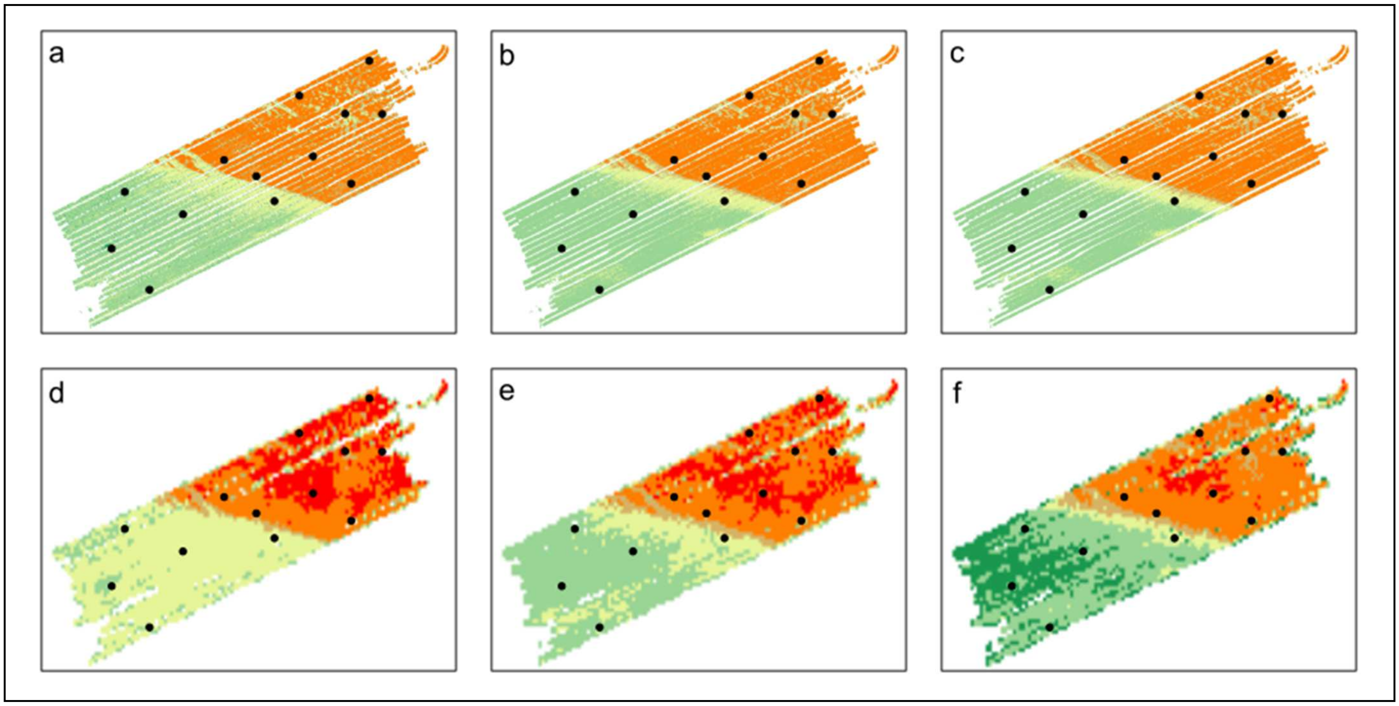

Fig. 3. Backscatter-based classification maps of the Schiermonnikoog area, using the Bayesian method (a-c) and hierarchical clustering of the angular variation of backscatter strength (d-f), for 90 kHz (a, d), 300 kHz (b, e) and 450 kHz (c, f).

over the two areas but was never higher than 0.30 mm in the area north of Ameland. Grain sizes in the area north of Schiermonnikoog were similar west of the bathymetric drop, but higher and more variable in the east. All sampling stations were characterized by sandy sediment, with sand percentages over 90 % in all but three stations. Mud percentages were low, under or slightly above 2 % in most stations, rising to 4.02 % and 6.82 % in two eastern stations of the Schiermonnikoog area. Gravel percentages were similarly low, below 2 %, only rising to 3.77 % in the trough of the Ameland area and up to 17.99 % east of the bathymetric drop in the Schiermonnikoog area. Stones were absent from most stations in the Ameland area and their volume percentages only rose above 1 % in the eastern stations of the Schiermonnikoog area, with a maximum of 4.57 %. Species densities tended to be higher in the eastern half of the Schiermonnikoog area, with mollusk densities reaching values of up to 337.91 ind m^{-2} and echinoderms up to 205.13 ind m^{-2}. Densities of the sand mason worm *L. conchilega* showed similar patterns, with values up to 1469.23 ind m^{-2}, but had additional high densities, up to 948.72 ind m^{-2} in the trough of the Ameland area. Volume percentages of living bivalves were high, up to 0.27 %, in the eastern half of the Schiermonnikoog area, but reached similar or even higher values (up to 0.56 %) in some stations south of the trough in the Ameland area. Dead shells were again present in highest percentages in the east of the Schiermonnikoog area, with values up to 2.29 %.

C. *Relationship between backscatter and ecological data*

The RDA clearly separated stations based on their acoustic classification (Fig. 4). The ecological data could explain classification based on hierarchical clustering of the angular variation in backscatter strength better than Bayesian classification, based on their adjusted R^2-values of 0.67 and 0.54, respectively. The RDA model result for classification based on hierarchical clustering was significant ($p < 0.001$), but only the first axis was significant as well ($p < 0.001$). Spread along the first ordination axis, following a gradient from low to high backscatter classes over three frequencies, was mostly determined by percentages of sand and gravel, dead shells and the densities of *L. conchilega*, with minor contributions of the percentage of mud and living bivalves (Fig. 4).

IV. Discussion and Conclusion

In searching a classification method that could explain both the distribution of physical seafloor characteristics and of ecological variables, our measured ecological variables could least explain the Bayesian classification. Although the method has been shown to distinguish well between different sediment types [15], it does not account for angular variation of the backscatter strength. This angular variation may, however, contain further information on the characteristics of the seafloor [18], which likely contributed to it being favored over the Bayesian classification method. One drawback of our method of hierarchical clustering of angular variation of backscatter strength is its significantly lower resolution (a factor 50 to 100), resulting from the feature extraction of half swaths only.

The distribution of the ecological variables aligns with expectations for the studied areas. With its relatively smooth seafloor in the west and heterogeneous east, the Schiermonnikoog area was probably located on the transition between the sand wave region also represented in the Ameland area, and the Borkum Reef Ground. This latter region, characterized by rocky reefs dispersed on a sandy bottom, is indeed known to harbor dense *L. conchilega* beds in its sandy areas [7]. Likewise, *L. conchilega* is known to favor sandbank troughs over crests, therefore concentrating in the trough of the Ameland area [19]. Dead shells and live bivalves seem to follow

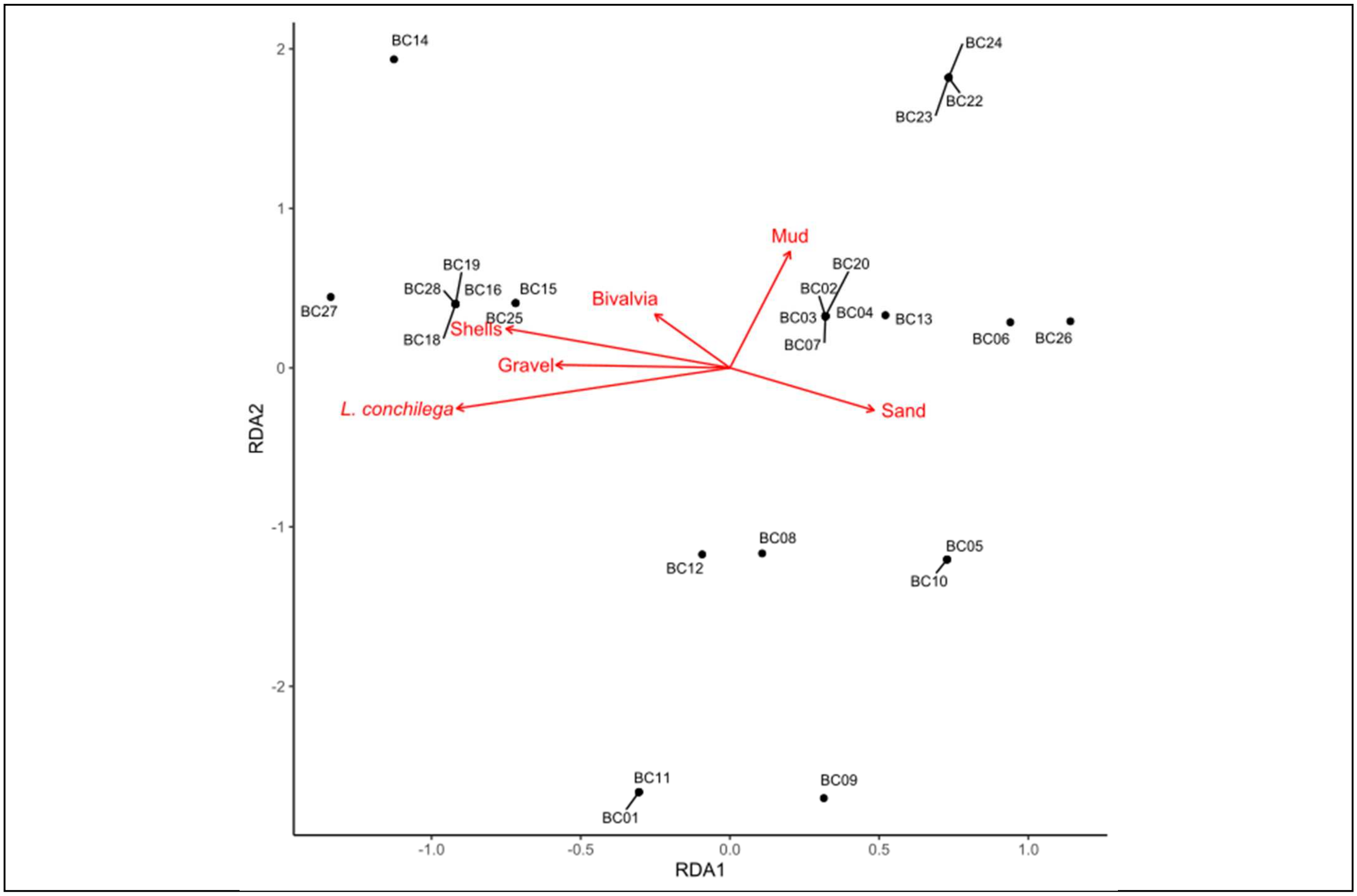

Fig. 4. RDA biplot of the multi-spectral backscatter classifications of the boxcore locations, constrained by the selected ecological variables (indicated as arrows).

similar, but slightly different distribution patterns, likely caused by post-mortem transport of shells [20], [21]. Unlike dead shells, living bivalves seemed to reach high concentrations in an area south of the trough, vaguely corresponding with a broad band of higher backscatter strength. However, the low correlation of the volume percentage of bivalves with the backscatter strength classification, as indicated by the RDA, suggests that other variables may be at play, but which ones remains unclear. The stronger correlations with dead shells, gravel, *L. conchilega* and sand are probably largely driven by the sharp distinction between the eastern and western half of the Schiermonnikoog area. The classification map in that area could be interpreted as a gradient of increasing backscatter strength from west to east, where lower classes in the west correspond to a sandy seafloor with low densities of benthos and low percentages or absence of shells and gravel. The higher classes in the east point at a high sediment heterogeneity (indicated by a patchier coloration on the map), with gravel, shells and high-density patches of *L. conchilega*. As these variables are present both at the surface and buried in the sediment, they are likely to affect volume scattering within the sediment matrix [22]. Interspersed within this region are muddier patches, corresponding to lower backscatter strengths and therefore a lower class number.

By using multiple frequencies, we were able to construct three different classification maps for each of the two studied areas. As the signal at each frequency may have a distinct penetration depth into the sediment, furthermore depending on the seafloor morphology and sediment composition [23], [24], the corresponding backscatter strength classification maps show different information about the composition of surface and shallow subsurface sediments for each frequency. Combining these data in multivariate analysis, such as the redundancy analysis we performed, allowed us to study and interpret the relationships between seafloor composition and ecology on the one hand and its acoustic response on the other, into further detail than would be possible with only one frequency. However, increasing the density of bottom samples would still improve the interpretation of our data, especially when it comes to interpolation of ecological parameters into the areas between samples. Even though we were able to find some probabilistic links between backscatter classification and the ecological and sedimentological composition of the seafloor, more research is needed to find reliable relationships.

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