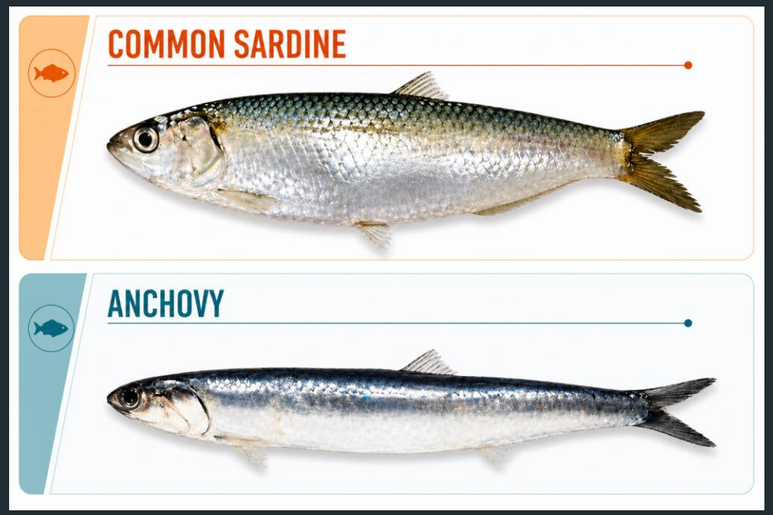
Spatio-temporal variations of biological traits of anchovy (*Engraulis ringens*) and common sardine (*Strangomera bentincki)* in central-zone Chile, as a response to environmental drivers: bases for a sustainable fisheries management.

C.M. Canales (1), N. Sánchez (1), K. Walker (2)

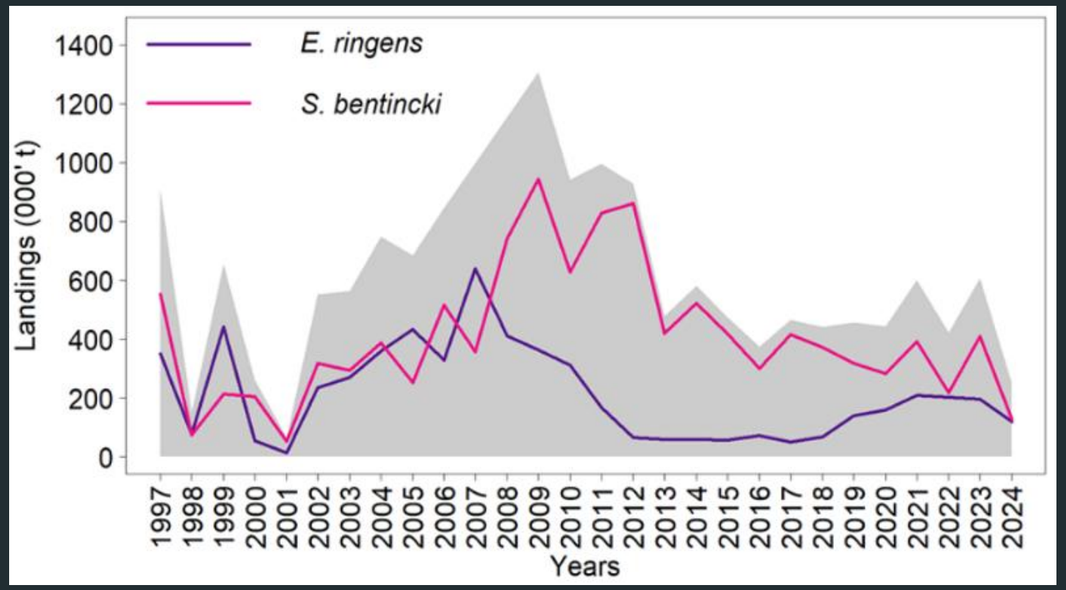
(1) Pontificia Universidad Católica de Valparaíso (PUCV), Chile
(2) Instituto de Fomento Pesquero (IFOP), Chile

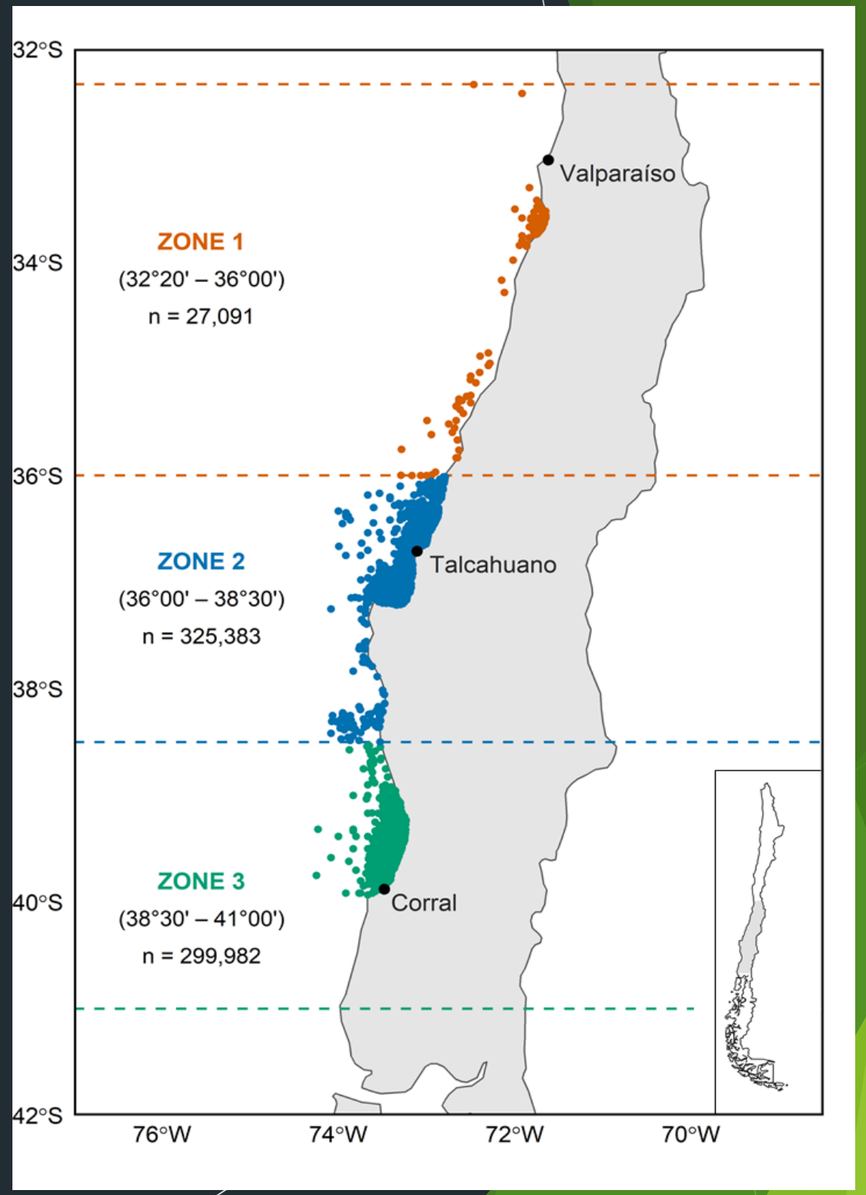
Species and study zone



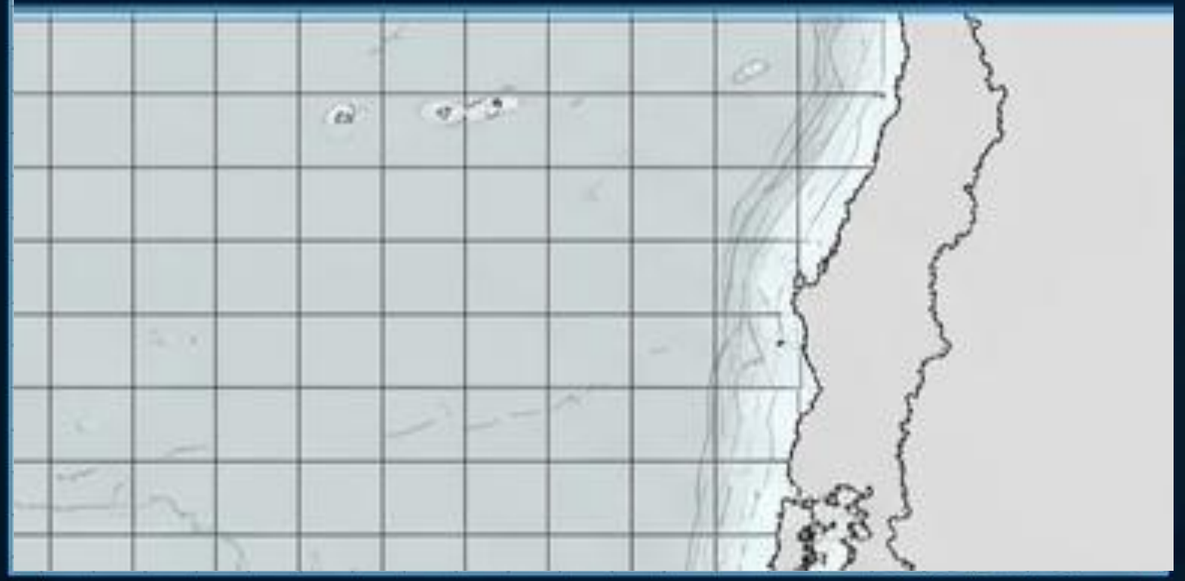
(*Strangomera bentincki*)

(*Engraulis ringens*)





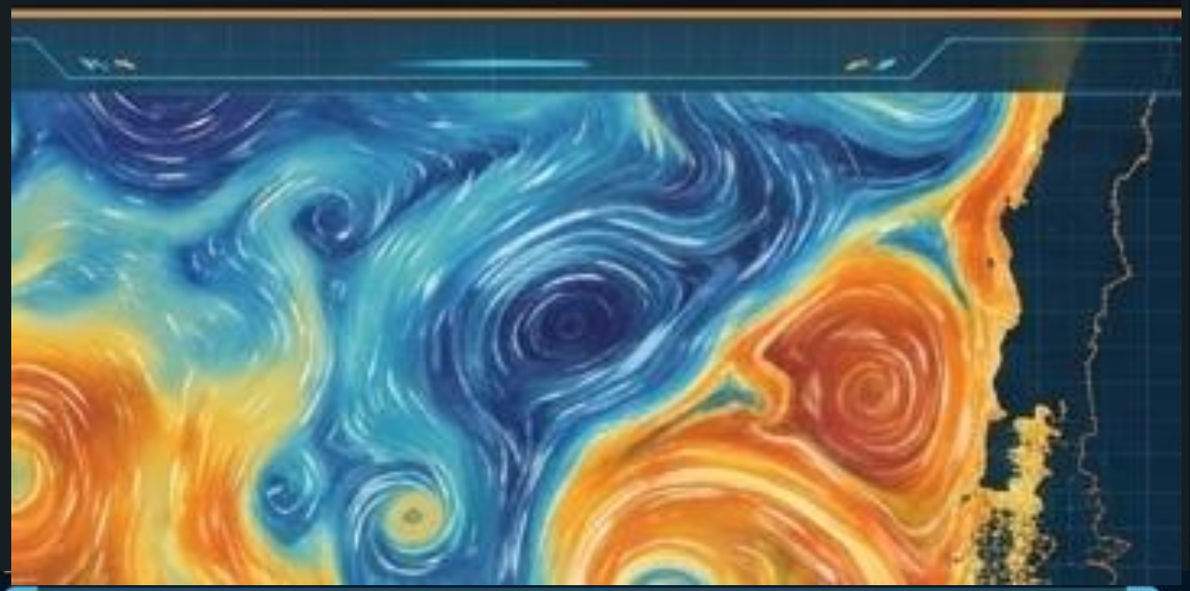
The Traditional Paradigm



One single stock, one single threshold.
Fisheries management assumes homogeneous populations with uniform biological responses.

Critical failure: Ignores the adaptive plasticity and high climatic sensitivity of small pelagic fish.

The Ecosystem Reality



Extreme spatio-temporal variability.
Environmental drivers (temperature, sea level, productivity) dictate growth, maturity, and biomass.

Climate change redistributes oceanic productivity.
Managing by assuming a regional average generates hidden overexploitation and economic underutilization.

23 years (2001-2023) of biological sampling (IFOP)

Biological Sampling

460,925 specimens of Common Sardine (*S. bentincki*).
271,704 specimens of Anchoveta (*E. ringens*).

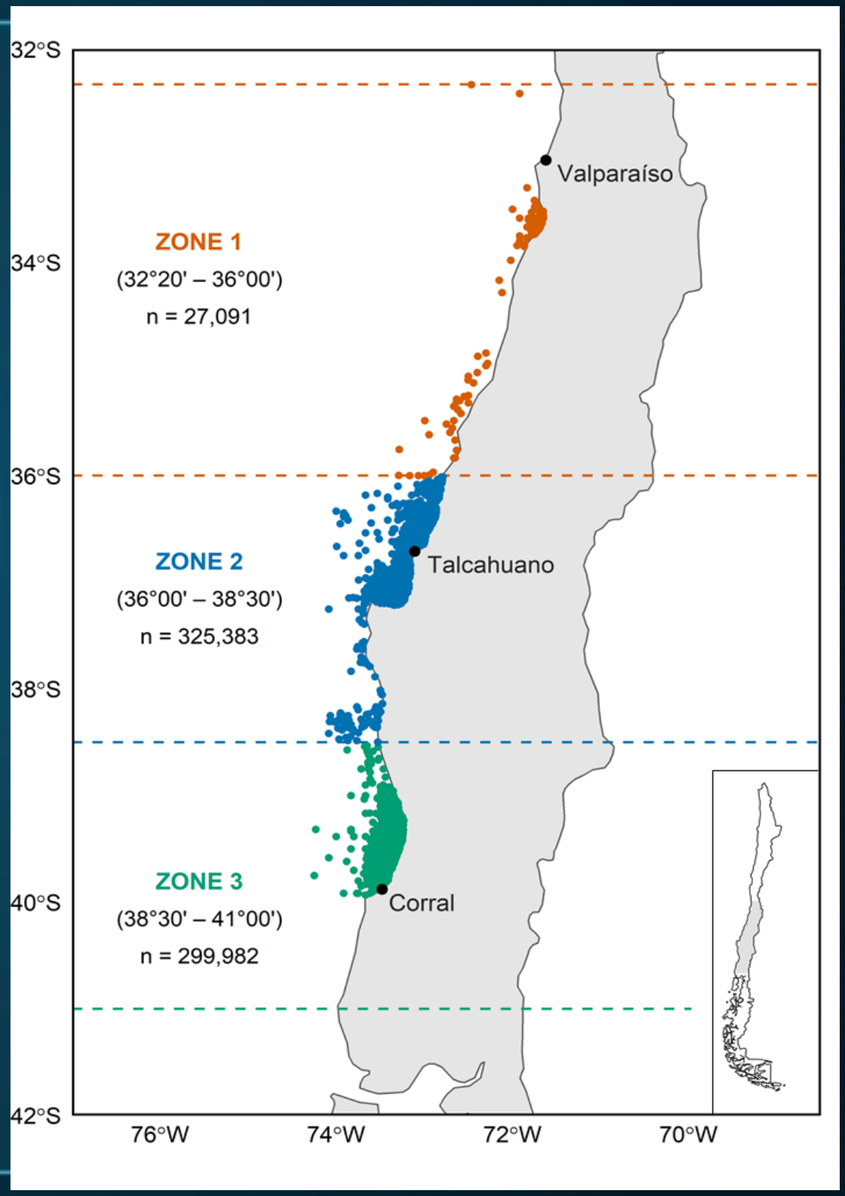
Variables; Total weight (TW), Gonad weight (GoW), Gutted weight (GuW), Maturity (Mat) and Total length (TL)

Satellite Oceanography

Variables; Chlorophyll-a (Chl-a), Primary production (PP), Biomass zooplankton (ZooC), Sea Surface temperature (SST) and Mean Sea Level (MSL)

Coastal stations

Variables; Sea Surface Temperature (SST) and Mean Sea Level (MSL)



Generalized Lineal Models (GLM)

Biological variables;
Total weight (TW),
Gonad weight (GoW),
Gutted weight (GuW
Total length (TL),
Matirity (Mat)

Oceanographic Variables;
Chlorophyll-a (Chl-a),
Primary production (PP),
Biomass zooplankton (ZooC),
Sea Surface temperature (SST)
Mean Sea Level (MSL)

BIOLOGICAL TRAITS

Variable	Distribution (Error)	Link function	Linear predictor	Interaction
TL	Gaussian	Identity	year + zone + quarter + sex	zone × quarter
TW, GoW, GuW*	Gaussian	Identity	year + zone + quarter + sex + log(TL)	zone × quarter
Mat	Binomial	Logit	year + zone + TL	–

ENVIRONMENTAL VARIABLES

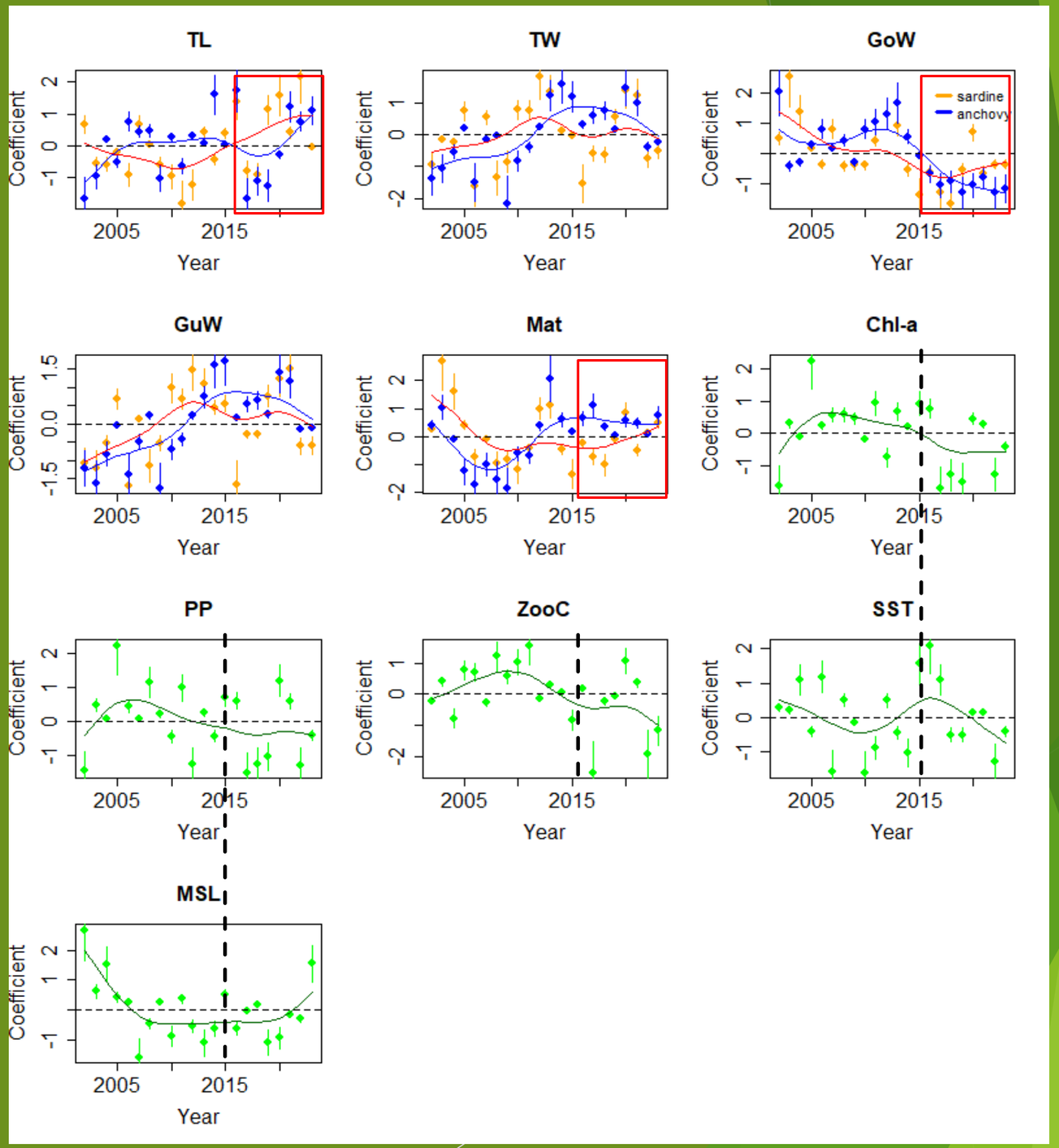
Variables	Distribution (Error)	Link function	Linear predictor	Interaction
Chl-a, PP, ZooC, SST, MSL	Gaussian	Identity	year + zone + quarter	zone × quarter

Annual effects of GLMs

- Main phase changes **around 2015-2016,** years of one of the **most important El Niño – ENSO** events

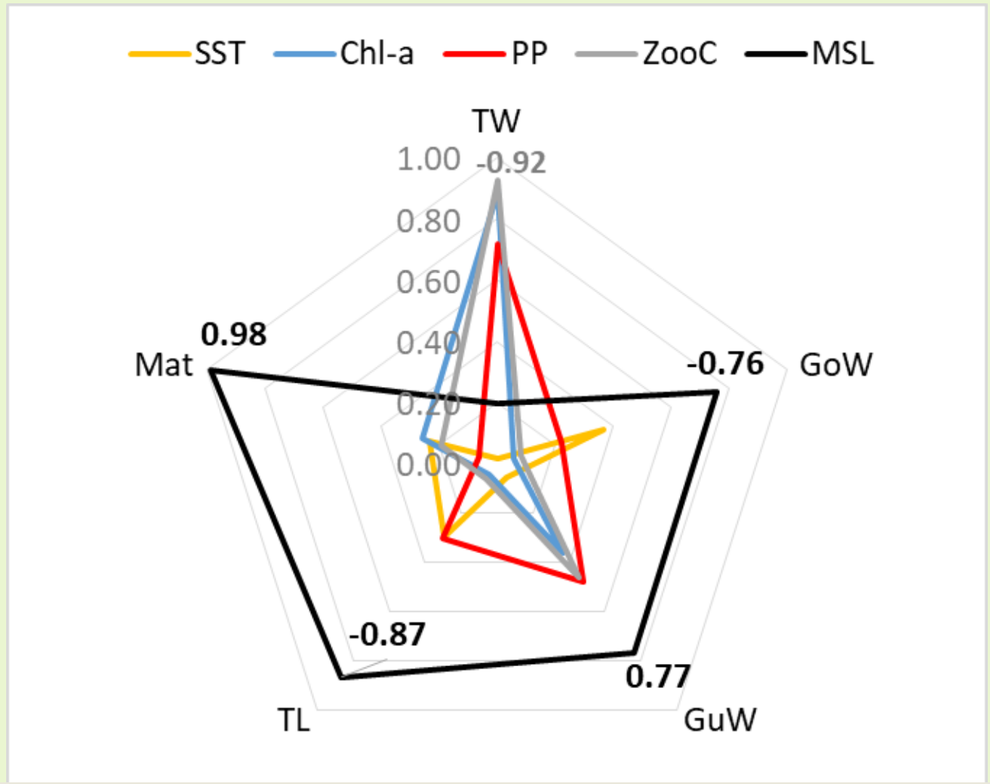
- After 2015, **drastic drop** in Chl-a, PP and ZooC

- **As resilience response**: lower gonadic levels (GoW), increases in length, and maintenance of maturity



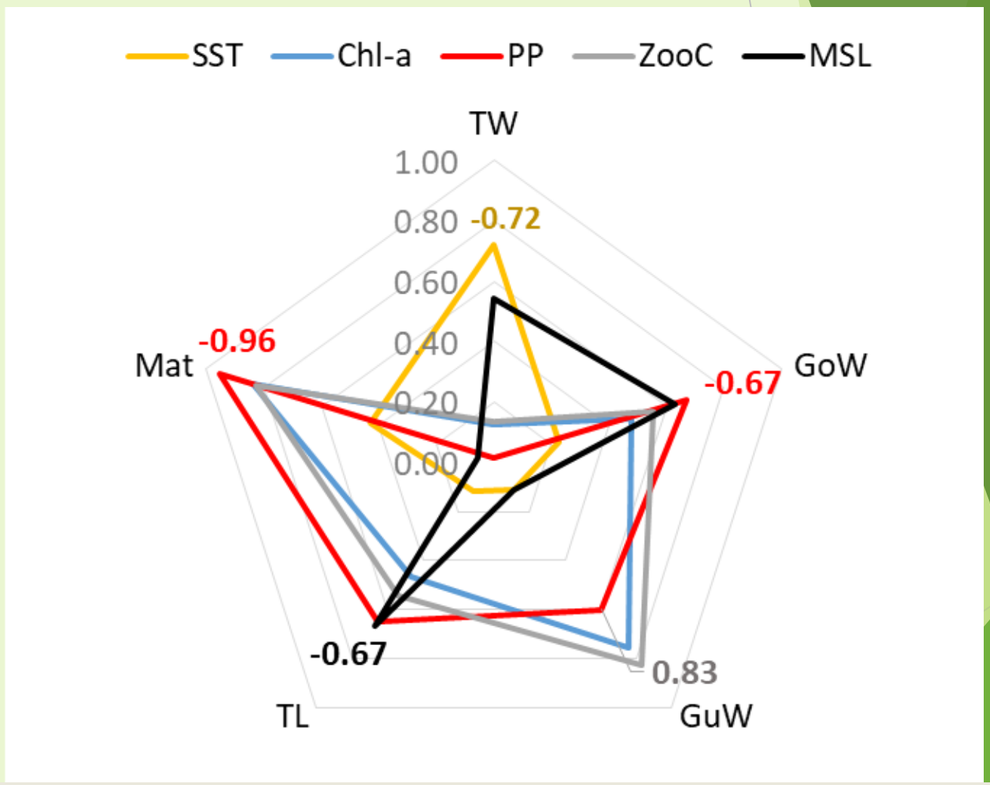
Main environmental drivers on biological traits (Pearson's correlation coefficient)

Sardine



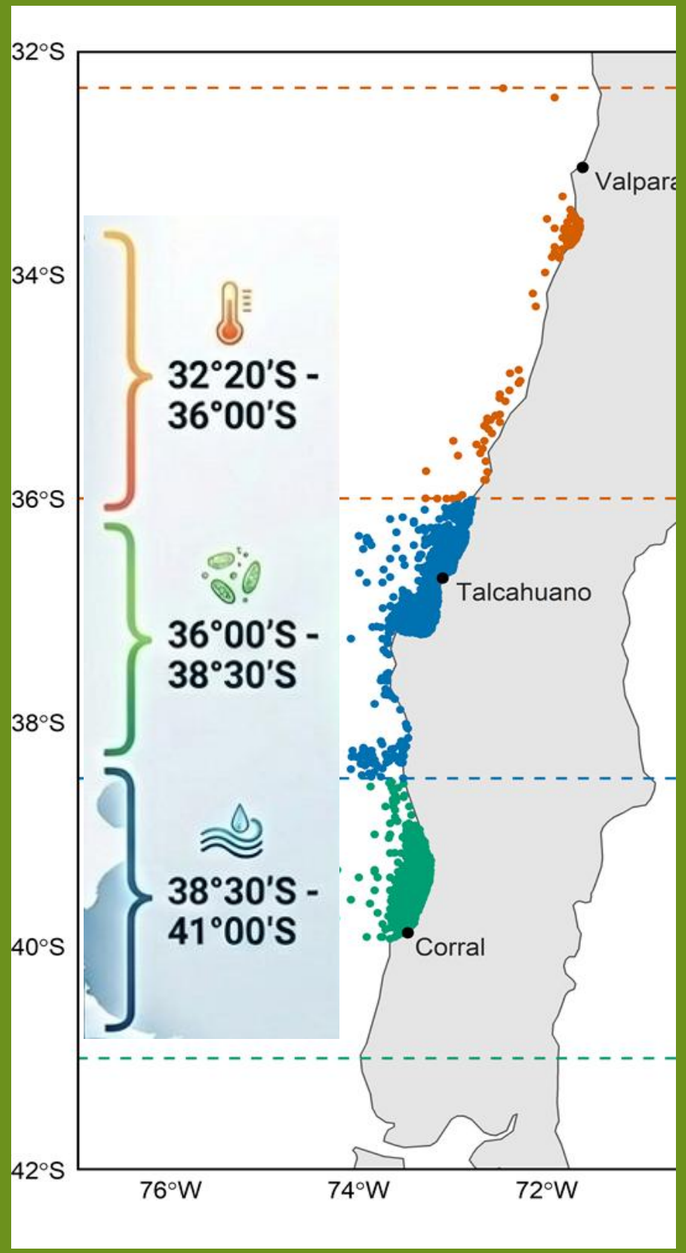
MSL has the greatest influence on most biological traits, primarily on maturity and TL. Maturity increases with MSL at the same time TL drops.

Anchovy



PP, Chl-a and ZooC have great influence on most biological traits, mainly both maturity and GuW. Maturity drops at the same time PP increases.

Spatial effects:



	Common sardine					Anchovy					Environmental variables				
	TW	GoW	GuW	TL	Mat	TW	GoW	GuW	TL	Mat	Chl-a	PP	ZooC	SST	MSL
Zone 1	1.21	1.04	1.19	-1.06	1.14	1.12	1.46	0.70	-1.46	1.09	-1.01	-0.97	0.61	1.41	-0.81
Zone 2	0.36	0.03	0.37	-0.01	0.06	1.60	-0.55	0.91	0.67	0.42	0.09	0.73	1.07	-0.63	-0.22
Zone 3	-1.07	-1.35	-1.11	1.34	-1.30	-0.80	-0.74	-1.24	0.19	-1.26	-0.42	-0.75	-0.67	-0.77	-0.42

Zone 1: Higher SST and Zooplankton concentration. Lower Chl-a, primary productivity (PP) and Mean Sea Level (MSL), related to smaller fish with larger maturity and body weight

Zone 2: Transition zone. The productivity epicenter, máximum of Chl-a and PP. Bigger anchovy fish and médium-sized sardines

Zone 3: Colder environment and lower oceanographic conditions, related to larger fish with low maturity and less body weight

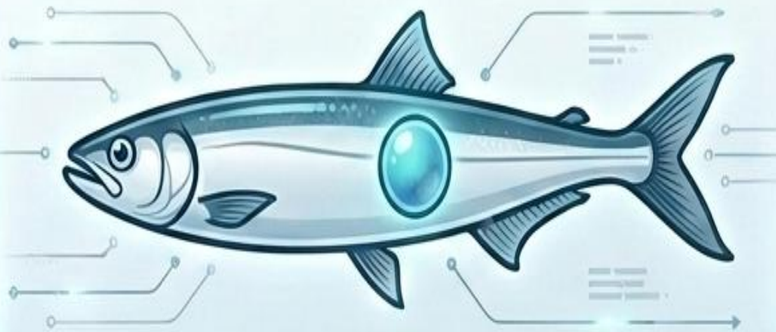
The Thermal-Metabolic Paradox (The Eco-Biological Engine)

Path A: The Metabolic Accelerator
(Zone 1 - Warm Waters)

Mechanism: High temperatures (SST) accelerate maturation.

Result: Smaller size (short fish) + Greater body mass (gutted weight) + Early sexual maturity. Energy is invested in reproduction, not somatic growth.

Path B: The Growth Elongator
(Zone 3 - Cold Waters)

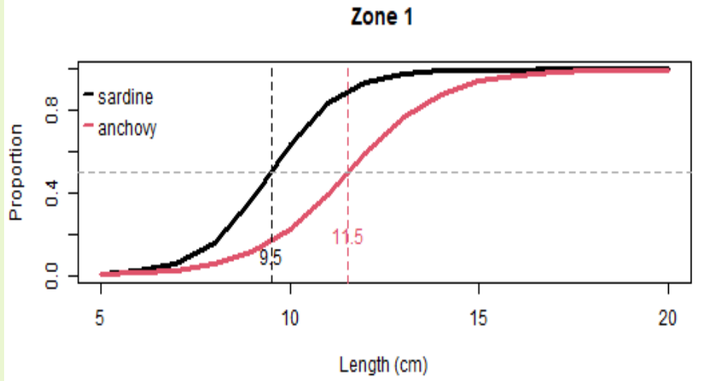


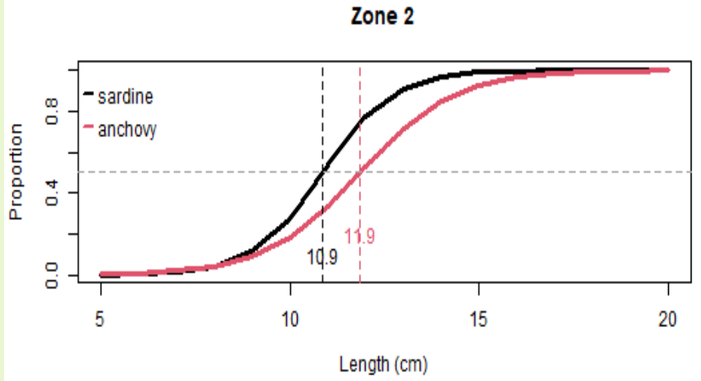
Mechanism: Low temperatures delay reproductive investment.

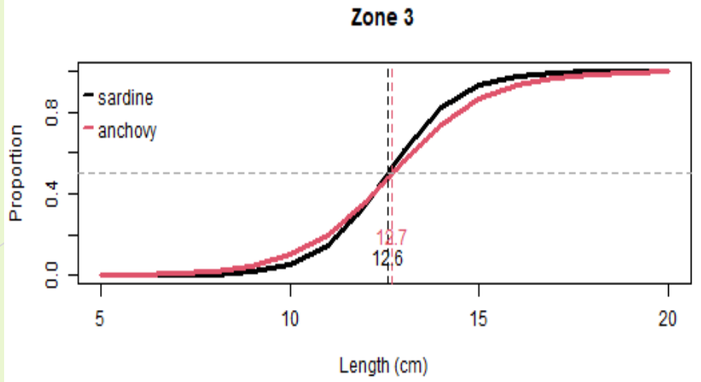
Result: Greater total length (TL) + Lower relative weight + Late sexual maturity. Prolonged growth strategy.

Insight: Size is not a universal indicator of age. A small fish in the north can be a mature adult, while in the south, a fish of the same size is still a juvenile.

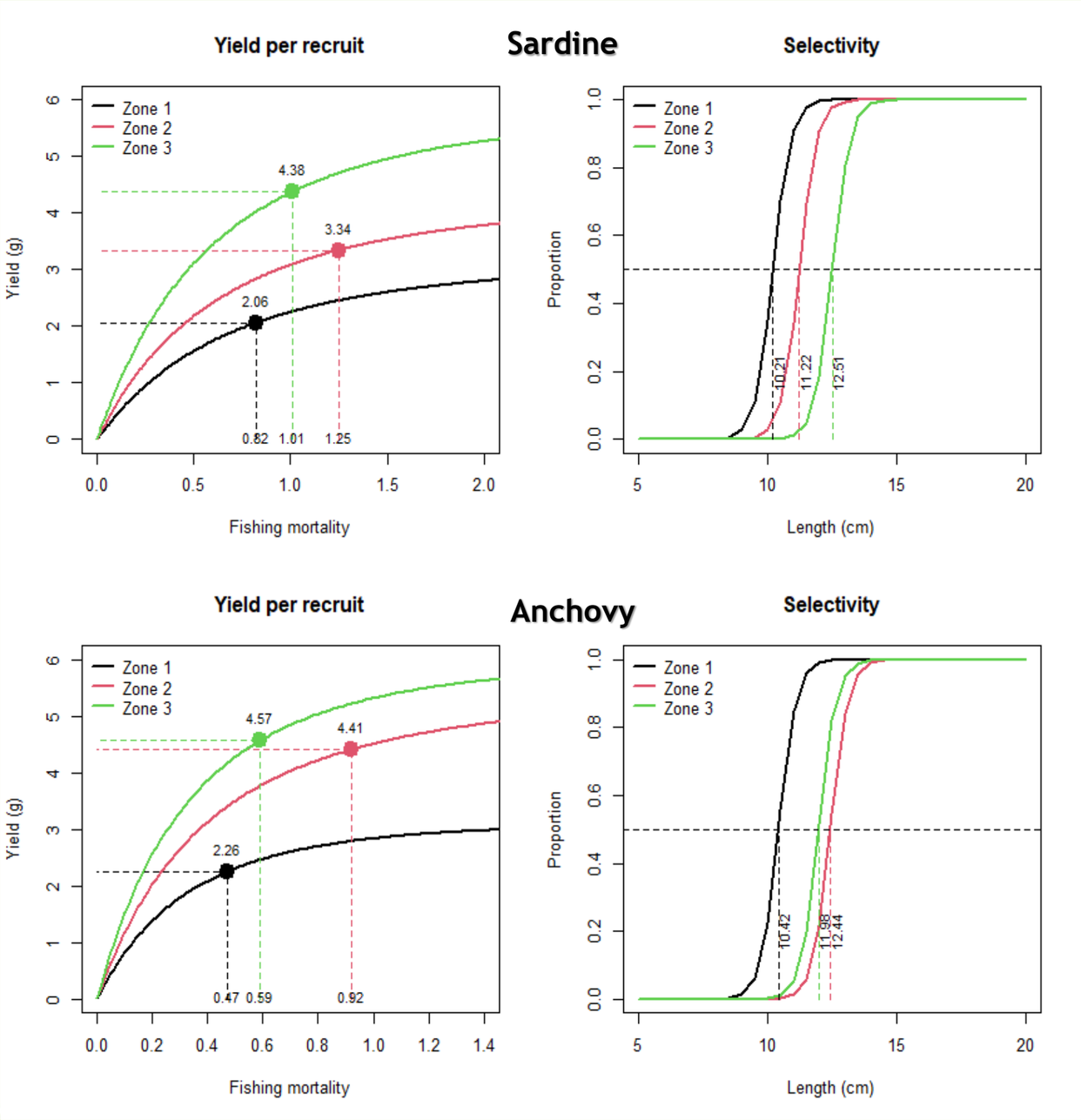
Similar maturity at-length only in anchovy







Potential implications for fishery management



- Substantial differences in maximum tolerable fishing mortality by zone (Fmsy)
- Zone 2 tolerates the highest fishing mortality, while Zone 1 is a precautionary area
- Maximum fishing yield is obtained at intermediate fishing effort (Zone 3)

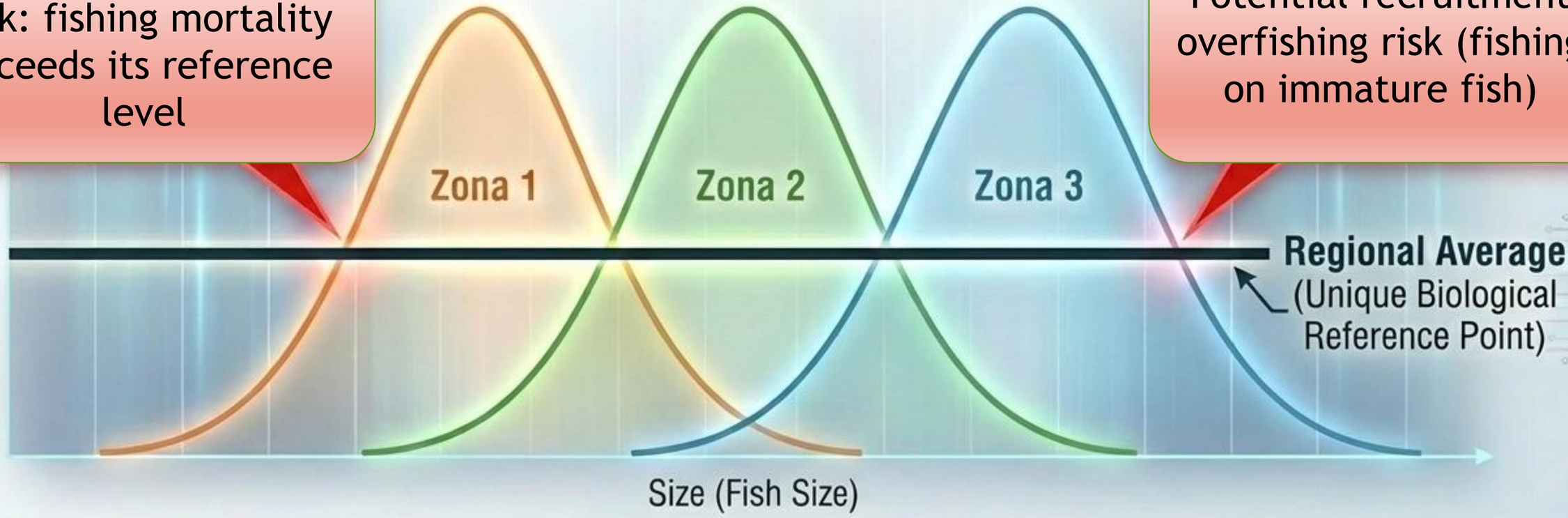
The Zonal Reality Matrix

	Zone 1 (North)	Zone 2 (Center)	Zone 3 (South)
Size at First Maturity (L50m)	Precocious Maturity. Sardine: **9.5 cm** | Anchoveta: **11.5 cm**	Transition (Intermediate)	Late Maturity. Sardine: **12.6 cm** | Anchoveta: **12.7 cm**
Tolerance to Fishing Mortality (Fmsy)	Low (Requires strict precautionary management)	Maximum Tolerance (Fmsy = **1.25** Sardine, **0.92** Anchoveta). **1.5 to 1.9** times greater capacity than Zone 1.	Intermediate
Yield Per Recruit Potential (YPR)	Low mass yield potential.	Moderate-high yield.	Maximum Yield (**4.38g** Sardine | **4.57g** Anchoveta). **Doubles** the fishing potential of the north with correct selectivity.

The Danger of Averages

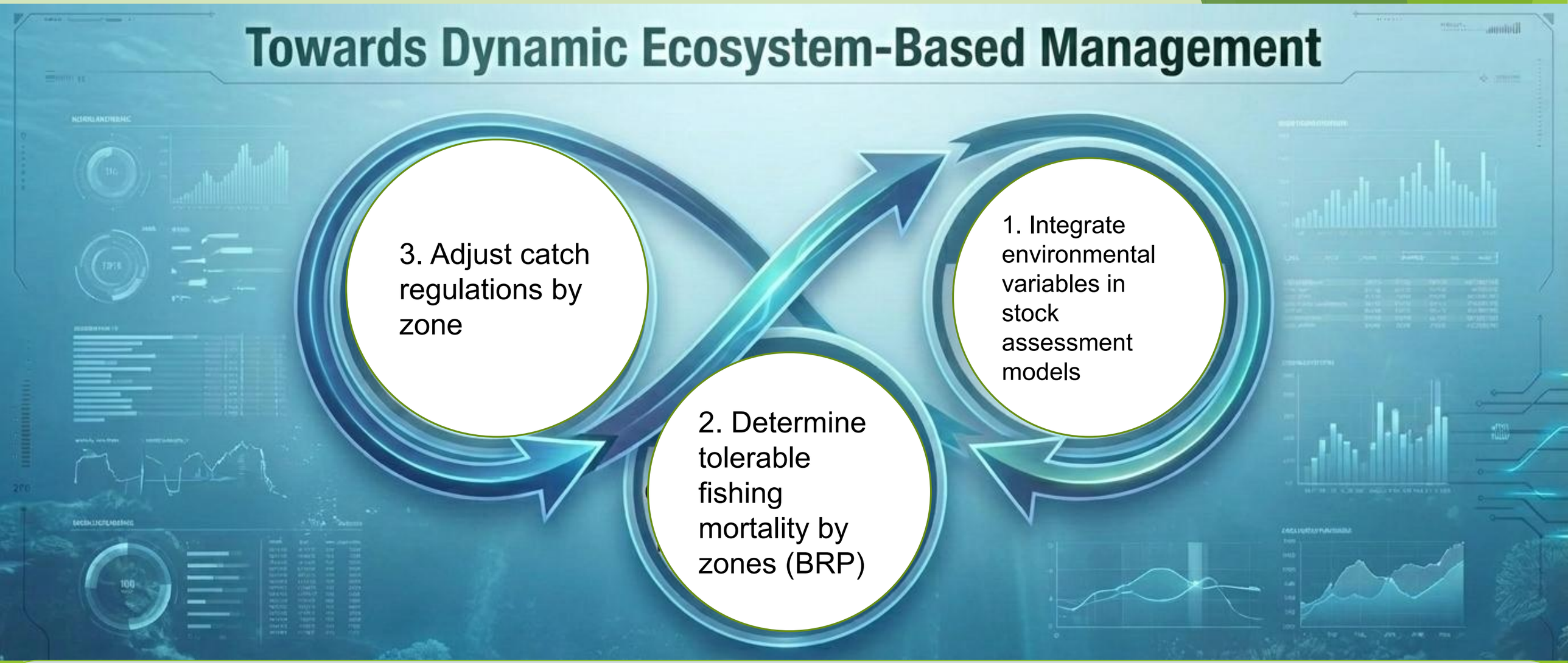
Potential overfishing risk: fishing mortality exceeds its reference level

Potential recruitment overfishing risk (fishing on immature fish)



A Biological Reference Point (BRP) calculated as a regional average results mathematically in the **overfishing of Zone 1** and unnecessarily **restricts the productivity** of **Zone 3**.

Towards Dynamic Ecosystem-Based Management



Ignoring spatial heterogeneity overestimates the regional diagnosis and underestimates the risk of local overfishing. Sustainability in the face of climate change requires fisheries policy to be as dynamic as the ocean itself

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