Database

Marine Sensitivity 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.

The term vulnerabilitycombination of exposure and sensitivity (V) is a function of exposureThe magnitude of the change in the environment (E), sensitivityThe magnitude of response to the change (S) and adaptive capacityThe 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) (A).

$$V = f(E, S, A) \tag{1.1}$$

$$cell_S = \sum_{spp} p * w \tag{1.2}$$

The raster of sensitivity (S) contains cells representing a sum across species (spp) of presence (p) multiplied by the sensitivity weight (w) (Equation 1.2).

1.1 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

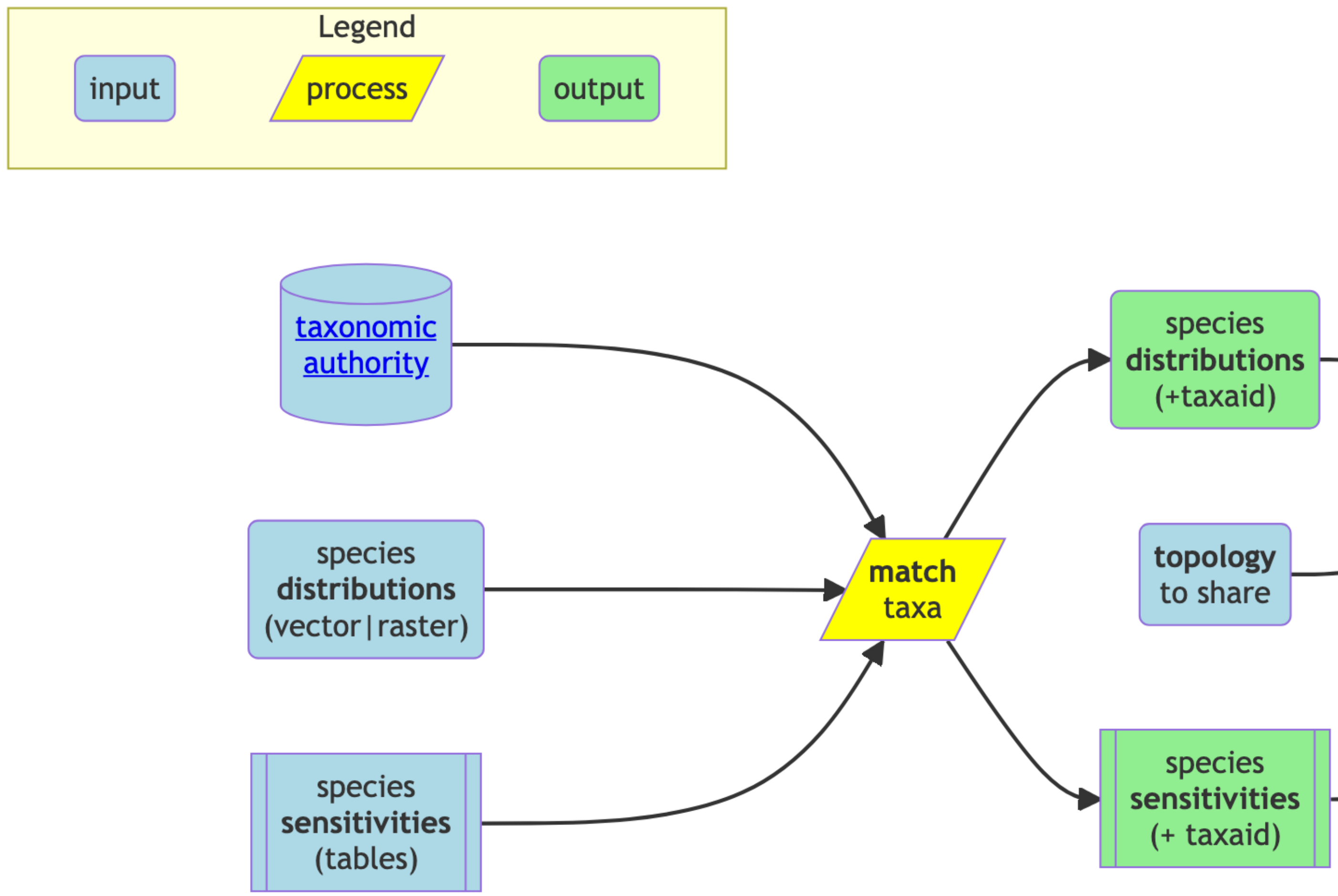

Figure 1.1: Flowchart of process for incorporating marine species sensitivities with distributions and generating a holistic vulnerability map.

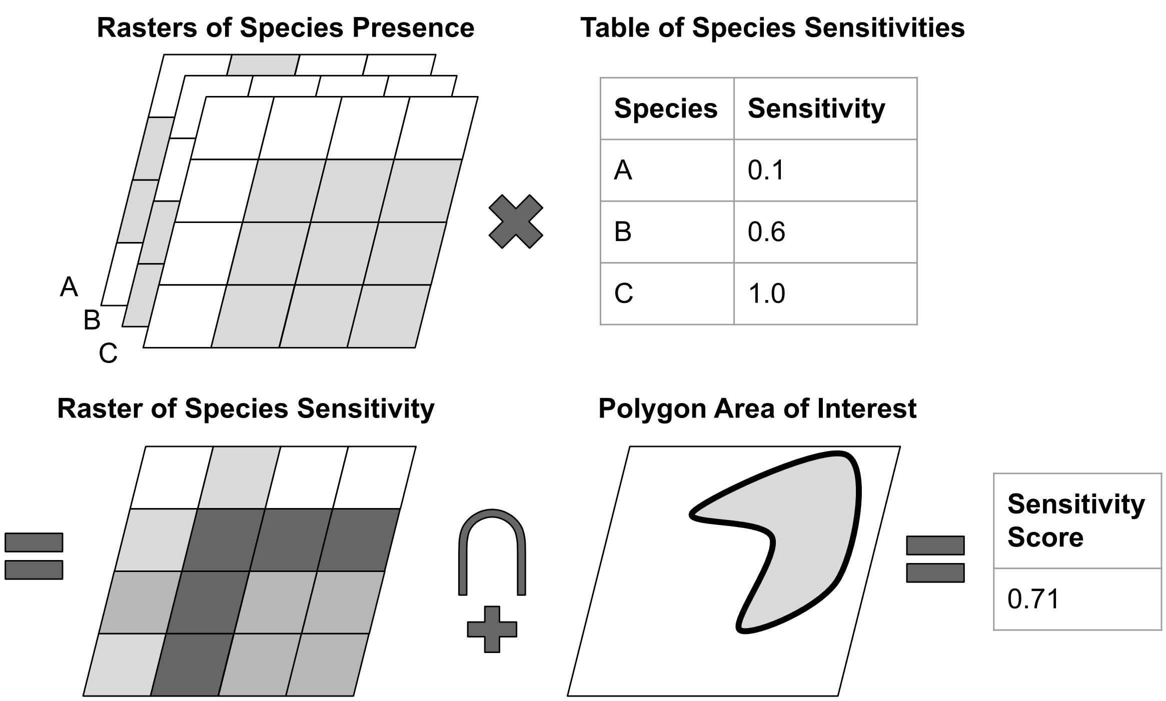

Figure 1.2: Overview of process.

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.

1.2 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-usable 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.

1.2.1 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 1.3).

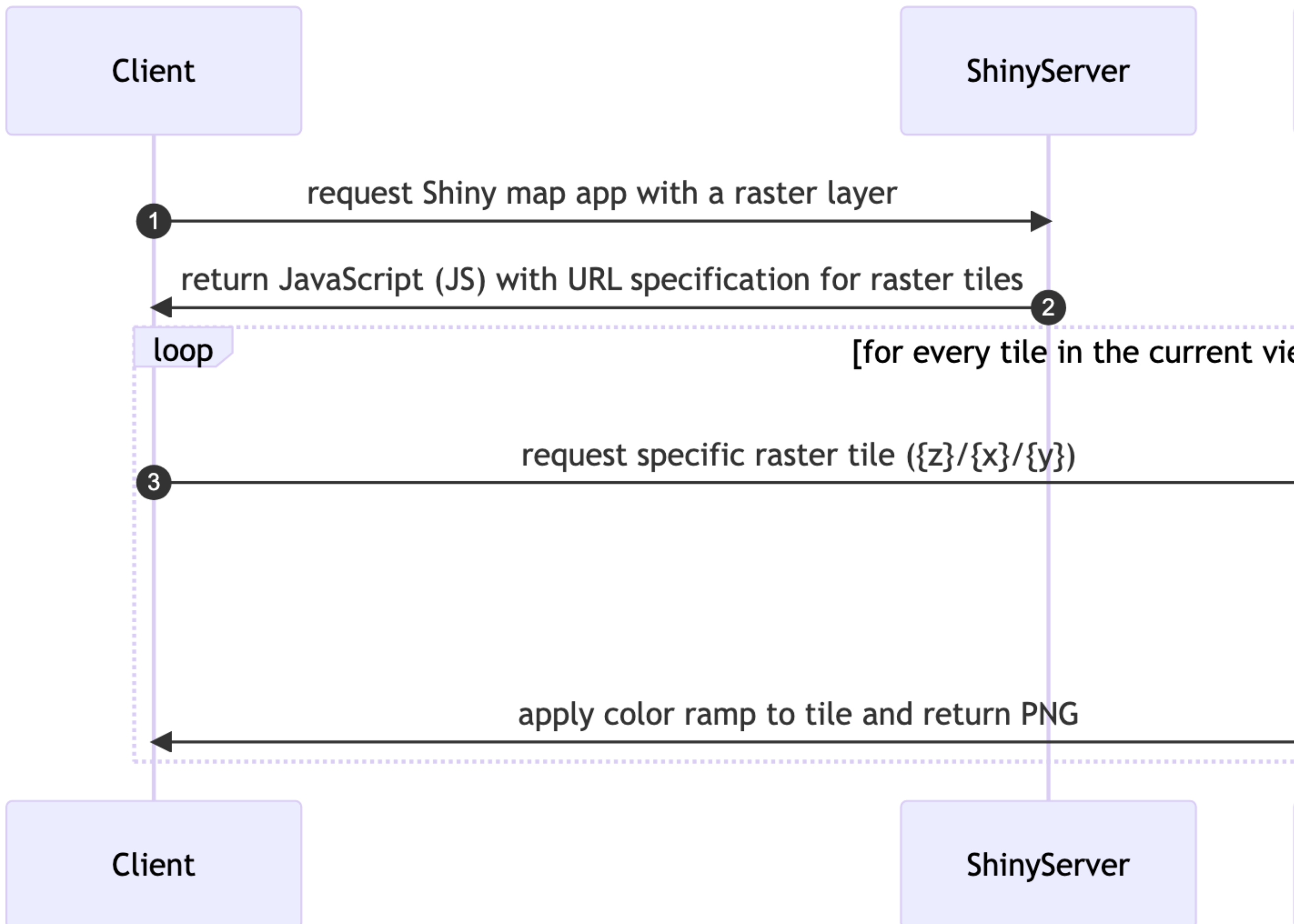

Figure 1.3: Sequence diagram implementing large raster interactive display using Cloud-Optimized GeoTIFFs (COGs) and Titiler in a Shiny mapping app.

1.2.2 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 1.4).

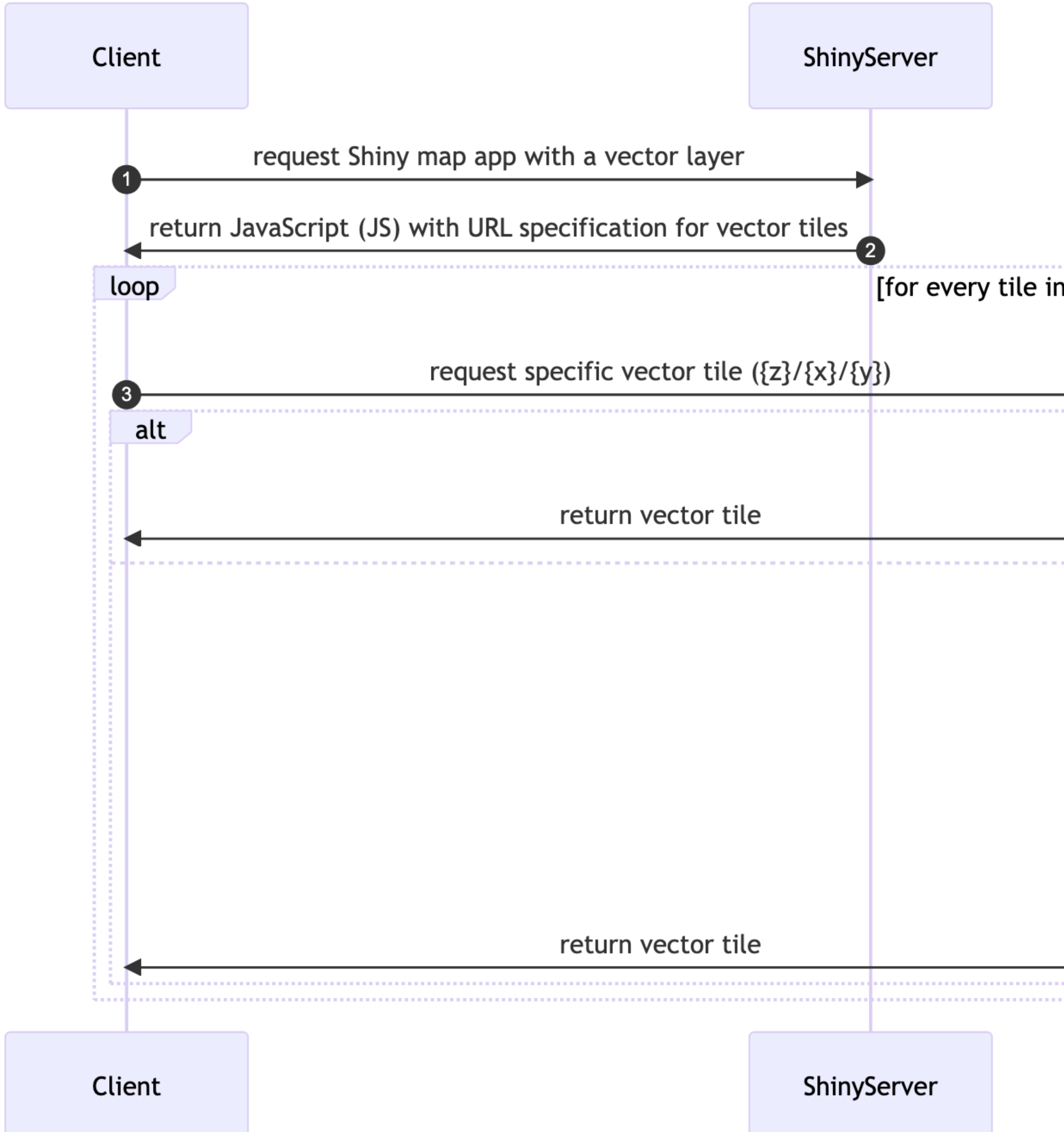

Figure 1.4: Sequence diagram implementing large vector interactive display using Mapbox Vector Tiles (MVTs) and pg_tileserv in a Shiny mapping app.

Part I

Components

2 API

There are actually three APIs, each used for different purposes:

1. **api**
   custom API: using R plumber
   source: MarineSensitivity/api

2. **swagger**
   generic database API: using PostGREST
   source: Postgres database, non-spatial

3. **tile**
   spatial database API: using pg_tileserv for serving vector tiles
   source: Postgres database, spatial

3 Apps

4 Database

4.1 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.

4.2 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

5 Docs

6 Libraries

or maybe later Python module

7 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).

7.1 Setup

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

7.2 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

  More info..
- **api**
  custom API: using R plumber

  More info..

- **swagger**
  generic database API: using PostGREST

  More info..

- **tile**
  spatial database API: using pg_tileserv for serving vector tiles

  More info..

8 Workflows

```
librarian::shelf(
  dplyr, gh, glue, knitr, tidyjson,
  quiet = T)
# OLD: renv
#   # renv::dependencies(); renv::snapshot()
#   library(dplyr); library(gh); library(glue); library(knitr); library(tidyjson)
# NEW: r-lib/actions/setup-r-dependencies@v2
#   sapply(c("dplyr","gh","glue","knitr","tidyjson"), usethis::use_package)

org   <- "MarineSensitivity"
```

8.1 Get Descriptions

```
gh(glue("GET /orgs/{org}/repos")) |>
  spread_all() |>
  as_tibble() |>
  select(name, description) |>
  arrange(name) |>
  kable()
```

name	description
MarineSensitivity.github.io	default website
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)
msens	R library of functions for mapping marine sensitivities, sponsored by BOEM

name	description
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

9 Summary

In summary, this book has no content whatsoever.

```r
1 + 1
```

```
[1] 2
```

References

Boyce, Daniel G., Derek P. Tittensor, Cristina Garilao, Stephanie Henson, Kristin Kaschner, Kathleen Kesner-Reyes, Alex Pigot, et al. 2022. "A Climate Risk Index for Marine Life." *Nature Climate Change* 12 (9): 854–62. https://doi.org/10.1038/s41558-022-01437-y.

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Ross, Pauline M., Elliot Scanes, Maria Byrne, Tracy D. Ainsworth, Jennifer M. Donelson, Shawna A. Foo, Pat Hutchings, Vengatesen Thiyagarajan, and Laura M. Parker. 2023. "Surviving the Anthropocene: The Resilience of Marine Animals to Climate Change." In. CRC Press.

Weis, Shawn W. Margles, Vera N. Agostini, Lynnette M. Roth, Ben Gilmer, Steven R. Schill, John English Knowles, and Ruth Blyther. 2016. "Assessing Vulnerability: An Integrated Approach for Mapping Adaptive Capacity, Sensitivity, and Exposure." *Climatic Change* 136 (3-4): 615–29. https://doi.org/10.1007/s10584-016-1642-0.

Zacharias, Mark A., and Edward J. Gregr. 2005. "Sensitivity and Vulnerability in Marine Environments: An Approach to Identifying Vulnerable Marine Areas." *Conservation Biology* 19 (1): 86–97. https://doi.org/10.1111/j.1523-1739.2005.00148.x.

Glossary

term	definition
acclimation	The adjustment of an organism to experimental conditions in the laboratory without an adjustment in their genetics. Acclimation has been used to describe phenotypically plastic responses of organisms generated under controlled laboratory and experimental manipulations when the factor of interest can be isolated.
Acclimation	The adjustment of an organism to experimental conditions in the laboratory without an adjustment in their genetics. Acclimation has been used to describe phenotypically plastic responses of organisms generated under controlled laboratory and experimental manipulations when the factor of interest can be isolated. Source: Ross et al. (2023)
Acclimatisation	The adjustment of an organism to environmental conditions in the field or environment rather than the laboratory without an adjustment in their genetics. Acclimatisation has been used to describe phenotypically plastic responses in natural conditions. Source: Ross et al. (2023)
adaptation	the ability to change in response to the change
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: Ross 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
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 ability to recover from the change

term	definition
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
Sensitivity	The magnitude of response to the change
stressor	the stimulus that causes stress to an organism
Stressor	The stimulus that causes stress to an organism
vulnerability	combination of exposure and sensitivity
Vulnerability	combination of exposure and sensitivity

(Ross et al. 2023)

Glossary.

(Weis et al. 2016)

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

Vulnerability (V) is a function of exposure (E), sensitivity (S) and adaptive capacity (A).

(Jones and Cheung 2018)

Such vulnerability assessments recognize that a species' vulnerability to climate change depends on an interaction between its intrinsic biological or ecological characteristics (sensitivity and adaptive capacity) and the extrinsic threats or stimuli (exposure and hazard) (Figure 1). In this study, we adopted the climate vulnerability and risk assessment framework used by the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Field et al. (2014).

Sensitivity of a species, referred to here as the susceptibility to impacts from climate change, is affected by species' biological and ecological traits. Species' sensitivity may be moderated by their

adaptive capacity, which reflects a species' ability to adapt and thus cope with, or avoid, the impacts of climate change.

As the unit of assessment is an individual species, we consider a species' ability to shift in distribution to avoid or minimize negative impacts from changing habitat conditions on its viability as an adaptive response to climate change. Specifically, in this study, we focus on characteristics that determine a species ability to show this response, within its current distribution. Thus, the spatial response of a distribution shift may itself be influenced by adaptive characteristics included here. The combination of a species' sensitivity and (lack of) adaptive capacity determines its vulnerability to climate change. Ultimately, the risk of impacts of climate change on the species is determined by its vulnerability as well as the potential occurrence of climate-related ocean changes (i.e., hazards such as warming, ocean acidification) and the degree of exposure to such event (i.e., exposure) (Figure 1).

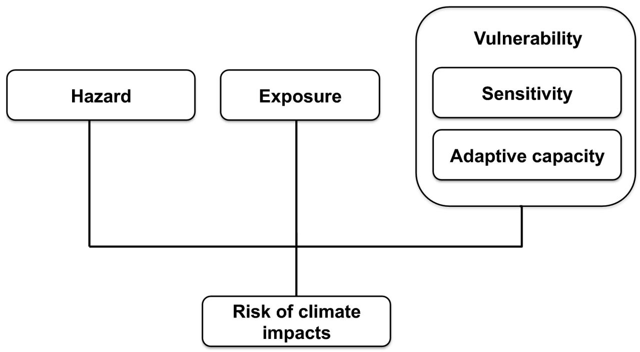

Figure 1: Framework for assessing climate change vulnerability and risk adopted by the fifth assessment report of the IPCC (Field et al., 2014)

(Zacharias and Gregr 2005)

Definitions of Sensitivity and Vulnerability

Sensitivity and vulnerability are central concepts in the protection of marine ecosystems, yet the marine literature provides few explicit definitions (Holt et al. 1997; Tyler-Walters & Jackson 1999). Consequently, their meaning often relies on the context in which they are used. To avoid context-dependent definitions of these terms, we took the following value-neutral approach to defining sensitivity and vulnerability.

It is axiomatic that all marine features have either evolved (in the case of biotic features) or been formed (in the case of abiotic features) within a certain range of environmental conditions. We define *stress* as a deviation of these environmental conditions beyond the expected range. *Sensitivity* is the degree to which marine features respond to such stress. Specifically, sensitivity is measured using one or more indicators (of species, communities, and habitats) that respond to one or more natural or anthropogenic stressors. These responses are potentially nonlinear and are likely to include interactions between stressors. In this context, sensitivity does not inherently assume the characteristics of fragility or intolerance with which it is often associated. There is no implied judgement that an increased association between the indicator and the stressor reduces a feature's probability of ***persistence***. Nevertheless, as exposure to a chronic perturbation or stress increases, the persistence of that feature is diminished.

Vulnerability is the probability that a feature will be exposed to a ***stressor*** to which it is ***sensitive***. In other words, vulnerability is the likelihood of ***exposure*** to a relevant external stress factor (sensu Tyler-Walters & Jackson 1999), combined in some way with the ***exposure*** (duration, magnitude, rate of change) to that stress.

Subsumed under the concepts of sensitivity and vulnerability are the concepts of ***stability*** and ***fragility***. Although these terms lack general consensus on their definitions, Holling (1986) states that

stability is the tendency of a system to attain or retain an equilibrium condition of steady state or stable oscillation.

Resilience is the ability of a system to maintain its structure and behavioral patterns when subjected to ***disturbance***. A feature, therefore, that is stable or resilient in the presence of a stressor is not sensitive to that stress as we have defined it. Also, a feature that is sensitive to a stressor for which it has a low probability of exposure is not vulnerable.

Our definitions of *sensitivity* and *vulnerability* are consistent with the ESI approach used for oil spill response and countermeasures (Gundlach & Hayes 1978). Under the ESI approach a resource is defined as sensitive to oil if it would be harmed by physical contact with oil or concentrations of oil in water. A resource is defined as vulnerable if it is likely that it would be exposed to oil or high concentrations of oil for long enough periods for the oil to affect it. Vulnerability in terms of oil spills on shorelines, therefore, is a function of duration of exposure, recognizing that certain resources are vulnerable to oiling regardless of duration.

Our definition of a VMA, which incorporates the concepts of sensitivity and vulnerability, is a geographically definable area containing features that are sensitive to natural and/or anthropogenic stressors they are likely to encounter. Features may be biotic (species, communities) or abiotic (habitats) structures or processes.

We caution against equating VMAs as we have defined them (and their sensitivity and vulnerability components) with terms such as *priority areas*, *biodiversity hotspots*, *critical habitat*, *environmental significance*, and *areas of interest*, which are often used to identify areas of special concern or areas requiring management attention. Although certain VMAs may also represent priority areas or hotspots, depending on how these terms are defined and applied, an area may be sensitive or vulnerable but not meet criteria commonly used (e.g., species diversity) to identify these areas. In addition, although our definitions of *sensitivity* and *vulnerability* may contribute to measures or assessments of ecological (or ecosystem) integrity, these concepts are again different. Lastly, identification of an area as sensitive or vulnerable does not suggest that an area should be recommended as a marine protected area (MPA) or marine reserve or that MPAs are the only management tool applicable to the management and conservation of VMAs.

(Boyce et al. 2022)

climate change vulnerability assessments (CCVAs)

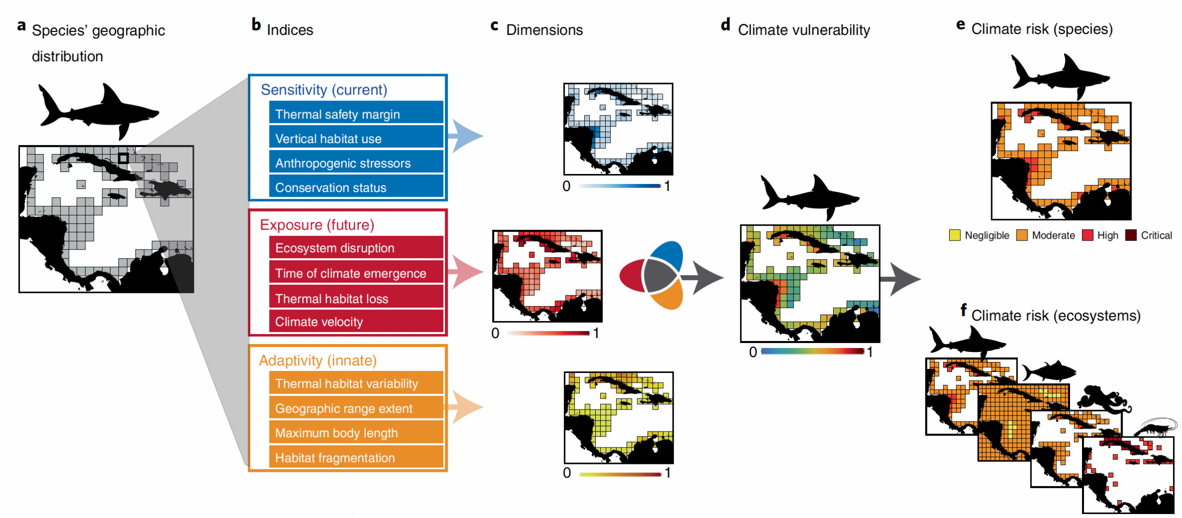

Figure 2: **a**–**e**, Within each grid cell (1° × 1° here) across the native geographic distribution of a species (**a**), 12 standardized climate indices are calculated (**b**) and used to define the three dimensions of climate vulnerability (**c**): present-day sensitivity (blue), projected future exposure (red) and innate adaptivity (yellow). The dimensions are used to calculate the species' climate vulnerability (**d**), and the relative vulnerability scores are translated into absolute climate risk categories (**e**). **f**, Species maps are superimposed to assess the climate vulnerability and risk for marine ecosystems. Basemaps in **a**,**c**–**e** from Natural Earth.

- Distribution (xy)
  of species
- Indices (n=12):
  species weights
  - Exposure (current)
    - Thermal safety margin
    - Vertical habitat use
    - Anthropogenic stressors
    - Conservation status
  - Sensitivity (future)

        - Ecosystem disruption
        - Time of climate emergence
        - Thermal habitat loss
        - Climate velocity
    - Adaptivity (innate)
        - Thermal habitat variability
        - Geographic range extent
        - Maximum body length
        - Habitat fragmentation

- Dimensions (D)
    - Exposure (E)
    - Sensitivity (S)
    - Adaptivity (A)
- (Climate) Vulnerability

$$V = E * S * A$$

- (Climate) Risk (R)
    - Species (sp)
    - Ecosystem

$$R_{eco} = \sum sp$$

From the supplement:

> Following an early IPCC definition7 and subsequent broad adoption (4–6,8–10), species' climate
>
> **vulnerability** has been defined by three dimensions: their sensitivity, exposure, and adaptive capacity (adaptivity) to climate change.
>
> **Sensitivity** refers to the propensity for a species to be adversely affected by its exposure to climate change.
>
> **Exposure** refers to the extent to which species will be subjected to hazardous climate changes, including the magnitude of the effects.

Adaptivity refers to the potential of species to adapt to any adverse exposure to climate change.

These dimensions have close analogies in other disciplines, including community ecology and dynamic complex systems theory (11–13). For example,
sensitivity is analogous to the ecological concept of ***resistance***,
exposure is analogous to ***reactivity***, and
adaptivity is analogous to ***resilience*** (14–16).