

Marine Sensitivity

Project Documentation

Ben Best

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Preface

This is a Quarto book.

1 Introduction

This Marine Sensitivity (MS) project of [BOEM](#) seeks to assess the sensitivity of marine species to offshore energy development, whether oil & gas or wind. By combining the best available species distributions with known species sensitivities we can map out areas of the ocean that are most vulnerable to human activities. This information can be used to inform decisions about where to place energy infrastructure and/or implement mitigations to minimize impacts on the marine environment.

This is a process, not a product. Information is imperfect, especially given the large expanse of US waters. Distributions and abundance of species change, modified increasingly by climate change and human activities. Knowledge on species sensitivities continues to expand with more research. And finally the methods for both modeling and distributing all this information continue to improve. We aim to provide a transparent and reproducible process that can be regularly updated as new data and methods become available.

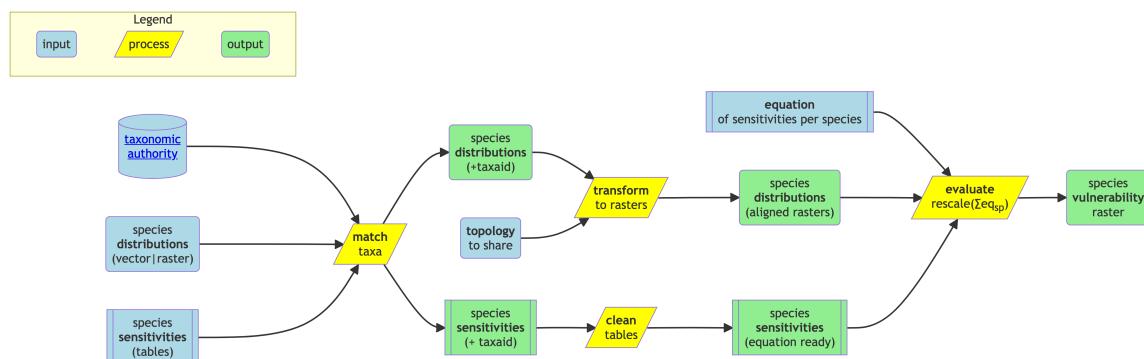


Figure 1.1: Flowchart of process for incorporating marine species sensitivities with distributions and generating a holistic vulnerability map.

Part I

Science

2 Science

The term vulnerability (V) is a function of exposure (E), sensitivity (S) and adaptive capacity (A) (Equation 2.1).

$$V = f(E, S, A) \quad (2.1)$$

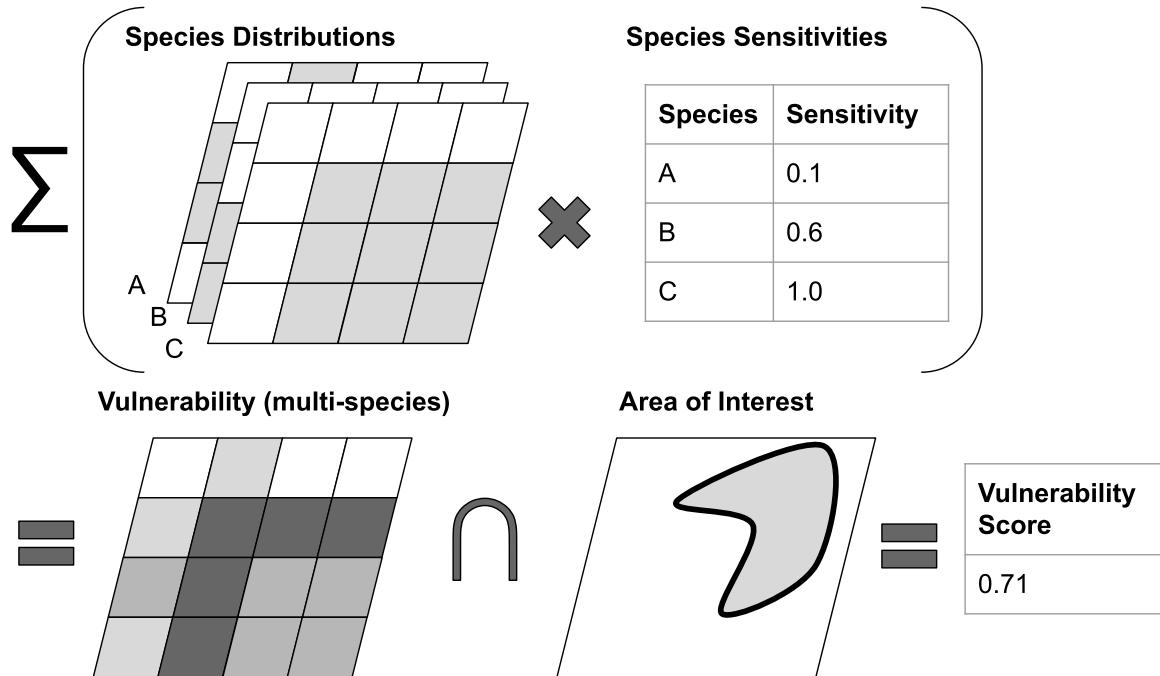


Figure 2.1: Overview of process.

$$cell_V = \sum_{spp} p * w \quad (2.2)$$

The raster of vulnerability (V) contains cells representing a sum across species (spp) of presence (p) multiplied by the sensitivity weight (w) (Equation 2.2).

3 Stressors

3.1 Offshore Wind Energy

Evaluation of stressors from the offshore wind industry needs to be evaluated based on human activities given the phase of development, whether pre-construction, construction, operation or decommissioning (Figure 3.1).

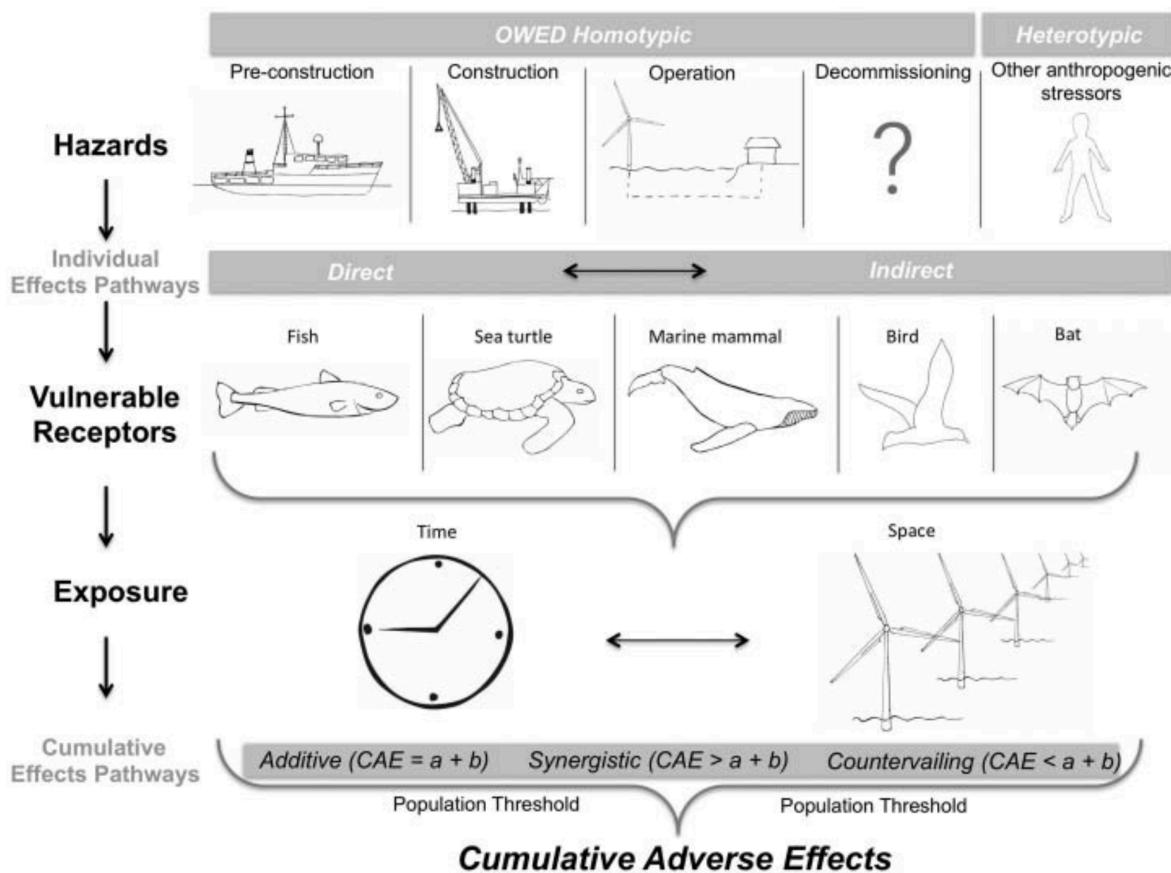


Figure 3.1: Cumulative adverse effects of offshore wind energy development on wildlife (Goodale and Milman 2016).

3.2 Oil & Gas

4 Receptors

Receptors are the species and habitats that are potentially impacted by the human activity.

4.1 Species

4.1.1 Corals

4.1.2 Invertebrates

4.1.3 Fish

4.1.4 Marine Mammals

4.1.5 Seabirds

4.1.6 Sea Turtles

4.2 Habitats

4.2.1 Coral Reefs

4.2.2 Hydrothermal Vents

4.2.3 Kelp Forests

4.2.4 Mangrove Forests

4.2.5 Seamounts

4.3 Primary Productivity

Primary productivity is specified in the explicit mandate for BOEM's management, per the Outer Continental Shelf Lands Act (OCSLA), Section 18(a)(2) of the OCSLA Amendments

of 1978 specifying 8 factors the USDOI must consider in the timing and location of OCS oil and gas activities, including “the relative environmental sensitivity and marine productivity of different areas of the OCS.” (Balcom et al. 2011)

We processed the Vertically Generalized Production Model (VGPM) product from [Oregon State’s Ocean Productivity Lab](#) (using the script `vg.R`) (Figure 4.1).

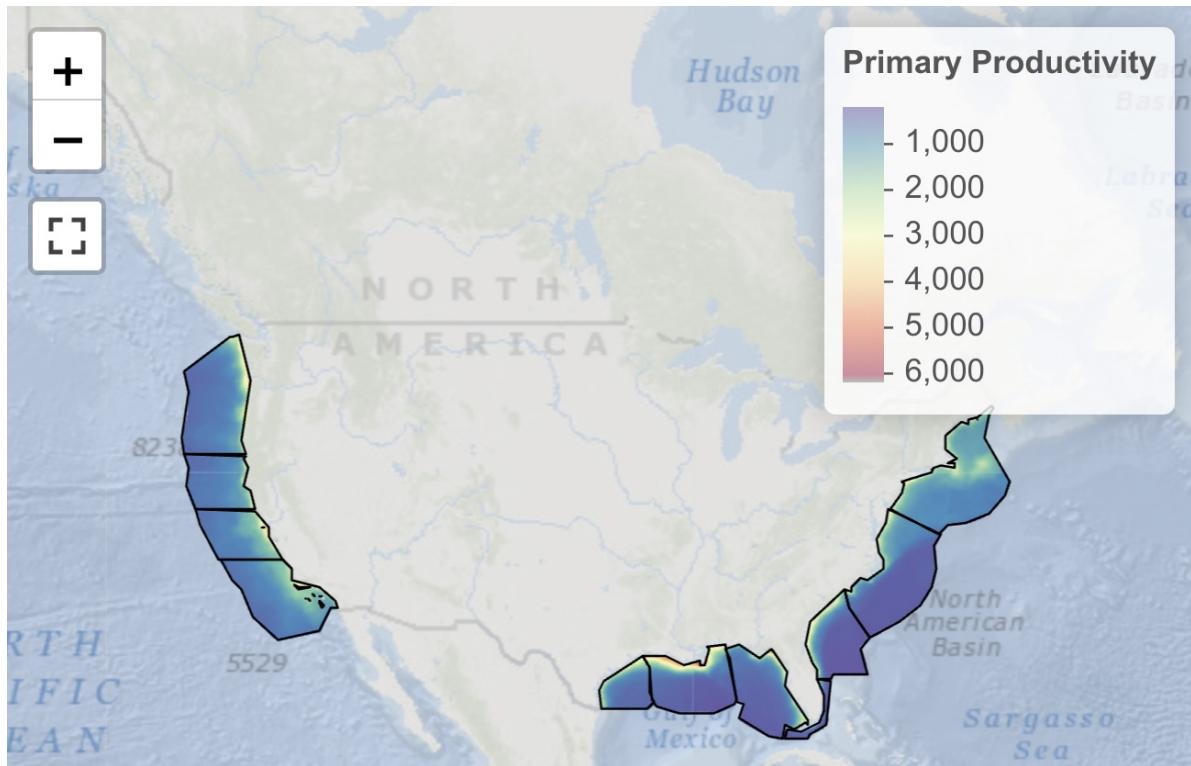


Figure 4.1: Primary productivity throughout the continental United States averaged across months of 2021, as measured by Oregon State’s Vertically Generalized Production Model (VGPM). Expansion is anticipated across the entire US EEZ and for more recent years.

5 Exposure

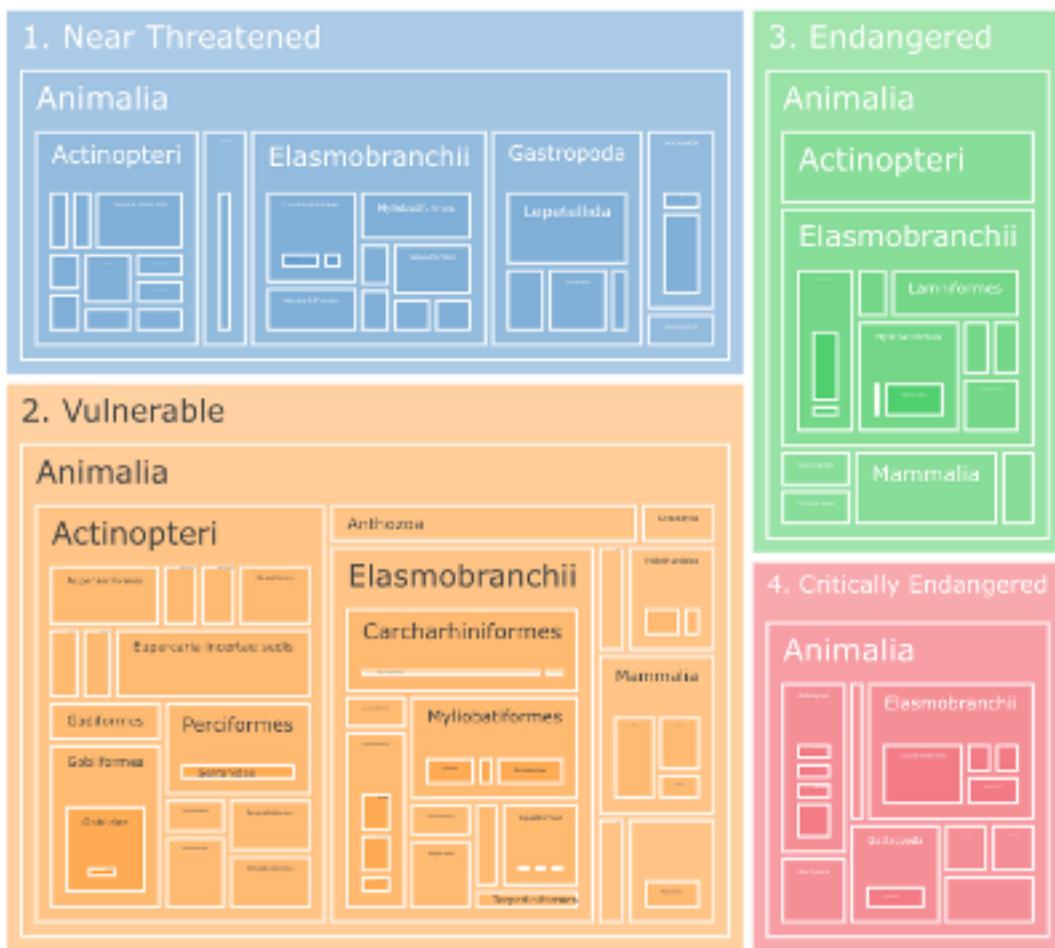
Cumulative exposure (Figure 3.1) is important for understanding impacts to a population.

6 Scoring

6.1 Visualization

We are in process with sorting the scoring methodology informed by visualization approaches.

6.1.1 Treemap



- Audience: scientists
- Show contribution of each element to a given pixel or area of interest
- Elements can be hierarchical across Sensitivity metrics and/or taxonomy
- Interactively zoom, e.g.: 4. Critically Endangered > Animalia > Mammalia



6.1.2 Flower Plot

- **Petal Length**

“One question was about the meaning of the numbers on the pedal plot. I explained that a higher sensitivity score indicates an area that could be susceptible to minor perturbations, while a lower score suggests an area that is more robust to minor changes.”

- TW

- **OHI**

In the original Ocean Health Index (Halpern et al. 2012), the length of the petal reflected the percent towards maximum sustainability of the given goal. The framework is also based on a reference point, either spatially or temporally (Samhouri et al. 2012).

– RESA ’25

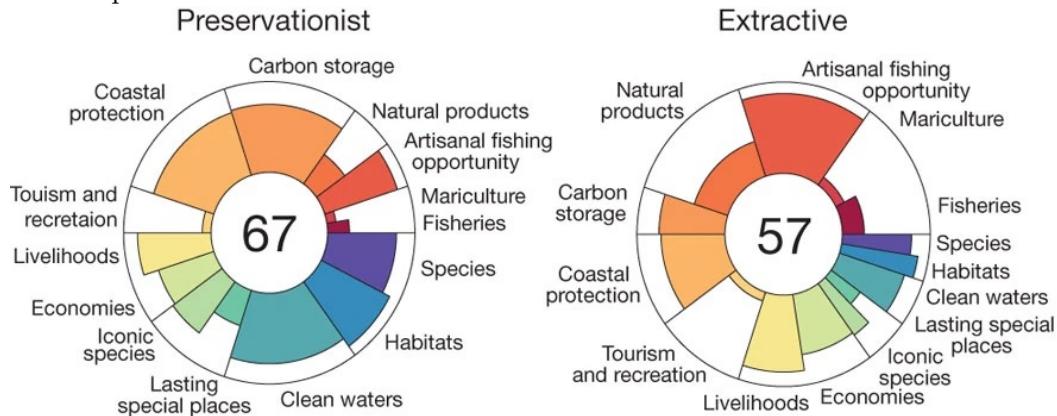
It makes sense to make the most vulnerable the highest score, so a low score is preferable (versus a preferred high score for sustainability of an OHI goal). We'll need to determine what the "highest" score means as a reference point and consider **SMART criteria**. (Specific, Measurable, Assignable, Realistic, Time-related). Will the reference point be the same globally or vary based on some regional maximum?

- Petal Width (and possibly varying weights)

“Another question was about how we manage the weights. I mentioned that we are not currently applying weights, but someone seemed concerned about it. We can discuss this further if needed.” - TW

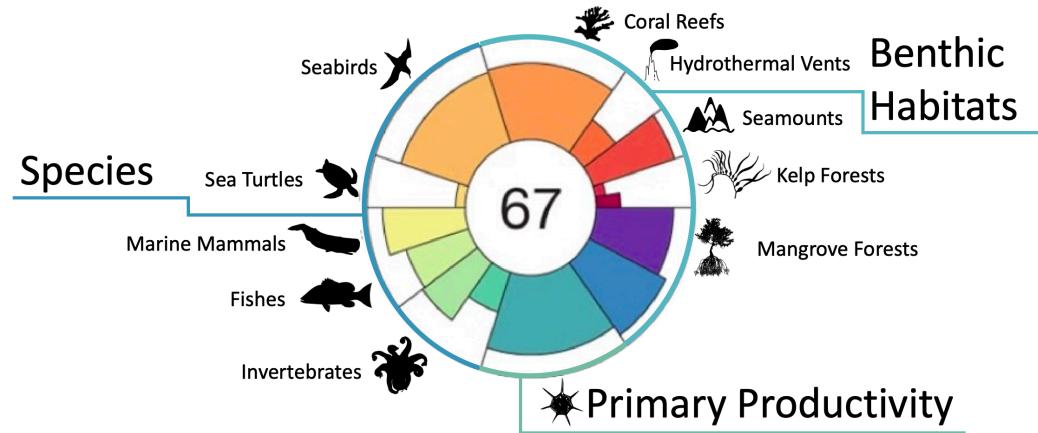
- OHI

For the OHI flower plot, the width of the petal represents its weight contributing to the weighted average score in the center of the flower. The varying importance of each goal is based on societally held values with potentially different value sets, such as preservationist vs extractive:



– RESA ’25

For the RESA '25, when looking at Species, Habitats and Primary Productivity, how shall they be weighted to factor into a final score? Shall species groups be simply weighted based on the number of species within, total biomass, extinction risk, commercial value, etc? And then Species versus less numerous Benthic Habitats and a singular value for Primary Productivity? I will conduct a literature survey to assign sensible value sets, but an App could also apply a user-defined value set to assign weights. That gets messy, but if transparent and easy ideally would lead to scientific consensus with a workshop and/or survey.



Part II

Software

7 Software

7.0.1 Interactive Applications

We have developed a series of interactive applications to explore the data and results of the MS project. These applications allow users to visualize the data, explore the results, and interact with the data in a more intuitive way. The applications are built using the [shiny](#) package in R, which allows us to easily create a user interface with complex reactivity for an interactive web application easily accessed through a web browser. The applications are designed to be user-friendly and intuitive, with interactive maps, charts, and tables that allow users to explore the data in a more dynamic way.

7.0.2 Overcoming Challenges with Large Spatial Data

The MS project incorporates many large spatial datasets that are problematic to render in a typical interactive application. For instance, the most common interactive mapping R package [leaflet](#) has a 4MB limitation for displaying rasters (see “Large Raster Warning” in [Raster Images • leaflet](#)). Vectors (i.e., points, lines and polygons) get smoothed when containing many vertices, but contiguity gets lost between polygons and rendering degrades to non-visible depending on the internet speed of the user’s connection.

To work around these limitations, we have implemented “cloud native” web services and formats (see also [Cloud-Optimized Geospatial Formats Guide](#)). Our implementations effectively reduce the size of any given spatial object based on the zoom level of the user’s browser. For rasters, we use cloud-optimized GeoTIFFs (COGs) and for vectors, we use Mapbox Vector Tiles (MVT). These formats are designed to be fast and efficient for web mapping applications, and they allow us to display large spatial datasets in an interactive web application without sacrificing performance or usability. Let’s take a closer look at implementation of each.

7.0.2.1 Raster: Cloud-Optimized GeoTIFFs (COGs) and Titiler

Historically, to read a raster, such as a GeoTIFF, from the web, the client software would have to read the entire file before rendering. Cloud Optimized GeoTIFFs ([COGs](#)) take advantage of [HTTP GET range requests](#) to read only the part of the file needed for rendering. So a COG stores quadtree simplifications of the original raster at multiple zoom levels and metadata for accessing their byte ranges in the file in the metadata header. This allows the client software

to request only the parts of the file needed for rendering, which can greatly reduce the amount of data transferred and speed up rendering. This is for accessing the raw data in pixel values, e.g., for a raster of species distribution then the abundance of a species in each cell. We would want to also apply a color ramp to visualize the data. The open-source ([TiTiler](#)) software is a lightweight web service that serves up these color ramped tiles on the fly. So COGs can be stored on a simple file server (like Amazon S3 or Azure Blob Storage) and served up as interactive web maps with TiTiler as an intermediary between the COG files and the client accessing the interactive Shiny mapping app (Figure 7.1).

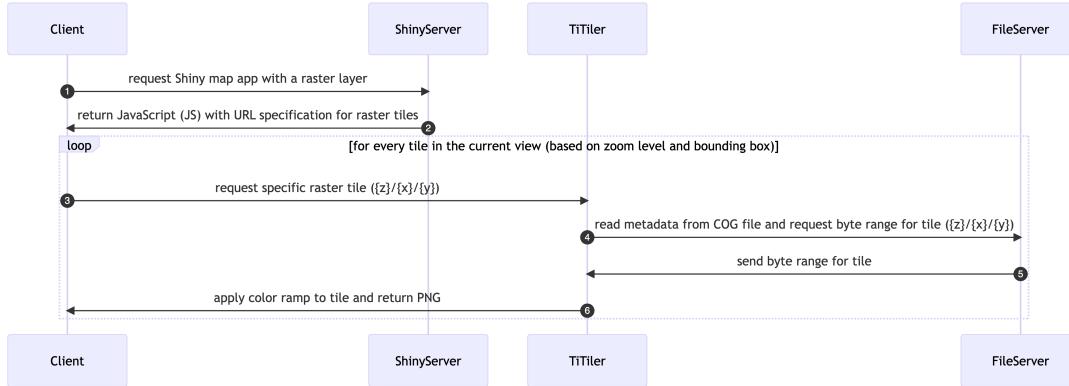


Figure 7.1: Sequence diagram implementing large raster interactive display using Cloud-Optimized GeoTIFFs (COGs) and Titiler in a Shiny mapping app.

7.0.2.2 Vector: Mapbox Vector Tiles (MVTs) and pg_tileserv

Although “cloud native” vector formats exist for simple file storage (see [Cloud-Optimized Geospatial Formats Guide](#)), none of these allow for flexible filtering and manipulation. Instead, we use PostgreSQL with the spatial extension ([PostGIS](#)) to store the vector data and serve it as Mapbox Vector Tiles ([MVTs](#)) using the [pg_tileserv](#) web service written in the language Go, which is very fast. This means that we don’t have to pre-render the MVTs (such as you might do with [tippecanoe](#)), but can instead serve the raw vector data directly from the database and let [pg_tileserv](#) handle the rendering on the fly. Filters (in the form of [CQL](#)) can be applied to the request. Symbology is rendered client-side via JavaScript, which allows for interactive hover and click events on vector objects (e.g., BOEM aliquot). Some speed-up is enabled by implementing a [Varnish](#) cache service in between. We can even write our own database functions for customized rendering, such as H3 hexagonal summaries. This allows us to serve vector data as web maps with minimal configuration and setup, and it provides a fast and efficient way to display large vector datasets in an interactive web application (Figure 7.2).

7.0.3 Github Repositories

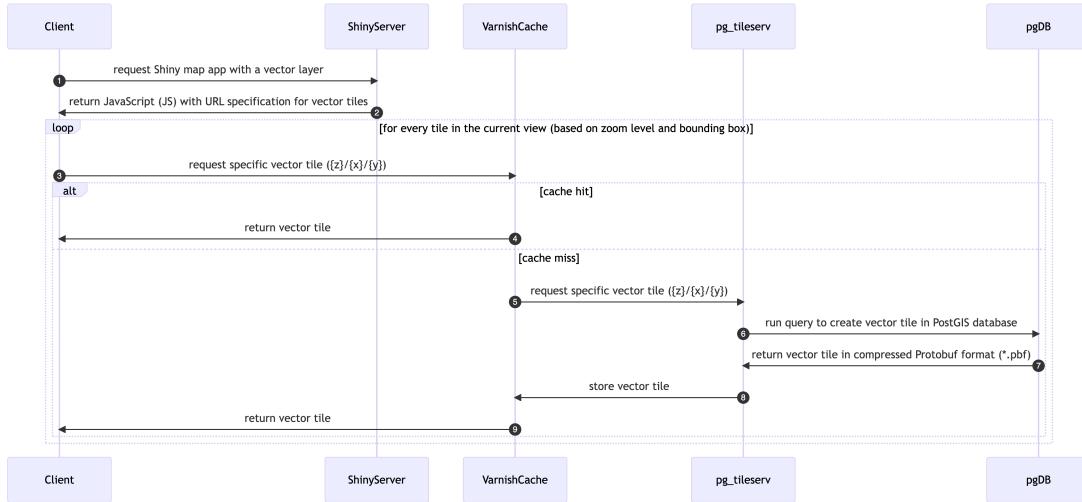
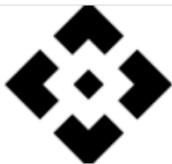


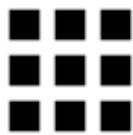
Figure 7.2: Sequence diagram implementing large vector interactive display using Mapbox Vector Tiles (MVTs) and pg_tileserv in a Shiny mapping app.

repo	description
api	application programming interface (API) using R Plumber package
apps	Shiny applications
docs	documentation for BOEM's offshore environmental sensitivity index products
manuscripts	Manuscripts with review of sensitivities by industry and receptors (species, habitats, human uses)
MarineSensitivity.github.io	default website
msens	R library of functions for mapping marine sensitivities, sponsored by BOEM
objectives	repository for issues spanning multiple repositories and doing big picture roadmapping
server	server setup for R Shiny apps, RStudio IDE, R Plumber API, PostGIS database, pg_tileserv
workflows	scripts for testing data analytics and visualization as well as production workflows

7.0.4 Software Components



APIs
application programming
interfaces (APIs)



Apps
interactive applications using
Shiny



Database
PostgreSQL database
extended spatially with
PostGIS



Docs
technical documentation



Libraries
documented functions as an R
package



Server
server software configuration
using Docker



Workflows
scripts for exploring plus
production workflows

8 Server

The server is for serving up any web services outside those of Github (e.g., [website](#), [docs](#) and R package [msens](#)) using [Docker](#) (see the [docker-compose.yml](#); with reverse proxying from subdomains to ports by [Caddy](#)).

8.1 Setup

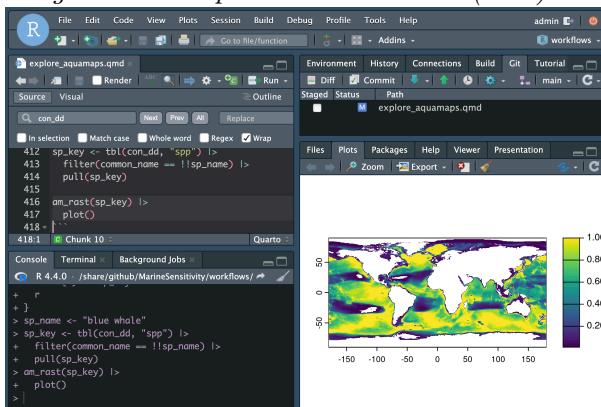
For instructions on launching an Amazon instance and installing the server software, see [Server Setup · MarineSensitivity/server Wiki](#).

8.2 Services

The server is running the following services:

- **RStudio**

integrated development environment (IDE) to code and debug directly on the server

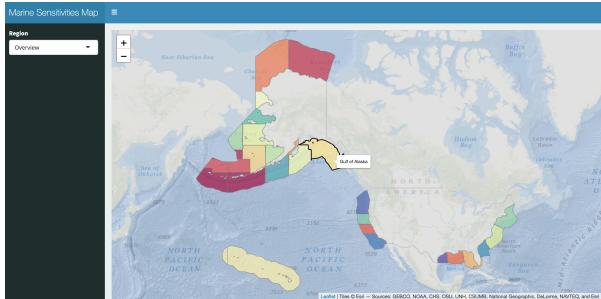


[More info...](#)

- **Shiny**

interactive applications

e.g., [shiny.marinesensitivity.org/map](#)



[More info..](#)

- [PGadmin](#)

PostGreSQL database administration interface

Screenshot of the PgAdmin PostgreSQL database administration interface. The left sidebar shows the Object Explorer with tables like 'ply_rgns' and 'ply_rgns_s05'. The main area shows a query result for 'public.ply_rgns_s05' with 27 rows. A Geometry Viewer panel on the right displays a map of the world with blue-shaded regions corresponding to the data in the table. The status bar at the bottom indicates 'Total rows: 27 of 27' and 'Query complete 00:00:01.068'.

[More info..](#)

- [api](#)

custom API: using R plumber

Screenshot of the MarineSensitivities Custom API using the Swagger interface. The top navigation bar shows the URL <https://api.marinesensitivities.org/openapi.json>. The main page displays the API description and a list of endpoints under the 'default' server. The 'Servers' dropdown shows the URL <https://api.marinesensitivities.org/>. The endpoint list includes:

- default**
 - GET /echo** Echo back the input
 - GET /plot** Plot a histogram
 - POST /sum** Return the sum of two numbers
 - GET /** redirect to the swagger interface

[More info..](#)

- [swagger](#)

generic database API: using PostGREST

standard public schema

Dialect: **HTTP**

Introspection

- geography_columns**
 - GET /geography_columns**
 - POST /geography_columns**
 - DELETE /geography_columns**
 - PATCH /geography_columns**
- geometry_columns**
 - GET /geometry_columns**

More info..

- **tile**

spatial database API: using pg_tileserv for serving vector tiles

pg_tileserv

Service Metadata

- [index.json](#) for layer list

Table Layers

- aquamaps.cells ([preview](#) | [json](#))
- public.ply_rgns ([preview](#) | [json](#))
- public.ply_rgns_s05 ([preview](#) | [json](#))
- public.ply_shfis ([preview](#) | [json](#))
- public.ply_shfis_s05 ([preview](#) | [json](#))
- public.sdm_geometries ([preview](#) | [json](#))
- raw.boem_ak_blk_clip ([preview](#) | [json](#))
- raw.boem_ak_prot_clip ([preview](#) | [json](#))
- raw.boem_ad_aq ([preview](#) | [json](#))
- raw.boem_at_blk_clip ([preview](#) | [json](#))
- raw.boem_at_prot_clip ([preview](#) | [json](#))
- raw.boem_gom_blk_clip ([preview](#) | [json](#))
- raw.boem_gom_prot_clip ([preview](#) | [json](#))
- raw.boem_pc_aq ([preview](#) | [json](#))
- raw.boem_pc_blk_clip ([preview](#) | [json](#))
- raw.boem_pc_prot_clip ([preview](#) | [json](#))
- raw.boem_usa_mhk_plan ([preview](#) | [json](#))
- raw.boem_usa_wind_lease ([preview](#) | [json](#))
- raw.boem_usa_wind_plan ([preview](#) | [json](#))
- raw.mr_eaz ([preview](#) | [json](#))

Function Layers

- [public.sdm_spatial](#) ([preview](#) | [json](#))

Serves the Species Distribution Model given parameters: dataset_key, species_key, popn, time_interval, variable.

More info..

9 Database

9.1 Table and Column Naming Conventions

- Table names are plural and use all lower case.
- Unique identifiers are suffixed with:
 - *_id for unique integer keys;
 - *_key for unique string keys;
 - *_seq for auto-incrementing sequence integer keys.
- Column names are singular and use snake_case.
- Foreign keys are named with the singular form of the table they reference, followed by _id.
- Primary keys are named id.

9.2 Species Distribution Models

See entity relationship diagram (ERD) for the species distribution models (SDM) database tables in this workflow:

- [Create SDM Tables](#)

And example of ingesting SDM outputs into the database in this workflow:

- [Ingest GoMex cetacean & sea turtle SDMs](#)

10 Workflows

Workflows are scripts for testing data analytics and visualization as well as production workflows for ingesting data. See:

- marinesensitivity.org/workflows
rendered html pages from the scripts (as Quarto notebooks)
- github.com/MarineSensitivity/workflows
source code in the Github repository

11 APIs

There three APIs, each used for different purposes:

1. api

custom API: using R plumber
source: [MarineSensitivity/api](#)

The screenshot shows the MarineSensitivity Custom API documentation generated by Swagger. At the top, there's a navigation bar with the title "MarineSensitivity Custom API 1.0.0 OAS3", the URL "https://api.marinesensitivities.org/openapi.json", and a "Explore" button. Below the navigation, there's a "Servers" dropdown set to "https://api.marinesensitivities.org/". The main content area is titled "default" and contains four API endpoints:

- GET /echo**: Echo back the input.
- GET /plot**: Plot a histogram.
- POST /sum**: Return the sum of two numbers.
- GET /**: redirect to the swagger interface.

2. swagger

generic database API: using PostGREST
source: Postgres database, non-spatial

The screenshot shows the standard public schema documentation generated by PostGREST. At the top, there's a navigation bar with the title "standard public schema 1.0.0 OAS3", the URL "https://rest.MarineSensitivity.org/", and a "Explore" button. Below the navigation, there's a "Schemes" dropdown set to "HTTP". The main content area is titled "Introspection" and lists several endpoints:

- GET /**: OpenAPI description (No document).
- geography_columns**
 - GET /geography_columns**
- geometry_columns**
 - GET /geometry_columns**
 - POST /geometry_columns**
 - DELETE /geometry_columns**
 - PATCH /geometry_columns**

3. tile

spatial database API: using pg_tileserv for serving vector tiles

source: Postgres database, spatial

pg_tileserv

Service Metadata

- [index.json](#) for layer list

Table Layers

- aquamaps.cells ([preview](#) | [json](#))
- public.ply_rgns ([preview](#) | [json](#))
- public.ply_rgns_s05 ([preview](#) | [json](#))
- public.ply_shfts ([preview](#) | [json](#))
- public.ply_shfts_s05 ([preview](#) | [json](#))
- public.sdm_geometries ([preview](#) | [json](#))
- raw.boem_ak_blk_clip ([preview](#) | [json](#))
- raw.boem_ak_prot_clip ([preview](#) | [json](#))
- raw.boem_atl_atlq ([preview](#) | [json](#))
- raw.boem_atl_blk_clip ([preview](#) | [json](#))
- raw.boem_atl_prot_clip ([preview](#) | [json](#))
- raw.boem_gom_blk_clip ([preview](#) | [json](#))
- raw.boem_gom_prot_clip ([preview](#) | [json](#))
- raw.boem_pc_atlq ([preview](#) | [json](#))
- raw.boem_pc_blk_clip ([preview](#) | [json](#))
- raw.boem_pc_prot_clip ([preview](#) | [json](#))
- raw.boem_usa_mnh_plan ([preview](#) | [json](#))
- raw.boem_usa_wind_lease ([preview](#) | [json](#))
- raw.boem_usa_wind_plan ([preview](#) | [json](#))
- raw.mr_eez ([preview](#) | [json](#))

Function Layers

- [public.sdm_spatial](#) ([preview](#) | [json](#))

Serves the Species Distribution Model given parameters: dataset_key, species_key, popn, time_interval, variable.

12 Libraries

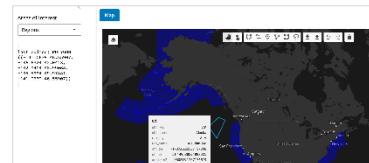
By creating an R package, we can document functions and make them easily available to other users.

- [msens](#)

R library of functions for mapping marine sensitivities, sponsored by BOEM

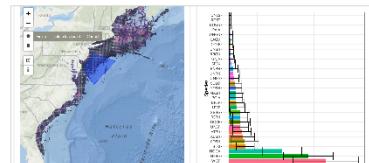
Functions can *read* data from the one [APIs](#) (which communicate with the [Database](#)), *analyze* the data, *visualize* the results and store some smaller *data*.

13 Apps



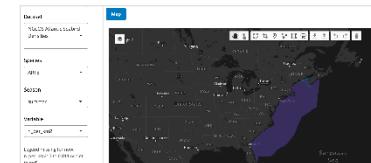
Areas of Interest
AREAS VECTOR

Map high resolution Areas of Interest (using vector tiles) for visualization (and later summarization).



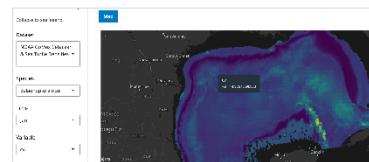
Bird Hotspots
DISTRIBUTIONS HOTSPOTS

Bird hotspots application showing hotspot probability for species present given drawn Area of Interest.



Distributions, Raster
DISTRIBUTIONS RASTER

Show species distributions with high resolution rasters as cloud-optimized GeoTIFFs (COGs).



Distributions, Vector
DISTRIBUTIONS VECTOR

Show species distributions with high resolution vectors (as vector tiles).



Regional Map
AREAS

Basic interactive map of BOEM regions.



Vulnerability Mapper
DISTRIBUTIONS VULNERABILITIES
RASTER

Combine species distribution models (raster) and vulnerability metrics (tables) to identify areas of high conservation concern.

See also details of individual applications in the Appendix.

14 Docs

Technical documentation is principally in this book:

- marinesensitivity.org/docs
the main documentation site
- github.com/MarineSensitivity/docs
source code in the Github repository

But there are also some other self-documenting resources:

- marinesensitivity.org/msens
documented R functions

15 Summary

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References

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Glossary

acclimatisation the adjustment of an organism to environmental conditions in the field or environment rather than the laboratory without an adjustment in their genetics. Acclimation has been used to describe phenotypically plastic responses in natural conditions. Source: Ross et al. (2023).

adaptation the evolutionary mechanism where natural selection of traits is genetically passed on, typically over many generations, to create an organism suited to the environment. Source: [rossRoss et al. (2023)

adaptive capacity the capacity of the ecosystem or organism to improve and reorganise in response to stress such as climate change through phenotypic plasticity (acclimation, acclimatisation) or adaptation, distributional shifts, and rapid evolution of traits suited to new conditions. Source: Ross et al. (2023).

epigenetics the modification of phenotype plasticity of an organism through altered gene expression without an alteration to the DNA sequence. ‘Epi’ means above the DNA and includes DNA methylation, modification of histones, and non-coding RNA. Source: Ross et al. (2023).

exposure the magnitude of the change in the environment

fecundity the maximum physiological potential reproductive output of an organism to produce offspring (reproductive output). This differs from fertility, which is the number of offspring born. Source: Ross et al. (2023)

MBON Marine Biodiversity Observation Network; see [MarineBON.org](#)

resilience the capacity of an ecosystem, society, or organism to absorb disturbance and reorganise while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks. Resilience reflects the degree to which a complex adaptive system is determined by its capacity to reorganise and adapt in order to avoid being disturbed again. Source: Ross et al. (2023).

sensitivity the magnitude of response to the change

stressor the stimulus that causes stress to an organism

vulnerability combination of exposure and sensitivity

Part III

Applications

Areas of Interest

Map high resolution Areas of Interest (using vector tiles) for visualization (and later summarization).

- [website](#)
- [code](#)

Area Explorer

The screenshot shows the 'Area Explorer' interface. On the left, there's a sidebar with a dropdown menu set to 'Regions'. Below it, a code snippet shows the last edit of a polygon:

```
last edited: POLYGON((-141.0639 46.55907, -136.6324 42.0423, -132.0404 48.99068, -135.5994 49.97881, -141.0639 46.55907))
```

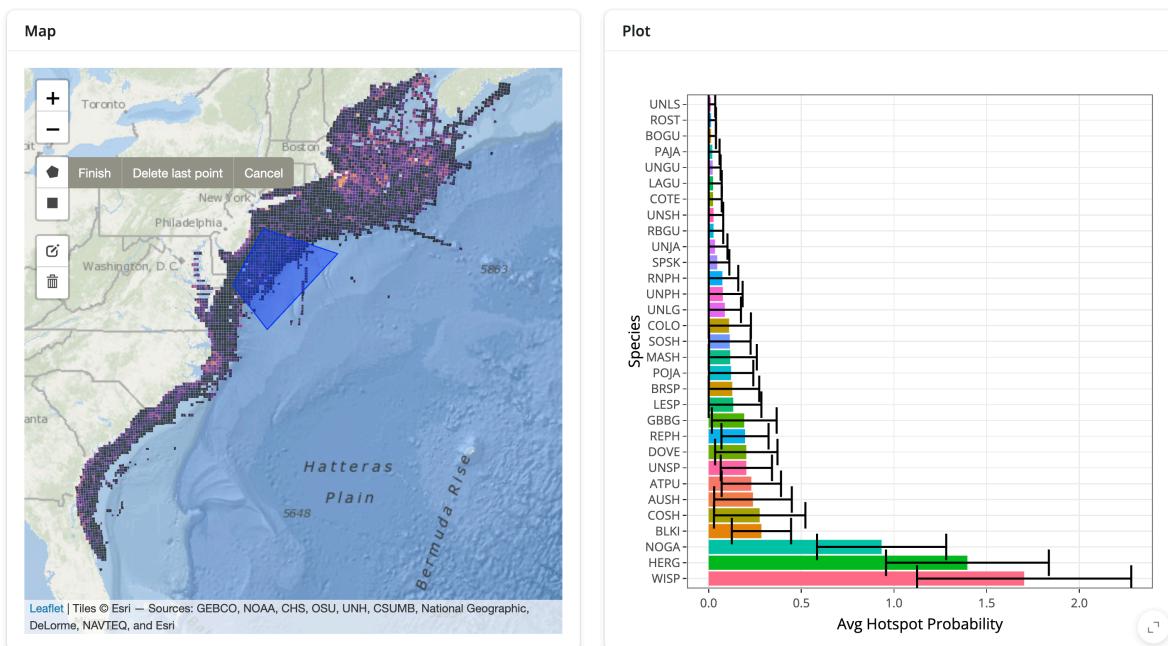
The main area is a map of North America with a blue polygon highlighting the Aleutian Arc region off the coast of Alaska. A tooltip provides detailed information about this area:

aoi	shlf_key	shlf_name	rgn_key	rgn_name	ctr_lon	ctr_lat	area_km2	geometry
			AK	Alaska	ALA	Aleutian Arc	-178.56252307137368	null
							51.149538291898025	
							860518.1237176519	

Bird Hotspots

Bird hotspots application showing hotspot probability for species present given drawn Area of Interest.

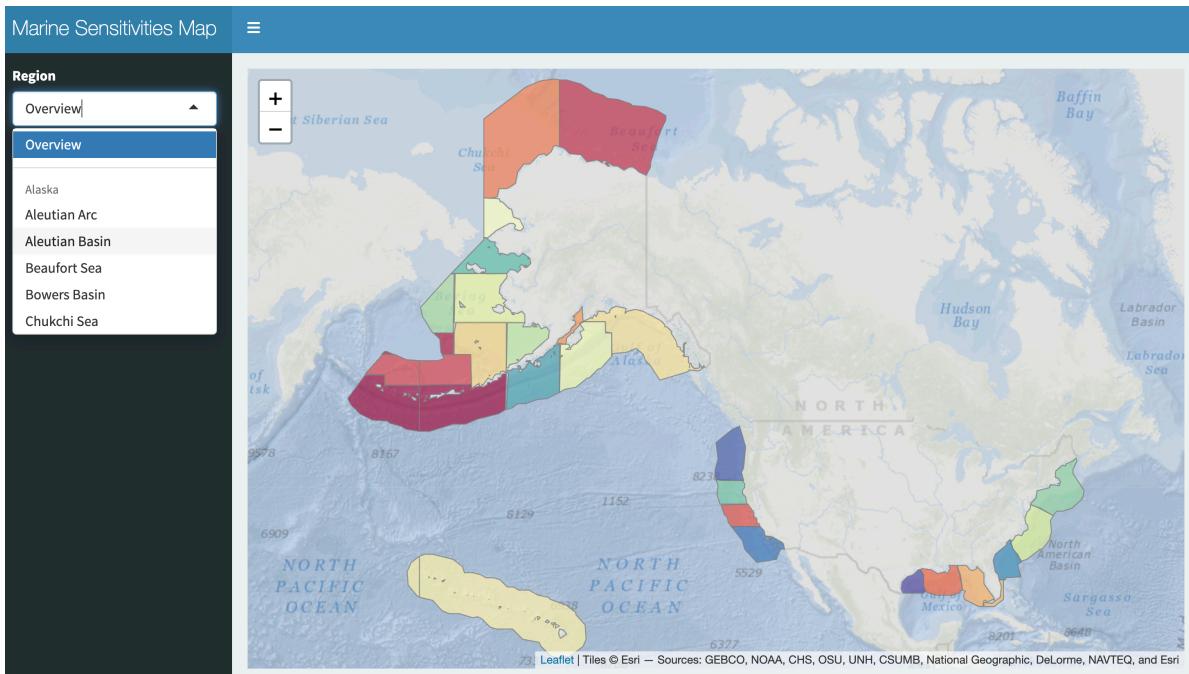
- [🌐 website](#)
- [📄 code](#)



Regional Map

Basic interactive map of BOEM regions.

- [🌐 website](#)
- [🔗 code](#)

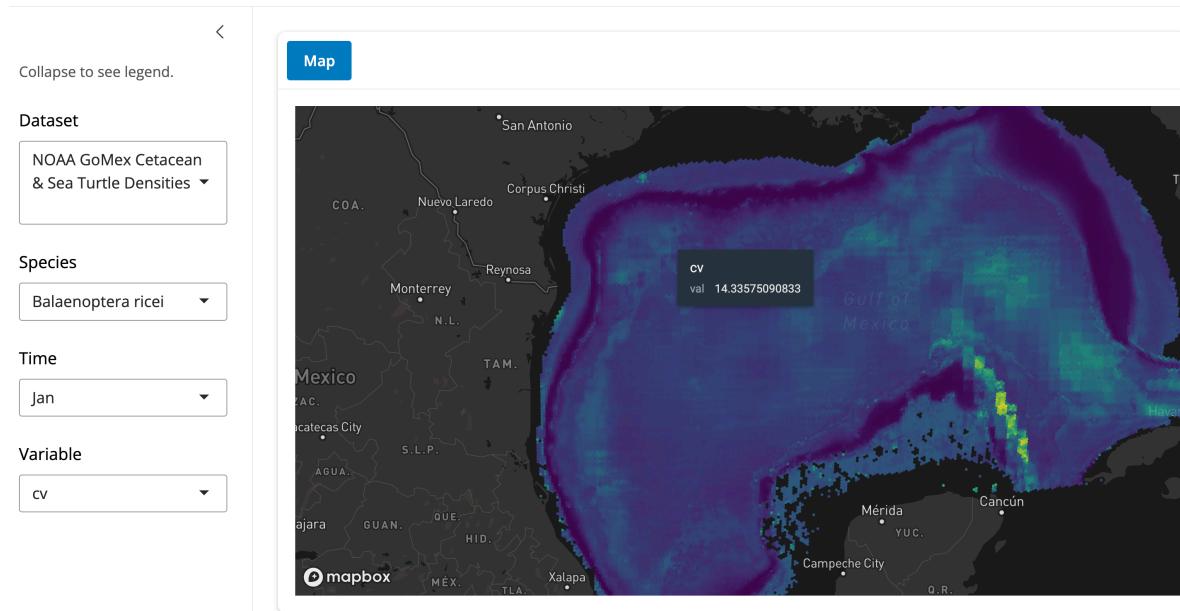


Distributions, Vector

Show species distributions with high resolution vectors (as vector tiles).

- [website](#)
- [code](#)

SDM Explorer

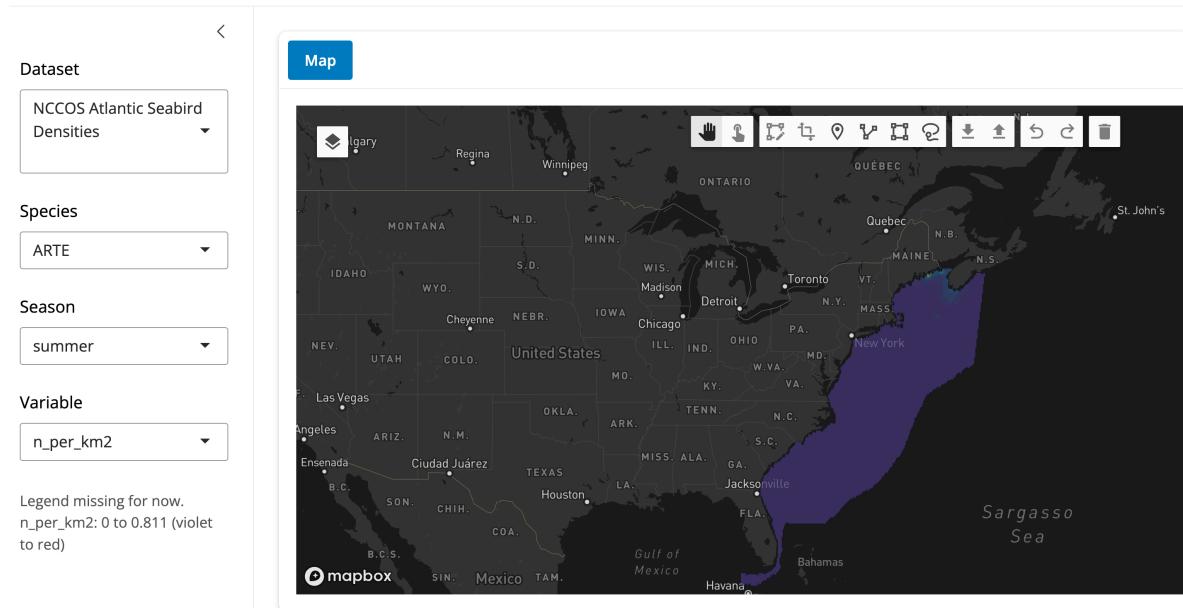


Distributions, Raster

Show species distributions with high resolution rasters as cloud-optimized GeoTIFFs (COGs).

- [🌐 website](#)
- [📄 code](#)

SDM Raster Explorer



Vulnerability Mapper

Combine species distribution models (raster) and vulnerability metrics (tables) to identify areas of high conservation concern.

- [!\[\]\(2c8d305fe0b09cd1c250cfab86a151f9_img.jpg\) website](#)
- [!\[\]\(7dc69c02936bae3531fc863043815131_img.jpg\) code](#)

