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The Pelagic Seascape of the Gulf of California

Romeo Saldívar-Lucio
rsaldivar@cicese.edu.mx

Secretaría de Ciencia, Humanidades, Tecnología e Innovación

Armando Trasviña-Castro
Centro de Investigación Científica y de Educación Superior de Ensenada

Eduardo González-Rodríguez
Centro de Investigación Científica y de Educación Superior de Ensenada

Cotsikayala Pacheco-Ramírez
Centro de Investigación Científica y de Educación Superior de Ensenada

José Alejandro Ramos-Rodríguez
Centro de Investigación Científica y de Educación Superior de Ensenada

Héctor Villalobos
Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas

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Romeo Saldívar-Lucio[1,*], Armando Trasviña-Castro[2], Eduardo González-Rodríguez[2,**], Cotsikayala Pacheco-Ramírez[2], Alejandro Ramos-Rodríguez[2,3], Héctor Villalobos[4]

1. SECIHTI-Centro de Investigación Científica y Educación Superior de Ensenada (CICESE), Unidad Académica La Paz (UALP), La Paz, México. Miraflores No. 334 entre Mulegé y La Paz, Fraccionamiento Bella Vista, La Paz, BCS, México.

2. CICESE-Unidad Académica La Paz (UALP). Miraflores No. 334 entre Mulegé y La Paz, Fraccionamiento Bella Vista, La Paz, BCS, México.

3. Universidad Autónoma de Baja California Sur (UABCS), Km 5.5 Carretera 1, La Paz, B.C.S., México.

4. Instituto Politécnico Nacional, Centro Interdisciplinario de Ciencias Marinas (CICMAR-IPN), La Paz BCS, México.

Corresponding author:

* Dr. Romeo Saldívar-Lucio, rsaldivar@cicese.edu.mx, ORCID: 0000-0002-9893-3540 SECIHTI-Centro de Investigación Científica y Educación Superior de Ensenada, Baja California (CICESE) – Unidad Académica La Paz (UALP).

** Dr. Eduardo González-Rodríguez, egonzale@cicese.edu.mx, ORCID: 0000-0003-0734-0019 Centro de Investigación Científica y Educación Superior de Ensenada, Baja California (CICESE) – Unidad Académica La Paz (UALP).

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ABSTRACT

Context. Pelagic seascapes describe the ocean as a changing mosaic of habitats defined by multiple environmental properties. Their ecological relevance remains insufficiently evaluated in dynamic regional systems.

Objectives. We evaluated whether the globally derived Pelagic Seascape Habitat Classification captures seasonal and interannual variability in the Gulf of California (GC) and assessed its correspondence with environmental conditions and biological responses.

Methods. Monthly habitat coverage and habitat diversity (Shannon index) were analysed for 2003–2024 alongside net primary productivity and sea level anomalies. Seasonal and El Niño–Southern Oscillation (ENSO) configurations were compared with documented biological changes and pelagic fisheries landings reported in the region.

Results. The pelagic habitat C21 reached a maximum coverage of 94.3%, showing the greatest expansion potential among the habitat categories. Winter and negative ENSO conditions were associated with greater C21 coverage, higher productivity, lower sea level, and lower habitat diversity. Summer and positive ENSO conditions coincided with C21 contraction and expansion of C15, C3, and C13, together with lower productivity and greater habitat heterogeneity. Interannual changes in the pelagic seascape corresponded well with documented responses of jumbo squid, euphausiids and reported pelagic fisheries catches.

Conclusions. Pelagic seascapes capture coherent environmental and ecological variability in the Gulf of California, supporting their use as regional indicators of ecosystem state and as a framework for tracking climate-related ecosystem change. Their broader application to ecosystem monitoring and fisheries management requires regional validation and would benefit from reduced product latency.

Keywords Pelagic seascapes; Habitat heterogeneity; Gulf of California; ENSO; Ecosystem indicators; Fisheries oceanography.

1. Introduction

The marine biodiversity and fisheries catch are highly influenced by the ocean's dynamics (Cisneros-Mata 2010; Erisman et al. 2011). The knowledge regarding the condition of marine ecosystems in specific places and moments of time is one of the significant knowledge with various applications to make our interactions with the ocean better (e.g., adaptive conservation or fisheries management). However, the characterization of the marine environment is quite complicated since each condition results from the interaction of multiple variables and processes. Traditionally, this issue has been an obstacle to environmental scientists who traditionally used few variables (e.g., sea surface temperature) and thus failed to pay attention to some crucial aspects of the oceanic processes (Kavanaugh et al. 2016; Pittman et al. 2021). It happens mostly since, in contrast to the terrestrial ecosystems, the ocean is the dynamic environment represented by layered patches which are changing their properties continuously (Steele 1991; Kavanaugh et al. 2016).

For this reason, landscape ecology theory offers an approach for comprehending the issues of heterogeneity and its ecological implications in space and time (Scales et al. 2017; Pittman et al. 2021). It has been traditionally concerned with relatively stable habitat characteristics (Pittman et al. 2011), and consequently, a common perspective on seascapes has been formulated, which applies mostly to stationary ecosystems like coral reefs, seagrass beds, rocky reefs, and seamounts (Wedding et al. 2008). It works well, but not in the case of the pelagic ocean, whose habitats are mobile.

Application of the principles of landscape ecology to the pelagic realm creates a completely different framework altogether. Organisms and oceanographic forces interact to create habitats

that are constantly evolving in terms of both spatial and temporal scales (Kavanaugh et al. 2014; Kavanaugh et al. 2016). The habitat is constantly undergoing restructuring through a combination of physical and biogeochemical processes. For example, turbulence in interaction with the photosynthetic activities of the microorganisms produces variability in terms of space and time. This evolving three-dimensional arrangement distinguishes pelagic seascapes from conventional marine landscapes.

Building on this conceptual basis, the pelagic seascape framework has been increasingly applied to describe and interpret environmentally meaningful patterns in the ocean. For example, in the northern Mediterranean Sea, pelagic seascape characterization has been used to model the spatial distribution of Atlantic bluefin tuna spawning areas, capturing variability associated with fronts, mesoscale eddies, and surface currents (Álvarez-Berástegui et al. 2016). Similarly, satellite-derived seascapes have been used to identify dynamic biogeographic domains consistent with phytoplankton community structure (Montes et al. 2020), while other studies have revealed strong linkages between pelagic conditions and benthic ecosystem dynamics, such as coral reef recruitment and species composition (de Azevedo Mazzuco and Fraga Bernardino 2022). Additional applications have demonstrated their utility in predicting human activities, including fishing vessel incursions into restricted areas (Woodill et al. 2021). Together, these studies highlight the versatility of pelagic seascapes as an integrative framework linking physical, biological, and anthropogenic processes.

Although pelagic seascapes are increasingly used for monitoring and management, their ecological validity and regional applicability remain insufficiently tested, particularly in regions characterized

by complex and highly dynamic oceanographic processes (Kavanaugh et al. 2016; Pittman et al. 2021). The present study evaluates the performance of the Pelagic Seascape Habitat Classification (PSHC) developed by the National Oceanic and Atmospheric Administration and Marine Biodiversity Observation Network (NOAA/MBON) in the Gulf of California (GC), a region characterized by strong seasonal and interannual variability and well-documented physical and biological dynamics. We hypothesize that if the PSHC reproduce known seasonal and interannual variability in the GC, it can be interpreted as an ecologically meaningful indicator of regional ecosystem state.

1.1. The Gulf of California

The Gulf of California (GC; Fig. 1) is a semi-enclosed basin approximately 1,200 km in length and 150 km in width, separated from the eastern North Pacific Ocean by the Baja California Peninsula (Lavín and Marinone 2003). Oceanographic conditions at the mouth of the Gulf are strongly influenced by equatorial and central Pacific waters, with the warm season progressively propagating northward toward the Midriff Islands region (Álvarez-Borrego and Schwartzlose 1979; Ripa 1997; Lluch-Cota et al. 2007). Seasonal variability in sea surface temperature is driven by direct solar heating, advection, and mixing processes associated with tides and coastal upwelling (Soto-Mardones et al. 1999; Lavín and Marinone 2003).

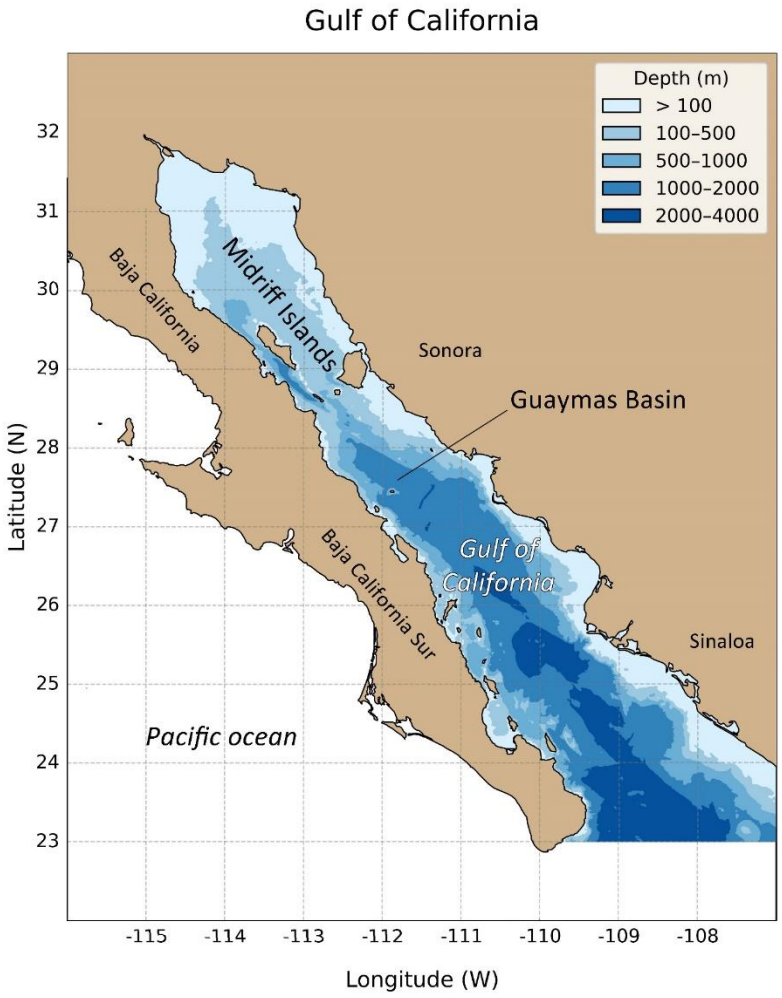
Atmospheric forcing is characterized by weak southeasterly winds during summer and strong northwesterly winds during winter. Ocean circulation responds to this wind regime and, together with tidal forcing and air–sea heat exchange, defines the dominant circulation patterns within the

Gulf. These processes promote nutrient enrichment through winter upwelling along the eastern coast and sustained tidal mixing throughout the year, particularly in the Midriff Islands region (28–29° N), where topographic effects enhance vertical mixing (Lluch-Cota et al. 2007). Interannual variability is primarily driven by changes in equatorial circulation associated with the El Niño–Southern Oscillation (ENSO) (Baumgartner and Christensen 1985). Although the influence of the Pacific Ocean and the California Current within the Gulf has been documented, its relative importance is often secondary to the strong seasonal and interannual variability that characterizes the region (Baumgartner and Christensen 1985; Lavín and Marinone 2003; Palacios-Hernández et al. 2023).

The GC is also recognized as one of the most biologically diverse marine regions globally and is considered a Large Marine Ecosystem due to its high productivity and species richness, including numerous endemics, endangered, threatened, and protected species (Arreguín-Sánchez et al. 2017). Its waters host approximately 130 species of copepods, 4,852 species of macroinvertebrates (767 endemic), 891 species of fish (90 endemic), 181 species of birds (2 endemic), 5 species of sea turtles, and 34 species of marine mammals, including the emblematic vaquita (*Phocoena sinus*) (Lluch-Cota et al. 2010; Arreguín-Sánchez et al. 2017).

The annual mean net primary productivity of the GC is approximately 124 Tg C yr^{-1} (González-Rodríguez et al. 2026). This high productivity underpins the Gulf's importance as a strategic region for marine fisheries in Mexico, with annual catches of approximately 1.2 million tons, representing nearly 75% of the national marine harvest and an estimated value of about 600 million USD (DOF 2012; CONAPESCA 2013). Small pelagic fisheries account for approximately 40% of national

147 marine landings, while shrimp fisheries are the most significant in terms of economic value and
148 employment (Lluch-Cota et al. 2010; Carta Nacional Pesquera 2018). In addition to these industrial
149 fisheries, numerous small-scale coastal fisheries operate throughout the region, representing
150 critical activities for local livelihoods and social well-being (Lluch-Cota et al. 2007, 2010).



151
152 **Figure 1.** Gulf of California in northwestern Mexico, showing bathymetry, the Midriff Islands,
153 Guaymas Basin, and bordering Mexican states.

154 The goal of this paper is to evaluate whether a globally derived Pelagic Seascape Habitat
155 Classification (NOAA/MBON) captures known seasonal and interannual variability in the Gulf of
156 California, thereby assessing its capacity to represent environmentally and ecologically

meaningful states of this highly dynamic marine region. The next section describes the data and methods. The results section presents the seasonal and interannual variability of pelagic seascapes in the GC and their relationships with environmental and biological indicators. This is followed by a discussion emphasizing the ecological interpretation of the observed patterns, their consistency with known regional variability, the implications and limitations of the classification.

2. Methods

2.1. Environmental data

2.1.1. Pelagic seascapes

The Marine Biodiversity Observation Network (MBON) defines 33 spatially explicit pelagic seascapes, representing water masses with distinct biogeochemical characteristics identified through a model based on satellite-derived observations. These pelagic seascapes are classified and used as a biogeographic framework to describe the dynamics of ocean habitats (Kavanaugh et al. 2016; NOAA CoastWatch 2025). The resulting classifications provide information on the quality and spatial extent of different habitats or oceanographic features. The environmental characteristics of the pelagic habitat categories observed in the Gulf of California are summarized in Table S1. We downloaded data from January 2003 to December 2024 in monthly frequency and spatial resolution of 5×5km from: https://coastwatch.noaa.gov/cwn/products/seascape-pelagic-habitat-classification.html

2.1.2. Net primary productivity

Net Primary Productivity (NPP) data, from 2003 to 2024, with spatial resolution (4 x 4 km) were obtained from monthly level 3 products of the Vertically Generalized Production Model (VGPM) via NOAA CoastWatch https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMH1ppmday.graph.

NPP values were classified into three categories based on percentile values below Q25, between Q25 and Q75, and above Q75, representing oligotrophic, average, and high-productivity conditions, respectively. Monthly climatologies were then computed for the percentage of area occupied by each NPP category, as well as for the area covered by each pelagic habitat within the Gulf of California. These metrics were used to assess the temporal coherence between pelagic seascape variability and changes in ecosystem productivity.

2.1.3. Sea level anomalies

Sea level anomaly (SLA) data were obtained from the Copernicus Marine Service, based on satellite altimetry products provided by the European Space Agency. Monthly means for the period 2003–2024 were obtained from the product cmems_obs-sl_glo_phy-ssh_my_allsat-l4-duacs-0.125deg_P1M-m , with a spatial resolution of 0.125° × 0.125°. We used SLA data as an indicator of mesoscale variability to examine its coherence with changes in the pelagic seascape of the Gulf of California. SLA values were also classified into three categories based on percentile values below Q25, between Q25 and Q75, and above Q75, with the objective to distinguish low, average and high SLA conditions inside the GC. This SLA classification was then used to study the seasonal and interannual coherence with pelagic seascape configurations.

2.2. Analysis

To characterize the distinctive features of pelagic seascapes in the Gulf of California, monthly data from January 2003 to December 2024 were obtained from the NOAA CoastWatch PSHC product (Kavanaugh et al. 2016; NOAA CoastWatch 2025). The data were downloaded in NetCDF (*.nc)

format and subsequently restructured for use in the R programming environment as a level-4 "satin" class object. All analyses were conducted using the satin library in R, which facilitated data extraction, manipulation, and visualization (Villalobos and González-Rodríguez 2022). The study area was spatially subset to the Gulf of California, and the percentage of monthly pixels occupied by each pelagic habitat category was calculated. Valid pixel counts were also used to identify the dominant pelagic habitats, defined as those reaching the maximum percentage of area coverage over the total study period.

To compare the potential spatial dominance among habitat categories, we calculated a relative dominance potential (RDP) based on the maximum monthly area coverage reached by each habitat over the study period. For habitat category (*i*), RDP was calculated as:

$$RDP_i = \frac{M_i}{\sum_{j=1}^{n} M_j} \times 100$$

where (M_i) is the maximum percentage of the Gulf of California occupied by habitat (i), and (*n*) is the total number of habitat categories observed. The index therefore expresses the maximum expansion potential of each habitat relative to that of all habitat categories. For descriptive purposes, RDP values were grouped arbitrary into five dominance classes: Trace, Low, Moderate, High and Very high. These categories were used only to facilitate comparison among habitat classes and do not represent ecological thresholds (Table S2).

The diversity of pelagic habitats in the Gulf of California was calculated using the *vegan* package (version 2.6-10) in R and the diversity( ) function (Oksanen et al. 2025; R Core Team 2025). The index was computed according to the following formulation:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

where p_i represents the proportion of area occupied by the *i*-th pelagic habitat category, and S is the total number of habitat categories present in the study area. Therefore, variations in H′ in the pelagic realm can be interpreted as indicators of changes in ecosystem structure, where higher diversity reflects increased pelagic habitat heterogeneity with potential implications for trophic interactions and biodiversity patterns, whereas lower diversity suggests simplified habitat configurations that may constrain ecological niches and biological responses.

2.2.1. Multivariate visualization

To identify patterns and potential associations between pelagic seascapes and known sources of seasonal and interannual variability, we generated a heatmap in R using ComplexHeatmap::pheatmap() (Gu et al. 2016; Gu 2022). The ordering of rows and columns was not determined by clustering-distance or linkage results. The heatmap was used primarily as a multivariate visualization tool of previously structured data according to interannual, seasonal and habitat coverage criteria, rather than as a classification procedure. Although this visualization approach is widely used in genomic expression analyses, it has strong potential for application in other fields due to its effectiveness in displaying multidimensional relationships (Gu et al. 2016).

For the Gulf of California dataset, each row represented a monthly observation, and each pelagic habitat column represented the percentage of the Gulf occupied by that habitat during that month. The temporal structure was organized a priori according to ENSO phase and season, and observations were ordered within these groups according to an increasing gradient of C21

coverage, with the highest C21 values located toward the top of the heatmap. ENSO phases were classified from the Multivariate ENSO Index version 2 (MEI.v2) as negative (< −0.5), neutral (−0.5 to 0.5), and positive (> 0.5) (NOAA Physical Sciences Laboratory; Zhang et al., 2019). The MEI.v2 series is based on JRA-3Q reanalysis fields and NOAA OLR Climate Data Record observations (NOAA PSL, accessed April 2025). Seasonal categories were defined as winter (January–April), transition (May–June and November–December), and summer (July–October).

Season and ENSO phase were included as row annotations. Environmental characteristics associated with the pelagic habitat categories—sea surface temperature (SST), salinity (SSS), and chlorophyll-a concentration (CHL)—were incorporated as column annotations an correspond to the characteristic values reported for each pelagic habitat class by NOAA/CoastWatch (https://coastwatch.noaa.gov/cwn/products/seascape-pelagic-habitat-classification.html). Finally, NPP and SLA were displayed as row-aligned environmental indicators to complement environmental context and facilitate comparison with the monthly pelagic seascape configurations. NPP indicates the area percentage of the GC covered by high net primary conditions (> Q75), while SLA shows the area (%) covered by high sea level anomalies (> Q75).

2.2.2. Biological context

The observed changes in the pelagic seascape of the Gulf of California and their potential biological responses were analysed using two complementary approaches: A) documented changes in pelagic organisms; B) Examining fisheries landings records (avisos de arribo) reported by regional fisheries offices (CONAPESCA) and their coherence with the dominant pelagic habitat variability.

a) Documented changes in pelagic organisms

First, to identify documented changes reported in the literature, Google Scholar was used as the primary search engine, employing terms such as “Gulf of California,” “variability in the Gulf of California,” “fisheries in the Gulf of California,” and “productivity in the Gulf of California.” Studies were selected based on their description of biological, ecological, and hydrographic changes, with preference given to those covering multiple years within the period 2003–2024. The extracted information was then compared and discussed in relation to the observed variability in pelagic seascapes. Although this is not an exhaustive review, this approach provides a representative synthesis of the dominant biological and ecological trends reported for the region. Interannual biological responses identified in the literature were schematized in combination with anomaly time series representing pelagic seascapes, net primary productivity (NPP), and sea level anomalies (SLA). NPP was expressed as anomalies in the percentage of area within the Gulf (%) falling in the upper quantile (>Q75; high-productivity conditions), whereas SLA was represented as the proportion of the Gulf (%) within the lower quantile (<Q25; low sea level conditions associated with reduced sea surface temperature). Anomalies for each variable were calculated by removing the corresponding monthly climatology from monthly values along the time series. Non-parametric correlation analyses were also applied to interannual time series to quantify the strength of association between pairs of variables.

b) Fisheries landings

Pelagic fisheries landings (avisos de arribo) reported by regional fisheries offices (CONAPESCA) were compared versus the dominant pelagic habitat (C21) and the pelagic habitats diversity index (H′). The historical registers of fisheries landings from January 2006 to December 2024, were

provided by Dra. María del Carmen Jiménez Quiroz, from the Research Institute for Sustainable Fisheries and Aquaculture in México (IMIPAS). Developing R code, we selected the registers from 25 fishing offices around the Gulf of California, corresponding to the Mexican states of Sinaloa, Sonora, Baja California and Baja California Sur. Then, we extracted catch data expressed in thousand tons corresponding to pelagic fisheries in the region, accounting for 14 multispecies fishing groups; calamar, jurel, sierra, tiburón, pámpano, bonito, atún, barrilete, anchoveta, macarela, sardina, esmedregal, peto, cintilla.

3. Results

Table 1. Descriptive statistics of the Gulf of California area percentage covered by each pelagic habitat category.

Habitat category	Max	Min	Mean	SD	CV (%)
C21	94.3	5.5	35.6	24.1	68
C15	79.3	2	46.9	18.7	40
C3	42.6	<1	6.7	10.1	150
C13	30.7	<1	4.4	6.5	147
C11	30.9	<1	2.5	4.9	194
C9	20.6	<1	1.5	3.2	215
C7	55	<1	1.5	6.3	422
C14	17.1	<1	<1	1.6	478
C17	6.9	<1	<1	1	218
C8	1.6	<1	<1	0.2	530
C27	1.1	<1	<1	0.1	247

Max=maximum coverage; Min=minimum coverage; Mean=average; SD=standard deviation; CV=coefficient of variation (%)

Table 1 identifies C15 and C21 as the two dominant pelagic habitat categories, although their patterns of dominance differ (see Table S2). While C15 had the highest mean coverage (46.9%), C21 exhibited the greatest expansion potential with the highest maximum coverage (94.3%) and standard deviation (24.1%). The remaining habitat categories, including C3, C13, C11, C9, and C7, had mean coverage below 7%, but occasionally expanded substantially, reaching approximately 30–40% in C3 and C11 and up to 55% in C7. The high coefficients of variation of these less frequent habitats (e.g., C7, CV = 422%) indicate episodic expansion–contraction events rather than persistent dominance within the Gulf. These differences are also reflected in their relative dominance potential, with C21 showing the highest value, followed by C15, C7, and C3 (Table. S2).

3.1. Seasonal cycle

In winter, habitat C21 (Fig. 2, yellow) occupies most of the GC, covering approximately 67% in January and February, decreasing to 41% by April, when it is restricted to coastal areas and to the northern portion. As the cold season ends and the summer approximates, other habitats gradually expand from south to north (Fig. 2). The habitat C15 (Fig. 2, green) increases from about 25% in February to more than 60% in May and June (Fig. 2; Fig. 3, upper panel). From June to October, the area covered by C21 remains below 25%, before expanding again to over 50% in December, accompanied by the contraction of habitats like C3, C11 and C9 (Fig. 2, Fig. 3 upper panel). This seasonal expansion–contraction pattern between C21 and C15 indicates that winter conditions are dominated by waters characterized by intermediate temperatures (~22.54 °C), moderate salinity (~34.46 psu), and relatively high chlorophyll concentrations (~2.09 $mg \cdot m^{-3}$). In contrast, summer

329 conditions are associated with higher temperatures (~25.35 °C), higher salinity (~35.4 psu), and
330 lower chlorophyll concentrations (~0.32 $mg \cdot m^{-3}$; Table S1).

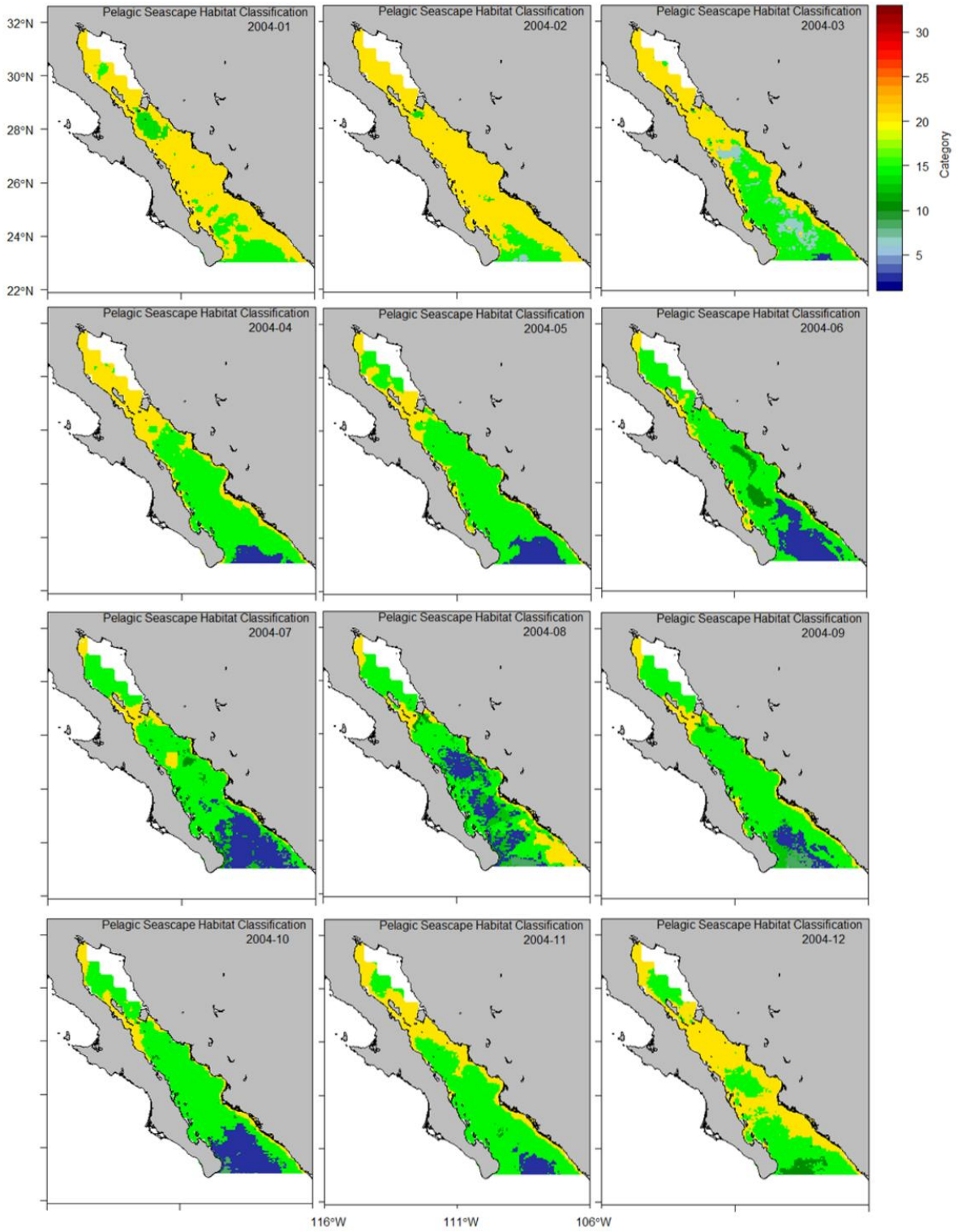
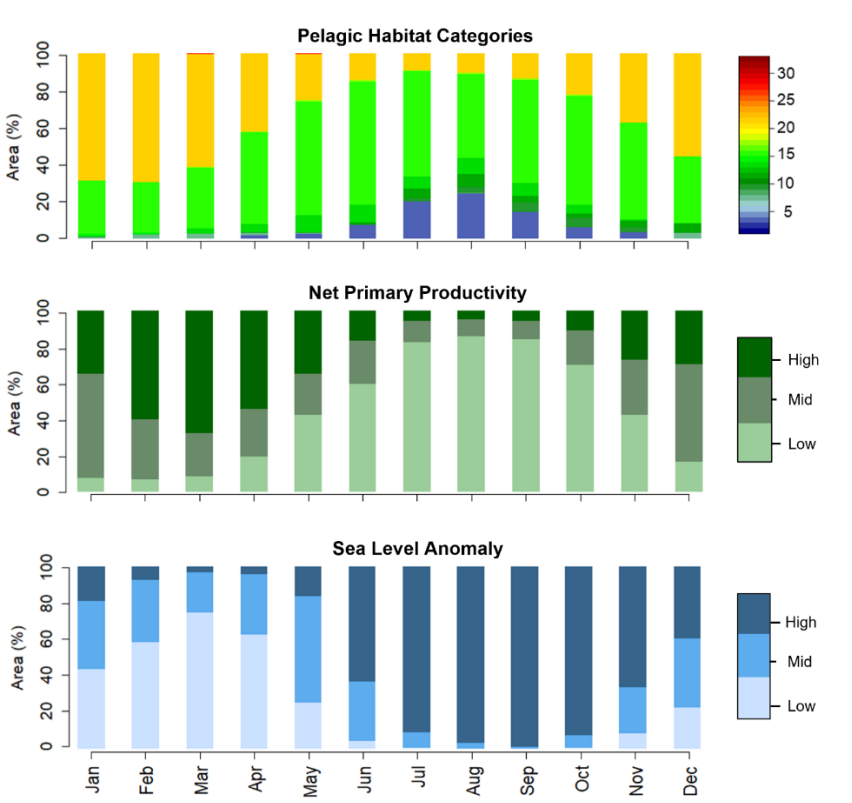


Figure 2. Example of the seasonal cycle of pelagic seascapes in the Gulf of California during 2004. Monthly maps show the spatial distribution of habitat categories corresponding to the numbered classes in the legend.

335 The seasonal changes of pelagic habitats follow similar patterns in other environmental variables
336 of the GC. Net primary productivity (NPP) also exhibits a pronounced seasonal cycle in the GC,
337 encompassing oligotrophic (Low), mesotrophic (Mid), and eutrophic (High) conditions (Fig. 3;
338 central panel). Oligotrophic conditions (light green bars) expand during the warm season (July–
339 October), passing from 6% to 80% of the GC total area. In contrast, eutrophic conditions (dark
340 green bars) reach their largest areas during late winter and spring (30–70%), meanwhile the
341 transition periods cover 25–40% of the Gulf. Mesotrophic conditions (gray-green bars) increase
342 from December to February (30–50%), but decline towards July–September, decreasing to values
343 near 10% (Fig. 3; central panel).

344

345 Areas covered by low, mid, and high sea level anomalies (SLA) are presented in the lower panel
346 of Fig. 3. Low SLA conditions (light blue) expand progressively towards the end of winter (from
347 November to March), increasing from approximately 10% to 70% of the Gulf of California. These
348 closely coincide both with increasing areas of high primary productivity and the expansion of the
349 pelagic habitat C21. In contrast, high SLA conditions (dark blue) dominate during the summer
350 months, covering more than 90% of the Gulf from August to October. In this period there is an
351 expansion of oligotrophic conditions (central panel), a contraction of pelagic habitat C21, and an
352 increase in the diversity of pelagic habitats (Fig. 3 upper panel). This spring transition closely
353 reflects the well-known seasonal cycle of the Gulf across all three variables shown in Fig. 3. This
354 transition also reflects the shift from productive, relatively homogeneous conditions in winter-
355 spring to less productive and more heterogeneous environmental conditions in the summer.



356

357 **Figure 3.** Monthly climatologies for the Gulf of California. Upper panel, area covered by pelagic
358 habitats; middle panel, area occupied by high, mid, and low net primary productivity conditions;
359 lower panel, area covered by high, mid, and low sea level anomalies.

360

361 Winter-spring conditions are characterized by low sea level, and elevated primary productivity,
362 promoting the expansion of dominant habitats such as C21 and resulting in a relatively
363 homogeneous pelagic seascape. As the system transitions into summer, increasing sea level and
364 reduced productivity lead to the contraction of dominant habitats and the emergence of a more
365 diverse set of habitat categories, reflecting higher environmental heterogeneity. This seasonal
366 reorganization highlights the sensitivity of pelagic seascapes to underlying oceanographic
367 processes and its inherent potential as integrative indicators of ecosystem state and variability.
368 Overall, the seasonal cycle of pelagic seascapes in the Gulf of California reflects a tightly coupled

system in which physical forcing, ecosystem productivity, and habitat configuration evolve coherently throughout the year.

3.2 Interannual variability and ENSO influence

Fig. 4 shows a pronounced seasonal cycle in the spatial coverage of pelagic habitat classes in the Gulf of California, superimposed on substantial interannual variability from 2003 to 2024. The dominant habitats exhibit recurrent annual expansion–contraction patterns, although the magnitude of these seasonal changes varies among years. C21 (yellow) shows particularly large winter expansions during 2004–2009, 2011–2012, and 2017–2023, whereas its winter coverage is reduced in 2010 and more persistently during 2013–2016. C15 (lime green) displays a more regular seasonal pattern, but the magnitude of its winter contraction also varies among years and generally contrasts with changes in C21 coverage.

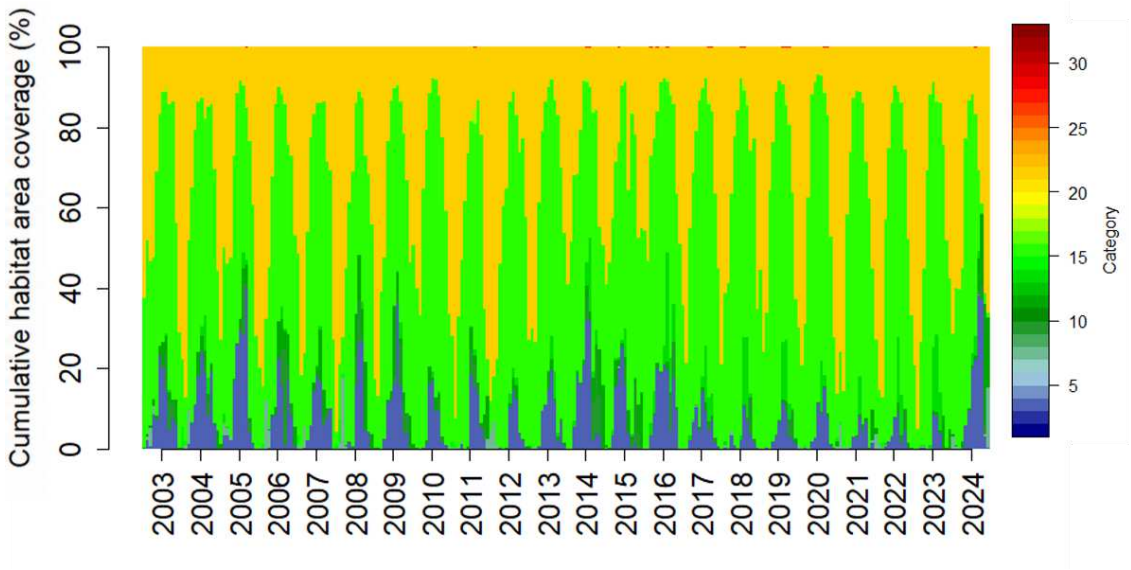
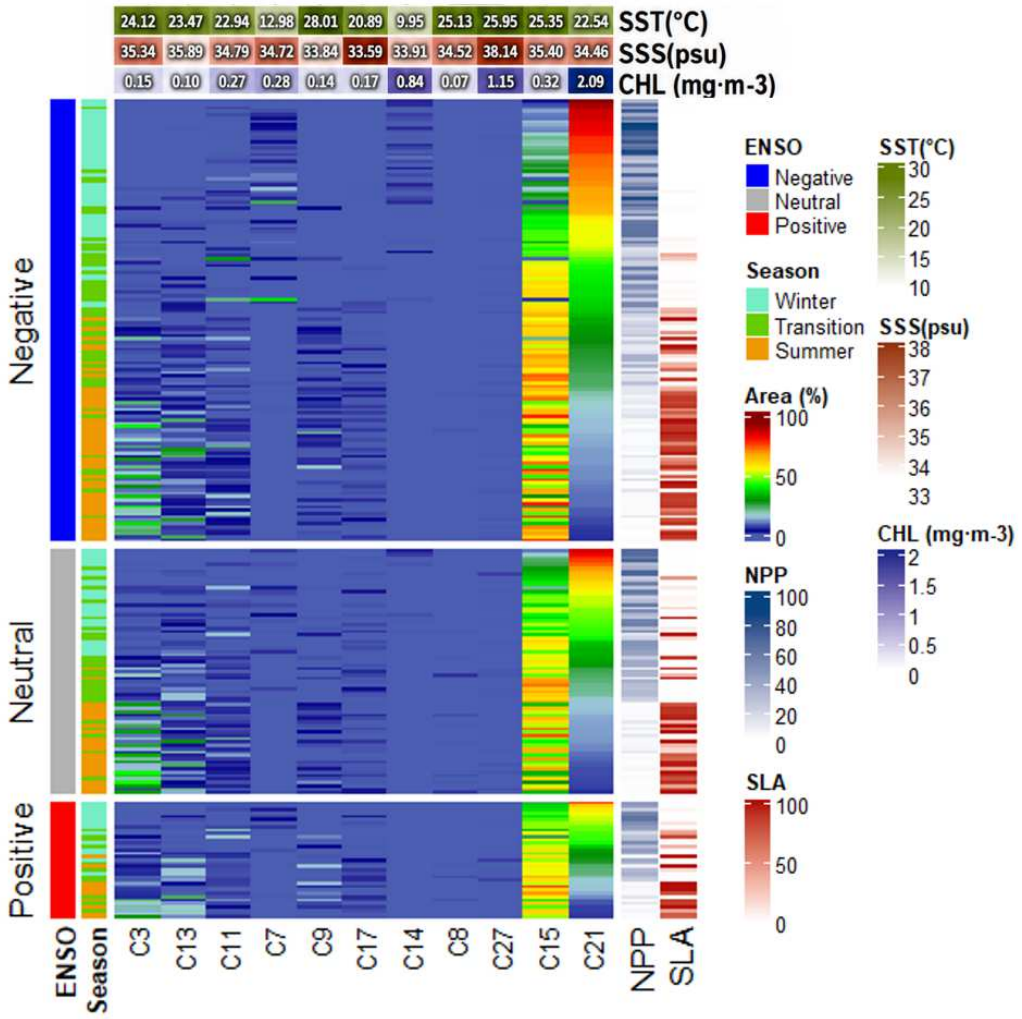


Figure 4. Seasonal and interannual variability in the area covered by pelagic habitats in the Gulf of California during 2003–2024. Stacked colours represent habitat categories, with their combined coverage summing to 100%.

385 Other habitat classes, including C3 (dark blue), C13 (medium green), and C11 (darker green),
386 become more prominent when the dominance of C21 and C15 decreases, contributing to a more
387 heterogeneous pelagic seascape. C3, for example, shows notable expansions in 2005, 2014–2016,
388 and 2024, whereas its coverage remains comparatively low during 2017–2023. Overall, the figure
389 indicates that pelagic seascape variability is structured by a strong seasonal cycle whose expression
390 is modulated by interannual changes in the relative dominance and spatial extent of the main
391 habitat classes (Fig. 4).

392

393 By breaking the temporal structure of data, the classification of monthly observations according
394 to ENSO phase, season, and the gradient of C21 coverage provided further insights (see Sect.
395 2.2.1). The result is a detailed visualization of how pelagic habitat configurations are distributed
396 across seasonal and interannual conditions in the Gulf of California (Fig. 5). The clearest
397 configuration occurs when negative ENSO conditions coincide with winter: C21 becomes strongly
398 dominant, reaching up to 94% of the Gulf, while the contribution of most other habitat classes
399 remains comparatively low. C21 is characterized by relatively low temperature and salinity and
400 high chlorophyll concentration (22.54 °C, 34.46 psu, and 2.09 $mg \cdot m^{-3}$, respectively), in contrast
401 with classes such as C15, which is characterized by 25.35 °C, 35.40 psu, and 0.32 $mg \cdot m^{-3}$.



402

403 **Fig. 5** Heatmap of pelagic habitats in the Gulf of California, organised by ENSO phase, season,
404 and the coverage gradient of C21. Left annotations indicate ENSO phase and season. Column
405 annotations show characteristic sea surface temperature (SST), sea surface salinity (SSS), and
406 chlorophyll-a (CHL) values for each class. Right annotations show the percentage of Gulf area
407 with high net primary productivity (NPP; >Q75) and high sea level anomalies (SLA; >Q75).

408

409 The NPP and SLA row annotations further show that observations with greater C21 coverage
410 generally coincide with increased coverage of high-NPP conditions and reduced occurrence of
411 high-SLA conditions, a configuration consistent with a productive and relatively homogeneous

412 pelagic habitat state. Less common habitats such as C7 and C14, which are characterized by
413 comparatively low SST values, also occur under some of these conditions (Fig. 5).

414

415 The heatmap also shows that this pattern remains strongly modulated by seasonality. Even under
416 negative ENSO conditions, C21 contracts substantially during summer, averaging approximately
417 14% of the Gulf and ranging from 5% to 30% between July and October. Thus, negative ENSO
418 conditions are associated with stronger winter dominance of C21, but the characteristic seasonal
419 expansion–contraction cycle remains evident (Fig. 5).

420

421 A contrasting configuration emerges as C21 contracts. Habitats C15, C3, C13, C11, and C7 occupy
422 larger fractions of the Gulf, producing a more heterogeneous pelagic seascape. This configuration
423 occurs more frequently during positive ENSO phases and warmer seasonal conditions. The
424 expansion of C15, C3, and C13 introduces habitat classes characterized by lower chlorophyll
425 concentrations (0.32–0.10 $mg \cdot m^{-3}$) and a broader range of characteristic temperatures (25.35,
426 24.12, and 23.47 °C). At the same time, lower C21 coverage generally coincides with reduced
427 high-NPP coverage and greater high-SLA coverage. The expansion of multiple habitat classes is
428 therefore consistent with reduced dominance and fragmentation of the C21-dominated
429 configuration and with the emergence of several alternative pelagic habitat conditions (Fig. 5).

430

431 Rare habitats such as C8 and C27 occur more frequently under neutral and positive ENSO
432 conditions. Overall, Fig. 5 reveals two broad pelagic seascape configurations: a C21-dominated
433 state associated with cooler, higher-chlorophyll class characteristics, greater high-NPP coverage,

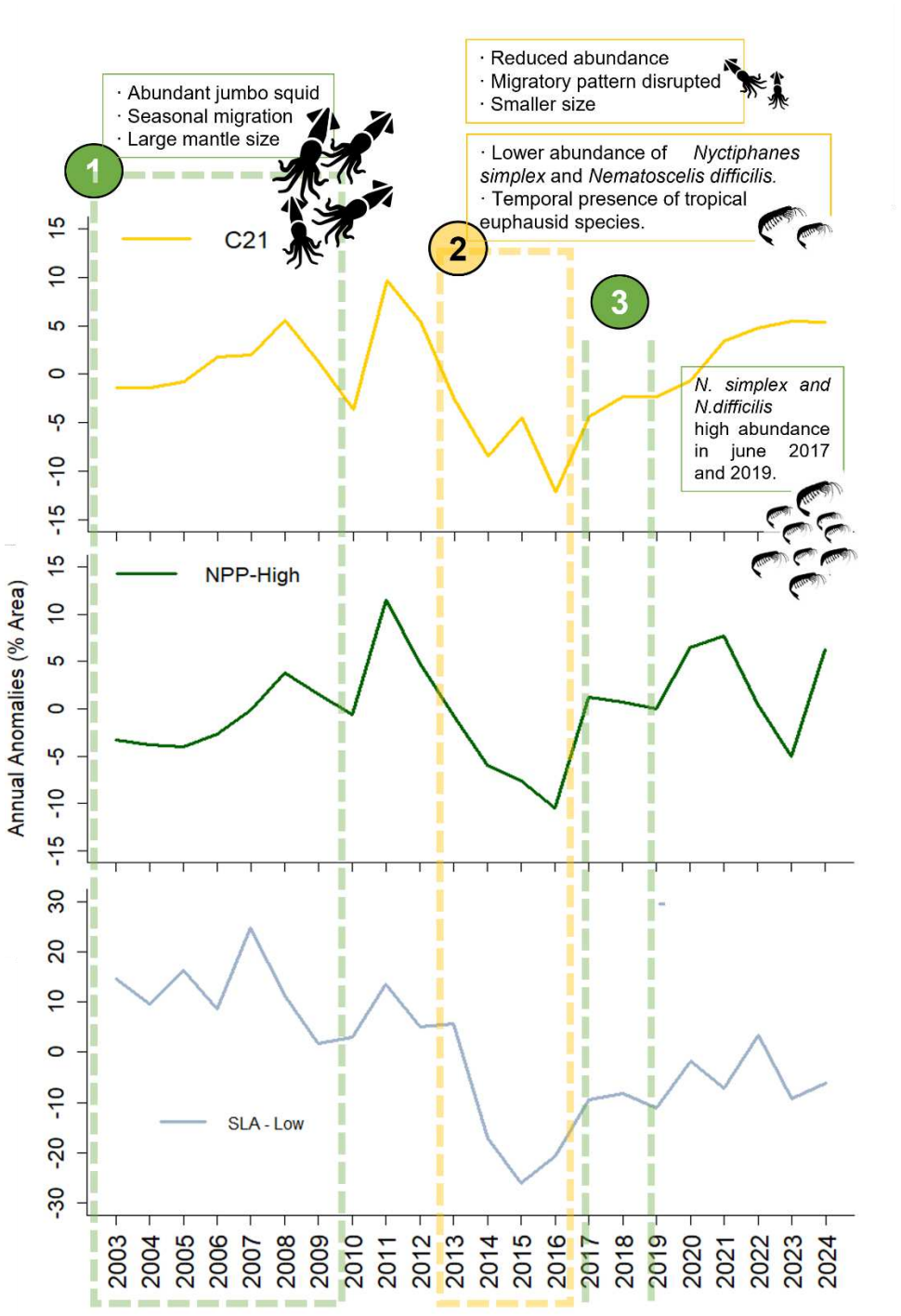
and relatively homogeneous habitat composition; and a more heterogeneous configuration characterized by reduced C21 dominance, the expansion of warmer and lower-chlorophyll habitat classes, reduced high-NPP coverage, and greater high-SLA coverage. These patterns show how seasonal and ENSO conditions are associated with changes in the organization of the pelagic seascape of the GC.

The relationships observed in the multivariate visualization were further supported by pairwise Spearman correlations. C21 coverage was strongly negatively correlated with the area occupied by low-NPP conditions ($\rho = -0.86$, $p < 0.001$), strongly positively correlated with high-NPP conditions ($\rho = 0.92$, $p < 0.001$) and low-SLA conditions ($\rho = 0.72$, $p < 0.001$; Fig. S1). Meanwhile, habitat diversity (H′) was positively associated with low-NPP conditions ($\rho = 0.47$, $p < 0.05$) and negatively associated with high-NPP conditions ($\rho = -0.49$, $p < 0.05$; Fig. S1).

3.3. Biological response

Fig. 6 synthesize the interannual changes in the area covered by C21 in relation to net primary productivity, sea level anomalies and biological changes. This comparison highlights the strong correspondence between the pelagic seascape reconfigurations and pelagic fauna response (e.g. jumbo squid and euphausiids). Three main periods can be recognized: (1) Persistent high productivity 2003-2012, when area coverage by C21 persists above average, coinciding with jumbo squid high abundance, regular migratory patterns, and individuals with large mantle sizes; (2) Collapsed productivity 2013-2016, observing a contraction in C21, accompanied by the decline in jumbo squid abundance, disruption of its migratory pattern, and the predominance of smaller

456 body sizes relative to the previous period and observing also the reduction in subtropical
457 euphausiid abundance and the temporary occurrence of tropical euphausiids; (3) Productivity
458 pulses in 2017 and 2019, when C21 exhibited a gradual and moderate expansion approaching to
459 average values, while a recovery in the abundance of the subtropical euphausiids *Nyctiphanes*
460 *simplex* and *Nematoscelis difficilis* was recorded (Fig. 6, Table 2).



461

462 **Fig. 6** Annual anomalies in C21 coverage, high net primary productivity coverage (NPP-High),
463 and low sea level anomaly coverage (SLA-Low), compared with documented biological changes
464 in the Gulf of California. Numbered periods correspond to the synthesis in Table 2; green and
465 yellow outlines indicate periods of productive conditions and reduced productivity, respectively.

Table 2. Documented biological and hydrographic changes and corresponding pelagic seascape changes in the Gulf of California.

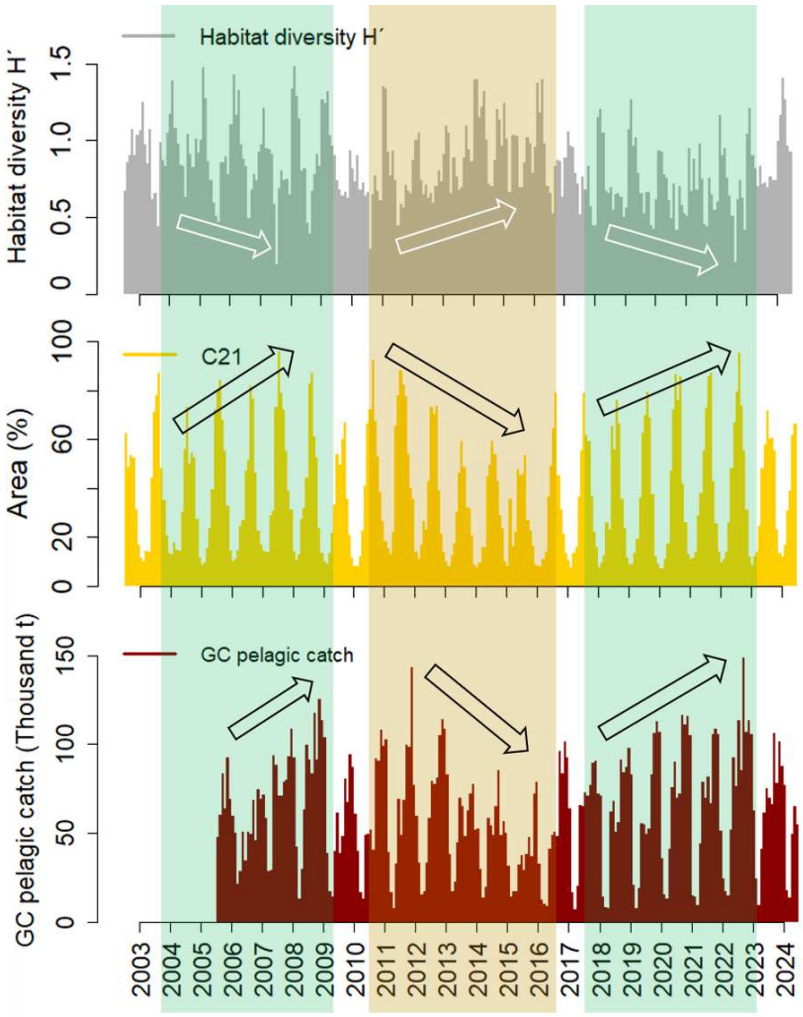
Timespan / references	Documented biological changes	Hydrographic changes	Observed changes in pelagic seascape
Before 2009-2010 Markaida et al. 2005; Gilly et al. 2022; Olivier et al. 2022	Prior to El Niño 2009–2010, jumbo squid matured at a large size and migrated seasonally across the Guaymas Basin in phase with alternating periods of elevated productivity along the mainland and peninsular coasts. In the southern GC, reef fish density was reported to increase but summer maximum species richness was reduced. In complement, dominant species increased their abundance.	Two decades prior to 2009, cooling conditions prevailed in the GC. In 2006–2008, the 22 °C isoline remained stable and above 30 m depth. From 2008 to 2009 (and afterwards), such isoline deepened to about 60 m. Low oxygen concentrations became gradually shallower from 2006 to 2009, affecting multiple ocean layers, partly below 90 m depth.	The area covered by C21 showed an increasing trend from 2003 to 2009, going from 60 to 80% during the months of greatest expansion (winter). The gradual predominance of C21 corresponds to the reduction of H′, which can be observed during the winter minimums, registering the lowest values in 2008 and 2009.
2010, 2013-2016 Frawley et al. 2019; Palacios-Hernández et al. 2023; Trasviña-Castro et al. 2024; Salvadeo et al. 2024	After the predominance of El Niño conditions by late 2009, the migratory pathway was disrupted and the squid population was presumably fragmented as a new fishery emerged in the Midriff Islands (GC). Size and landings decreased with some short-lived recoveries, but the fishery in the Guaymas Basin failed to re-establish, at least until 2018. Tropical euphausiid species were temporarily registered in the GC during 2013, the marine heatwave in 2014, and El Niño 2015–2016. Considerably lower abundance was recorded for *Nyctiphanes simplex* and *Nematoscelis difficilis*, two euphausiid species of temperate and subtropical affinities, respectively. Fish per charter trip of sport and commercial fisheries decreased 50% by El Niño 2015–2016 from pre-2010 levels.	Prolonged warming conditions persisted. Progressive subsurface warming (0–200 m) starting with El Niño 2009–2010 persisted further in combination with the 2014 marine heatwave and El Niño 2015–2016. Sea surface height across the central and southern GC increased, deepening subsurface nutriclines and thermoclines. Primary productivity decreased as highly stratified, low-nutrient water was trapped in the central GC. Winter winds diminished and mesoscale circulation patterns changed, reducing enrichment, concentration, and retention. Depleted upwelling activity was also observed at the entrance of the GC from late 2013 to mid-2016.	A predominant trend of C21 contraction was observed in 2009–2016, when its area was reduced from 80 to 40% during winters. The period 2014–2016 was the most persistent with small areas covered by C21 (~40%). In 2017 and 2018, the expansion of C21 increased to approximately 60%, but decreased rapidly compared to years such as 2011 or 2012, when it persisted with similar values for several months. The most notable changes in H′ were observed in the winter minima, as they gradually increased from 2010 to 2016. This means that winters represented less dominance and greater H′ diversity.

Timespan / references	Documented biological changes	Hydrographic changes	Observed changes in pelagic seascape
2017 & 2019 Gilly et al. 2022; Olivier et al. 2022; García-Fernández et al. 2023	Euphausiid species of temperate and subtropical affinities showed very high abundances in June 2017 and 2019. Different commercial and sport fisheries experienced major changes coincident with cooling conditions. Fish assemblages in 2017 were more related to those in 2011 than in previous years.	The years 2017 and 2019 had smaller positive anomalies and even negative anomalies of SST, accompanied by relative cooling at depth, similar to levels found in 2013. Chlorophyll measurements during oceanographic cruises show higher concentrations in 2017 and 2019 from the surface to 200 m depth when compared to 2016 and 2018.	In 2017–2019, the gradual expansion of the area covered by C21 was observed, from about 70% to 80%. In the same period, H′ maintained stable winter minimums, but increased in summer maximums.

468

469

470 We observed a marked interannual correspondence among pelagic habitat diversity (H′), the spatial
471 extent of habitat C21, and the commercial catches of pelagic species in the GC (Fig. 7). Three
472 contrasting periods can be identified: During 2006–2009, C21 expanded accompanied by
473 relatively low habitat diversity and a progressive increase in pelagic catches. In contrast, the period
474 2011–2016 was characterized by a contraction of C21, coinciding with elevated H′ values and a
475 substantial decline in commercial catches. Finally, from 2017 to 2024, C21 exhibited a moderate
476 recovery approaching to average coverage, while habitat diversity decreased and pelagic catches
477 increased again. These results suggest an inverse relationship between habitat diversity and the
478 extent of C21, where catches appear to vary positively with the expansion of C21 and negatively
479 with periods of increased pelagic habitat heterogeneity (Fig. 7).



480

481 **Figure 7.** Monthly time series of pelagic habitat diversity (H′; upper panel), C21 area coverage

482 (middle panel), and pelagic fisheries catch (lower panel) in the Gulf of California. Arrows indicate

483 interannual trends; green shading marks periods of increasing productivity and yellow shading

484 marks declining productivity.

485

4. Discussion

4.1. Pelagic seascapes follow the Gulf seasonal structure

The present study demonstrates that the Pelagic Seascape Habitat Classification evaluated in this study, captures meaningful environmental and ecological variability in the Gulf of California (GC), reproducing both, the seasonal organization of the system and major interannual transitions documented during the last two decades. The strong coherence observed among pelagic habitat configuration, net primary productivity (NPP), sea level anomalies (SLA), habitat diversity (H′), fisheries variability, and independently documented biological responses suggests that pelagic seascapes are not merely statistical environmental partitions, but in the GC they may function as emergent integrative descriptors of ecosystem state (Kavanaugh et al. 2014, 2016; Montes et al. 2020; de Azevedo Mazzuco and Fraga Bernardino 2022).

At the seasonal scale, the observed dynamics of pelagic habitats closely reproduced the canonical winter–summer cycle of the Gulf of California (Figs. 3). Winter conditions were characterized by the expansion of habitat C21, which covered up to 67% of the Gulf during January–February and exceeded 90% during some negative ENSO winters (Fig. 5). This period coincided with low SLA, elevated chlorophyll concentrations (~2.09 $mg \cdot m^{-3}$), high NPP, and reduced habitat diversity (H′), collectively reflecting a productive and relatively homogeneous pelagic environment (Fig. 5). In contrast, summer conditions - expanded oligotrophic conditions- promoted the contraction of C21 (<25%), expansion of habitats C15, C3 and higher H′ values, indicating a more heterogeneous and stratified seascape (Figs. 2–4).

508 These patterns are highly consistent with the seasonal hydrographic structure of the GC, where
509 winter cooling, vertical mixing, and intensified nutrient supply promote elevated biological
510 productivity, whereas summer stratification favours oligotrophic conditions and greater
511 environmental heterogeneity (Castro et al. 1994; Soto-Mardones et al. 1999; Marinone 2003).

512

513 The close coupling among pelagic habitats, NPP, and SLA suggests that the seascape framework
514 effectively integrates multiple dimensions of ocean variability into ecologically interpretable
515 habitat states. This integrative capacity represents one of the principal conceptual advances of
516 pelagic seascape ecology, which seeks to move beyond single-variable descriptions toward
517 multidimensional representations of ocean structure and function (Kavanaugh et al. 2014; Scales
518 et al. 2017). In the GC, the expansion of C21 appears to reflect productive and physically coherent
519 conditions associated with relatively low temperature and reduced habitat heterogeneity, whereas
520 increased H′ values indicate the fragmentation of dominant habitat states and the emergence of
521 multiple pelagic conditions under warmer and more stratified environments.

522

523 **4.2 Interannual seascape reconfigurations**

524 At the interannual scale, pelagic seascapes tracked major hydrographic transitions (i.e.
525 temperature, chlorophyll-a, mesoscale circulation) that have been independently documented in
526 the GC during the last two decades (Frawley et al. 2019; Hakspiel-Segura et al. 2022; Trasviña-
527 Castro et al. 2024). From 2003 to 2009, C21 progressively expanded during winter from
528 approximately 60% to 80% of the Gulf, while H′ minima declined markedly (Figs. 6-7; Table 2).
529 This period coincided with the persistence of relatively cool conditions in the GC prior to the

2009–2010 El Niño event, when the 22 °C isotherm remained shallower than ~30 m depth and productive conditions predominated (Gilly et al. 2022). Therefore, the observed multiannual expansion of C21, together with progressively lower H′ minima, appears consistent with a productive pelagic state characterized by reduced habitat heterogeneity and associated with cooler conditions, elevated chlorophyll, and higher NPP (Figs. 6-7).

Observations from several components of the GC in the 2003–2009 period, indicate strong coupling between biological organization and the prevailing hydrographic structure (Table 2). At the zooplankton level, the euphausiid *Nyctiphanes simplex* reached widespread high densities during cold, well-mixed conditions, whereas its abundance declined markedly during the stratified warmer conditions, demonstrating a close response to hydrography and providing the necessary basis for interpreting interannual change (Gómez-Gutiérrez et al. 2010; Fig. 6; Table 2). Larval fish assemblages also respond systematically to circulation changes, coastal currents, mesoscale eddies, and intense tidal mixing, indicating that hydrographic structure strongly organized pelagic fish habitats in the GC (Sánchez-Velasco et al. 2009). Changes in pelagic habitats also appear to be relevant in shallow-water ecosystems: during 2003–2009, reef fish density increased in the southern GC, while dominant species became more abundant despite a reduction in summer species richness (Olivier et al. 2022).

At higher trophic levels, observations from Ballenas Channel showed spatial overlap between fin whales (*Balaenoptera physalus*) and their principal euphausiid prey (*Nyctiphanes simplex*), illustrating trophic connectivity between productive pelagic habitats, zooplankton, and marine predators (Ladrón-de-Guevara et al. 2015). During this period (2003-2009), jumbo squid

553 (*Dosidicus gigas*) remained characteristic of the central Gulf population and exhibited extensive
554 feeding activity by horizontal and vertical migrations. Retrospective analyses further indicated that
555 a large-size jumbo squid phenotype remained dominant through 2009, before the marked
556 biological reorganization associated with the 2009–2010 El Niño and subsequent warming
557 (Frawley et al. 2019; Gilly et al. 2022; Fig. 6; Table 2).

558

559 Although these responses involve different ecosystem components, they collectively support the
560 interpretation of a productive seascape state consistent with the prevailing environmental
561 conditions and broader biological changes documented in the GC. In this context, the low H′ values
562 observed during winters dominated by C21 should not be interpreted as reduced ecological
563 importance, but rather as reflecting the predominance of a productive pelagic habitat state with
564 reduced habitat heterogeneity (Fig. 7).

565

566 A contrasting ecosystem configuration emerged after the 2009–2010 El Niño event and intensified
567 during the 2014-2015 marine heatwave "The Blob" and El Niño 2015–2016. During this interval,
568 C21 exhibited a sustained contraction, decreasing from ~80% to ~40% during winters, while H′
569 minima progressively increased (Figs. 6-7). This transition coincided with prolonged warming
570 conditions, increased sea surface height, deeper thermoclines and nutriclines, diminished winter
571 winds, reduced mesoscale enrichment, and weakened upwelling at the entrance of the Gulf (Gilly
572 et al. 2022; Palacios-Hernández et al. 2023; Trasviña-Castro et al. 2024). In combination, these
573 processes promoted highly stratified and nutrient-poor conditions at the central and southern GC
574 (Table 2).

575 The biological responses observed during this second period (2010-2016) were remarkably
576 coherent with the pelagic seascape transition indicating a productivity decreasing scenario (Figs.
577 6-7; Table 2). Following the 2009–2010 El Niño, the migratory pathway of jumbo squid became
578 disrupted, the Guaymas Basin fishery collapsed, and squid size and landings declined substantially
579 (Frawley et al. 2019). Simultaneously, tropical euphausiid species temporarily appeared in the
580 Gulf during the 2013 warming period, the 2014 marine heatwave, and El Niño 2015–2016,
581 whereas the subtropical and temperate-affinity species *Nyctiphanes simplex* and *Nematoscelis*
582 *difficilis* exhibited substantially lower abundances (García-Fernández et al. 2023).

583

584 Commercial fisheries of pelagic species also experienced major declines in the period 2012 - 2016
585 (Fig. 7). Sport fisheries were not the exception and exhibited a substantial decline, with catch per
586 unit effort decreasing by approximately 50% from pre-2010 levels by the 2015–2016 El Niño and
587 remaining low thereafter (Gilly et al. 2022). Overall, these ecosystem responses were coherent
588 with the observed contraction of C21 and elevated H′, reflecting a transition to warmer, less
589 productive and more heterogeneous pelagic conditions, being more evident in the period 2011 –
590 2016, but potentially extending further (Fig. 7).

591

592 Importantly, increased habitat diversity during the reported warm period should not necessarily be
593 interpreted as evidence of improved ecosystem condition. Although greater environmental
594 heterogeneity is often associated with higher biodiversity potential and ecosystem health in
595 terrestrial and marine systems, in dynamic pelagic seascapes elevated H′ may also reflect the
596 fragmentation and reduced dominance of regionally extensive habitat states. In the GC, the
597 increase in H′ during 2010–2016 coincided with the contraction of C21, reduced productivity,

598 declining fisheries catches, and broader ecosystem disruption (Figs. 6-7; Table 2), suggesting that
599 greater habitat diversity during this period reflected the coexistence of multiple low-productivity
600 pelagic habitats rather than enhanced ecosystem functioning.

601

602 After 2016, we observed a partial recovery of productive conditions in the period 2017–2024 (Fig.
603 6), followed by the documented increase of temperate and subtropical euphausiid species in 2017
604 and 2019 (Table 2) and the augmented catches in pelagic fisheries (Fig. 7). During this period,
605 C21 expanded again from ~70% to 80% during winters, while H′ winter minima stabilized and H′
606 summer increased (Figs. 7). These changes coincided with weaker SST anomalies, relative
607 subsurface cooling, and increased chlorophyll concentrations throughout the upper 200 m
608 compared with 2016 and 2018 (Gilly et al. 2022; Table 2). Another biological responses were also
609 documented; for instance, fish assemblages became more similar to those observed during 2011
610 rather than during the warming years immediately prior to 2016 (García-Fernández et al. 2023).
611 Although the recovery of C21 and primary productivity was moderate compared with the pre-2010
612 period, these results suggest that pelagic seascapes are sensitive enough to capture intermediate
613 ecosystem transitions and partial reorganizations following large-scale climatic perturbations
614 (Figs. 6-7; Table 2).

615

616 **4.3 Implications and limitations of pelagic seascape classifications**

617 The close correspondence observed between pelagic seascapes and documented ecosystem
618 variability supports the ecological relevance of the NOAA/MBON Pelagic Seascape Habitat
619 Classification at regional scales. Previous studies have highlighted the potential of pelagic

seascapes for identifying biologically meaningful habitat structure, predicting species distributions, and supporting ecosystem monitoring (Álvarez-Berástegui et al. 2016; Montes et al. 2020; Woodill et al. 2021). However, relatively few studies have rigorously evaluated whether globally derived seascape classifications capture known regional ecosystem dynamics in highly variable marine systems. The present results suggest that, despite being derived from global satellite products, pelagic seascapes retain sufficient sensitivity to represent regional environmental organization and associated biological responses in the GC.

Nevertheless, the present study also highlights important limitations and conceptual challenges associated with global pelagic seascape classifications. The ecological interpretation of a particular habitat class is inherently context dependent and may vary among oceanographic regions. For example, the productive conditions associated with C21 in the GC may not necessarily represent equivalent ecological states elsewhere. Furthermore, the classification relies primarily on surface satellite variables and therefore cannot fully resolve subsurface habitat structure, oxygen dynamics, or vertical ecological processes that are known to strongly influence pelagic ecosystems (Kavanaugh et al. 2016; Pittman et al. 2021). This limitation is particularly relevant in the GC, where subsurface warming, shoaling oxygen minima, and thermocline variability exert major ecological controls (Gilly et al. 2022, García-Fernández et al. 2023; Herrera-Becerril et al. 2025).

The results therefore support the perspective in pelagic seascape ecology that global seascape products are most powerful when interpreted within regional and multiscale ecological frameworks rather than as universal habitat classifications. Recent syntheses increasingly emphasize that pelagic ecosystems are hierarchically organized and strongly scale dependent,

643 requiring the integration of basin-scale climatic forcing with regional hydrographic and ecological
644 processes (Scales et al. 2017; Pittman et al. 2021). In this context, pelagic seascapes may be best
645 understood as dynamic ecosystem indicators whose ecological meaning emerges through regional
646 validation.

647

648 **5. Conclusions**

649 Improving our understanding of how oceanographic variability shapes marine ecosystems is
650 essential for identifying dominant environmental conditions and interpreting their ecological
651 consequences. This study shows that the NOAA/MBON Pelagic Seascape Habitat Classification
652 captures the dominant seasonal and interannual variability of the Gulf of California (GC),
653 supporting the hypothesis that pelagic seascapes can function as ecologically meaningful
654 indicators of regional ecosystem state. The spatial and temporal organization of pelagic habitats
655 was consistent with known hydrographic dynamics of the GC, including the transition between
656 productive winter conditions and stratified summer states, as well as major ecosystem
657 reorganizations associated with ENSO variability, the 2014 marine heatwave, and the prolonged
658 warming of 2010–2016. These results indicate that globally derived pelagic seascape
659 classifications can retain ecological relevance at regional scales by integrating multiple dimensions
660 of environmental variability into spatially explicit habitat states. However, their interpretation
661 remains context dependent and requires regional validation, particularly because important
662 subsurface processes and trophic mechanisms cannot be fully resolved from surface-based
663 classifications alone. The classification also shows considerable potential as a diagnostic and
664 monitoring tool. At present, however, the product is generally available only several months after
665 observation, which limits its application for near-real-time monitoring and early warning.

Reducing this latency would substantially increase its operational value for ecosystem assessment and management. In the GC, the integration of pelagic seascape information into environmental assessment could support decision-making for fisheries organizations, aquaculture operations, ecotourism activities, and Marine Protected Area management, while also providing a framework for interpreting climate-driven ecosystem changes.

Overall, this study advances the application of pelagic seascapes from a primarily descriptive framework toward a more process-oriented approach for ecosystem assessment. The observed coherence among habitat structure, oceanographic variability, documented biological responses, and pelagic fisheries catches highlights their potential as integrative indicators of ecosystem state and as useful tools for fisheries oceanography and ecosystem-based management in a changing ocean.

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Statements and Declarations

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Competing interests

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Author contributions

Conceptualization: RSL, ATC
Methodology: RSL, EGR, HV
Data collection and acquisition: RSL, ARR, CPR, EGR, HV
Data curation and processing: RSL, ARR, CPR, HV
Formal analysis: RSL, HV, EGR
Visualization: RSL, CPR
Interpretation of results: RSL, ATC, EGR.
Writing—original draft: RSL
Writing—review and editing: all authors.

Data availability

The satellite datasets analysed in this study were obtained from NOAA CoastWatch, Copernicus Marine Service and the NASA Jet Propulsion Laboratory as described in Methods.

NOAA CoastWatch: https://coastwatch.noaa.gov/cwn/products/seascape-pelagic-habitat-classification.html

NOAA CoastWatch: https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMH1ppmday.graph.

Copernicus Marine Service: https://data.marine.copernicus.eu/product/SEALEVEL_GLO_PHY_L4_MY_008_047/services

NOAA PSL: https://psl.noaa.gov/enso/mei/

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