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Portuguese Institute for the Sea and Atmosphere (IPMA)  
Centre of Mathematics (CMAT, University of Minho)

## Spatio-Temporal Modeling of Juvenile Sardine: Integrating Fisheries Data and Environment

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Navigating Changes in Small Pelagic Fish and Forage Communities: Climate, Ecosystems, and Sustainable Fisheries  
May 4 - 8, 2026 | La Paz, Mexico

ICES  
CMAT

FAO  
Small Pelagic Fish and Forage Symposium 2026

2030  
United Nations Agenda  
Sustainable Development Goals



# Fishery Data Sources & Challenges

## Fishery-independent data (FID) - scientific surveys

- ✔ Structured design.
- 🌍 Wide spatial coverage.
- 🕒 Short time span.
- 📊 **Many zeros.**
- 🔍 **Our scientific eye - broad but limited in time.**

## Fishery-dependent data (FDD) - commercial fisheries

- 🐟 Opportunistic (e.g., logbooks, AIS).
- 🕒 Long time span.
- 📍 Habitat-restricted sampling.
- ⚠️ **Preferential sampling\* (PS).**
- 👤 **Fishers' eye - detailed but biased toward fishing grounds.**

💡 *Two complementary, but imperfect views of the ocean.*

\*Preferential Sampling: When the location of the data depends on the density of the fish.

- Better **understand European sardine juvenile spatial distribution** by **integrating different data sources.**



## Scientific Surveys (FID)

- ▷ **JUVESAR** 2013-2017 + **IBERAS** 2018.
- ▷ 2362 sardine NASC values.
- ▷ **Biomass index** ( $mg\ m^{-2}$ ).
- ▷ **Structured but sparse.**
- ▷ 2 distinct ships.



## Commercial Fleet (FDD)

- ▷ Commercial data from through AIS.
- ▷ 1687 sardine biomass values.
- ▷ **Catch rate** ( $Kg\ h^{-1}$ ).
- ▷ **Dense but biased.**
- ▷ 73 different vessels.

⚠ Unit Mismatch

⚠ Zero-Inflation

⚠ Heterogeneity

## I. Ecological Process ("Truth")

**Latent Spatio-Temporal Field  $S(x, t)$**

Driven by: Environment (e.g., SST, Chl-a, ocean currents)



# Bridging the Gaps: A Hierarchical Spatio-Temporal Approach

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## II & III. "Observation Filters"

### Scientific filter

- Standardized Design
- Catchability  $q$



### Fishing behavior

- Preferential sampling (PS)
- Modeled as IPP
- Catchability  $k(v)$
- Sea status, distance to the harbour, etc



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Estimation of spatial distribution by joint modelling integrating FID and FDD.

## Methodological details

### 1. Zero-Inflation

Hurdle model framework:  
*Bernoulli* (Presence-absence) +  
*Gamma* (Biomass)

### 2. Preferential Sampling

Inhomogeneous Poisson Process  
(IPP) linked to fish density  $S(x, t)$

### 3. Spatial Structure

Matern covariance with Barrier  
Model to deal with coastlines

### 4. Vessel Effects

Catchability  $k(v)$  standardized  
across commercial fleets

# Layer 1: Ecological Process

Modelling juvenile sardine density through environmental drivers

## Latent Field $S(\mathbf{x}, t)$

A continuous space-time process representing the **true** juvenile abundance.

To handling zero-inflation, two sub-processes are generated:

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Observed Biomass

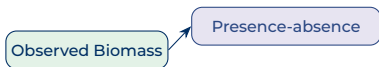
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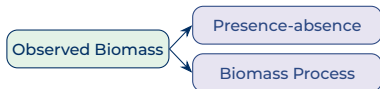
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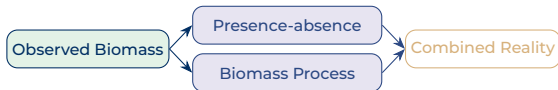
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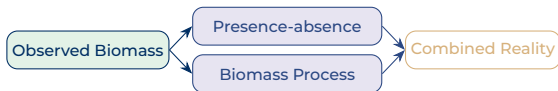
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### Hurdle model:

Presence-absence  $\sim f(\text{Environment}) + \text{Spatial} + \text{Spatio-temporal}$

Biomass  $\sim f'(\text{Environment}') + \text{Spatial}' + \text{Spatio-temporal}'$

- ▶ **smoother effects**  $f(\cdot)$  and  $f'(\cdot)$  of **covariates** with **time-lagged effects** (Silva et al., 2024).

**Note:** Spatial correlation is modelled according to "Nearby locations have similar abundances" and deal with physical constraints by using Barrier Model (Bakka et al., 2019).

## Drivers (Data Inputs)

These drivers explain the **fixed effects**  $f(\cdot)$ .

- 🌡️ Sea surface temperature;
- 🌿 Chlorophyll-a;
- 📊 Bathymetry;
- 🌊 Ocean currents.

Source: COPERNICUS Marine Service

### Preferential Sampling (PS)



Fishers maximize catch by **aggregation on "known hotspots"** of fish density  $S(x, t)$ .



Treating this like standardized data **leads to massive overestimation** of biomass in unsampled areas.



Modelling the probability of a data point existing in a given time and place.

# Layer 2: Sampling Process (Fisher behavior)

## Modelling Fisher Behavior & Preferential Sampling

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#### Shared latent process model:

**Sampling intensity**  $\lambda(x, t)$ : Number of sample units/observations within a cell.

Fishing intensity  $\sim f(\text{External factors}) + \beta' \text{Spatial} + \beta \text{Spatial}'$

- ▷  $\beta$  and  $\beta'$  denotes the **relationship between fisher behavior and species distribution** (e.g.,  $\beta > 0$  indicates that fishing activity concentrates where abundance is high).

#### Drivers (Data Inputs)

**These explain why fishers go where they go, besides just the fish.**



Bathymetry ( $m$ );



Sea surface wave significant height ( $m$ );



Wind ( $km/h$ ).

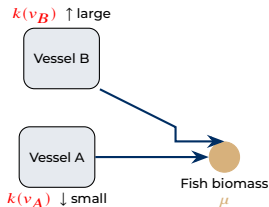
Sources: COPERNICUS Marine Service & COPERNICUS Climate Change Service

## Layer 3: Catchability (Vessel efficiency)

Standardizing the vision of scientific surveys and commercial fleets

### Catchability ( $q$ and $k(v)$ )

- ⚠ **Not all observations are created equal.** Different vessels have different efficiency (e.g., gear, size, technology, crew).
- 💡 We treat catchability not as a constant, but as a **dynamic process that varies by vessel.**

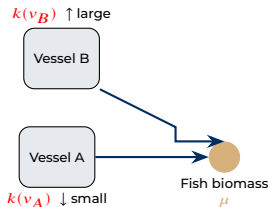


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## Methodology:




Relative biomass = Catchability  $\times$  True Biomass

-  **FID - Constant catchability per ship considered,  $k(v) = q$ .**  
*One or few ships are considered.*
-  **FDD - Vessel-specific  $k(v)$  accounts for technical attributes and skipper effect (random effect):**

Catchability  $\sim$  Vessel features

## Drivers (Data Inputs)

These factors define the efficiency of each vessel.

-  Tonnage;
-  Length;
-  Power of main engine.

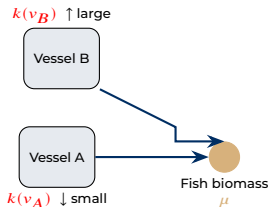
Sources: Fleet Register

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$$\text{Catchability} \sim \text{Vessel features}$$

- 🚀 By the end of this layer, acoustic density ( $mg\ m^{-2}$ ) and catch weight ( $kg\ h^{-1}$ ) have been **converted into a single, comparable language.**

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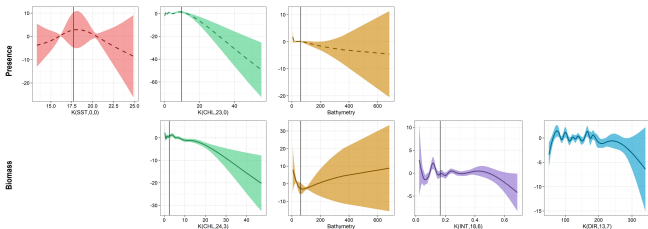
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# Decoding the Ecological Process


## Environmental drivers for Presence vs. Relative Biomass




### Presence-Absence (The "Where"):


 **SST:** The probability of presence is highest at 18°C. Below 15°C, they simply aren't there.


 **Chlorophyll:** Presence is high at low concentrations but drops off as it gets too high.


 *Temperature acts as the primary filter - it determines the spatial boundaries of the nursery.*


### Biomass (The "How Much"):

 **Chlorophyll:** Biomass is highest at low-to-moderate Chl-a levels and then drops significantly.

 **Bathymetry:** Biomass peaks sharply in the very shallow areas (< 50m).

 **Current intensity:** High biomass is associated with moderate current speeds.

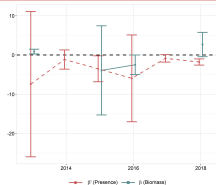
 **Current direction:** Cyclical effects for directions west-east and north south.

 **Highest concentrations of juveniles** are associated with **shallow waters, edge of plumes, retention zones** where the water moves just enough to bring in nutrients but doesn't "sweep" them away, and **upwelling occurrence**.

# Decoding Fisher Behavior: Targeting & Constraints

Environmental drivers for Presence vs. Relative Biomass

## Preferential Sampling (Targeting):

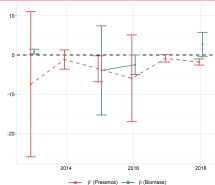


⊕ Weak PS for juveniles

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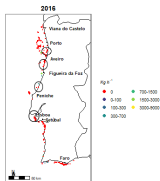
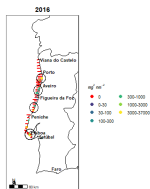
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## Particular case of 2016:



Fishing activity is observed in areas with no and positive biomass -> uncertainty about presence

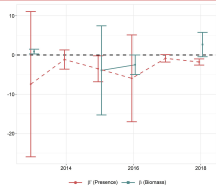



More fishing points where biomass is low than where is high -> negative relationship with biomass

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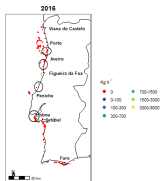
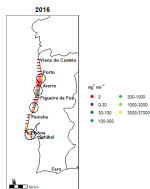
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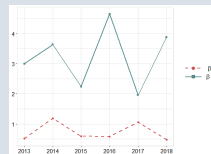



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## Comparing with previous sardine adults study (*Silva et al., 2026*):

These studies comprise different window time of the year.



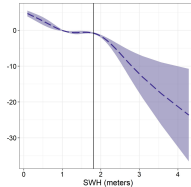
 High values proves adults are a primary target

 Other targeting species?

# Decoding Fisher Behavior: Targeting & Constraints

Environmental drivers for Presence vs. Relative Biomass

## Operational Constraints:

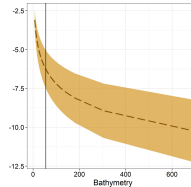


**Graphic interpretation:** Stable effort level that suddenly "crashes" after 1.8-2.0 meters.

## Why?

Big waves may:

- compromise **vessel's stability**;
- cause **the net to tear or become tangled** easily.



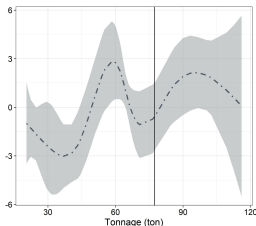
**Graphic interpretation:** Non-linear decline in effort as depth increases.

## Why?

- **Fuel costs and logistics** (bathymetry can be seen as a proxy for distance to the port);
- **Target species** since sardine juveniles are coastal;
- Purse-seine **nets features** (e.g., depth).

# Decoding Catchability

Accounting for vessel efficiency



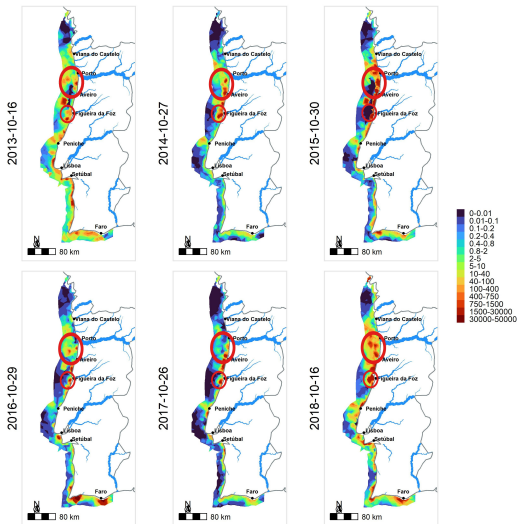
**Graphic Interpretation:** A highly non-linear relationship with a clear "efficiency peak" at 60 tons.

- **Spot at 60 tons:** These are the most optimized for juvenile purse-seine fishery - **large enough to carry but agile enough for coastal work.**
- The dip after 60 tons followed by another peak near 90–100 tons suggests **different vessel classes** (using distinct technology or larger nets).



# The Latent Field Revealed: Daily Juvenile Hotspots

Spatio-temporal predictions of the underlying biological process

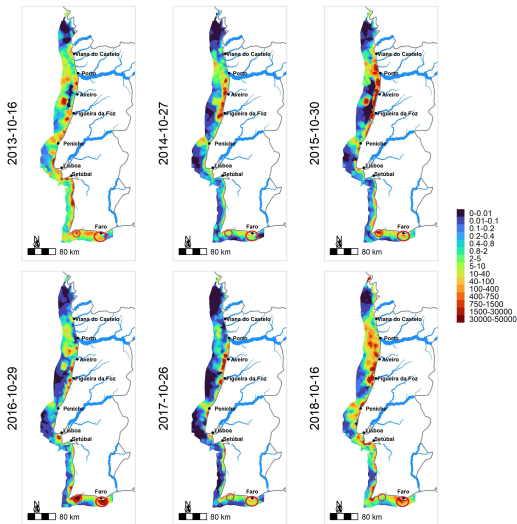


## Persistent Hotspots:

- **Northern Shelf:** Consistent high-density agregations observed from Aveiro to Porto and near Figueira da Foz.

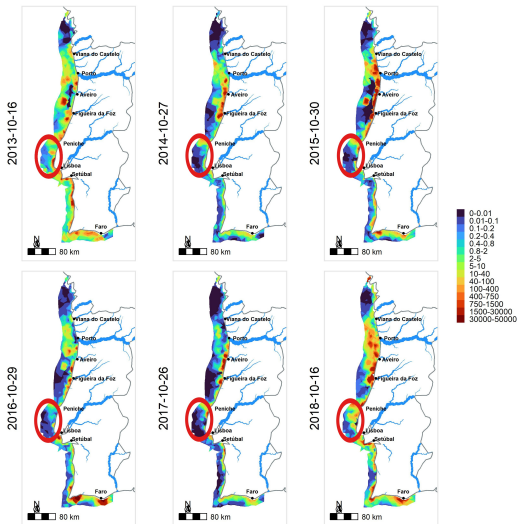
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## Persistent Hotspots:

- **Northern Shelf: Consistent high-density aggregations** observed from Aveiro to Porto and near Figueira da Foz.
- **Southern Algarve Patch: Persistent smaller aggregation** near the south coast.

## Inter-annual Dynamics:

- **Lisboa-Peniche Front.**



## Ecological Process:

- **Environmental Drivers:** Juvenile distribution is driven by a specific **thermal niche** (18°C) and **high Chlorophyll-a concentration**.
- **Spatial Stability:** Northern shelf (Aveiro-Porto) is a persistent stronghold.



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## Future work



**Full-Cycle Analysis:** Extend the study to the entire year to capture the seasonal variations.



Expand the model to adjacent marine regions - planned under Activity 1 of PICES-ICES WG53.

## Thank you for your attention

This study was supported by Portuguese funds through the **UID/00013: Centro de Matemática da Universidade do Minho (CMAT/UM)** and by the **European Maritime and Fisheries Fund (MAR-01.04.02-FEAMP-0009)** through the **SARDINHA2030** project.



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