Technical Summary

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Table of contents

List of Figures

List of Tables

1 Abstract

The Bureau of Ocean Energy Management (BOEM) has developed the Marine Sensitivity Toolkit (MST), a cutting-edge, cloud-native system for assessing the relative environmental sensitivity of marine ecosystems to offshore energy development across U.S. waters. This toolkit integrates over 17,000 spatially explicit species distribution models, comprehensive extinction risk data, and satellite-based primary productivity to deliver a transparent, reproducible, and scalable assessment framework. The MST operates at a high-resolution 0.05° grid, enabling detailed, cell-by-cell analysis that captures nuanced ecological patterns often missed by previous coarse assessments. Sensitivity scoring combines species presence, extinction risk, and productivity, all rescaled within ecologically meaningful ecoregions. The MST is designed for transparency and rapid updates, ensuring that BOEM's decisions are grounded in the best available science as mandated by Executive Order 14303: Restoring Gold Standard Science.

2 Background

The Bureau of Ocean Energy Management (BOEM) is legally mandated by Section 18(a)(2)(G) of the Outer Continental Shelf Lands Act (OCSLA) to consider "the relative environmental sensitivity and marine productivity of different areas of the OCS" when making decisions regarding offshore energy development. This analysis is essential for guiding the placement of energy infrastructure and for implementing mitigation measures to minimize impacts on the marine environment.

In direct response to Executive Order 14303: Restoring Gold Standard Science (Federal Register, May 29, 2025), BOEM has modernized its approach by developing and implementing the Marine Sensitivity Toolkit (MST). This innovative, cloud-native toolkit fundamentally revamps BOEM's previous Relative Environmental Sensitivity Analysis (RESA) (BOEM 2018), delivering a transparent, reproducible, and scalable system that fully aligns with the Executive Order's requirements for scientific integrity, transparency, and the use of best-available science.

The MST marks a significant advancement over prior RESA methodologies. Earlier approaches (Niedoroda et al. 2014) often relied on aggregated data from a limited set of broad species groups and surrogate species, lacking spatially explicit information for individual organisms.

As a result, previous assessments were typically coarse and area-wide, frequently missing critical ecological variation and fine-scale patterns across the OCS. In contrast, the MST utilizes a high-resolution 0.05° grid (averaging 5 km in the lower 48 states and 3.6 km in Alaska), enabling detailed, cell-by-cell analysis that captures nuanced ecological patterns.

Further offshore, observational data becomes increasingly sparse. And observation data is generally only applicable to the time and place of occurrence, unless a relationship is modeled between the environment and the observations. In which case, species distribution models can be applied across the seascape (Elith and Leathwick 2009).

A cornerstone of the MST is its integration of over 17,000 spatially explicit species distribution models, comprehensive extinction risk data (using IUCN Red List categories), and satellite-based primary productivity. This robust data integration delivers a more accurate, comprehensive, and scientifically defensible assessment of marine sensitivity across U.S. waters.

Sensitivity scoring within the MST is fully transparent and quantitative, combining species presence, extinction risk, and productivity, all rescaled within ecologically meaningful ecoregions. The MST is cloud-native, open-source, and designed for transparency, reproducibility, and rapid updates. All 27 OCS planning areas, including the new High Arctic, are included in the sensitivity analysis. The smallest unit of analysis is a 0.05° cell, ensuring fine-scale resolution. Planning Area scores are aggregated from these cells based on percent overlap and are rescaled within each BOEM Ecoregion (BOEM 2018) to ensure comparability across diverse ecological contexts. The High Arctic Planning Area is treated as its own dedicated ecoregion. As the 2025–2030 Program advances, BOEM will continue to refine and enhance this sensitivity analysis, upholding the principles and directives of Executive Order 14303 and ensuring that decisions are grounded in the best available science.

3 Objectives

4 Methods

The Marine Sensitivity Toolkit (MST) is BOEM's comprehensive, next-generation system for assessing the vulnerability of marine ecosystems to offshore energy development across U.S. waters. The MST builds on BOEM's established framework by integrating advanced species distribution models, extinction risk assessments, and primary productivity data to deliver a unified, spatially explicit vulnerability score. The MST's conceptual framework is grounded in ecological risk assessment, where vulnerability (V) is a function of exposure (E), sensitivity (S), and adaptive capacity (A):

$$V = f(E, S, A)$$

The more exposed and sensitive an area is—and the less able it is to recover—the more vulnerable it is to impacts from offshore activities. For spatial implementation, the vulnerability of a cell (v_c) is calculated as the sum across all species in the given taxonomic group (S_g) of the products for the species presence in the cell ($p_s c$) and a species weight (w_s), which is the risk of that species going extinct:

$$v_c = \sum_{1}^{S_g} p_{sc} * w_s$$

In other words, for each cell in the ocean, we add up the sensitivity of all the species found there.

- v_c is the vulnerability of a cell.
- p_{sc} is how likely species s is to be present in that cell (from 0 to 1).
- w_s is how at-risk that species is of going extinct (also from 0 to 1; ranging from Least Concern 0.2 to Critically Endangered as 1).
- S_g is the total number of species in that taxonomic group.

If a cell has many species that are both likely to be present and at high risk of extinction, it gets a higher sensitivity score. This helps us find places where rare or threatened species are concentrated. Ecoregional rescaling makes it easy to compare areas within the same region and planning area aggregation gives us an overall sensitivity score for each planning area, taking into account both the sensitivity of each part and how big each part is.

4.0.1 Data Sources and Processing

The MST draws on the best available data and methods:

- **Species Distribution Models**: 17,550 models, primarily from AquaMaps, downscaled from 0.5° to 0.05° resolution.
- **Extinction Risk**: IUCN Red List categories, with risk scores assigned as follows: Critically Endangered (1.0), Endangered (0.8), Vulnerable (0.6), Near Threatened (0.4), and Least Concern (0.2).
- **Primary Productivity**: Net Primary Productivity (NPP) calculated using the Vertically Generalized Production Model (VGPM) with VIIRS satellite data for the most recently completed decade of model results year (2014 to 2023).

Scores from individual grid cells are aggregated to BOEM Planning Areas using area-weighted averages, providing sensitivity scores for each planning area.

Table 1: Extinction risk categories from the international IUCN Red List as well as USA Endangered Species Act (ESA) categories and assigned numeric risk scores.

Code	Category	Risk Score	Weight
CR	Critically Endangered (IUCN)	1.0	Highest
EN	Endangered (IUCN, ESA)	0.8	High
VU	Vulnerable (IUCN) / Threatened (ESA)	0.6	Moderate
NT	Near Threatened (IUCN)	0.4	Low
LC	Least Concern (IUCN)	0.2	Lowest

4.0.2 Geographic Scope

The MST uses BOEM Ecoregions as its primary geographic units. These ecoregions are defined by Large Marine Ecosystem boundaries, bathymetry, hydrography, productivity, and species composition. The analysis is conducted at a 0.05° grid resolution, providing detailed coverage across U.S. waters.

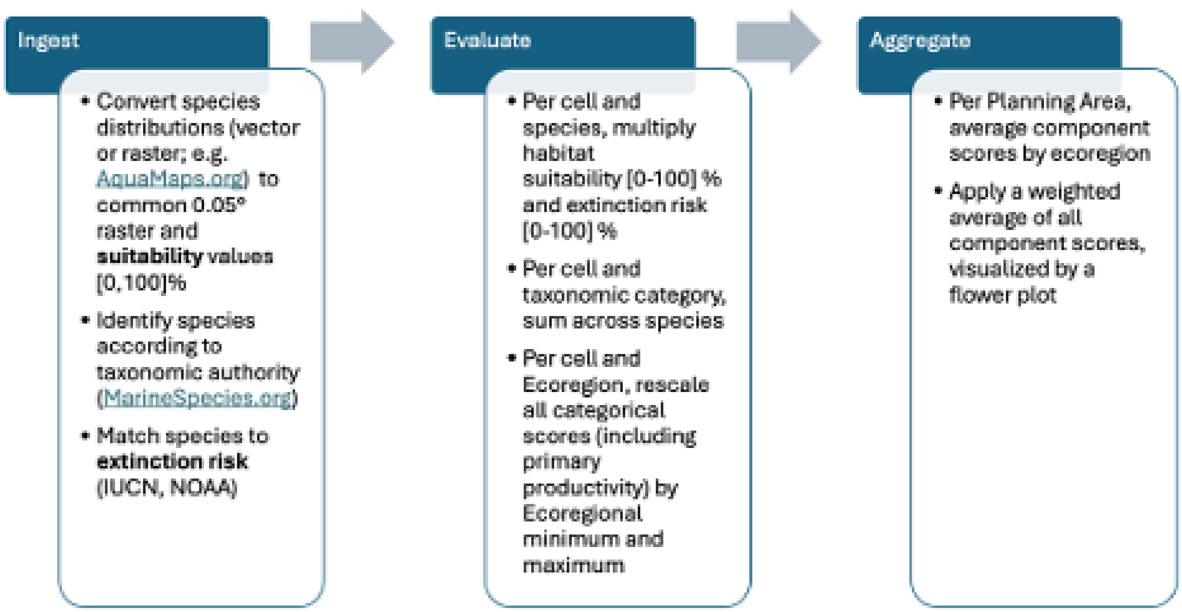

Figure 1: Environmental Sensitivity Score Methodology.

Visualization and Decision Support :The MST utilizes interactive visualizations, such as the Flower Plot, to convey complex vulnerability assessment results. This tool allows stakeholders and scientists to understand the underlying components contributing to an area's vulnerability to offshore energy development. The length of each petal reflects the sensitivity score for a particular component or taxonomic group, while future iterations may use petal width to represent component weighting. By visualizing these component scores, the Flower Plot helps decision-makers quickly identify which ecological elements are driving vulnerability in a given location, supporting more informed spatial planning and impact assessment.

5 Results

5.1 Species Distributions

Table 2: Datasets contributing to the study.

Dataset	**Response**	**Geography**	**Taxonomy**	**# Species in USA**
AquaMaps	Suitability [1 - 100%]	Global	All, except birds	16,871
BirdLife Birds of the World	Range [50%]	Global	birds	457
NMFS Critical Habitat for USA	Range [70%,90%]	USA	mixed	92
FWS Critical Habitat	Range [70%,90%]	USA	mixed	27
FWS Current Range Maps	Range [50%]	USA	mixed	33

5.2 Primary Productivity

5.3 Maps of Environmental Sensitivity by Pixel

5.4 Maps of Environmental Sensitivity by Planning Area

5.5 Flower Plot Scores of Environmental Sensitivity by Planning Area

5.6 Online Mapping Application

The MST includes an interactive web application that allows users to explore the sensitivity scores across different planning areas and taxonomic groups. This tool provides a user-friendly interface for visualizing the data and understanding the spatial distribution of marine sensitivity.

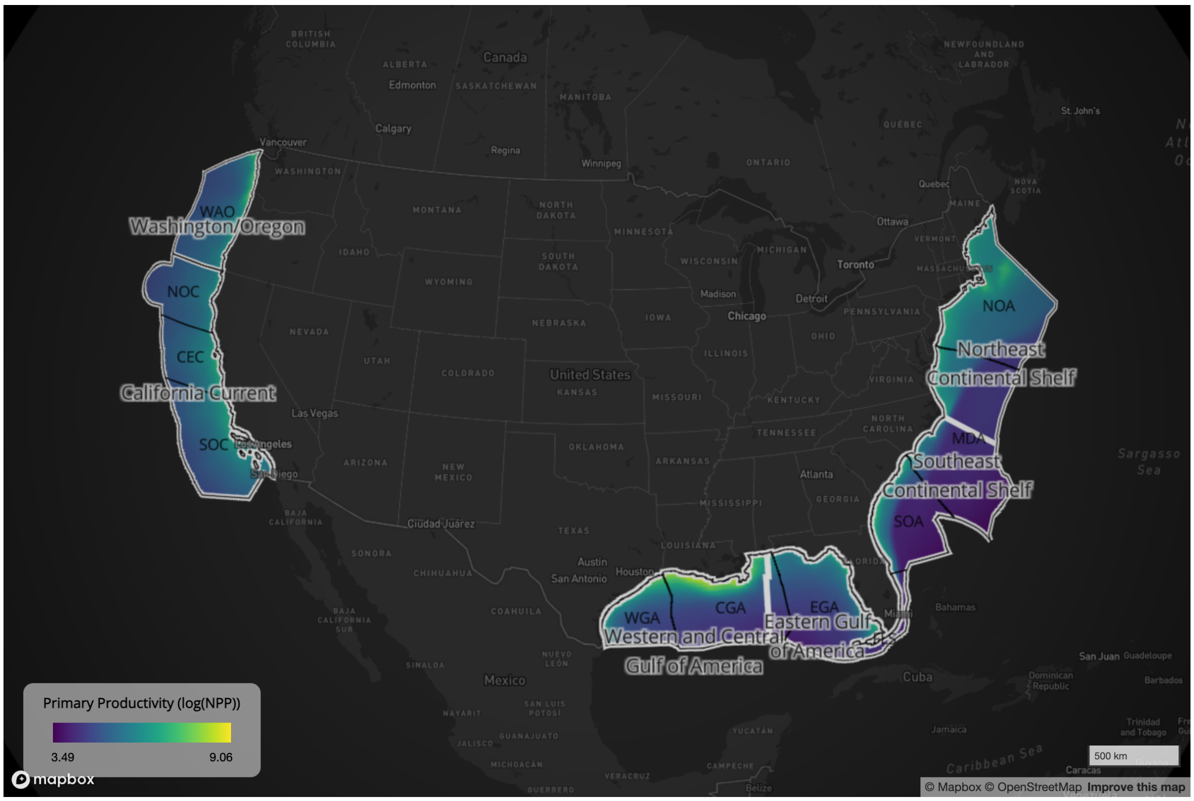

Figure 2: Map of Contiguous US Primary Productivity by pixel.

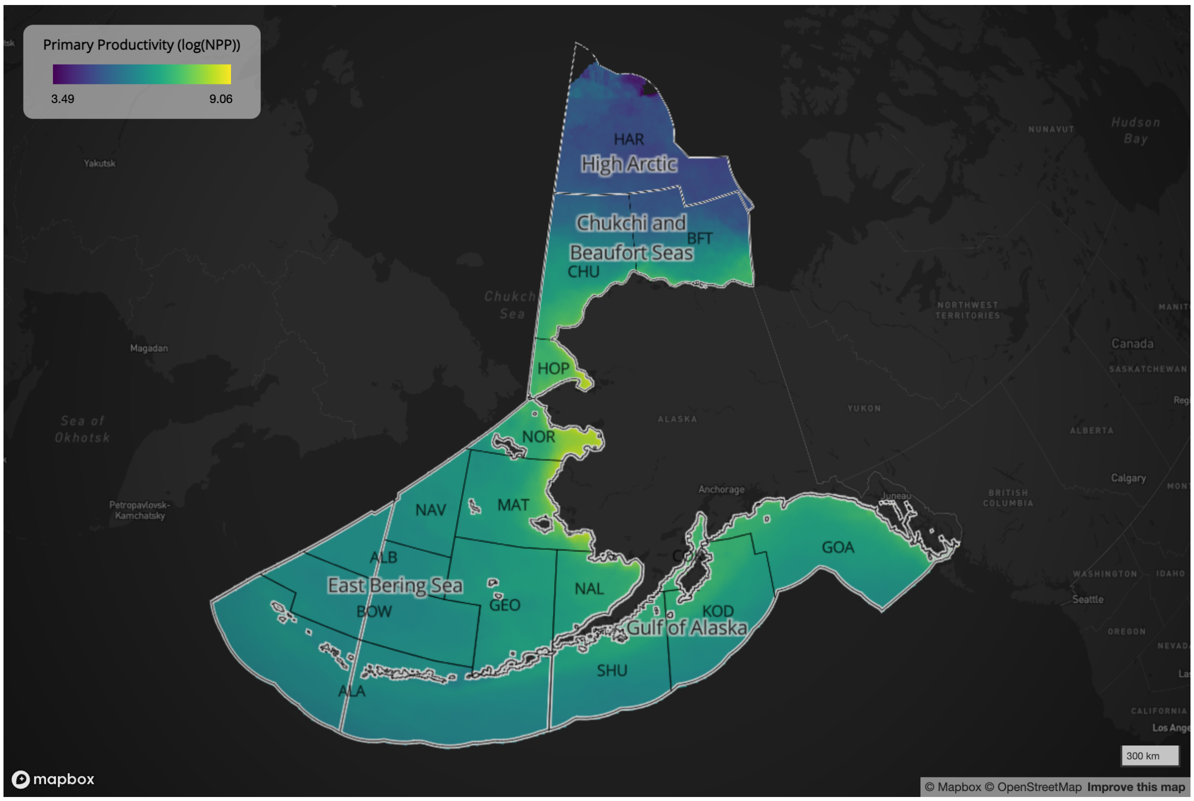

Figure 3: Map of Alaska Primary Productivity by pixel.

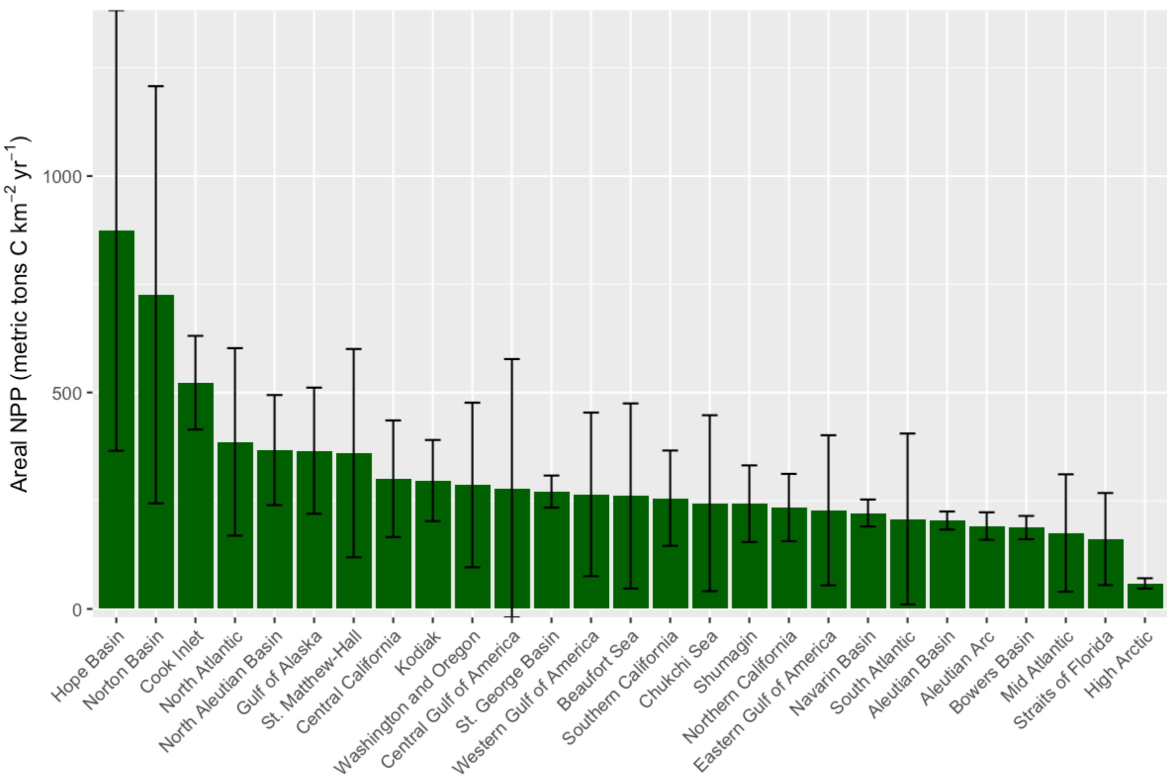

Figure 4: Plot of net primary production (NPP) per Planning Area. Values represent the mean and the standard deviation of 10 annual values for the 2014–2023 period, standardized per unit area.

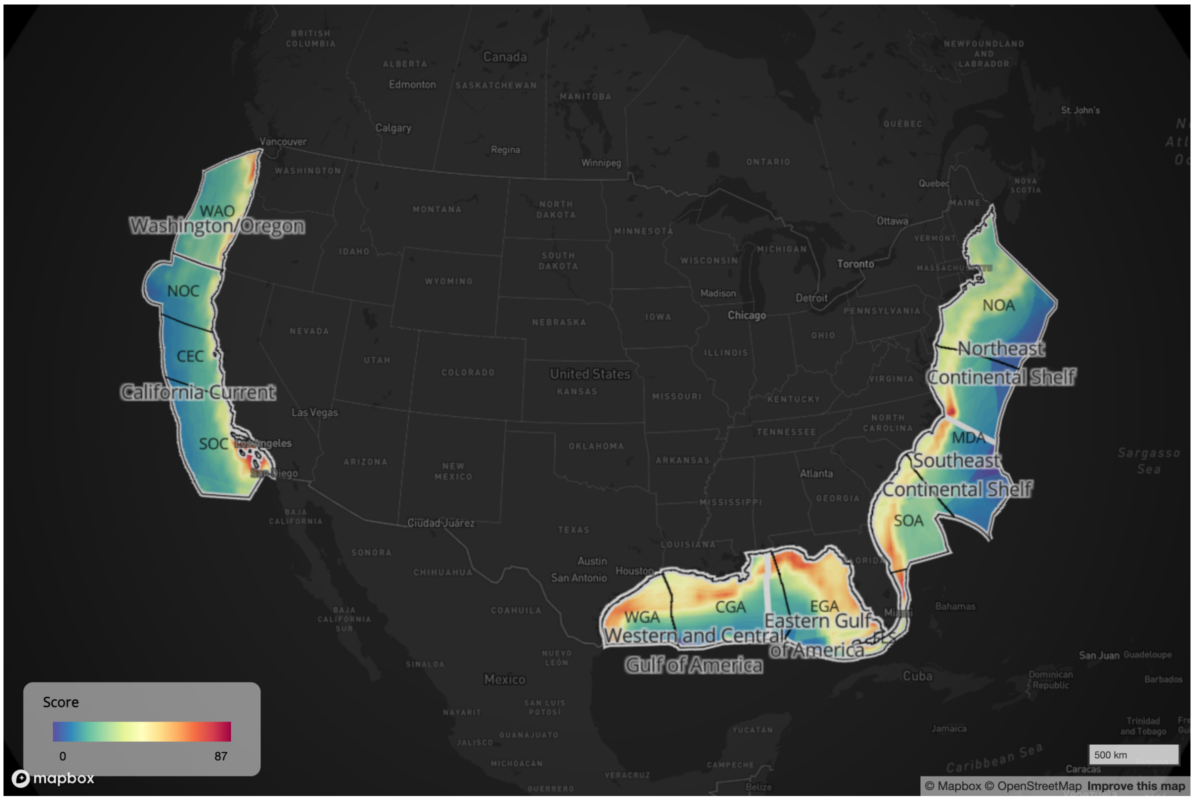

Figure 5: Map of Contiguous US scores by pixel.

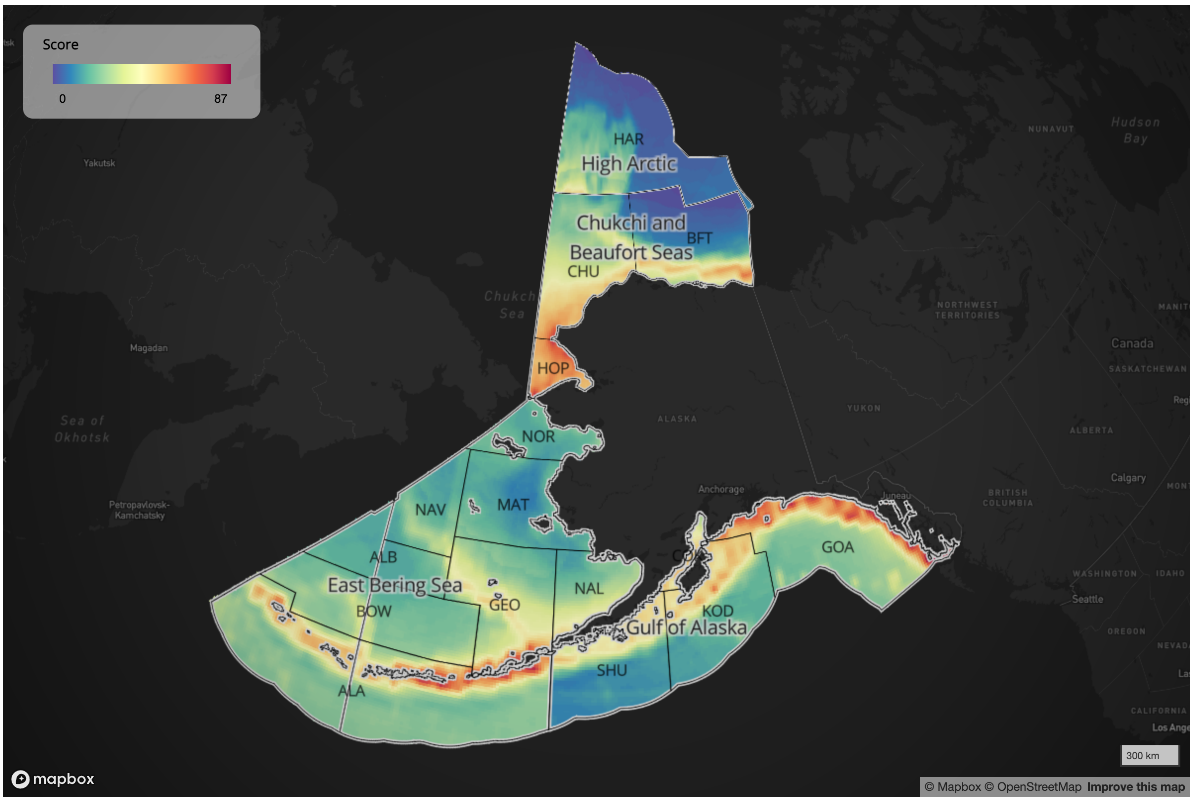

Figure 6: Map of Alaska scores by pixel.

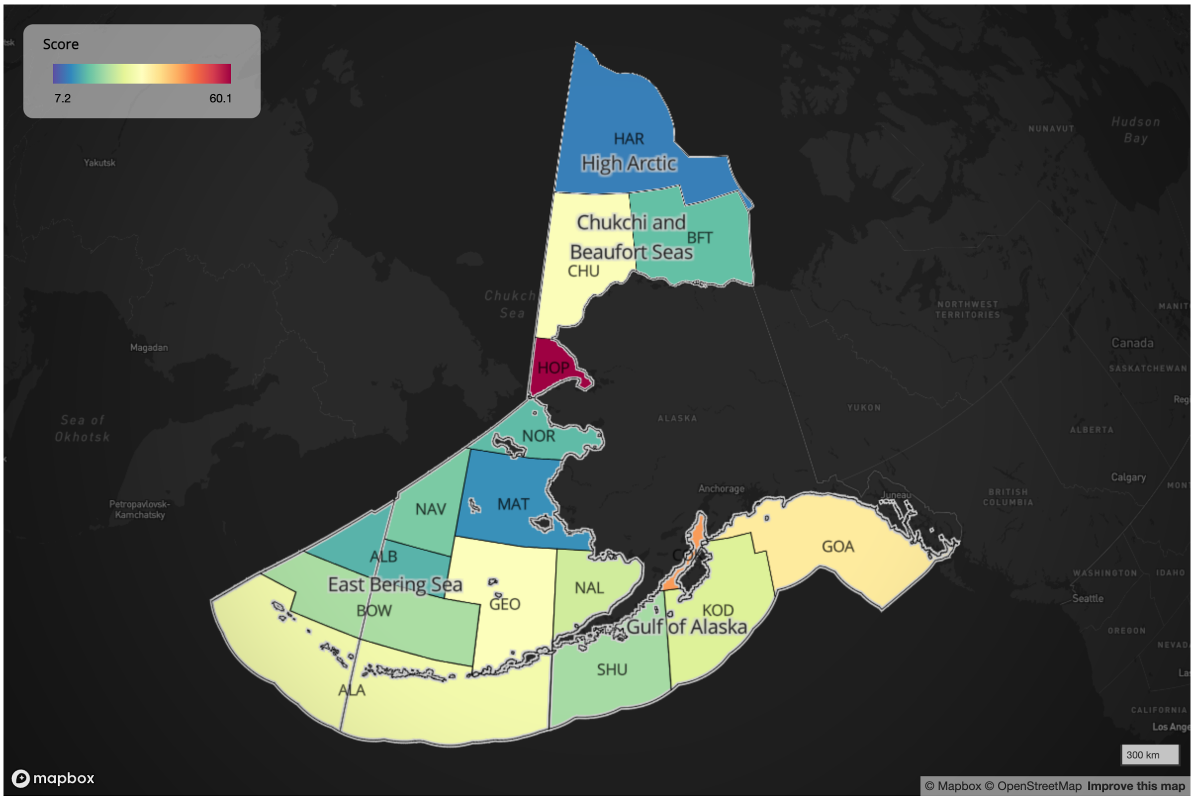

Figure 7: Map of Contiguous US scores by Planning Area.

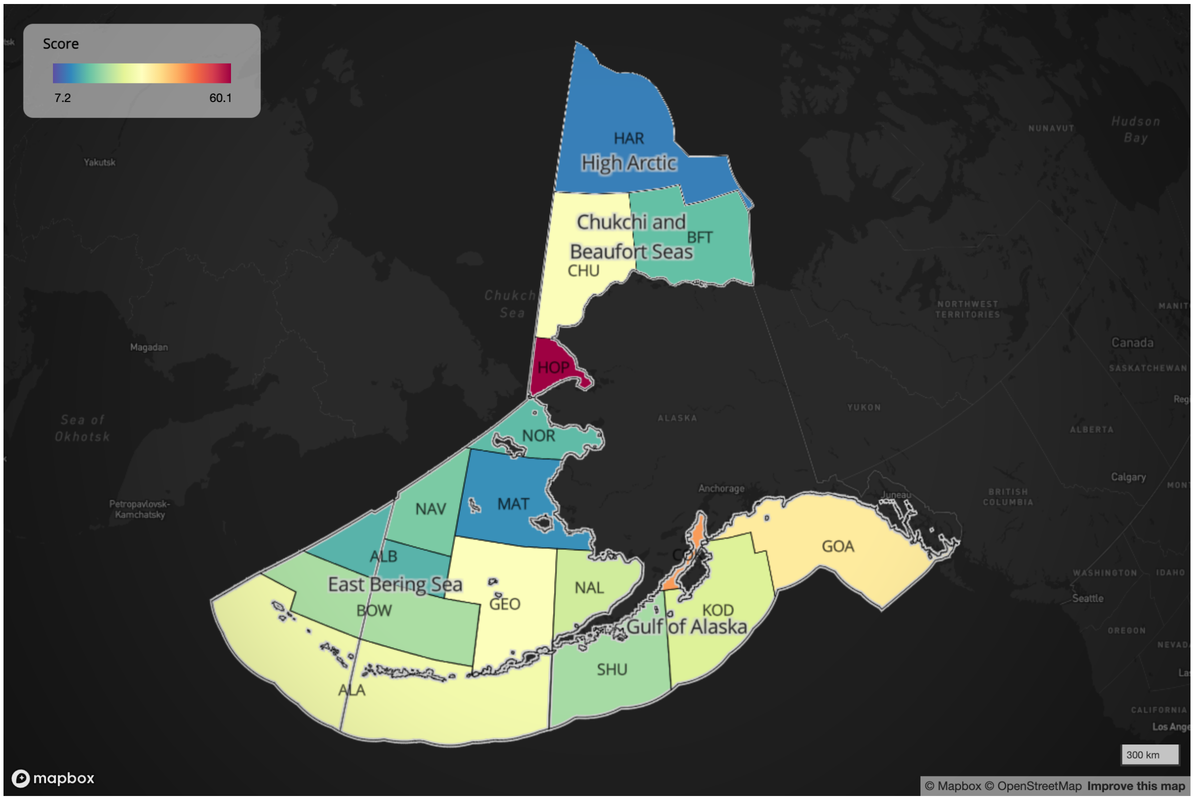

Figure 8: Map of Alaska scores by Planning Area.

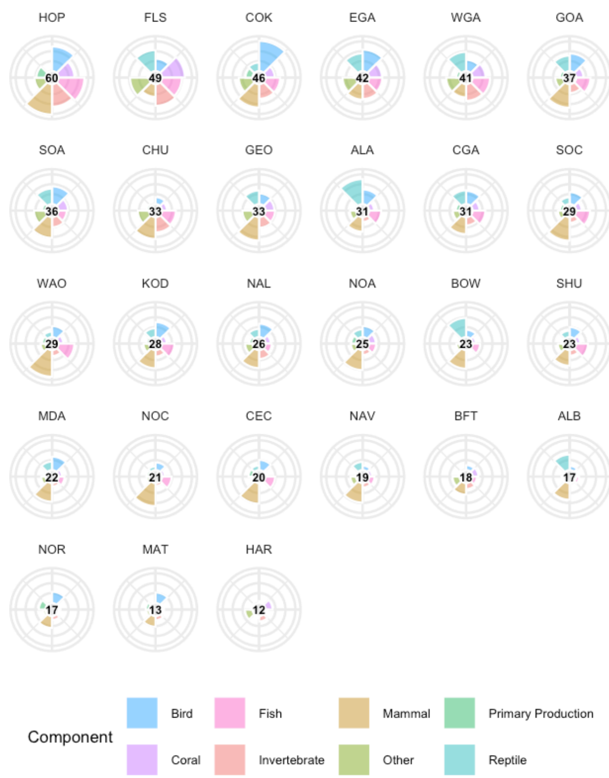

Figure 9: Component and aggregate scores of Marine Environmental Sensitivity in each BOEM Planning Area summarized across taxonomic groups and Primary Productivity. The "petals" of the flower plot represent the component scores and the overall score is given by average number in the middle.

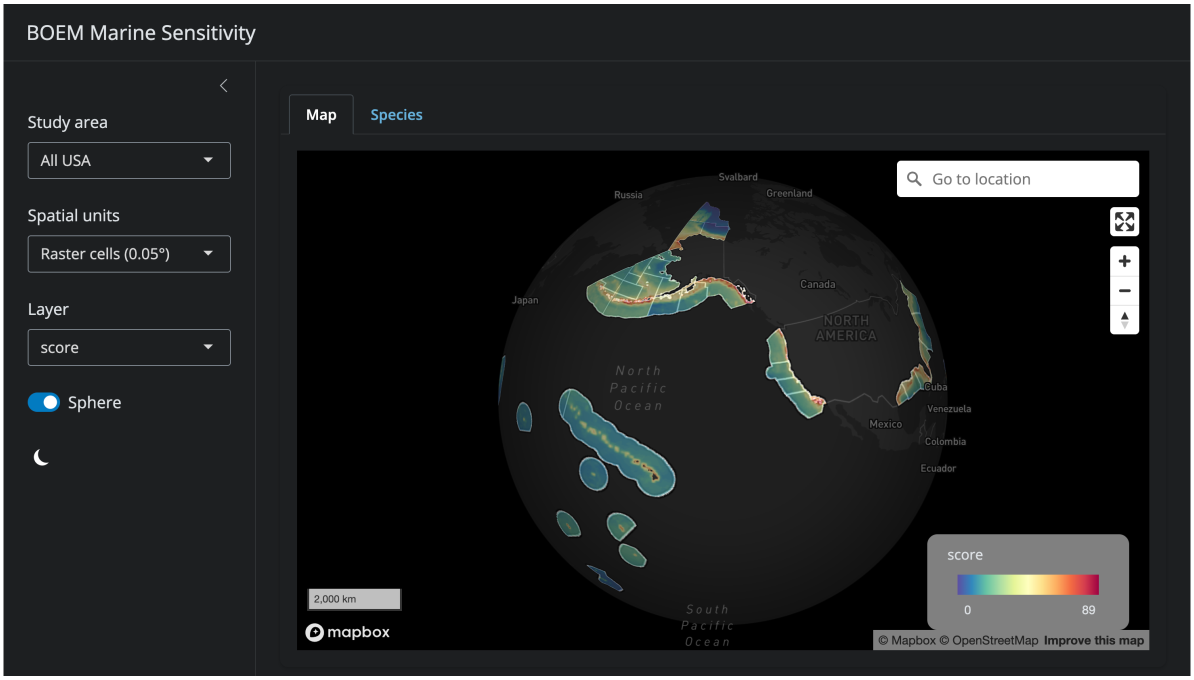

Figure 10: Screenshot of the main app: mapgl showing the raster score for all USA waters.

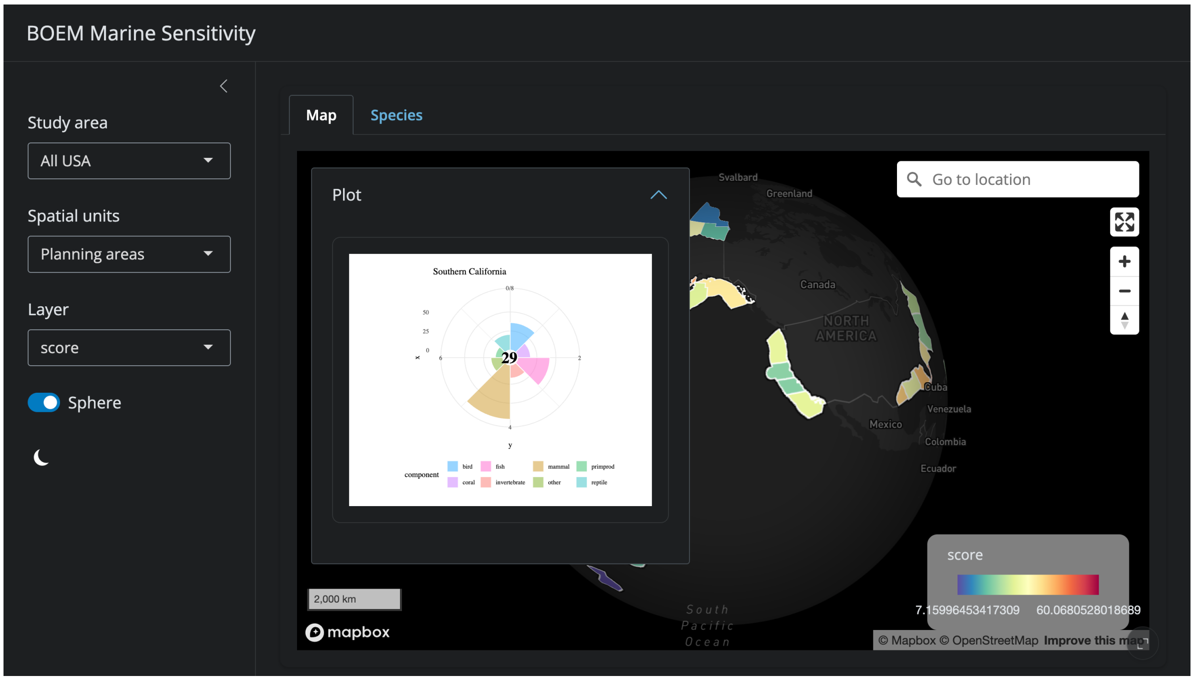

Figure 11: Screenshot of the main app: mapgl showing the Planning Area with flower plot containing component scores as petals and overall score in the middle.

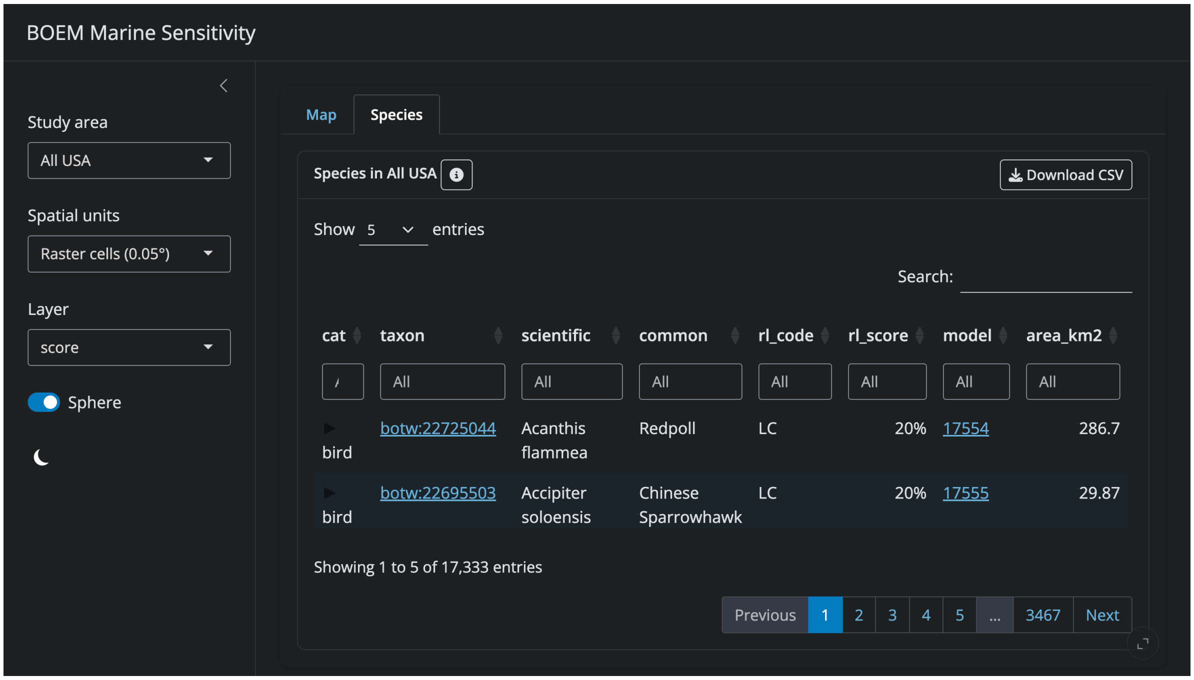

Figure 12: Screenshot of the main app: mapgl showing the Species table. Clicking on the information icon explains the columns and how to interpret the values.

The main app mapgl app (Figure 10; Figure 11; Figure 12) shows the overall scores and any underlying components by 0.05° raster cell or Planning Area, all masked by the chosen Study area. The model link in the Species table (Figure 12) links to the species distribution app mapsp (Figure 13), which shows the distribution of the species, in this case for the blue whale, which is globally distributed.

5.7 Reproducible Infrastructure

The MST is built using open-source tools and is designed for transparency and reproducibility. The entire workflow, from data acquisition to sensitivity scoring, is documented and available for review. This ensures that the analysis can be updated as new data becomes available or as methodologies evolve.

The tasks and full scope of this work is iterative in nature. In Phase 1, the project iterated on 6 core infrastucture components corresponding to the Github repositories that demonstrated work towards the project goals. In Phase 2, we are adding Database and Website as infrastucture components.

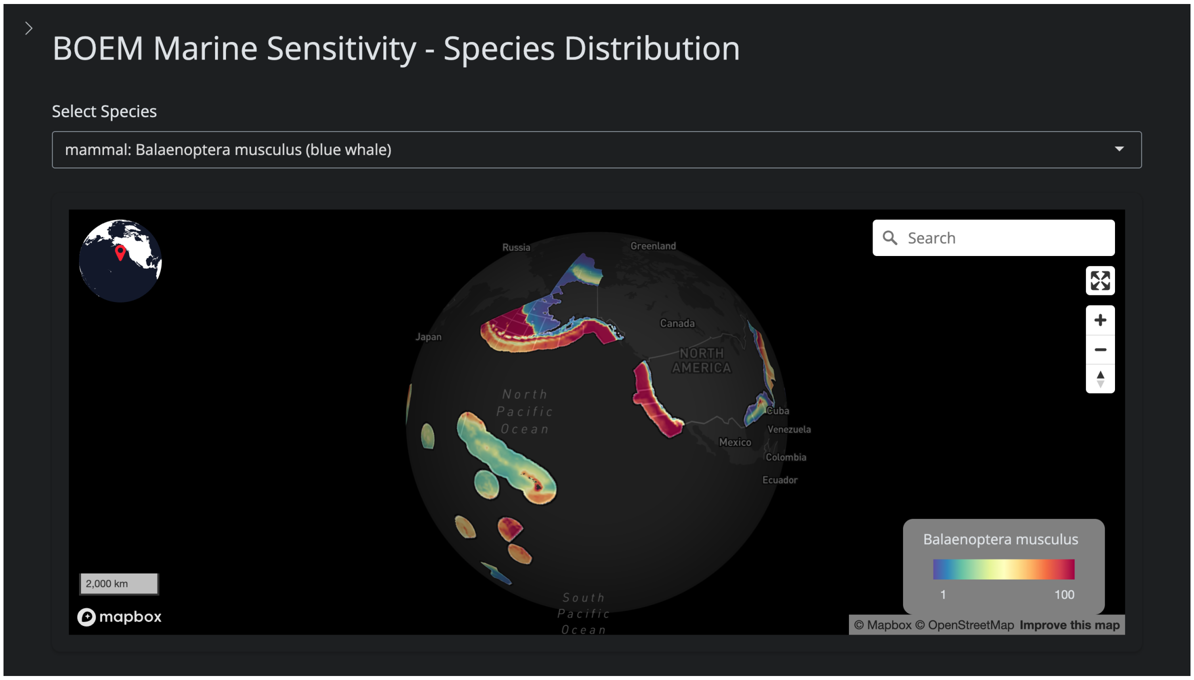

Figure 13: Screenshot of the species distribution app: mapsp showing the species distribution, in this case for the blue whale which is globally distributed.

5.7.1 Server

Server
All server software is setup using containerized open-source software with Docker to readily spin up the necessary services (particularly: Shiny, RStudio, R Plumber, PostGIS, caddy and pg_tileserv, titiler).

5.7.2 Database

A spatially enabled Postgres database serves the vector data, while being supplemented by the performance and portability of DuckDB for generating on-the-fly rasters of biodiversity metrics.

5.7.3 Workflows

Workflows
The scientific workflows comprise of notebooks that perform exploration, creation and ingestion processes while rendering markdown and chunks of scientific languages (R or Python) into rendered html for inspection and archive.

5.7.4 APIs

APIs
The application programming interfaces (API) enable standardized retrieval of data products from the server with simple parameters for visualization and analytics, such as the vector tile API at tile.marinesensitivity.org (via pg_tileserv), raster tile API at titiler.marinesensitivity.org (via TiTiler) or the custom API at api.marinesensitivity.org (via Plumber).

5.7.5 Libraries

Libraries
Packaging functions with documentation enables reusability across analysis and visualization for simplifying existing applications while extending functionality to outside projects. Phase 2 will build upon the existing msens for analyzing biodiversity data on the desktop, while adding another library for internally ingesting and maintaining the database.

5.7.6 Apps

Apps
The applications have all been built with the R Shiny framework. From Phase 1, the core application is at shiny.marinesensitivity.org/mapgl, and links out to the individual species mapper shiny.marinesensitivity.org/mapsp. Other experimental applications can be found at marinesensitivity.org/docs/apps.html. We anticipate expanding upon the core applications and continuing to experiment with others in Phase 2. The apps actively use functions from the libraries, APIs and direct database calls.

5.7.7 Docs

Docs
The documentation is principally a book (rendered from Quarto) oriented for scientific and technical audiences, but also applies to documentation throughout the project for reproducibility and usability.

5.7.8 Website

Website
The website marinesensitivity.org provides the project landing page with the general public as the initial audience, with content and links (such as to the docs) for deeper understanding.

6 Conclusions

As illustrated in Figure 6, Table 2…

6.1 Next Steps

The MST is designed to be a living system that can be updated as new data becomes available or as methodologies evolve. Future enhancements may include incorporating additional data sources and refining sensitivity scoring methods.

6.1.1 Refinement and Expansion of Environmental Sensitivity Models

Currently, some models produce biologically unrealistic outputs (e.g., the Pacific Walrus model reflecting outdated historical extents). Therefore, we will revise and constrain species ranges using corroborating evidence from contemporary datasets, such as OBIS and GBIF occurrences. This will ensure all model outputs are based on validated, present-day species data.

The AquaMaps dataset, although numerous with species distributions, sometimes includes historic extents and not present-day extents for which the species are currently found. In Phase 1, we did not have the resources to validate all species distributions, but in Phase 2, we will use the OBIS and GBIF occurrence data to validate the AquaMaps distributions. For instance, we will experiment with applying occurrence filters across different time windows (e.g. 10, 20 and 50 years) and to different areas (e.g., Ecoregions and Planning Areas). We will also compare results with other independent distributional datasets (e.g., IUCN Spatial range maps). This will help us identify and correct aberrant species distributions within the models, such as the Pacific Walrus model reflecting outdated historical extents.

6.1.2 Enhancement and Utilization of the Marine Sensitivity Toolkit (MST) and Geospatial Tools

In Phase 1, we ended up using a DuckDB database to ingest, store and render all the distributions and biodiversity metrics. In Phase 2, we will export these to cloud-optimized GeoTIFFs (COGs) and organize them into spatio-temporal asset catalogs (STACs). This will enable faster rendering in the applications (e.g., see app: sdm-cog, which uses COGs and the TiTiler API) and easier reuse by the general public (e.g., stackstac example). We will also explore customizing our own TiTiler endpoint to generating raster outputs based on various input parameters, such as taxa and stressor. Besides the pixel, we will explore using Uber's H3 hexagons, which are hierachical in nature, and play well with our existing mapping software (mapgl) in that only the hexagon identifier needs to be transmitted to the client and the client library can render the hexagon geometry (e.g., H3 Tutorial: Suitability Analysis | Observable). We will also explore using PMTiles, which also work with our mapping software, to provide easily stored vector tiles (i.e., on S3 or any web server and do not require the PostGIS + pg_tileserv stack or similar) and the ability to join them with arbitrary attribute data for rendering as choropleths. This will be useful for summarizing to any area of interest, as well as visualizing any set of polygons. Finally, we will keep abreast of the ever-changing technical landscape with regards to Cloud-Optimized Geospatial Formats, and take advantage of new technical possibilities.

6.1.3 Production of Updated Environmental Sensitivity Products

In Phase 1, these products were communicated through an app (app: mapgl) or outputs from various workflows (workflows: calc_scores, msens-summary). In Phase 2, functions will be documented into the msens library and outputs will be updated and output as needed based on dependency changes (i.e., a directed acyclic graph (DAG); probably using targets library) formulating a true data pipeline. Formats will be made available in preferred geographic format for vector (e.g., shapefile, geopackage, or geojson), raster (e.g., GeoTIFF, COG) and image format (png, gif, pdf). Masking by Study area will be an option for any spatial output.

6.1.4 Development of Decision Support Dashboard and Interactive Application

The main app mapgl app (Figure 10; Figure 11; Figure 12) shows the overall scores and any underlying components by 0.05° raster cell or Planning Area, all masked by the chosen Study area. The model link in the Species table (Figure 12) links to the species distribution app mapsp (Figure 13), which shows the distribution of the species, in this case for the blue whale, which is globally distributed.

In Phase 2, the app will be further enhanced to allow for selecting arbitrary areas from a drawn polygon, uploaded shapefile or gazetteer identifier. We will further build out the entire taxonomic tree for each species and allow selection at higher taxonomic classifications for merged products. Other features will be acquired from internal and external user feedback.

6.1.5 Creation of Comprehensive Data Products

"We shall create and deliver a range of data products for users, from technical outputs like an API (using R plumber) for technical users to accessible reports detailing the status and trends of key environmental indicators. Model outputs, such as shapefiles and/or geopackages, shall also be provided to BOEM."

These data products will include reports that are generated from the latest data and bundled with the latest model outputs in various desired formats. These and archived versions of past iterations will be made available directly through the website. This will be in addition to the programmatic level APIs, made easier to use through functions documented in R libraries with explanatory vignettes.

6.1.6 Reproducibility and Transparency

We will continue to ensure that all code are stored in publicly accessible GitHub repositories under github.com/MarineSensitivity built in Phase 1. In Phase 2, the README in each repository will be cleaned up with clearer instructions. Github tags for specific version histories will be added to each repository corresponding with the overall Marine Sensitivity model iteration. Each iteration will be fully reproducible from source data using the DAG approach (see Section 6.1.3).

6.1.7 Visualization and Analytical Support for the National Oil and Gas Program

In Phase 1, map figures were generated largely from screenshots of the web interface. In Phase 2, we will implement automatic generation of high quality static figures, including crisp vector graphics suitable for PDF. Another feature we look forward to implementing in Phase 2 is the story-maps feature. For instance, we can build little explainer apps that scrollytell through map layers to explain model inputs and construction. These explainer apps can be standalone or embedded in the website in a broader context.

6.1.8 Data and Tool Transfer to BOEM Server

In Phase 1, we established a server for project use, but technical hurdles prevented its ready use. In Phase 2, we will work through those technical hurdles to make all code and data entirely maintainable internally to BOEM.

7 Study Products

[text]

Additional Products Resulting from this Study (peer-reviewed articles, conference presentations, videos, etc.)

[list of published or in press at the time of report submission]

8 Map of Study Area

[include here if appropriate and if not already shown in the report]

References

Elith, J., and J. Leathwick. 2009. "Conservation Prioritisation Using Species Distribution Modelling." *Spatial Conservation Prioritization: Quantitative Methods and Computational Tools*, 70–93.

Niedoroda, A, S Davis, M Bowen, E Nestler, J Rowe, R Balouskus, M Schroeder, B Gallaway, and R Fechhelm. 2014. "A Method for the Evaluation of the Relative Environmental Sensitivity and Marine Productivity of the Outer Continental Shelf."