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Identifying areas prone to coastal hypoxia - the role of topography

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Abstract. Hypoxia is an increasing problem in marine ecosystems around the world, and recent projections indicate that anoxic “dead zones” will be spreading in the forthcoming decades. While major advances have been made in our understanding of the drivers of hypoxia, it fundamentally hinges on patterns of water circulation that can be difficult to resolve in coastal regions. The complexity of many coastal areas and lack of detailed *in situ* data has hindered the development of models describing oxygen dynamics at a sufficient resolution for efficient management actions to take place. We hypothesized that the enclosed nature of seafloors facilitates hypoxia formation. We developed simple proxies of seafloor heterogeneity and modelled oxygen deficiency in complex coastal areas in the northern Baltic Sea. We discovered that topographically sheltered seafloors and sinkholes with stagnant water are prone to the development of hypoxia. Approximately half of the monitoring sites in Stockholm Archipelago and one third of sites in southern Finland experienced severe hypoxia (O_2<2 mg L^{-1}). Based only on topography, area potentially affected by hypoxia is smaller than anticipated. Developed models could boost the performance of numerical models, aid nutrient abatement measures, and pinpoint areas where management actions are most urgently needed.

1 Introduction

Hypoxia is a key stressor of marine environments, occurring in over 400 physically diverse marine ecosystems worldwide (Diaz and Rosenberg, 1995b;Conley et al., 2009b;Diaz and Rosenberg, 2008). Declining oxygen levels have been recorded in fjords, estuaries and in coastal and open-sea areas, such as Chesapeake Bay, Gulf of Mexico, Japan Sea, Baltic Sea and the Black Sea (Gilbert et al., 2010;Carstensen et al., 2014). It is clear that our oceans are losing their breath, and recent projections indicate that hypoxia and anoxic "dead zones" will be increasing in the forthcoming decades (Meier et al., 2011a;Frölicher et al., 2009;Meier et al., 2012a), with severe consequences for marine ecosystems (Breitburg et al. 2018).

The lack of oxygen alters the structure and functioning of benthic communities (Nilsson and Rosenberg, 2000;Gray et al., 2002;Karlson et al., 2002;Valanko et al., 2015), disrupts bioturbation activities (Timmermann et al., 2012;Villnas et al., 2013;Villnas et al., 2012;Norkko et al., 2015), changes predator-prey relationships (Eriksson et al., 2005) and may lead to mass mortalities of benthic animals (Vaquer-Sunyer and Duarte, 2008). Hypoxia does not only affect organisms of the seafloor, but also influences biogeochemical cycling and benthic-pelagic coupling (Gammal et al., 2017). Hypoxia can increase releases of nutrients from the sediment and thus promote planktonic primary production and sedimentation, which in turn leads to enhanced microbial consumption of oxygen (Conley et al., 2002;Middelburg and Levin, 2009;Kemp et al., 2009). This creates a self-sustaining process, often referred to as "vicious circle of eutrophication" (Vahtera et al., 2007), which may hamper the effects of nutrient abatement measures.

Biogeochemical processes contributing to hypoxia formation are well known. Factors affecting the development of hypoxia are usually associated with the production of organic matter, level of microbial activity and physical conditions creating stratification and limited exchange or mixing of water masses (Conley et al., 2009a;Rabalais et al., 2010;Conley et al., 2011;Fennel and Testa, 2019). Coastal hypoxia is common in areas with moderate or high anthropogenic nutrient loading, high primary productivity and complex seabed topography limiting lateral movement of the water. Shallow-water hypoxia is often seasonal. It is associated with warming water temperatures and enhanced microbial processes and oxygen demand (Buzzelli et al., 2002;Conley et al., 2011;Caballero-Alfonso et al., 2015;van Helmond et al., 2017).

Projecting patterns and spatial and temporal variability of hypoxia is necessary for developing effective management actions. Thus three-dimensional coupled hydrodynamic-biogeochemical models have been created for several sea areas around the world, such as Gulf of Mexico (Fennel et al., 2011;Fennel et al., 2016), Chesapeake Bay (Scully, 2013, 2016;Testa et al., 2014), the North Sea (Hordoir, 2018) and the Baltic Sea (Meier et al., 2011a;Meier et al., 2012a;Eilola et al., 2011;Eilola et al., 2009;Meier et al., 2012b). These models simulate various oceanographic, biogeochemical and biological processes using atmospheric and climatic forcing and information on nutrient loading from rivers. While such models are useful for studying processes at the scale of kilometers, and aid in defining hypoxia abatement at the basin-scale, their horizontal resolution is too coarse (often 1-2 nautical miles) for accurately describing processes in coastal areas. Lack of detailed data on water depth, currents, nutrient loads, stratification and local distribution of freshwater discharges (Breitburg et al., 2018) (not to mention computational limitations) usually prevent the application of biogeochemical models developed to large geographical areas at finer horizontal resolutions (<100 m).

Understanding spatial variability of hypoxia in topographically complex coastal environments has therefore been impeded by the lack of useful methods and systematic, good-quality data (Diaz and Rosenberg, 2008;Rabalais et al., 2010;Stramma et al., 2012). Finding alternative ways to pinpoint areas prone to coastal hypoxia could facilitate management and determining of efficient local eutrophication abatement measures. Several studies have suggested that the semi-enclosed nature of the seafloors, and associated limited water exchange, is a significant factor in the formation of hypoxia in coastal waters (Rabalais et al., 2010;Conley et al., 2011;Diaz and Rosenberg, 1995a;Virtasalo et al., 2005), but to our knowledge this hypothesis has not been tested or quantified.

Here, we estimate how topography, i.e. seascape structure, contributes to the formation of hypoxia. Analytical and theoretical frameworks developed specifically for terrestrial environments, such as landscape heterogeneity or patchiness, are analogous in marine environments, and are equally useful for evaluating links between ecological functions and spatial patterns in marine context. We hypothesized that structural complexity of seascapes facilitates the formation of hypoxia. We adopted techniques and metrics from landscape ecology and transferred them to marine environment, and (1) examined if spatial patterns in seascapes can explain the distribution of hypoxia, (2) defined the relative contribution of seascape structure to hypoxia formation and (3) estimated the potential ranges of hypoxic seafloors in coastal areas. To achieve this, we concentrated on extremely heterogeneous and complex archipelago areas in the northern Baltic Sea, where coastal hypoxia is a common and an increasing problem (Conley et al., 2011;Caballero-Alfonso et al., 2015).

2 Data and methods

2.1 Study area

The studied area covers the central northern Baltic coastal rim, 23 500 km^2 of Finnish territorial waters from the Bothnian Bay to the eastern Gulf of Finland, and 5100 km^2 of Swedish territorial waters in the Stockholm Archipelago in the Baltic Proper. Oxygen dynamics in the deeper areas of the Gulf of Finland and Stockholm Archipelago are strongly affected by oceanography and biogeochemistry of the central Baltic Proper, not reflecting the dynamics of coastal hypoxia (Laine et al., 1997), and were therefore excluded from this study. The outer archipelago of Finland is relatively exposed with various sediment and bottom habitat types, while the inner archipelago is more complex and shallower, but maintains a higher diversity of benthic habitats and sediment types (Valanko et al., 2015). The inner archipelago of Stockholm is an equally complex archipelago area, with a large number of islands, straits and coves. Freshwater outflow from Lake Mälaren creates an estuarine environment where freshwater meets the more saline water in the Baltic Proper.

In order to evaluate differences in oxygen deficiency between coastal areas, the study area was divided into five regions as defined by the EU Water Framework Directive (2000/60/EC) (WFD, 2000): the Archipelago Sea (AS), the Eastern Gulf of Finland (EGoF), the Gulf of Bothnia (GoB), Stockholm Archipelago (SA) and the western Gulf of Finland (WGoF) (Figure

1). Small skerries and sheltered bays characterize AS, EGoF and WGoF, whereas narrower band of archipelago forms relatively exposed shores in GoB. Deep, elongated channels of bedrock fractures can reach depths of over 100 m in AS, similarly to SA where narrow, deep valleys separate mosaics of islands and reefs. Substrate in both areas varies from soft unconsolidated sediments in sheltered locations to rocky substrates in exposed areas. At greater depths, soft sediments are common due to limited water movement. As a whole, the study area with rich topographic heterogeneity forms one of the most diverse seabed areas in the world (Kaskela et al., 2012). In many areas hypoxia is a result of strong water stratification, slow water exchange and complex seabed topography, creating pockets of stagnant water (Conley et al., 2011;Valanko et al., 2015;Jokinen et al., 2018). Thus, the area is ideal for testing hypotheses of topographical controls for hypoxia formation.

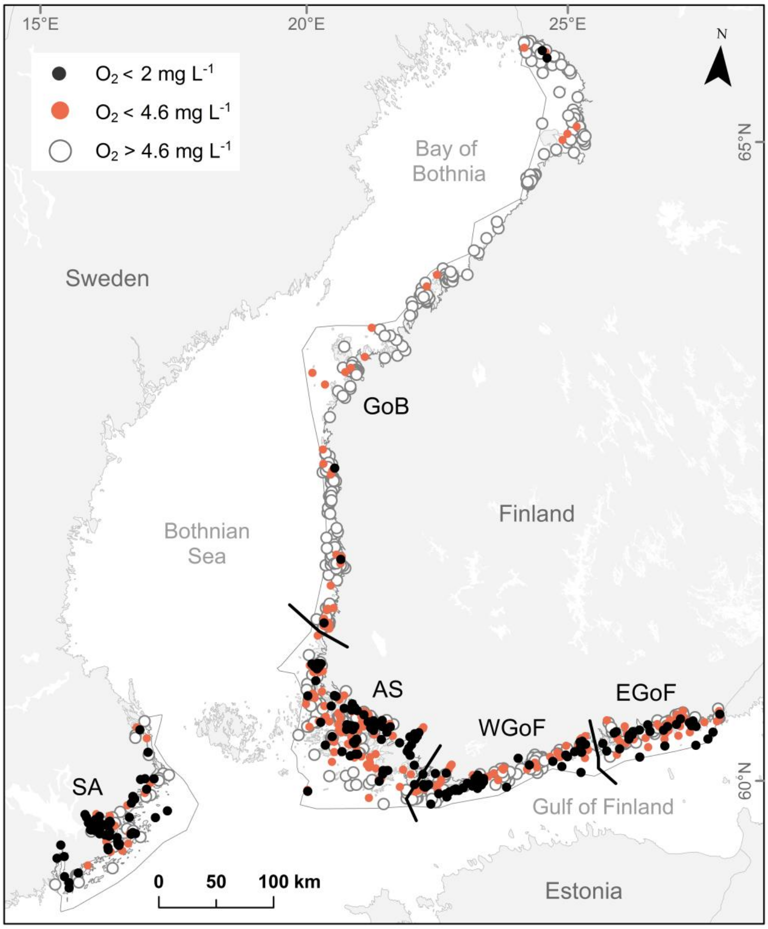

Figure 1. Study areas in Finland: AS – Archipelago Sea, WGoF – Western Gulf of Finland, EGoF – Eastern Gulf of Finland, GoB – Gulf of Bothnia, and Sweden: SA – Stockholm Archipelago. Orange dots represent sites of moderately hypoxic (O_2<4.6 mg L^{-1}) black dots severely hypoxic (O_2<2 mg L^{-1}) and white circles denote sites with O_2>4.6 mg L^{-1}. Grey and black lines illustrate boundaries of Water Framework Directive areas.

2.2 Hypoxia data

Bottom-water hypoxia is the main factor structuring benthic communities in the Baltic Sea (Norkko et al., 2015;Villnas et al., 2012). Two mg L $^{-1}$ of O_2 is usually considered a threshold where coastal organisms start to show symptoms of the lack of oxygen, and this limit has been commonly used in various global reviews (Diaz and Rosenberg, 1995b, 2008). Some studies have however concluded that 2 mg L $^{-1}$ is below the empirical sublethal and lethal oxygen limit for many species (Vaquer-Sunyer and Duarte, 2008;Conley et al., 2009b). Here we define hypoxia based on two ecologically meaningful limits: moderately hypoxic <4.6 mg L $^{-1}$ O_2 – as this has been estimated to be a minimum safe limit for species survival, behavior and functioning in benthic communities (Norkko et al., 2015) – and severely hypoxic <2 mg L^{-1} O_2, which describes dead zones for marine organisms (Vaquer-Sunyer and Duarte, 2008). As no reference values exist for severity of hypoxia to marine organisms based on the frequency of hypoxic events (Villnas et al., 2012;Norkko et al., 2015;Norkko et al., 2012), we here define a site to be prone to hypoxic events, i.e. occasionally hypoxic, if it experienced hypoxia (<2 mg L^{-1} and <4.6 mg L^{-1}) at least once during the study period. If hypoxia was recorded ≥20 % of the visits, it was categorized as frequently hypoxic. We consider this to be ecologically relevant, as species develop symptoms already from short exposures to hypoxia (Villnas et al., 2012;Norkko et al., 2015). This is also justified, as our oxygen data is from ~1 m above the seafloor, suggesting that the actual oxygen concentrations at sediment where benthic species live are probably lower.

Data from hypoxia profiles were collated from the national monitoring environmental data portals Hertta (http://www.syke.fi/en-US/Open_information) and SHARK (https://www.smhi.se/klimatdata/oceanografi/havsmiljodata/marinamiljoovervakningsdata). Data was available from 808 monitoring sites. Only months of August and September 2000–2016 were considered, as hypoxia is usually a seasonal phenomenon occurring in late summer when water temperatures are warmest (Conley et al., 2011).

2.3 Predictors

For modelling hypoxia occurrences, we developed five geomorphological metrics: (1) Bathymetric Position Indices (BPI) with varying search radii, (2) Depth-Attenuated Wave Exposure (SWM(d)), (3) Topographical Shelter Index (TSI), (4) Arc-Chord Rugosity (ACR) and (5) Vector Ruggedness Measure (VRM). BPI is a marine modification of the terrestrial version Topographic Position Index (TPI), originally developed for terrestrial watersheds (Weiss, 2001). BPI is a measure of a bathymetric surface to be higher (positive values) or lower (negative values) than the overall seascape. BPI values close to zero are either flat areas or areas with constant slope. Here, BPIs represent topographical depressions, sinkholes and crests at scales of 0.1, 0.3, 0.5, 0.8, and 2 km calculated with Benthic Terrain Modeler (v3.0)(Walbridge et al., 2018). SWM(d) estimates dominant wave frequency at a given location with the decay of wave exposure with depth, and takes into account diffraction and refraction of waves around islands (Bekkby et al., 2008). SWM(d) characterizes areas where water movement is slower, i.e. where water resides longer. In terrestrial realms, landform influence on windthrow patterns, i.e. exposure to winds, have been noted in several studies, e.g. (Kramer, 2001) and (Ashcroft et al., 2008). Here, we introduce an analogous version of "windthrown-prone" areas to the marine realm, i.e. a "wave-prone" metric: Topographical Shelter Index (TSI), which differentiates wave directions and takes into account the sheltering effects of islands (i.e. exposure above sea-level). Identification of "wave-prone" areas was calculated for the azimuths multiple of 15 (0°–345°), and for altitudes (corresponding to the angle of light source) ranging from 0.125° to 81°. For each altitude the produced "wave-prone areas" were combined to an index value for each grid cell. Surface roughness is a commonly used measure of topographical complexity in terrestrial studies, and has been used in marine realms as well (see e.g. (Dunn and Halpin, 2009) for modelling habitats of hard substrates and (Walker et al., 2009) for complexity of coral reef habitats). Here, we consider two approaches for estimating seascape rugosity; Arc-Chord Rugosity (ACR) and Vector Ruggedness Measure (VRM). ACR is a landscape metrics, which evaluates surface ruggedness using a ratio of contoured area (surface area) to the area of a plane of best fit, which is a function of the boundary data (Du Preez, 2015). VRM on the other hand, is a more conservative measure of surface roughness developed for wildlife habitat models, and is calculated using a moving 3×3 window where a unit vector orthogonal to the cell is decomposed using the three dimensional location of the cell center, the local slope and aspect. A resultant vector is divided by the number of cells in the moving window (SAPPINGTON et al., 2007). Both rugosity indices were used here to identify areas with complex marine geomorphology. Differences of predictor variables are illustrated in Fig. 2. We also included geographical study areas as predictors, in order to highlight the differences between WFD areas.

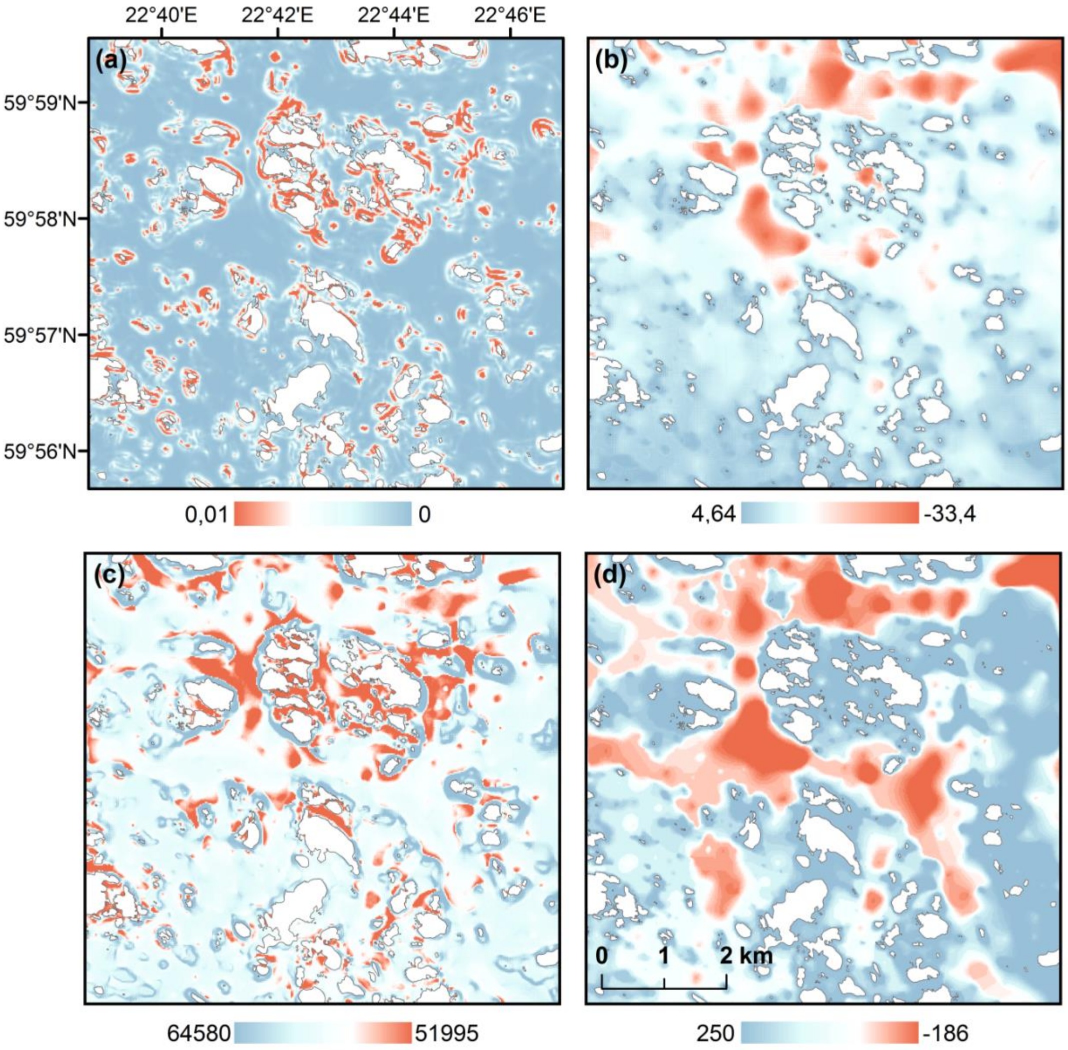

Figure 2. Predictor variables developed for hypoxia ensemble models: a) Vector Ruggedness Measure (VRM), b) Depth-Attenuated Wave Exposure (SWM(d)), c) Topographical Shelter Index (TSI) and Bathymetric Position Index (BPI) with a search radius of 2 km. Red color represents rugged seafloors (VRM), sheltered areas (SWM(d), TSI) and depressions (BPI2). Islands shown as white.

2.4 Hypoxia models

Based on the ecologically meaningful limits of hypoxia (see section "Hypoxia data"), we built four separate oxygen models based on frequency and severity of hypoxia: occasional with O_2 limits <4.6 and <2 mg L^{-1} (hereafter referred as $OH_{4.6}$ and OH_2) and frequent hypoxia with O_2 limits <4.6 and <2 mg L^{-1} (hereafter referred as $FH_{4.6}$ and FH_2). We used Generalize Boosted Regression Models (GBM) and its extension Boosted Regression Trees (BRT), a method from statistical and machine learning traditions (De'ath and Fabricius, 2000;Hastie et al., 2001;Schapire, 2003). BRT optimizes predictive performance through integrated stochastic gradient boosting (Natekin and Knoll, 2013), and forms the best model for prediction based on several models.

Ideal model tuning parameters (learning rate, bag fraction, tree complexity) for our hypoxia models were based on optimizing the model performance, i.e. minimizing the prediction error. The learning rate was set to 0.001 to determine the contribution of each successive tree to the final model. We varied the number of decision rules controlling model interaction levels, i.e. tree complexities, between 3 and 6. We shuffled the hypoxia data randomly into ten subsets for training (70 %) and testing (30 %), while preserving the prevalence ratio of hypoxia occurrence. Hypoxia models were developed based on 10-fold cross-validation, and resulting final, best models leading to smallest predictive errors were chosen to predict the probability of detecting hypoxia across the study region at a resolution of 20 m. We believe such a high resolution is necessary due to the complexity of archipelagoes of Finland and Sweden. Model predictions for the whole seascape were repeated ten times with different models, to identify areas where models agree on the area to be potentially hypoxic. Model performances were estimated against the independent data (test data 30 %), not used in model fitting in order to evaluate the potential overfitting of the models. Analyses were performed in R 3.5.0. (R, 2018) with R libraries ‘gbm’ (Greenwell et al., 2018), ‘PresenceAbsence’ (Freeman and Moisen, 2008) and relevant functions from (Elith et al., 2008).

Variable selection in BRT is internal by including only relevant predictors when building models. The importance of predictors is based on the time each predictor is chosen in each split, averaged over all trees. Higher scores (summed up to 100 %) indicate that a predictor has a strong influence on the response (Elith et al., 2008). Although BRT is not sensitive to collinearity of predictors, the ability to identify strongest predictors by decreasing the estimated importance score of highly correlated ones detriments the interpretability of models (Gregorutti et al., 2017). Selecting only optimal and a minimal set of variables for modelling, i.e. finding all relevant predictors and keeping the number of predictors as small as possible, reduces the risk of overfitting and improves the model accuracy. Here, most of the predictors describe seascape structure and are somehow related to the topography of the seabed. We estimated the potential to drop redundant predictors, i.e. those that would lead to marked improvement in model performance if left out from the model building. For this, we used internal backward feature selection in BRT. However, we did not find marked differences in predictive performances, and used all predictors.

Estimation of model fits and predictive performances was based on the ability to discriminate a hypoxic site from a normoxic one, evaluated with Area Under the Curve (AUC) (Jiménez-Valverde and Lobo, 2007) and simply with Percent Correctly Classified (PCC) (Freeman and Moisen, 2008). AUC is a measure of detection accuracy of true positives (sensitivity) and true negatives (specificity), and AUC values above 0.9 indicate excellent, 0.7–0.9 good, and below 0.7 poor predictions.

We transformed hypoxia probability predictions into binary classes of presence/absence, and estimated the relative area of potentially hypoxic due to topographical reasons. Although dichotomization of probability predictions flattens the information content, it facilitates the interpretation of results, and is needed for management purposes. Predicted range of hypoxia and the potential geographical extent enables the identification of problematic areas and facilitates management actions in a cost-effective way. There are various approaches for determining thresholds, which are based on the confusion matrix, i.e. how well the model captures true/false presences or true/false absences. Usually the threshold is defined to maximize the agreement between observed and predicted distributions. Widely used thresholds, such as 0.5, can be arbitrary unless the threshold equals prevalence of presences in the data, i.e. the frequency of occurrences (how many presences of the total dataset) (Liu et al., 2005). Here, we define thresholds objectively based on an agreement between predicted and observed hypoxia prevalence. This approach underestimates areas potentially hypoxic (see section "Hypoxia areas") and is expressed here as a conservative estimate.

3 RESULTS

3.1 Hypoxia in complex coastal archipelagos

During 2000–2016 hypoxia was rather common throughout the whole study region. In Finland, hypoxia mostly occurred on the southern coast, as in AS, EGoF and WGoF where hypoxic events were recorded frequently. Only ~30 % of coastal monitoring sites in AS, EGoF and SA were normoxic, i.e., oxygen concentrations were always above 4.6 mg L $^{-1}$ (cf. percentages in brackets in Fig. 3). Coastal areas in SA were also regularly hypoxic, with 70 % of the sites moderately ($O_2 <$ 4.6 mg L $^{-1}$) and 53 % severely ($O_2 <$ 2 mg L $^{-1}$) hypoxic. Severe hypoxia was quite a localized phenomenon in Finland, as it was recorded at ca. 30 % of sites in AS and EGoF. However, in WGoF there are sites where severe hypoxia is rather persistent, as every sampling event was recorded as hypoxic. Same applies to SA, as there are quite a few sites repeatedly severely hypoxic. Contrary to the northern study area, GoB, hypoxic events occurred rather infrequently, as in 98 % of sites O_2 was above 2 mg L $^{-1}$ and in 87 % O_2 was above 4.6 mg L $^{-1}$ (Fig. 3).

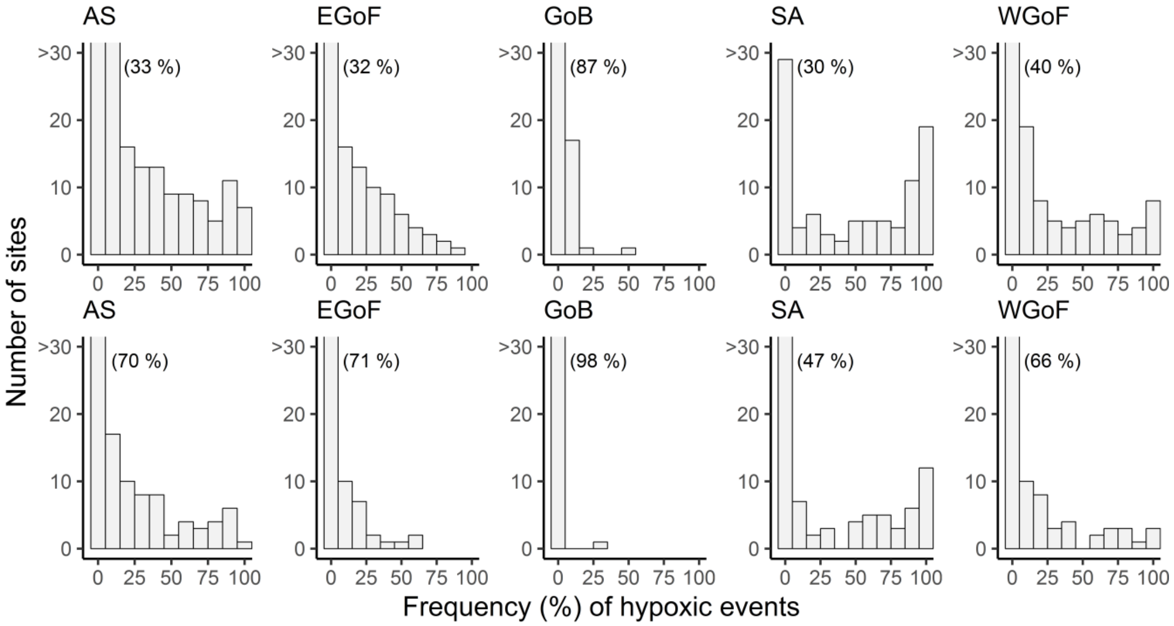

Figure 3. Frequencies of hypoxic events at coastal monitoring sites across Water Framework Directive areas (upper panels $O_2 <$ 4.6 mg L $^{-1}$, lower panels $O_2 <$ 2 mg L $^{-1}$). Numbers in brackets indicate the percentage of sites with $O_2 >$ 4.6 (upper panel) and $O_2 >$ 2 mg L $^{-1}$ (lower panel). Sites >30 are not shown.

3.2 Importance of predictors

Models developed on 566 sites, based on 10-fold cross-validation and ten repeated predictions, the most influential predictor (averaged across models) was SWM(d), with a mean contribution of 33 % (± 5 %) (Fig. 4). The contribution of SWM(d) was highest for frequent, severe hypoxia (FH_2) (41 ± 3 %), whereas for occasional, moderate hypoxia ($OH_{4.6}$) the influence was markedly lower (25 ± 5 %). This supports the hypothesis that in sheltered areas, where water movement is limited, severe oxygen deficiency is likely to develop. Noteworthy is also that depth was not the most important driver of hypoxia in coastal areas. Across models, BPIs identifying wider sinks (BPI2 and BPI0.8) were more influential than BPIs identifying smaller sinks (BPIs 0.1, 0.3 and 0.5), and terrain ruggedness measures, VRM and ACR, were more important for frequent severe hypoxia (FH_2) than for moderate hypoxia ($FH_{4.6}$). The relatively high contribution of topographical shelter (TSI 7 ± 2 %) indicates that, in areas where there are higher islands, the basins between are prone to hypoxia formation.

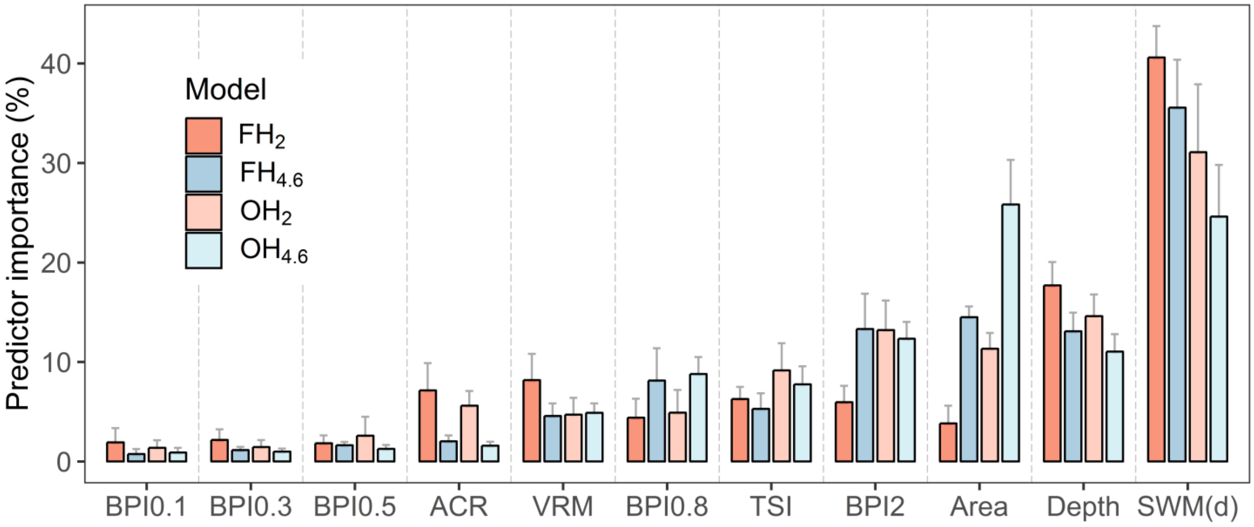

Figure 4. Importance of predictors based on ten prediction rounds. Predictors are colour-coded based on models. FH_2= frequent, severe hypoxia ($O_2 < 2$ mg L^{-1}), $FH_{4.6}$= frequent, moderate hypoxia ($O_2 < 4.6$ mg L^{-1}), OH_2= occasional, severe hypoxia ($O_2 < 2$ mg L^{-1}), and $OH_{4.6}$= occasional, moderate hypoxia ($O_2 < 4.6$ mg L^{-1}). Whiskers represent standard deviations.

3.3 Model performance

Predictive ability of models to detect sites as hypoxic across models was good, with a mean 10-fold cross-validated AUC of 0.85 (± 0.02) and mean AUC of 0.86 (± 0.03) when evaluated against independent test data for 242 sites (30 % of sites) (Fig. 5a). Models classified on average 88 % sites correctly (PCCcv in Fig. 5b), and performed only slightly worse when evaluated against independent data, with 81 % (± 3 %) correctly classified (PCCin in Fig. 5b). Models developed for frequent hypoxia (FH_2 and $FH_{4.6}$) were better (mean AUCin 0.88 ± 0.03) compared to occasional hypoxia models (mean AUCin 0.84 ± 0.04). This suggests that other factors beyond topographical proxies contribute relatively more to the occurrence of occasional hypoxia than for frequent hypoxia.

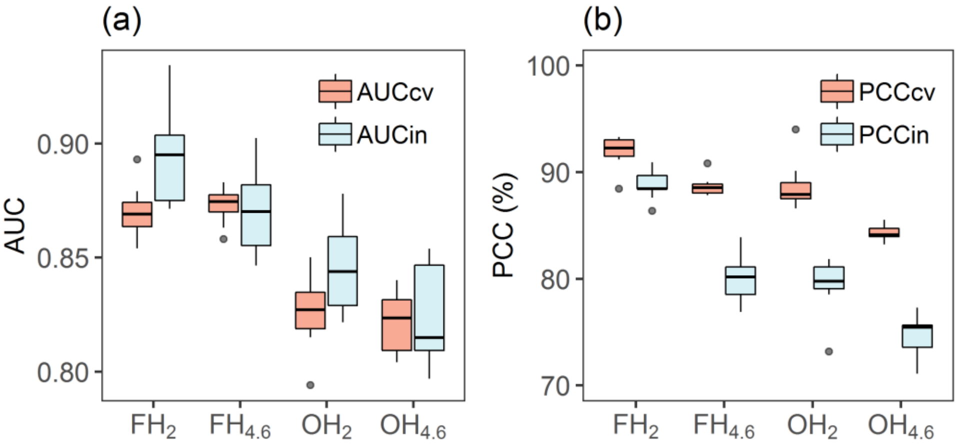

Figure 5. Model performances based on (a) Area Under the Curve values with 10-fold cross-validation (AUCcv), and against independent test data (30 % of sites) (AUCin), (b) Percent of Correctly Classified with 10-fold cross-validation (PCCcv) and against independent data (PCCin).

3.4 Hypoxic areas

Although hypoxia was commonly recorded in all WFD areas, except in GoB, the potential geographical extent of hypoxic seafloors shows rather different pattern. Based on models, topographically prone areas represent only a small part of the coastal areas, with less than 25 % affected (Fig. 6). Frequent, severe hypoxia ($O_2 < 2$ mg L^{-1}) was most prominent in AS and SA, although representing only a small fraction of the total areas (on average 1.5 and 3.7 %, respectively). Problematic areas based on the models are AS, SA and WGoF. Those areas seem to be topographically prone to oxygen deficiency. Moreover, around 10 % of areas in EGoF are vulnerable to occasional moderate hypoxia, but less to severe hypoxia. Areas predicted as hypoxic in GoB were less than < 2 %, which supports our hypothesis of the facilitating role that topography potential has. The prevalence of depressions, i.e. potential sinks in GoB is non-existent (Supporting Fig. 1), and the seafloor is less topographically complex than that in the other study areas.

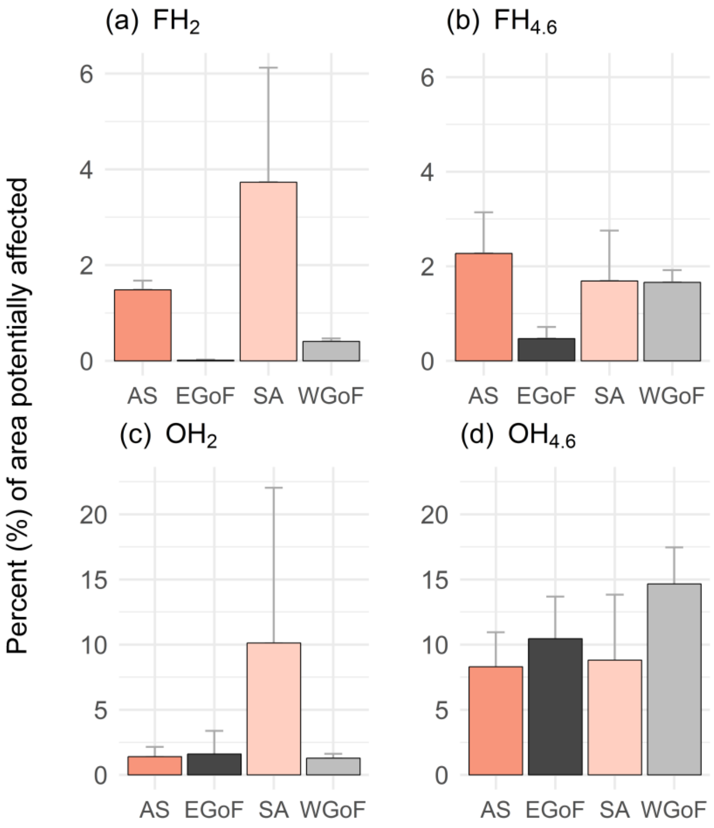

Figure 6. Percent (%) of areas potentially affected by hypoxia with varying frequencies (occasional and frequent) and hypoxia severities (O_2 <4.6 mg L^{-1} and O_2 <2 mg L^{-1}). AS=Archipelago Sea, EGoF=Eastern Gulf of Finland, SA=Stockholm Archipelago and WGoF=Western Gulf of Finland. GoB not reported as areas potentially affected were below 2 % across all models.

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4 DISCUSSION (1200)

Hypoxia has been increasing steadily since the 1960s, and dead zones are seizing the seafloor, suffocating marine organisms on the way (Diaz and Rosenberg, 2008). Understanding the factors affecting the severity and spatial extent of hypoxia is essential in order to estimate rates of deoxygenation and its consequences to the marine ecosystems (Breitburg et al., 2018). Earlier studies have reported coastal hypoxia to occur globally at more than 500 sites (Diaz and Rosenberg, 2008;Conley et al., 2011), of which 20 % were reported from the Baltic Sea (Conley et al., 2011). According to our results, over 50 % of sites in the complex archipelagoes of Finland and Sweden experienced hypoxia that is ecologically significant ($O^2 < 4.6$ mg L^{-1}). Especially alarming was the intensity of it. For instance, Stockholm Archipelago suffered frequently from severe hypoxia ($O_2 < 2$ mg L^{-1}), as approximately half of the coastal monitoring sites were hypoxic across our study period (Fig. 3). This demonstrates that deoxygenated seafloors are probably even more common in coastal environments than previously reported (Conley et al., 2011;Karlsson et al., 2010). As our study suggests, topographically prone areas to deoxygenation represent less than 25 % of seascapes. However, most of the underwater nature values in the Finnish sea areas are concentrated on relatively shallow areas where there exist enough light and suitable substrates (Virtanen et al., 2018;Lappalainen et al., 2019). Shallow areas also suffer from eutrophication and rising temperatures due to changing climate, and are most probably the ones that are particularly susceptible to hypoxia in the future (Breitburg et al., 2018).

Although extensive 3D models have been developed for the main basins of the Baltic Sea (Meier et al., 2012a;Meier et al., 2011b;Meier et al., 2014) the previous reports on the occurrence of coastal hypoxia have mostly been based on point observations (Conley et al., 2009a;Conley et al., 2011). Due to the lack of data, and computational limitations, no biogeochemical model has (yet) encompassed the complex Baltic Sea archipelago with a resolution needed for adjusting local management decisions. This study provides a novel methodology to predict and identify areas prone to coastal hypoxia without data on currents, stratification or biological variables, and without complex biogeochemical models. Our approach is applicable to other low-energy and non-tidal systems, such as large shallow bays and semi-enclosed or enclosed sea areas. The benefit of this approach is that it requires far less computational power than a fine-scale 3D numerical modelling. By using relatively simple proxies describing depressions of stagnant water, we were able to create detailed hypoxia maps for the entire Finnish coastal area (23 500 km^2) and Stockholm Archipelago (5100 km^2), thus enabling a quick view of potentially hypoxic waters (Fig. 7).

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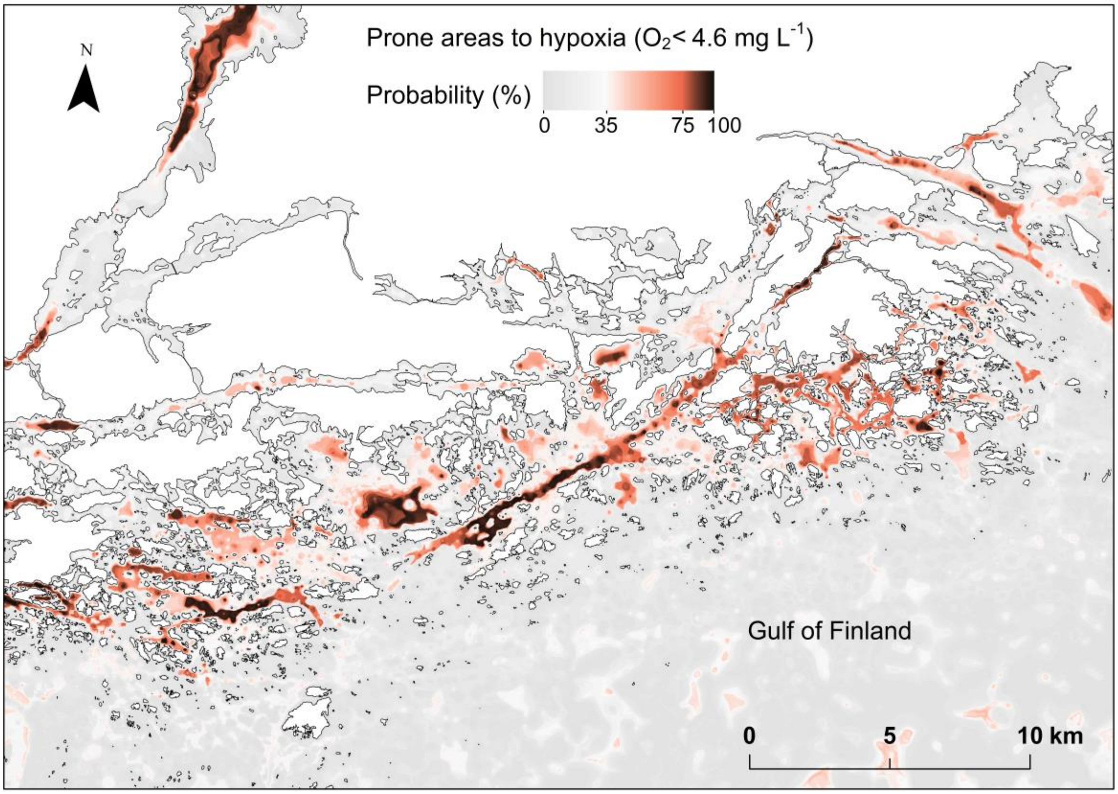

Figure 7. Modelled probability of detecting frequent hypoxia O_2 (<4.6 mg L^{-1}) in an example area in the south coast of Finland. Land shown as white color.

We quantified the facilitating role of seafloor complexity for the formation of hypoxia. Sheltered, topographically heterogeneous areas, where water exchange is limited are more susceptible for developing hypoxia according to our results. This statement is quite intuitive, but it has not previously been quantified. Noteworthy is that coastal hypoxia is not only related to depth; deep seafloors are not automatically hypoxic or anoxic. In our study, hypoxia was common in shallow and moderate depths of 10–45 m. For instance in the Archipelago Sea, deep (60–100 m) canyons are mostly normoxic, as strong currents tend to keep them oxygenated throughout the year (Virtasalo et al., 2005). Shallow areas can be restricted by slow water movement due to topographical reasons, thus creating opportunities for hypoxia formation.

We emphasize that our models only indicate where hypoxia may occur simply due to restricted water exchange. Many other factors, especially biogeochemical and biological processes, obviously modify the patterns and severity of hypoxia also in the coastal areas. Coastal systems, where oxygen deficiency has been projected to increase faster than in the open sea (Altieri and Gedan, 2015;Gilbert et al., 2010), are usually affected by external nutrient loading from the watershed. In larger basins and sea areas dominated by large river systems, such as the central Baltic Sea, Gulf of Mexico and Chesapeake Bay, large scale oceanographic and biogeochemical processes, or external loading, govern the depth and extent of hypoxia. This is the case also in the Baltic Sea. In areas where our models underestimate oxygen deficiency, major nutrient sources, e.g. rivers, cities or intensive agricultural areas, probably contribute to hypoxia formation. However, in extremely complex archipelago areas, such as Finnish and Swedish archipelagoes, physical factors limiting lateral and vertical movement of water probably facilitates, and in some areas even dictates the development of hypoxia.

There were spatial differences in the frequency and severity of hypoxia that can be explained by topographical characteristics of the areas, external loading, and interaction with the adjacent deeper basins. For instance, Stockholm Archipelago is part of a joint valley landscape with steep topography. The archipelago is extensive with deep, steep areas also in the inner parts where wave forcing is low, making it very susceptible for hypoxia, which was also confirmed by the model: severe hypoxia covered the largest percentage of seascapes of all study areas. In Finland, the inner archipelago is mostly shallow, with steep canyons occurring only in the Archipelago Sea. Geographically, hypoxia was in Finland most prominent in the Archipelago Sea and the Gulf of Finland, where the inner archipelago is isolated from the open sea, and the complex topography results in overall poor water exchange in the existing depressions.

In addition to SA, also AS and WGoF seemed to be prone to frequent hypoxia. In contrast, in EGoF hypoxia was a more occasional phenomenon. This may be caused by differences in external nutrient loading, but may be at least partly caused by the dependency of EGoF areas on the deep waters of the open parts of the Gulf of Finland. The Gulf of Finland is an embayment, 400 km long and 50–120 km wide, which has an open western boundary to the Baltic Proper. A ledge of anoxic water usually extends from the central Baltic into the Gulf of Finland along its deepest parts. Basin scale oceanographic and atmospheric processes influence how far east this ledge proceeds into the Gulf of Finland each year (Alenius et al., 2016). It is possible that when this anoxic ledge extends close to EGoF, it also worsens the oxygen situation of the EGoF archipelago.

In Gulf of Bothnia, hypoxia was markedly less frequent and severe than in the other study areas. GoB has a relatively open coastline with only few depressions (cf. Supporting Fig. 1) and strong wave forcing, which probably makes oxygen-rich water to be flushed into the archipelago areas. Another reason for the relatively good oxygen conditions of the Gulf of Bothnia is the topographical isolation from the high saline deep waters of the Baltic Proper by the relatively shallow sill between The Åland Islands and the Swedish coast. Consequently there is no halocline in the Gulf of Bothnia, which enhances mixing of water and prevents open sea hypoxia from developing (Leppäranta and Myrberg, 2009), which probably also affects the oxygen status of the coastal areas.

Such observations suggest that formation of coastal hypoxia is not totally independent from basin-scale oxygen dynamics. While we suggest that coastal hypoxia can be formed entirely based on local morphology and local biogeochemical processes, the relatively low occurrence of hypoxia in the Gulf of Bothnia, and differences in frequency of hypoxia in different parts of the Gulf of Finland, both highlight the interaction of coastal areas with the associated deeper basins.

While our results confirm that hypoxia in most study areas is a frequently occurring phenomenon, they also show that areas affected by hypoxia are geographically quite limited. Our modelling results indicate that overall 15 % of the coastal sea areas are occasionally afflicted by moderate hypoxia, and less than 4 % of sea areas are plagued by frequent severe hypoxia. The relatively small spatial extent of coastal hypoxia does not mean that it is not a harmful phenomenon. In Stockholm Archipelago, severe hypoxia is a pervasive and persistent phenomenon, and also in Finland, many local depressions are more often hypoxic than normoxic. Anoxic sinkholes probably act as local nutrient sources, releasing especially phosphorus to the water column, which further enhances pelagic primary production. Such a vicious circle tends to worsen the eutrophication and maintain the environment in a poor state (Pitkänen et al., 2001;Vahtera et al., 2007). In this way, even small sized anoxic depressions, especially if they are many, may affect the ecological status of the whole coastal area. Moreover, as climate change has been projected to increase water temperatures and worsen hypoxia in the Baltic Sea (Meier et al., 2011a), shallow archipelago areas that typically have high productivity, warm up quickly, and are topographically prone to hypoxia, may be especially vulnerable to the negative effects of climate change.

In order to establish reference conditions and implement necessary and cost-efficient measures to reach the goals of international agreements such as the EU Water Framework Directive (WFD, 2000/60/EC), the Marine Strategy Framework Directive (MSFD, 2008/56/EC) and the HELCOM Baltic Sea Action Plan (BSAP), in-depth knowledge of ecological functions and processes as well as natural preconditions is needed. Although eutrophication is a problem for the whole Baltic Sea, nutrient abatement measures are taken locally. We therefore need to know where the environmental benefits are maximized, and where natural conditions are likely to counteract any measures taken. As some places are naturally prone to hypoxia, our model could aid directing measures to places where they are most likely to be efficient, as well as explain why in some areas implemented measures do not have the desired effect. Our approach could be used to develop an “early-warning system” for identification of areas prone to oxygen loss, and to indicate where eutrophication mitigation actions are most urgently needed.

CONCLUSIONS

We quantified the facilitating role of seafloor complexity for the formation of hypoxia. Sheltered, topographically heterogeneous areas, where water exchange is limited are more susceptible for developing hypoxia. Our approach gives a practical baseline for various types of hypoxia related studies and consequent decision-making. Identifying areas prone to hypoxia helps to focus research, management and conservation actions in a cost-effective way.

AUTHOR CONTRIBUTION

EAV and MV designed the study, EAV and ANS performed all analyses, EAV wrote the main text and all authors contributed to the writing and editing of the manuscript.

DATA AVAILABILITY

Data and model codes will be submitted to Dryad data repository.

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