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Subsidies for ecosystem-based management in an offshore oil and gas exploration area, Santos Basin, Brazil

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This special issue examines the latest discoveries from the interdisciplinary project, "Regional Characterization of the Santos Basin – (PCR-BS)," designed by the Brazilian oil company Petrobras as part of its environmental program initiatives. Future environmental management practices are threatened by lack of comprehensive oceanographic knowledge in offshore oil & gas regions. This concern inspired this special issue. The 13 articles here present data primarily gathered during the 2019 campaigns. The study collected physical, chemical, sedimentological, and biological data from both benthic and pelagic environments in the basin. The findings are classified into four categories: methodological aspects, hydrographic conditions, and pelagic and benthic ecosystems. The scientific research presented in this special issue represents an initial effort towards reconciling sustainable oil and gas exploration and production with the preservation of regional biodiversity and environmental health.

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Methodological aspects

The Santos Basin, located in the South-Western Atlantic, covers a total area of 350,000 km² and extends to water depths of around 3,000 m. The Basin is one of the largest pre-salt oil reservoirs in the world, with an estimated recoverable oil reserve of 21.6 billion oil barrels. A detailed characterization of the area, as well as the methodological aspects of the 24 oceanographic cruises and the sampling protocols used are presented by Moreira et al. (2023). A total of 137 environmental variables were collected from the benthic system and 88 from the pelagic system. The integrated sampling approach adopted during the project proved to be fundamental for building a unified database and for carrying out robust statistical workflows based on machine learning (ML) algorithms (Fonseca and Vieira, 2023). The overall reasoning of the workflow is that all available data should be considered and modeled to anticipate ecosystem conditions in unsampled areas and future scenarios. The project used a combination of unsupervised and supervised learning modelling methods. The unsupervised learning algorithm chosen was the self-organizing maps, which were mainly used to detect groups of samples that shared common characteristics (*e.g.* Carreira et al., 2023). The Random Forest technique was used as a supervised method to make predictions for biodiversity and environmental data, such as meiofauna, chlorophyll-a, and the percentage of carbonates (Gallucci et al., 2023). The ML predictions based on the sampling campaign were then used to estimate the target variable across the whole basin, using a high-resolution 2 x 2 km bathymetrical grid as predictor (Figure 1). This second stage modelling, termed a meta-model (Fonseca and Vieira, 2023), enhances our understanding of the system for unknown sampling areas. Given the fact that the implementation of machine learning workflows largely depends on the researcher's programming skills, all machine learning analysis within this project was performed using iMESC, an open-source and user-friendly application (Vieira and Fonseca, 2022).

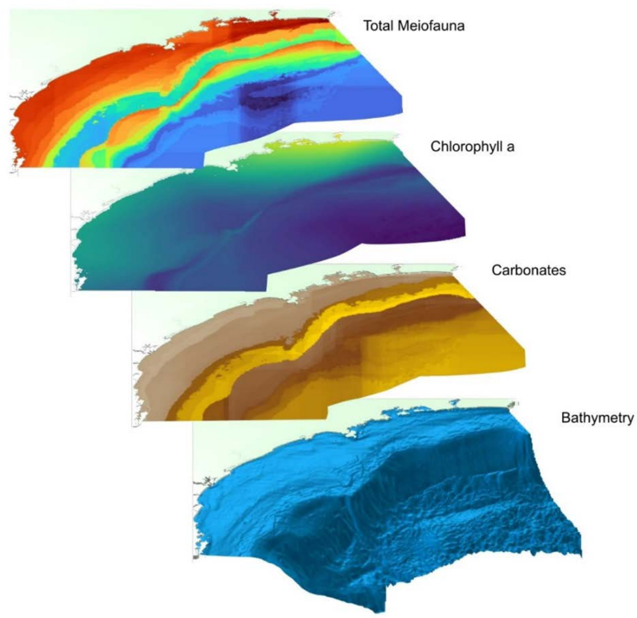

Figure 1. Schematic figure of the Santos Basin depicting the spatial variation obtained using machine learning models of four benthic variables: bathymetry, percentage of carbonates, concentration of chlorophyll-a, and total meiofauna density. Methodological details are given in Moreira et al. (2023) and Fonseca and Vieira. (2023).

Hydrographic conditions

Two articles describe the hydrographic conditions of the Santos Basin, serving as a basis for interpreting the major oceanographic processes that structure the region. They showed that the continental shelf can be divided into two sectors with distinct characteristics in relation to the São Sebastião areas: (1) in the Southwestern sector, the presence of Subtropical Shelf Water (STSW) modulates the hydrographic parameters, and (2), the Northeastern sector where the uplifting of the South Atlantic Central Water was the dominant process (Dottori et al., 2023). On the slope and São Paulo plateau, hydrographic circulation is dominated by both the Atlantic southwestern boundary (ASB) current regime and the remotely generated eddies (Silveira et al., 2023). The Brazilian Current, the Intermediate Western Boundary Current, and their mesoscale meanders form the ASB, whereas the eddies originate on the eastern side of the South Atlantic Basin. The interplay between these features is complex and dynamic. The authors observed that these eddies introduce water masses with higher salinities and heat into the basin. As reported by other manuscripts in this special issue, the hydrographic differences between the southern and northern sectors of the continental shelf and the particularities of the oceanographic conditions above the slope and Plateau shape the pelagic and benthic systems.

Pelagic ecosystem

The assimilation of inorganic carbon by the planktonic community in the Santos basin is spatially arranged (Kutner et al., 2023). Whereas the northern oceanic portion of the basin is more significantly contributed by chemosynthesis, emphasizing the role of the microbial community in this region, the coastal and the southern oceanic regions are mainly photosynthetic. Photosynthetic production was primarily explained by colored dissolved organic matter, dissolved oxygen, and conservative temperature; however, chemosynthetic production could not be explained by environmental variables, but rather by the presence of eddies. It has been suggested that eddies in the northern region may have extended oligotrophic conditions into oceanic waters, restricting photoautotrophs and promoting chemoautotrophs (Kutner et al., 2023). The authors emphasized that, in oligotrophic waters such as the Santos Basin, the interplay between physical and biological processes might be more important than trophic organization (Marañón et al., 2003). As for the planktonic community, the occurrence of seabird species is also spatially arranged (Valls et al., 2023). In total, 76 seabird species are present in the Santos Basin, using it for activities such as breeding, foraging, and as a migratory corridor for trans- or intra-hemispheric movement. Some species are found primarily above the continental shelf boundaries and are rare in the oceanic region. Differences in the occurrence of seabird species have also been observed between the northerly and southerly sectors of the basin.

Benthic ecosystem

The sedimentological and geological properties of the Basin, from a water depth of 25 m to 2,400 m, were described in detail by the project (Figueiredo et al., 2023; Hercos et al., 2023). The seismic data revealed that the Santos Basin's seascape exhibits high heterogeneity, featuring a broad continental shelf that narrows northward, multiple sedimentary terraces alongside the shelf break, a slope with channels, ravines, pockmark fields, lineaments, carbonate, and coral mounds, salt-related characteristics, and a large Plateau that covers most of the deeper zone (Hercos et al., 2023). Using a combination of newly obtained sedimentological and historical data, Figueiredo et al. (2023) affirmed the geomorphological features that had been detected by the seismic data. These, in turn, provided additional elements to describe the seafloor. Whereas the sediment properties varied between the northern and southern regions of the continental shelf, there was an abundance of carbonated sediments found at the shelf break. Conversely, the slope and São Paulo Plateau were muddier and spatially more homogeneous in comparison to the continental shelf.

The mosaics of sediment facies together with the pelagic processes are the drivers evoked to explain the spatial patterns of radioisotopes (Ferreira et al., 2023), organic matter (Carreira et al., 2023), foraminifera (Araújo et al., 2023), and meio- (Gallucci et al., 2023) and macrofauna (Moura et al., 2023). For instance, it was observed that the source of ^{228}Ra radioisotopes in the southernmost region of the continental shelf is different from that in the slope (^{226}Ra; Ferreira et al. 2023). The data suggest that the terrigenous material from the northward-flowing Brazilian Coastal Current brings in the material deposited in the southern region. On the other hand, the radioisotopes found in sediments in the continental slope, which is closer to the shelf break, are believed to have originated from the long-term decay of its isotopic parent, the ^{230}Th. The data collected on organic matter suggests that the Basin is divided into five sedimentary provinces, each with varying quantities and qualities of deposited material. These provinces are mainly arranged based on their bathymetry. The coastal zone at 25 m water depth is predominantly characterized by terrigenous organic matter. The continental shelf, however, showed differences between the northern and southern sectors. Interestingly, the slope is characterized by low quantities of organic matter but of high quality, indicating a fresh input.

The main variables structuring the benthic fauna were the sediment type and the quantity and quality of organic material. The study of the meiofauna covered the entire basin and, using machine learning techniques, revealed the existence of six benthic zones (Gallucci et al., 2023). Of these zones, three were found on the continental shelf (south, central and north), one on the shelf break, and two more that were arranged bathymetrically on the deeper zones. Due to the prevailing oceanographic processes, each benthic zone is subject to unique environmental conditions. The macrofauna and foraminifera also differed between the northern and southern sectors of the slope. All the benthic studies attributed the increase in density and diversity of species in the northern sector to the greater availability of fresh food provided by the organic enrichment caused by the upwelling events in the Cabo Frio region. Benthic studies have also shown that the lower slope and the São Paulo Plateau are different in terms of abundance and species richness, with the former being superior due to the high quality of sediments.

Perspectives for implementing an ecosystem-based management (EBM) approach in the Santos Basin

The PCR-BS was developed to establish ecosystem baselines for pelagic and benthic systems and to identify the primary driving forces that structure their biodiversity. The results obtained from this study will support future ecosystem-based management (EBM) and monitoring programs. Implementing EBM approaches is generally challenging due to the multidisciplinary nature and complexity of the system (Levin et al., 2017; Leslie et al., 2015; Link and Browman, 2014). Common challenges of implementing an EBM approach include distinguishing natural variability from human-mediated environmental changes, anticipating changes that may exceed a tipping point and trigger cascading effects, compromising the resilience of the system; developing adaptive management strategies that respond to the system's dynamic ecosystem and social demands; and regularly collecting environmental data with monitoring and assessment, which guide decision-making. To facilitate the effective implementation of EBM, the involvement of relevant stakeholders such as government agencies, local communities, scientists, and organizations is necessary. It is crucial to note that EBM should prioritize preventive measures, thus requiring more conservative decisions in the absence of sufficient scientific evidence to prevent harm (Norse et al., 2016). Especially when monitoring the oil and gas industry, an EBM approach must consider the problems associated with biodiversity loss caused by habitat destruction, physical disturbance, and chemical contamination resulting from the exploration and drilling phases or an oil spill (Cordes et al., 2016). Despite the challenges, it is imperative to implement an EBM approach based on high-quality scientific data to ensure the long-term preservation of marine ecosystems.

We have taken the initial step of mapping and integrating the ecosystem components and their descriptors (Figure 1). However, further steps are necessary to comprehend their interaction with the social system, which is crucial for balancing the benefits of ecosystem services under various social development scenarios. In this context, effective implementation of an EBM approach in the Santos Basin involves five crucial steps: 1) clarifying the objective of EBM; 2) selecting ecosystem and social indicators; 3) establishing a spatial-temporal monitoring sampling design; 4) determining risk thresholds for each indicator; 5) developing a responsive management strategy when a threshold is reached; and 6) continuously evaluating EBM. The results presented here demonstrate the feasibility of monitoring the integration of oceanographic processes that structure the Santos Basin using a set of environmental variables. Optimized monitoring programs can now be developed to maintain scientific standards while reducing operational costs and information processing time.

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