



## (1) Central message

The north–central Peruvian anchovy stock is embedded in a highly dynamic pelagic system shaped by environmental variability and fishing pressure. A key challenge is to place stock-state changes within an integrated pressure–response framework that separates external pressures, biological responses, candidate transition windows, and potential early signals of deterioration.

- **Core question.** When do natural and anthropogenic pressures shift, and do stock-state indicators respond synchronously, after a lag, or after cumulative exposure?
- **Analytical approach.** We organized the system into three comparable annual domains: *natural forcing*, *fishing pressure*, and *stock-state response*. Within each domain, indicators were grouped into temporal signals and compared using breakpoint windows, lagged and cumulative pressure structures, and nonlinear response curves.
- **Main contribution.** We provide a multivariate pressure–response diagnosis of the north–central anchovy system, linking natural forcing, fishing pressure, and stock-state responses through recurrent transition windows, lagged and cumulative effects, and candidate nonlinear response regions.

## (2) Study system

**Stock and system.** The north–central Peruvian anchovy stock, *Engraulis ringens* (Jenyns, 1842), was evaluated over 1970–2025 as a key pelagic stock in the Peruvian Humboldt Current System, which supports one of the world's major small pelagic fisheries.

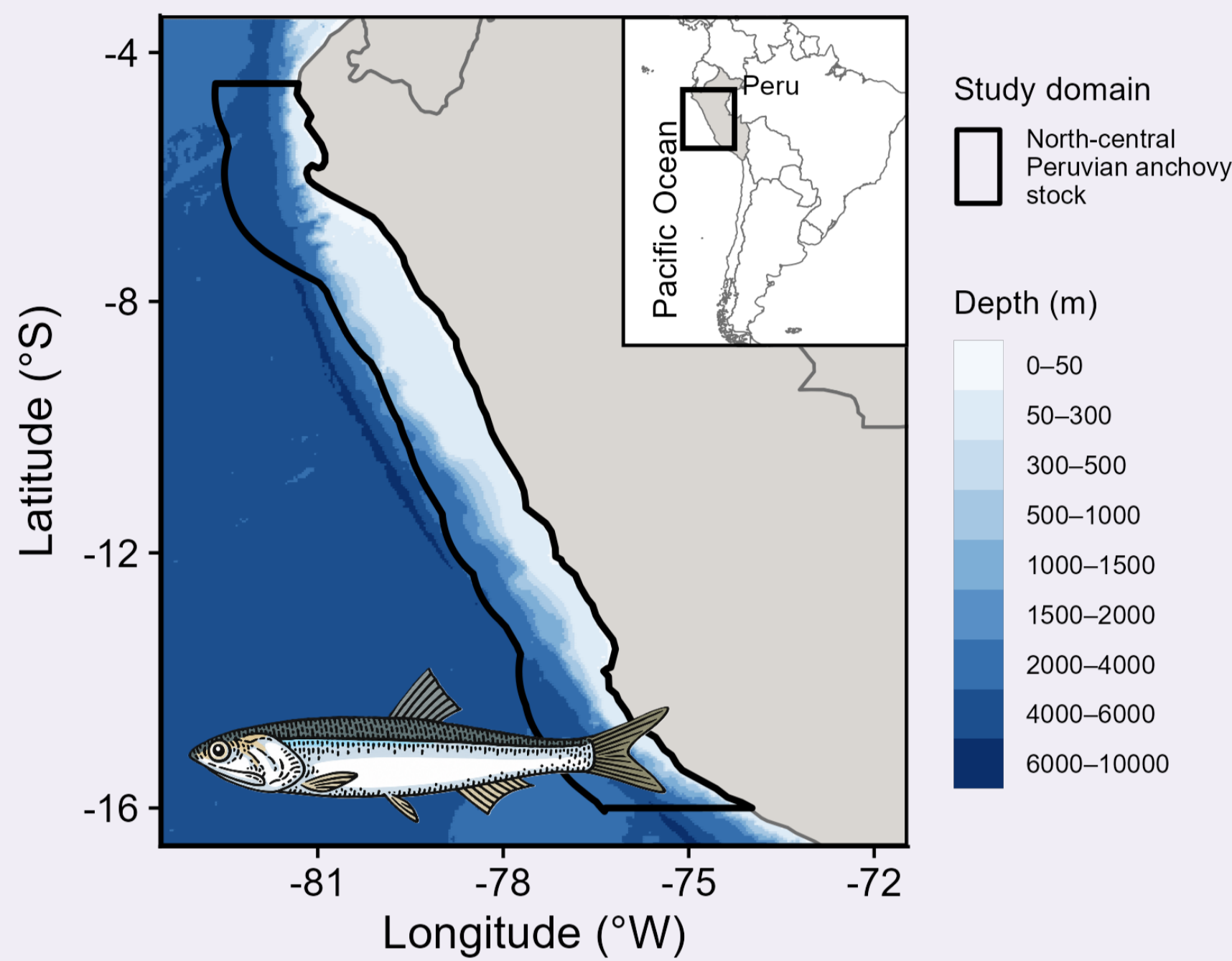


Fig. 1. Study domain of the north–central Peruvian anchovy stock within the coastal upwelling pelagic system of the Peruvian Humboldt Current.

**Why annual indicators?** Annual aggregation provides a common temporal scale to integrate biological, environmental, and fishery indicators, reducing seasonal noise and emphasizing long-term trends and cumulative pressure effects on stock-state responses.

## (4) Workflow for critical-point detection

### 1. Annual pressure–state matrix

$$X_t = [E_t | F_t | S_t], \quad t = 1970, \dots, 2024$$

### 2. Direction alignment and robust scaling

$$x_{i,t}^* = \eta_i x_{i,t}, \quad z_{i,t} = \frac{x_{i,t}^* - \bar{x}_i}{\text{MAD}(x_i^*)}, \quad \eta_i \in \{-1, +1\}$$

### 3. Redundancy screening and clustering

$$\rho_{ij} = \text{cor}(z_i, z_j), \quad d_{ij} = 1 - |\rho_{ij}|, \quad C_k = \{i : d_{ij} \leq d_0\}$$

### 4. Cluster-level temporal signals

$$C_{k,t} = \sum_{i \in C_k} w_i z_{i,t}, \quad C_{k,t} \Rightarrow \{\text{increase, decline, shift}\}$$

### 5. Nonlinear lagged and cumulative pressure–response form

$$\bar{P}_{m,t-(a:b)} = \frac{1}{b-a+1} \sum_{\ell=a}^b P_{m,t-\ell}, \quad S_{k,t} = \alpha_k + f_k(\bar{P}_{m,t-(a:b)}) + \varepsilon_{k,t}$$

### 6. Lead–lag comparison

$$r_{k,m}(\ell) = \text{cor}(S_{k,t}, P_{m,t-\ell}),$$

$\ell > 0$ : pressure leads,  $\ell = 0$ : synchronous,  $\ell < 0$ : stock leads

### 7. Candidate transition and response diagnosis

$$C_{k,t} = \begin{cases} \mu_k^- + \varepsilon_{k,t}, & t \leq \tau_k \\ \mu_k^+ + \varepsilon_{k,t}, & t > \tau_k \end{cases}, \quad \Delta_k = \mu_k^+ - \mu_k^-, \quad G_{k,m} = \max |g_{k,m}(P)|$$

**Output:** candidate transition windows, cumulative pressure windows, and high-gradient response regions defined by  $\tau_k$ ,  $\Delta_k$ ,  $\bar{P}_{m,t-(a:b)}$ ,  $G_{k,m}$ , and lead–lag structure.

## (8) Synthesis and ecological interpretation

**Synthesis.** Anchovy stock dynamics appear to reflect two coupled pathways: *habitat–trophic pathway*, acting mainly on biological quality, and *stock–fleet memory*, acting on stock quantity and occupancy.

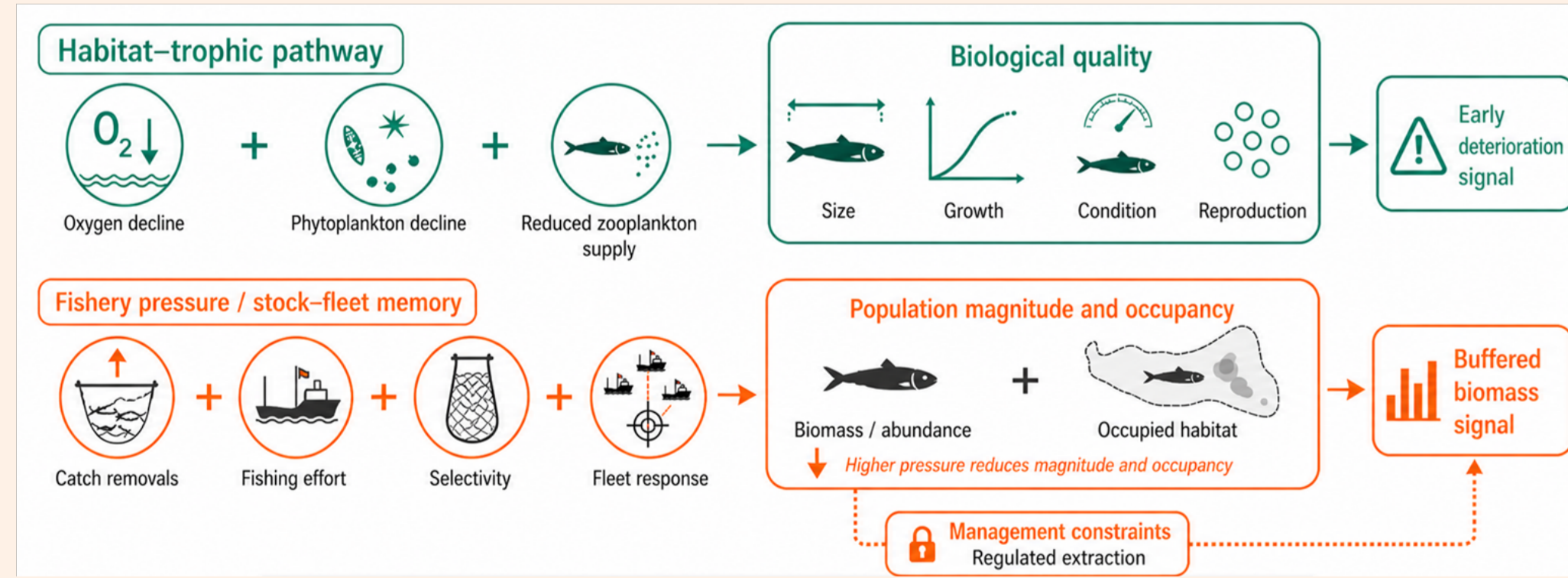


Fig. 5. Conceptual synthesis of environmental and fishery pathways affecting stock quantity, biological quality, and resilience.

**Key interpretation.** Higher fishery pressure was associated with lower stock magnitude–occupancy, but recent biomass-related signals appear relatively buffered, possibly reflecting regulatory constraints and density-dependent availability. In contrast, biological quality may deteriorate earlier under habitat–trophic stress.

## (9) What this study adds

This study contributes a **multivariate pressure–response diagnosis** that transforms heterogeneous biological, environmental, and fishery indicators into comparable annual temporal signals for joint analysis.

### Main contribution.

- Builds integrated temporal indices for stock state, natural forcing, and fishery pressure.
- Separates population magnitude–occupancy from biological quality–life-history responses.
- Connects transition windows, single-year and cumulative pressure–response relationships, and candidate nonlinear response regions in one workflow.
- Provides a reproducible basis to evaluate early biological deterioration and pressure-related stock responses beyond biomass-only diagnostics.

**Scientific value.** The approach moves anchovy assessment toward an integrated pressure–response perspective, where population magnitude, biological quality, habitat forcing, and fishery pressure are evaluated jointly through time.

## (3) Pressure–response framework

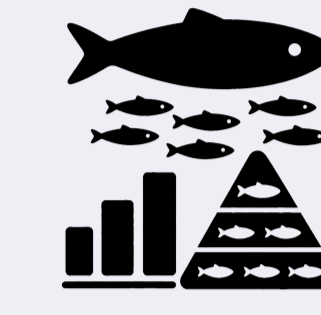
The Peruvian anchovy system was represented as an annual pressure–response framework linking *natural forcing* and *fishery pressure* with *stock-state responses* in population magnitude, biological quality, and spatial organization.

Single-year and cumulative pressure windows were used to compare same-year forcing with accumulated environmental or fishery conditions.

Following regime-shift and ecological-threshold theory, transitions were interpreted as three candidate configurations (Scheffer and Carpenter, 2003; deYoung et al., 2004; Andersen et al., 2009):

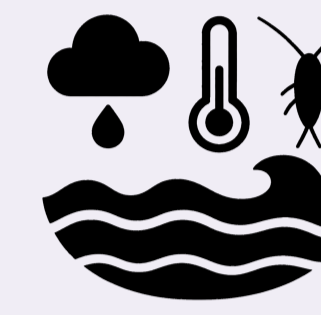
- **Pressure-driven shifts**, when stock changes track abrupt pressure changes;
- **Cumulative responses**, when biological state reflects accumulated fishing, habitat, or food–environment pressure;
- **Threshold-like responses**, when deterioration and recovery may follow nonlinear or asymmetric pathways.

Breakpoints were treated as candidate transitions rather than confirmed regime shifts because abrupt changes may also reflect autocorrelation or statistical artefacts (Andersen et al., 2009; Haines et al., 2024).



### Stock-state response

Biological indicators describing population magnitude, abundance, size structure, body condition (condition factor, fat content, and fullness index), somatic growth, reproduction, and spatial organization.



### Natural forcing

Environmental variability in the Niño 1+2 region, including physical–chemical habitat conditions, productivity, oxygenation, and zooplankton food supply (satellite- or reanalysis-derived indicators).



### Fishery pressure

Annual fishery indicators associated with catch, fishing mortality, effort, size-selective extraction, and spatial fleet dynamics (distance to coast, latitudinal distribution, occupied fishing area, and fleet inertia).

## (5) Temporal domains and coordinated shifts

Cluster-based indices summarized coherent temporal signals within the three diagnostic domains: stock state, natural forcing, and fishery pressure. Stock-state C1 reflected population magnitude–occupancy and shifted upward around 2000, whereas C2 captured biological quality–life-history structure and showed candidate breakpoints around 1990, 2006, and 2014. Natural forcing separated ENSO physical–chemical variability from the oxygen–production–food response, while fishery pressure separated extraction–effort from selectivity–space use. The years 2000, 2006, and 2014 emerged as recurrent candidate transition periods across domains, suggesting coordinated but pathway-specific changes in environmental forcing, fishing pressure, and stock-state responses.

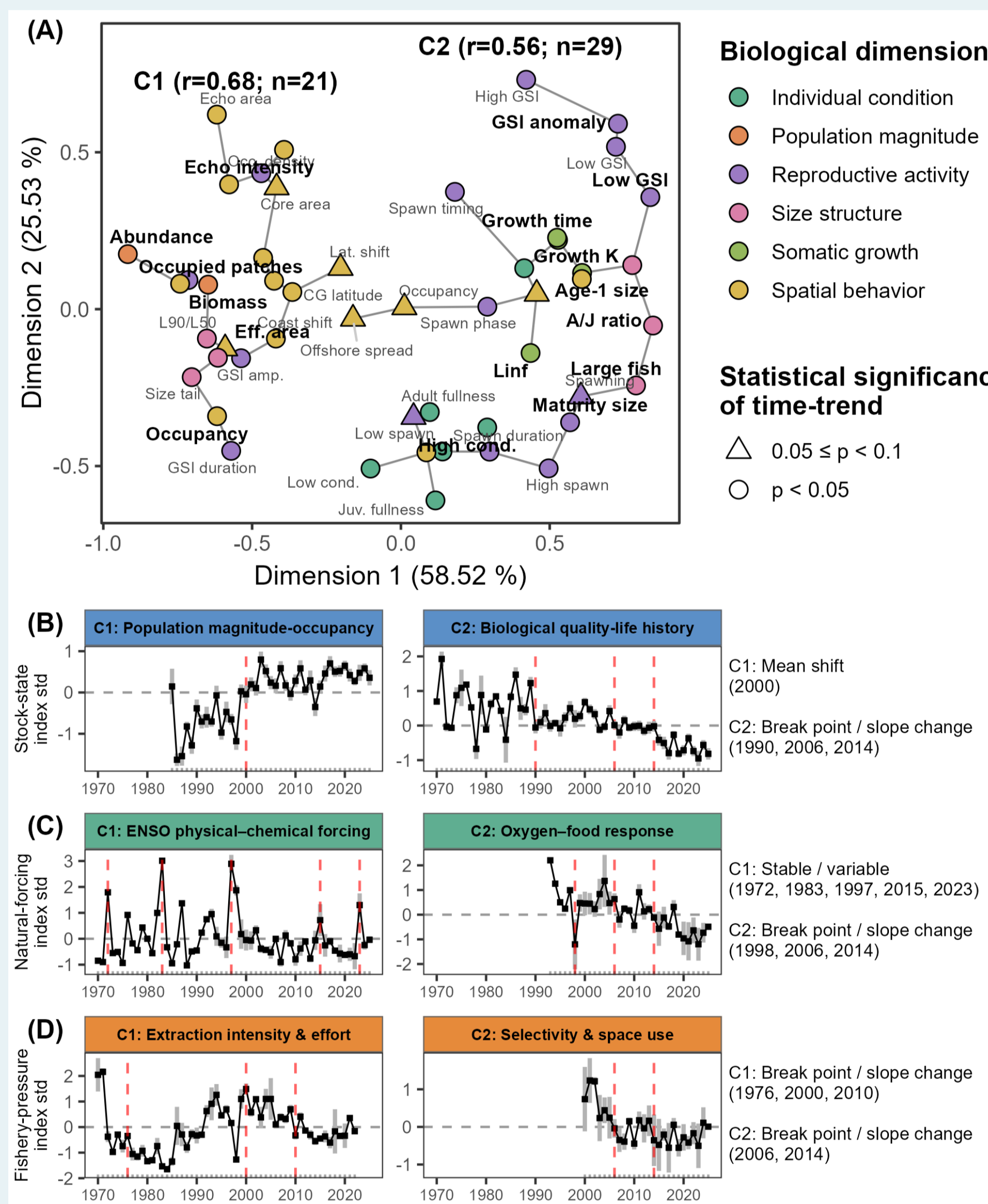


Fig. 2. Domain-level clustering and standardized trajectories across stock-state, environmental, and fishery-pressure domains. Red dashed lines mark candidate change points and recurrent transition periods across biological and pressure signals.

### Cluster interpretation.

- **Stock state:** C1 – population magnitude and occupied habitat; C2 – size, growth, condition, and reproduction.
- **Natural forcing:** C1 – ENSO-driven habitat reorganization; C2 – oxygenation, productivity, and zooplankton food supply.
- **Fishery pressure:** C1 – catch, mortality, and fleet effort; C2 – size selectivity and spatial redistribution of fishing.

### Most recurrent transition windows.

- **2000** recurrent across stock state and fishery pressure
- **2006** strongest mid-2000s window across stock, natural forcing, and fishery pressure
- **2014** recurrent late-period breakpoint across stock, natural forcing, and fishery pressure

## (10) Limitations and future work

### Limitations.

- Annual indicators capture long-term patterns but may mask seasonal mechanisms.
- Breakpoints and high-gradient regions are candidate transitions, not confirmed thresholds.
- Bivariate links limit causal inference and combined-pressure interpretation.
- Autocorrelation and low-frequency variability may affect change-point detection.

### Future work.

- Test natural–fishery pressure interactions.
- Quantify pressure contributions to population magnitude and biological quality.
- Assess cumulative effects on deterioration and recovery.
- Validate candidate zones with autocorrelation-aware or mechanistic models.

## (11) Management relevance and take-home message

**Management relevance.** Biomass alone may miss early deterioration in anchovy condition. The proposed diagnostic structure separates population magnitude, biological quality, environmental forcing, and fishery pressure, supporting decision-relevant monitoring beyond conventional biomass-based indicators.

**Take-home message.** The north–central anchovy stock should be monitored through a multidimensional pressure–response diagnosis. Joint tracking of population magnitude, biological quality, habitat–trophic forcing, and fishery pressure can improve early detection of deterioration and support precautionary, climate-informed management.

## (6) Pressure–response links

Pressure–response links suggested single-year, lagged, and cumulative associations, including synchronous ENSO forcing, delayed habitat–trophic responses, cumulative fishery pressure, and stock-driven fishery feedbacks.

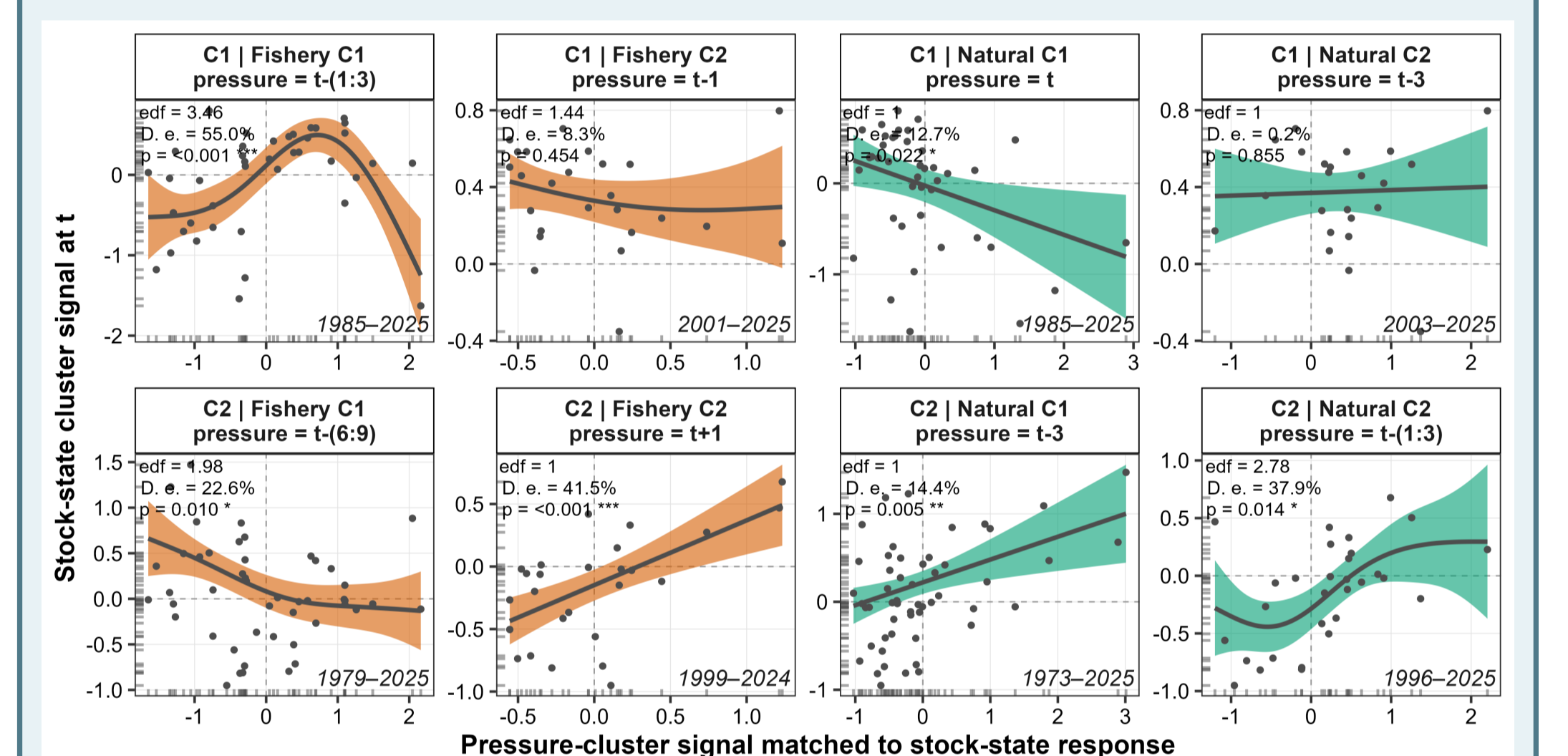


Fig. 3. Lagged, cumulative, and feedback pressure–response links;  $t - (a:b)$  denotes prior cumulative pressure and  $t + 1$  indicates stock-driven fishery feedback.

Link	Lag	Response type	Result interpretation
C1–Fishery C1	$t - (1:3)$	Cumulative recent fishing effect	Accumulated fishing pressure. Magnitude–occupancy responds nonlinearly. Short-term selectivity signal.
C1–Fishery C2	$t - 1$	Weak selectivity signal	Weak evidence for stock response.
C1–Natural C1	$t$	Synchronous ENSO habitat stress	Same-year ENSO forcing. Synchronous magnitude–occupancy.
C1–Natural C2	$t - 3$	Unsupported delayed oxygen–food link	Weak trophic association. Limited support for delayed response.
C2–Fishery C1	$t - (6:9)$	Cumulative fishing legacy	Long fishing-pressure window. Consistent with longer-term fishery legacy.
C2–Fishery C2	$t + 1$	Stock-driven fishery feedback	Stock precedes fishery. Fleet tracks availability and size.
C2–Natural C1	$t - 3$	Delayed post-ENSO response	Prior habitat reorganization. Biological quality responds after a delay.
C2–Natural C2	$t - (1:3)$	Cumulative habitat–trophic pathway	Prior oxygen–food conditions. Biological quality responds after a delay.

## (7) Candidate response regions

Significant GAM links were screened for high-gradient regions where natural or fishery pressures preceded strong stock-state responses, translating lagged and cumulative associations into candidate nonlinear pressure–response zones. These zones are candidates for biological interpretation, not confirmed ecological thresholds.

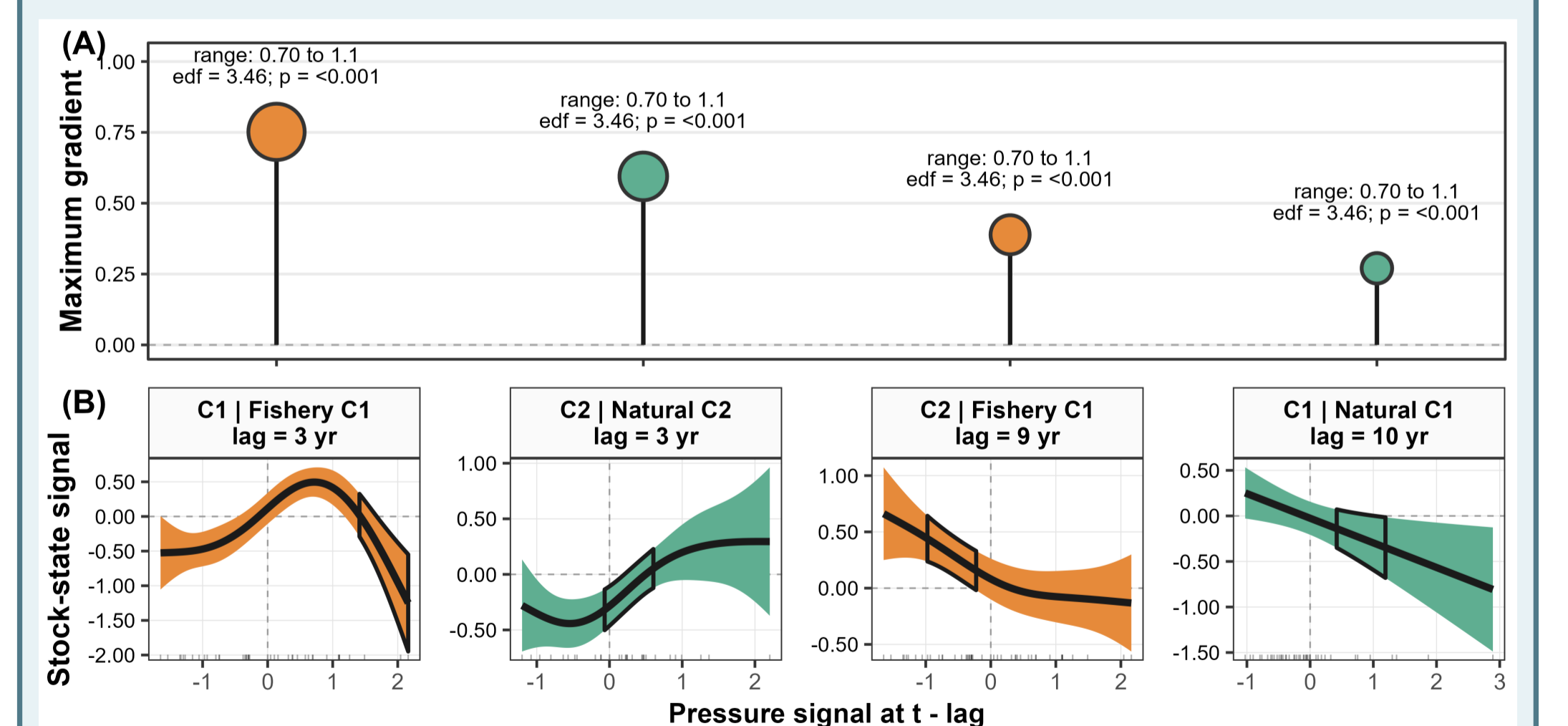


Fig. 4. Candidate high-gradient response regions from significant GAM links. Dark bands indicate rapid changes in fitted stock responses.

**Key result.** The strongest candidate region was associated with recent fishery pressure on stock magnitude–occupancy, while biological quality was linked mainly to prior oxygen–food conditions and longer-term fishery legacy.



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