CALIFORNIA'S FIFTH
CLIMATE CHANGE
ASSESSMENT

Climate Refugia for Pacific Sardine and Red Abalone in the California Current Ecosystem

An Original Research Report for:

California's Fifth Climate Change Assessment

CALIFORNIA NATURAL RESOURCES AGENCY

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About California's Fifth Climate Change Assessment

California's Climate Change Assessments are the state's scientific foundation for understanding future climate-related vulnerability across California's regions and systems. Senate Bill 1320 (Stern, 2020) requires the State to report the impacts and risks of climate change across California at least every five years, beginning with California's Fifth Climate Change Assessment (Fifth Assessment). Building on decades of climate research and previous Assessments, the Fifth Assessment presents new findings about California's climate future, with a dedicated focus on Tribal partnerships, public engagement, and communities most vulnerable to climate impacts.

The Fifth Assessment's research and tools are designed to fill knowledge gaps about California's climate future, inspire strategic climate actions, and shape planning, investments, and policies at the state, regional, and local scales. Guided by research priorities identified by state, Tribal, and local leaders, community representatives, and subject matter experts, its findings are designed to help illuminate potential climate futures, the challenges they may present, and the opportunities to build resilience through adaptation pathways.

For the full suite of Fifth Assessment research products, please visit: www.ClimateAssessment.ca.gov.

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Use of Artificial Intelligence (AI):
We acknowledge the use of AI tools in preparation of this report. Specifically, we used Github CoPilot and ChatGPT to troubleshoot errors with R code during the analysis. After using these tools, we reviewed and edited content as needed, and we take full responsibility for the contents and correctness of this report.

Abstract

Climate change is increasingly impacting California's marine ecosystems through rising sea temperatures, ocean acidification, and deoxygenation. This study identifies and quantifies climate change refugia—areas with relatively stable environmental conditions that buffer climate impacts—for two culturally and economically important California species: Pacific sardine (*Sardinops sagax*) and red abalone (*Haliotis rufescens*). Using an ensemble of high-resolution (1.86 square miles, 3 square km) dynamically downscaled ocean projections forced by CMIP5 Earth system models under the Representative Concentration Pathway (RCP) 8.5 scenario, we developed complementary modeling approaches to project future habitat suitability and identify persistent refugia through 2100.

For Pacific sardine, we used both statistical species distribution models and mechanistic physiological models to characterize suitable habitat based on sea surface temperature, chlorophyll, zooplankton biomass, and species-specific thermal tolerances. Our projections indicate that suitable habitat for Pacific sardine is likely to persist and expand in California waters, particularly in the Southern California Bight, with most suitable habitat shifting southward by the end of the century. Based on physiological observations of sardine in laboratory studies, analyses suggest that warming ocean waters off California's coast will not impact sardines' ability to thrive in State waters under projected warming scenarios.

For red abalone, we applied eight physiology-based definitions of environmental stress related to temperature, oxygen, and pH tolerance to identify climate refugia. Our analysis reveals widespread loss of suitable habitat across all California coastal regions by the end of the century. However, small pockets of refugia may persist, particularly around the Channel Islands mid-century, highlighting critical areas for targeted conservation efforts.

These findings provide essential information for adaptive fisheries management and marine conservation strategies. The projected persistence of sardine refugia supports optimistic scenarios for future fishery opportunities, while the contraction of abalone refugia underscores the urgent need for restoration and protection of remaining suitable habitats. Our work demonstrates the importance of high-resolution climate projections and species-specific physiological data in identifying climate refugia to support California's marine resource management under changing ocean conditions.

Keywords:
climate refugia, Pacific sardine, red abalone, species distribution models, marine spatial planning

List of acronyms:

CA	California
CCE	California Current Ecosystem
CDFW	California Department of Fish and Wildlife
CMIP5	Coupled Model Intercomparison Project Version 5
ESM	Earth system model
GAM	Generalised additive model
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model version 2M
GLMM	Generalised linear mixed model
HadGEM2-ES	Hadley Centre Global Environment Model version 2
IPSL-CM5A-MR	Institut Pierre-Simon Laplace Climate Model version 5
NEMUCSC	A customized version of the North Pacific Ecosystem Model for Understanding Regional Oceanography, run by the University of California Santa Cruz
RCP 8.5	Representative Concentration Pathway 8.5
ROMS	Regional Ocean Modelling System
SDM	Species distribution model

Highlights

- Pacific sardine climate refugia are projected to expand across California waters, particularly in the Southern California Bight, indicating widespread habitat gain under future climate scenarios and supporting optimistic fishery management scenarios.
- Red abalone climate refugia are generally projected to contract across California, regardless of refugia definition used, indicating widespread habitat loss and heightened vulnerability to climate change, requiring urgent conservation action.
- High-resolution (3-km) downscaled ocean projections reveal important spatial heterogeneity in climate impacts that would be missed by coarser global climate models, demonstrating the critical value of regional modeling for species-specific management planning.
- Mechanistic physiological models show Pacific sardines will retain high metabolic performance under projected warming, suggesting greater resilience and capacity to sustain normal physiological activity. In contrast, red abalone face multiple stressors including temperature extremes, oxygen depletion, and ocean acidification that compound their vulnerability.
- Small pockets of red abalone refugia may persist around the Channel Islands through mid-century, highlighting priority areas for kelp forest restoration and targeted conservation efforts to support species recovery.

WEB LINKS
https://jessica-bolin.shinyapps.io/redabaloneapp/
https://jessicabolin.github.io/abalone/index.html

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1: Introduction

Climate change is increasingly affecting California's coastal ecosystems, with rising sea temperatures, ocean acidification (reduction of pH), and deoxygenation (loss of dissolved oxygen concentration) posing significant threats to marine life (Dussin et al., 2019; Howard et al., 2020; Pozo Buil et al., 2021). The impact of episodic marine heat waves, El Niño events, and increasing ocean variability are not uniform across space or time (Cheresh & Fiechter, 2020). These changes threaten California's vibrant marine fishing and tourism economy, which depends on healthy ocean ecosystems.

1.1 Climate Change Refugia Concept

Climate change refugia are areas characterized by relatively stable climate conditions and therefore have lower environmental stress compared to the surrounding seascape (Morelli et al., 2016). For species that have limited mobility, such as invertebrates, regions with lower environmental stress are especially important because they cannot easily migrate away from stressful conditions. Refugia habitats may have the capacity to buffer the effects of climate change, allowing populations to persist even as the surrounding ocean is changing. Research on climate refugia in terrestrial habitats is rapidly growing (Morelli et al., 2020). In the oceans, comparatively less work has been done to identify climate refugia, especially with respect to their importance for sustaining fisheries.

1.2 Study Species and Management Context

This study focuses on two culturally and economically important California species that live in marine coastal and pelagic ecosystems and present different management challenges: Pacific sardine (*Sardinops sagax*) and red abalone (*Haliotis rufescens*).

Pacific sardine are small, fast-growing iconic species that serve as key forage resources for larger finfish and marine mammals. The commercial sardine fishery has a long history in California but has been closed since 2015 due to low stock biomass. Until the stock rebounds, fishers that previously targeted sardine have been forced to switch to less preferred species such as market squid. Sardine exhibit seasonal migration patterns, particularly when biomass is high, moving northward in warmer months and southward in cooler months. They typically inhabit warmer, more oligotrophic waters located between the California Current and coastal upwelling zones.

Red abalone are ecologically and culturally important mollusks that have experienced severe population declines due to overharvesting, disease, kelp declines, and environmental stress. These declines led to the complete closure of the commercial

fishery in 1997 and a temporary closure of the recreational fishery in 2018 (California Fish and Game Commission, 1997). Red abalone are particularly sensitive to rapid changes in temperature, low oxygen levels, and prolonged exposure to extreme conditions (Crosson & Friedman, 2018; Boch et al., 2017; Duncan et al., 2023), making them an ideal indicator species for climate change impacts.

1.3 Research Objectives and Approach

This study addresses several critical knowledge gaps in understanding climate refugia for California marine species. We use an ensemble of high-resolution (~3-km) dynamically downscaled projections for the California Current Ecosystem (CCE) to (1) characterize past and future ocean conditions in terms of temperature, dissolved oxygen, and pH; (2) identify how climate refugia for both focal species changes at mid- and end-century periods compared to historical favorable habitat distributions; and (3) evaluate implications for fisheries management and marine protected area effectiveness.

Our approach integrates multiple complementary modeling methods to capture uncertainty in refugia projections. For Pacific sardine, we employ both statistical species distribution models based on observed occurrences and mechanistic models based on laboratory-derived physiological constraints. For red abalone, we apply multiple physiology-based definitions of environmental stress grounded in experimental studies of abalone responses to warming, deoxygenation, and acidification.

2: Pacific Sardine Climate Refugia

2.1 Species Background and Management Context

Pacific sardine have historically supported valuable fisheries in the California Current System. The population collapsed in the 1950s, likely due to a combination of fishing pressure and unfavorable environmental conditions (McFarlane et al., 2002). This ecologically important forage species plays a critical role as prey for larger fish and marine mammals. The commercial sardine fishery in California, once robust, has been closed since 2015 due to low stock biomass. Until the stock recovers, fishers who previously targeted sardine have shifted to alternative, often less desirable, species such as market squid.

Despite extensive study, key biological aspects of sardine remain poorly understood, including drivers of recruitment, responses to warming, and the delineation of subpopulation structures (Free et al., 2023). Understanding whether and how climate change refugia can support climate-resilient sardine populations is critical to preparing California's fisheries under a changing climate.

2.2 Methods

2.2.1 Complementary Modeling Approaches

We developed two complementary modeling approaches to define climate refugia for Pacific sardine: a statistical hybrid species distribution model and a mechanistic model based on physiological constraints.

Hybrid Species Distribution Model

Our primary definition of sardine refugia is derived from a statistical species distribution model (SDM) approach, which characterizes habitat suitability based on environmental conditions associated with observed sardine occurrences and projects these relationships forward under climate scenarios. Predictor variables in the SDM were sourced from a regional ocean model coupled with a biogeochemical model configured for the central California Current System at 3-km resolution. We selected predictor variables that represent key ecological and physiological drivers of sardine distribution and productivity: sea surface temperature (°C), surface chlorophyll (mg· m-3), zooplankton biomass in the upper 50 m (mmolN/m^3), distance from the nearest land (meters), and annual spawning stock biomass (tons) of the northern California Current System sardine subpopulation (Figure 1).

We implemented the hybrid SDM using Generalized Linear Mixed Models (GLMMs) in the sdmTMB R package, both with and without spatiotemporal random fields (Figure 2). These dual implementations allow us to evaluate how underlying spatial structure

affects model predictions and projection uncertainty. By including spatiotemporal random fields, we account for latent spatial effects related to behavioral aggregation and migration patterns that vary seasonally (Figure 2).

Mechanistic Modeling Approach

We developed mechanistic SDMs that integrate physiological constraints related to temperature and body size using unpublished experimental data. This model provides an independent, process-based perspective on habitat suitability that complements the statistical approach. We fitted generalized additive models (GAMs) to predict routine and maximum metabolic rates in response to temperature and fish size, since thermal tolerances of sardines scale strongly with size. From the GAM predictions, we derived metabolic scope, defined as the difference between the maximum and routine metabolic rates, as a proxy for aerobic performance.

2.2.2 Climate Projections

We produced high-resolution projections for sardine habitat suitability for the end-of-century period (2070–2100), using outputs from three high-resolution (~3-km) downscaled projections for the central California Current System. These projections are forced with output from three CMIP5 Earth system models (ESMs) under the Representative Concentration Pathway (RCP) 8.5 scenario: GFDL-ESM2M, HadGEM2-ES, and IPSL-CM5A-MR.

2.3 Results

2.3.1 Habitat Projections

Our models show that the probability of occurrence for Pacific sardine is projected to increase off southern California by the end of the century, with new habitat emerging in the Southern California Bight (Figure 3). In both models, the predicted values represent the probability of suitable habitat for sardines, ranging from 0 (unsuitable) to 1 (highly suitable). These probabilities are derived from model estimates that relate observed sardine presence to environmental variables such as temperature, chlorophyll, and oxygen. Higher predicted values therefore indicate conditions more favorable for sardine occurrence, while lower values reflect areas with lower habitat probability. Historically, core sardine habitat along the US West Coast has been centered off central and northern California, with lower occurrence probabilities in the south. Thus, the projected increase in southern California represents a southward redistribution of suitable habitat (i.e., where north = 0 degrees) rather than an overall expansion. This shift is consistent across climate scenarios and model types, appearing more pronounced when accounting for underlying spatial patterns in sardine distribution.

Across all ESMs, suitable habitat is projected to shift southward by end-of-century. This is demonstrated by the southward displacement of the center of gravity of core habitat, which we defined using a 50% threshold of top habitat suitability values (Table 1). While the southward shift occurs regardless of whether spatial effects were included in the SDM, models incorporating these effects show a greater magnitude of movement across all models.

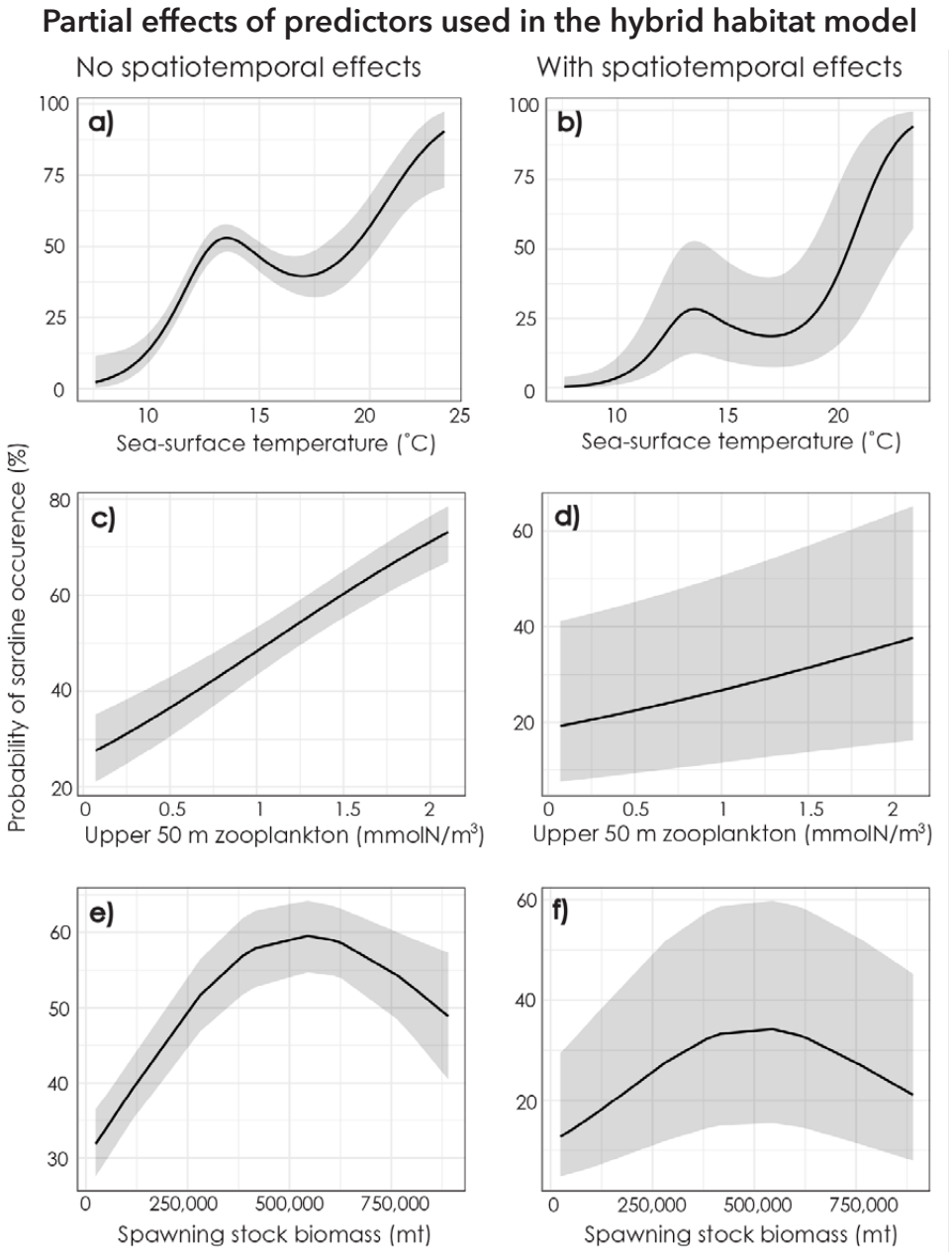


Figure 1: Final predictors used in the hybrid sardine habitat model from the 3-km ROMS and stock assessment. Panels a, c, and e represent the model without spatiotemporal effects. Panels b, d, and f represent the model with spatiotemporal effects.

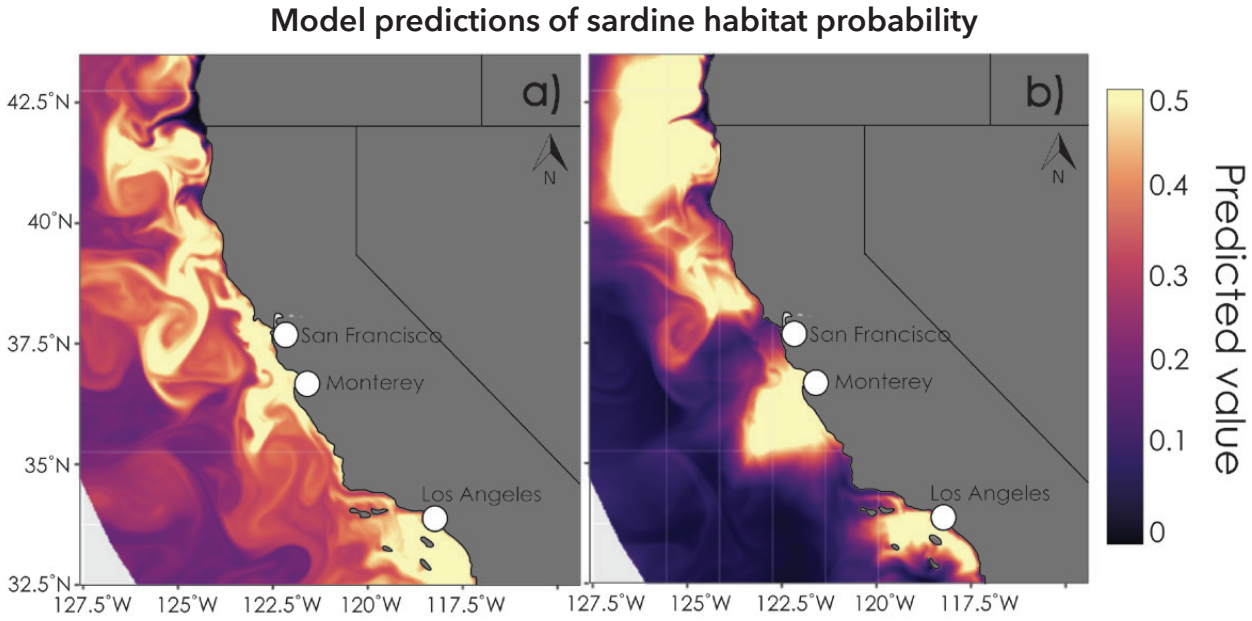


Figure 2: Model predictions of sardine habitat probability (0–0.5) using two modeling approaches for August 15, 2012. (a): generalized linear mixed model without a spatial field. (b): generalized linear mixed model including a spatial field.

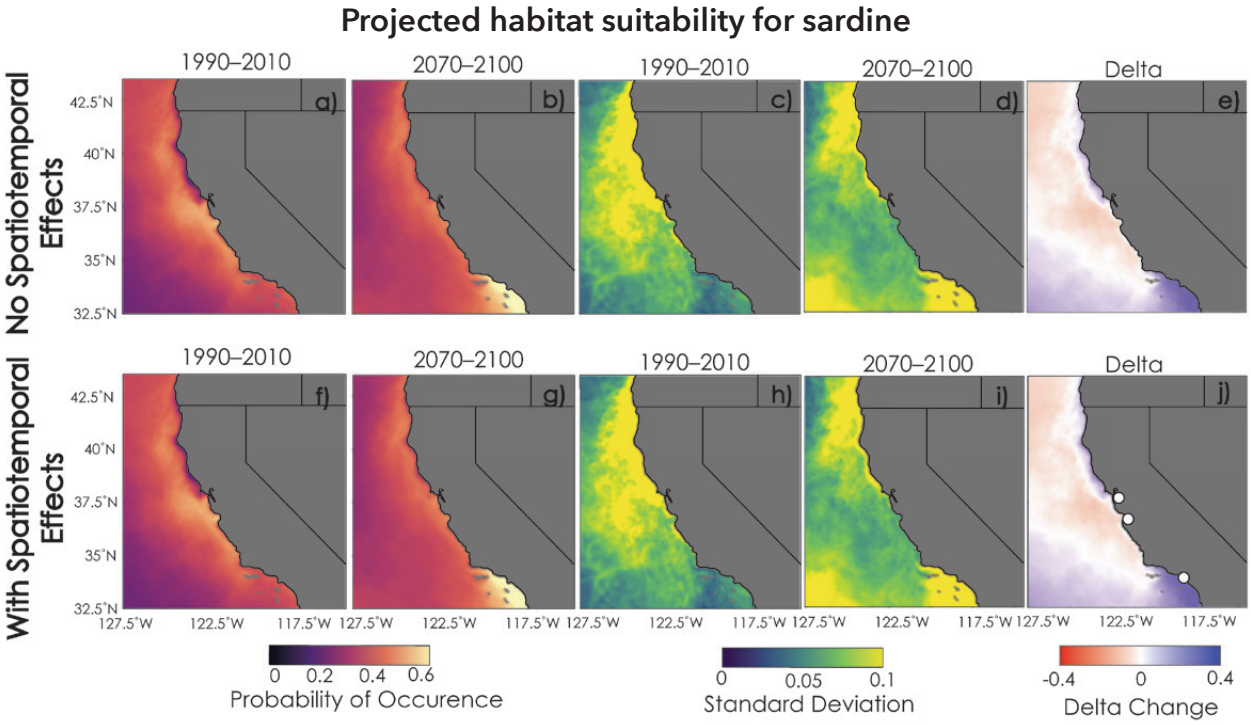


Figure 3: Projected habitat probability ensemble means of sardine for the historical (1990–2010) and end-of-century (2070–2100) periods. Top row: correlative SDM without spatiotemporal effects. Bottom row: correlative SDM with spatiotemporal effects. Panels a, b, f, g: probability of occurrence. Panels c, d, h, i: model uncertainty (i.e., standard deviation across the three ESMs). Panels e, j:difference between end-of-century and historical projections (where purple represents gain of habitat and red represents loss of habitat).

Table 1: Summary metrics of projected habitat shifts by ESM and model type.

Model	Distance (km)	Direction (degrees˚)	Percentage Change
GFDL (no ST effect)	23	150	+1.02%
HADL (no ST effect)	65	160	+3.62%
IPSL (no ST effect)	46	160	+2.46%
GFDL (with ST effect)	48	153	+0.97%
HADL (with ST effect)	140	160	+2.88%
IPSL (with ST effect)	100	161	+1.91%

*Distance = difference between the center of gravity of projected habitat for the future (2070–2100) and historical (1990–2010) periods. Direction = difference in latitude and longitude degrees. ST = spatial-temporal effect. Percentage change = change of core habitat between the future/historical period calculated as [(Future-historical)/historical]*100.*

2.3.2 Metabolic Performance

The mechanistic modeling results confirm that both routine and maximum metabolic rates increase with fish size and warmer temperatures (Figure 4). Under summer temperatures projected by the warmest of our ESMs, sardines are predicted to use only ~13% of their metabolic scope (Figures 5–6). While we considered oxygen concentration as a potential covariate, we did not include it in our final GAM due to the high tolerance of hypoxia shown by sardine.

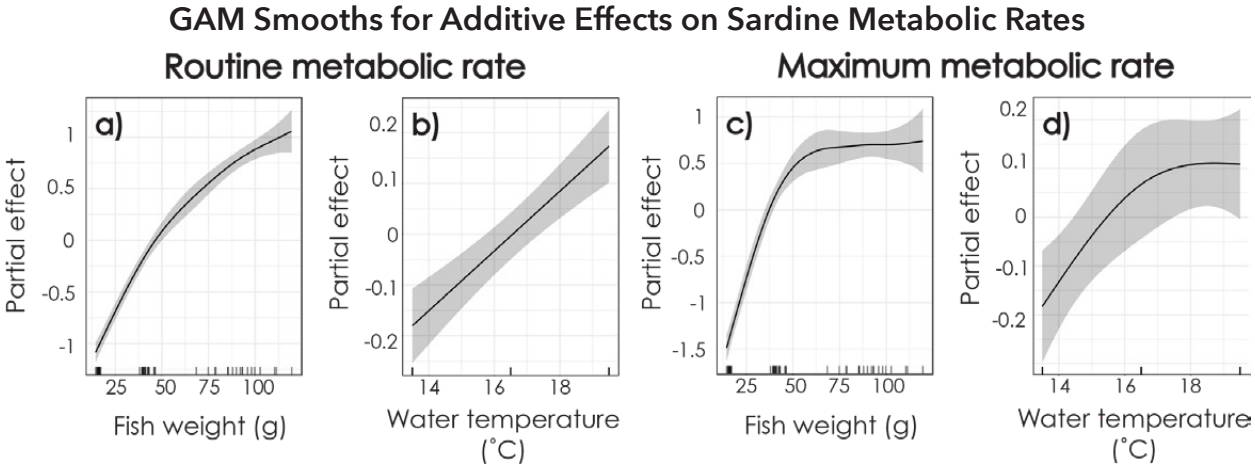


Figure 4: Plots of GAM smooths for the additive effects of fish weight (grams) and water temperature (˚C) for the routine (a, b) and maximum (c, d) metabolic rates of sardine.

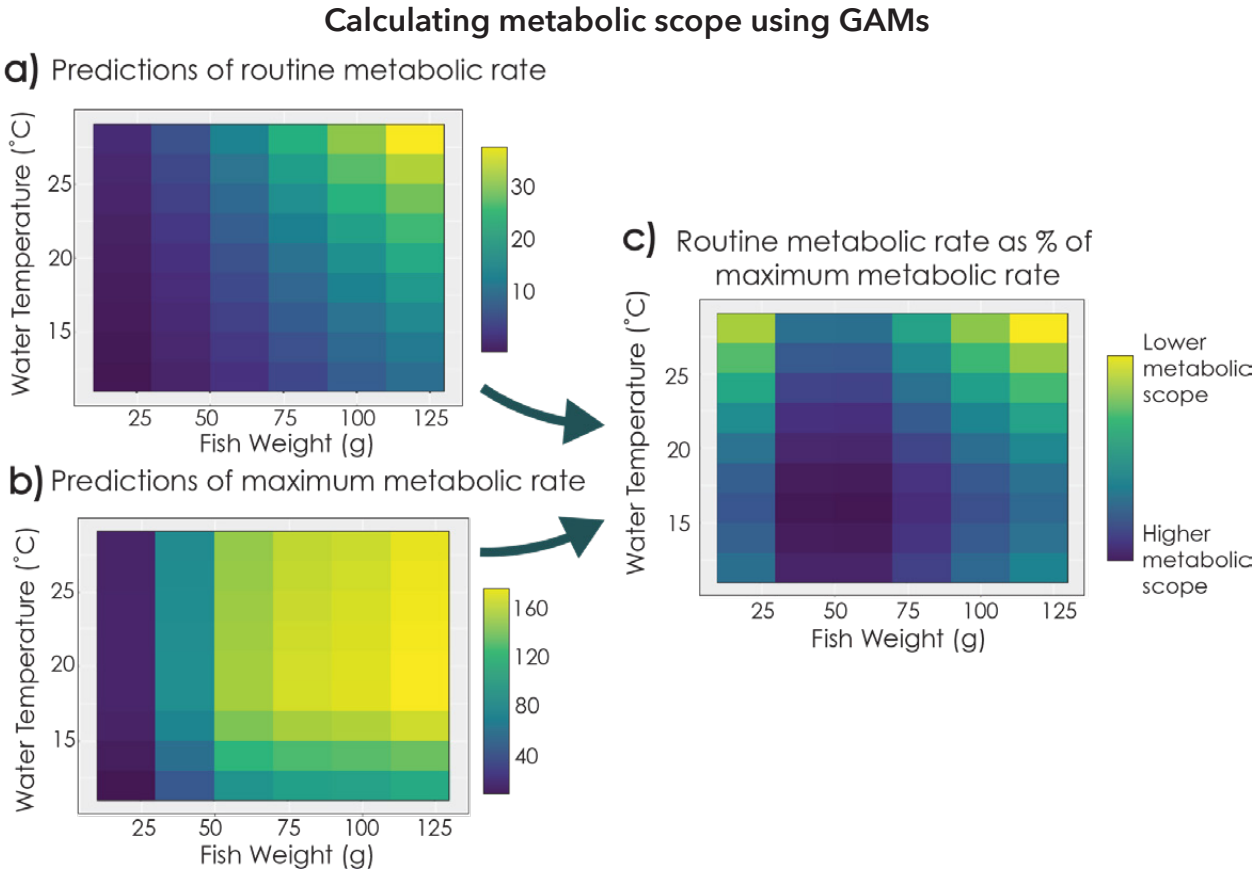


Figure 5: Calculating metabolic scope using GAMs. (a) Predicted routine metabolic rate. (b) Predicted maximum metabolic rate. (c) Predicted metabolic scope (% of maximum metabolic rate).

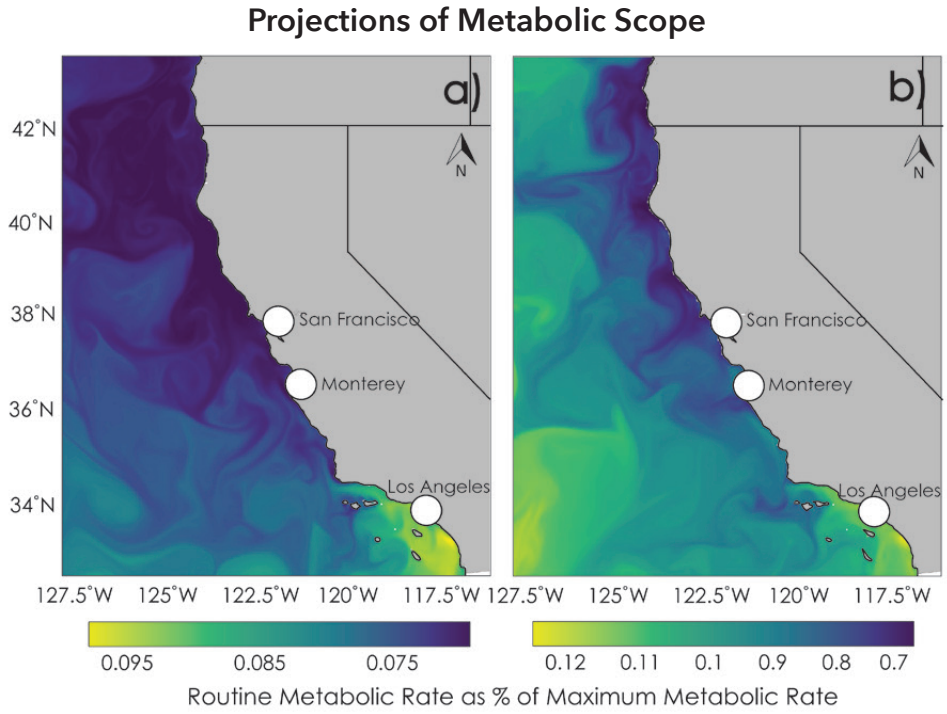


Figure 6: Projections of metabolic scope for September 7 in the historical period (Panel a: 1990, GFDL) and future period (Panel b: 2100, HADL). Units expressed as routine metabolic rate as a percentage of maximum metabolic rate.

2.3.3 Fishing Community Implications

We used commercial landing fish ticket data from PacFIN to investigate California ports with historically significant sardine landings (2000–2020). Only five ports—Monterey, Moss Landing, Port Hueneme, San Pedro, and Terminal Island—each contributed more than 1% of total landings, together accounting for 98.4% of statewide landings (Figure 7). We mapped historical fishing activity for each port and delineated fishing "footprints" by identifying the California Department of Fish and Wildlife (CDFW) blocks from which sardines were landed (Figure 8).

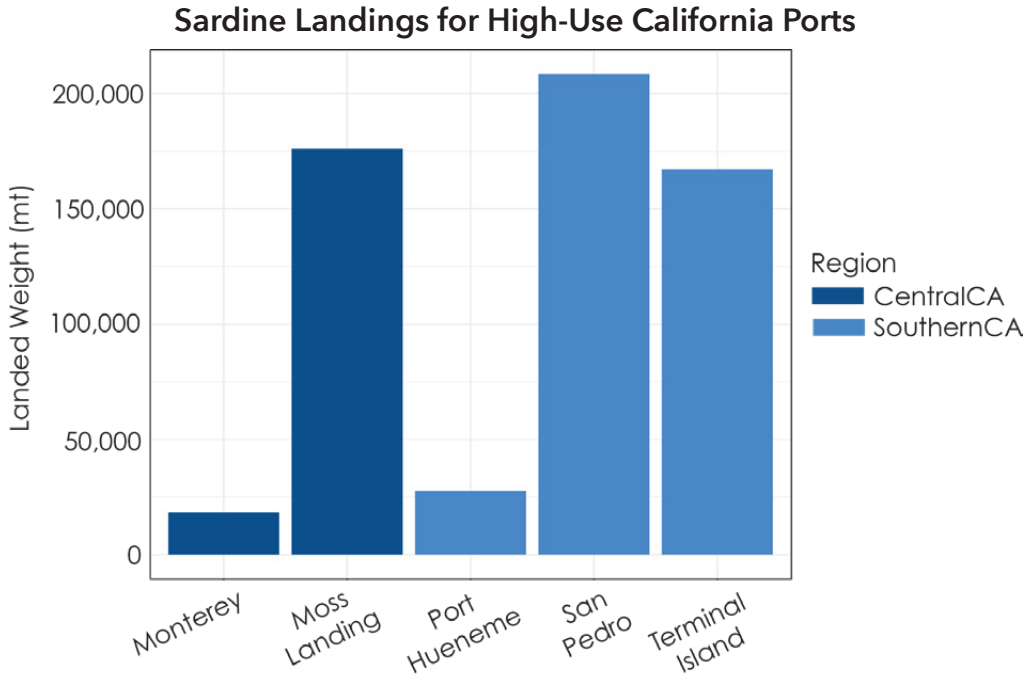


Figure 7: Contribution of sardine landings for the top five California ports from 2000–2020, colored by region (i.e., central or southern California). Data sourced from PacFIN historical fish tickets.

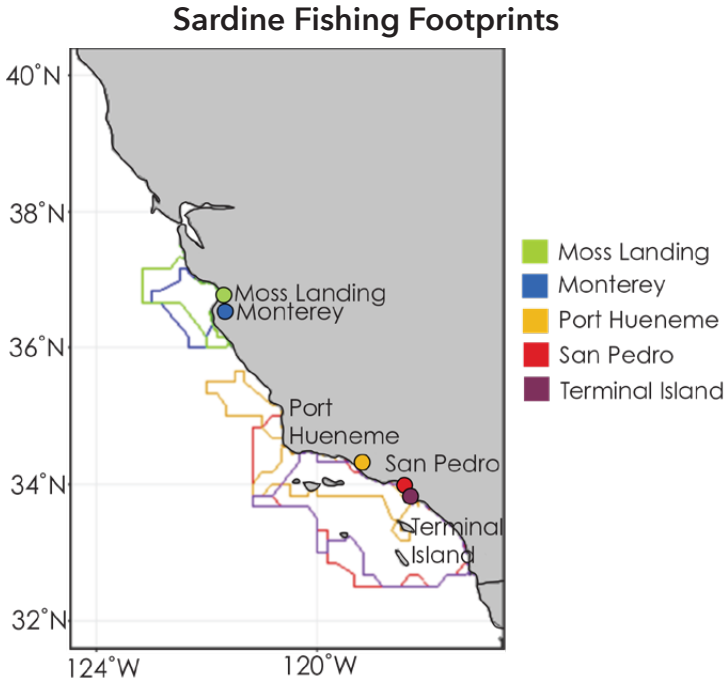


Figure 8: Fishing "footprint" associated with each port, representing a polygon around all fished CDFW blocks corresponding to the port. Blue = Monterey, green = Moss Landing, orange = Port Hueneme, red = San Pedro, and purple = Terminal Island.

2.4 Implications

Our study provides new evidence that suitable habitat for Pacific sardine is projected to persist, and in some regions expand, within California state waters through to 2100, despite the effects of climate change. Using both correlative and mechanistic approaches, we identified areas—particularly within the Southern California Bight and nearshore regions off central and northern California—that consistently maintain favorable environmental conditions, representing broad availability of climate refugia. The projected southward shift in core sardine habitat primarily reflects changes in ocean temperature, productivity, and circulation. Warming surface waters and enhanced stratification are projected to reduce nutrient input in northern regions but are partly offset in the Southern California Bight by intensified upwelling and wind-driven mixing, which maintain primary productivity and suitable prey conditions. These compensatory processes support sustained sardine metabolic performance and may explain the persistence of high habitat suitability in the Southern California Bight.

These spatial shifts highlight the need to align fisheries infrastructure, harvest strategies, and monitoring programs with changing habitat distributions. For example, adaptive management could include adjusting quota allocations, port-based monitoring, and fleet mobility to follow core habitat shifts. Agencies such as the California Department of Fish and Wildlife (CDFW) and the Ocean Protection Council (OPC) can use these results to anticipate where sardine fisheries are likely to remain viable and to plan for economic and ecological resilience in regions where fisheries may decline.

These findings underscore the importance of integrating climate projections into fisheries management frameworks to ensure that harvest strategies remain sustainable under future conditions. By linking predicted environmental drivers to biological responses, our findings provide a foundation for forward-looking fisheries management that incorporates climate resilience by focusing conservation and adaptation efforts on these emerging and persistent refugia.

3: Red Abalone Climate Refugia

3.1 Species Background and Management Context

Red abalone are ecologically and culturally important mollusks that have experienced severe population declines due to overharvesting, disease, kelp declines, and environmental stress (Rogers-Bennett et al., 2019; Rogers-Bennett & Catton, 2019; Rogers-Bennett et al., 2024; California Fish and Game Commission, 1997; State of California, 2018). These declines led to the complete closure of the commercial fishery in 1997 and a temporary closure of the recreational fishery in 2018 (California Fish and Game Commission, 1997; State of California, 2018). In addition to their ecological role, red abalone also hold profound cultural, spiritual, and subsistence significance for many Indigenous Peoples along the California coast, including the Chumash, Ohlone, Esselen, and other coastal Tribes. For thousands of years, abalone have been used in ceremony, art, and trade and as a valued food resource that connected coastal and inland communities. However, despite ongoing interest in abalone recovery and restoration, the future viability of red abalone populations remains uncertain under projected ocean change.

Laboratory and field studies have shown that red abalone are particularly sensitive to rapid changes in temperature, low oxygen levels, and prolonged exposure to extreme conditions (Rogers-Bennett & Catton, 2019; Boch et al., 2018; Diaz et al., 2000)—making them an ideal indicator species for identifying and evaluating potential climate refugia.

3.2 Methods

3.2.1 Defining Climate Refugia

To understand where red abalone might find persistently suitable habitat under changing ocean conditions, we used eight scientific definitions based on how environmental factors like temperature, oxygen, and acidity affect their survival, growth, and reproduction. These definitions include metrics related to sensitivity to sudden temperature changes, cumulative heat stress, disease risk, metabolic performance, and fertilization success. Each definition uses specific thresholds from the literature to determine when conditions become stressful for abalone (Table 2).

Table 2: List of definitions used to define climate refugia for red abalone

Description of stressful conditions for red abalone	Variable	Reference
When abalone experience lower short-term variability in temperature over 5–10 day moving window periods at a specific site	Temperature	Dowd & Denny, 2020; Provost et al., 2026.
When abalone experience lower degree heating days above a temperature threshold at a specific site	Temperature	Provost et al., 2026.
When temperature exposure remains within a percent-based threshold around the optimum temperature for red abalone, calculated using site-specific thermal performance curves	Temperature	Díaz et al., 2000; Provost et al., 2026; Barneche et al., 2014
When abalone in (i) normoxic conditions (i.e., 21 kPa) experience temperatures between 16–20˚C, or (ii) hypoxic conditions (i.e., 10.5 kPa) experience temperatures between 7–11˚C	Temperature, dissolved oxygen	Duncan et al., 2023
When abalone located north of Point Conception experience temperatures that are (i) between 15.5–20.5˚C, regardless of pH, or (ii) <15.5˚C and pH >7.5	Temperature, pH	Boch et al., 2018; Fagundes et al., 2020
When abalone experience temperatures below 18˚C	Temperature	Rogers-Bennett et al., 2010; Braid et al., 2005; Vilchis et al., 2005; Crosson & Friedman 2018
When dissolved oxygen >2 mg/L	Dissolved oxygen	Low et al., 2021
When temperatures are between 16–18˚C	Temperature	Duncan et al., 2023; Leighton, 1974; Diaz et al., 2000; Salinas et al., 2011

3.2.2 Projecting Future Refugia

We projected future ocean conditions along the California coast using an ensemble of three climate models, which provide daily estimates of bottom temperature, pH, and oxygen. For each location, we calculated how often the location met "safe"

thresholds of suitable habitat each year, using two persistence levels: a liberal cutoff, where favorable conditions occur at least half the year (50%), and a stricter, more conservative threshold requiring near year-round suitable habitat (95%).
To account for uncertainty and the complexity of abalone biology, we combined results across models and stress definitions to create ensemble maps. These show areas where multiple climate models and biological factors agree that conditions will remain suitable for abalone survival, growth, or reproduction in the mid- and late 21st century.

3.2.3 Case Study Regions

We applied this analysis statewide and within five case study areas: Mendocino, Sonoma, Monterey, Gaviota, and the Channel Islands. These sites were selected in consultation with researchers and practitioners involved in red abalone research and management. Each region has historically supported persistent kelp forests and red abalone populations, making them both biologically and culturally important.

3.3 Results

3.3.1 Statewide Projections

Our projections of climate refugia for red abalone, ensembled across all definitions, indicate a widespread decrease in refugia extent across all case study regions by the end of the century. This projected decline is generally consistent across the different temporal thresholds used to define refugia, though the magnitude of decrease varies (Figures 9–13). While the overall trend is robust, slight differences emerge depending on the specific definition applied, reflecting the sensitivity of refugia projections to the criteria used.

Projected persistence of climate refugia for the Channel Islands

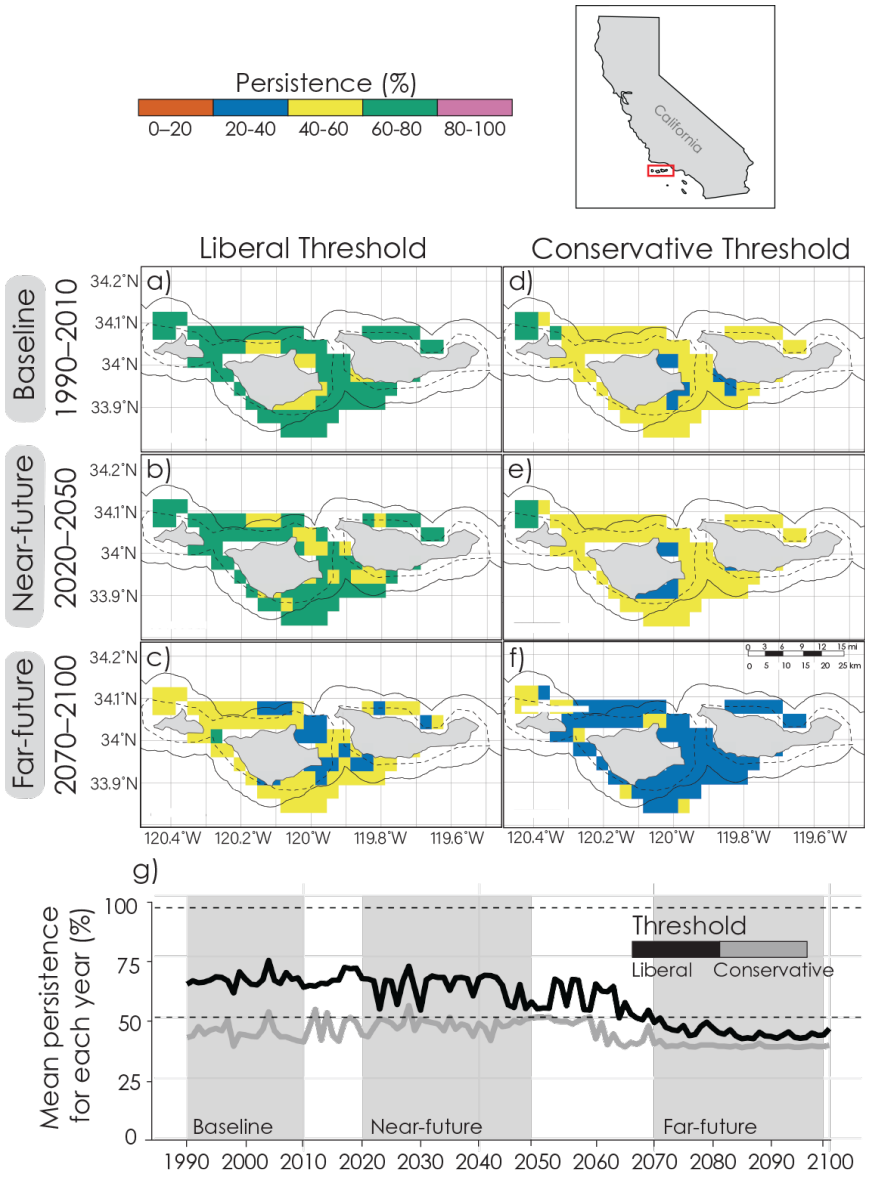


Figure 9: Projected refugia for the Channel Islands. Panels show maps of spatial persistence (a–f), defined as the percentage of time a given location is classified as refugia during the time period and temporal threshold of interest, and (g) annual time series, showing the percentage of each year that refugia conditions are met across all grid cells in the Channel Islands region. Solid black lines in (a–f) indicate the California state boundary and dashed lines indicate the 100-meter isobath. Two temporal thresholds are applied: a conservative threshold (grey line, favorable conditions met ≥95% of the time) and a liberal threshold (black line, conditions met ≥50% of the time). Solid grey boxes indicate time periods used in the analyses (baseline: 1990–2010, near-future: 2020–2050, and far-future 2070–2100). Refugia projections are aggregated across all eight definitions. The time series panel (g) displays the ensemble mean across three Earth System Models.

Projected persistence of climate refugia for the Mendocino coast

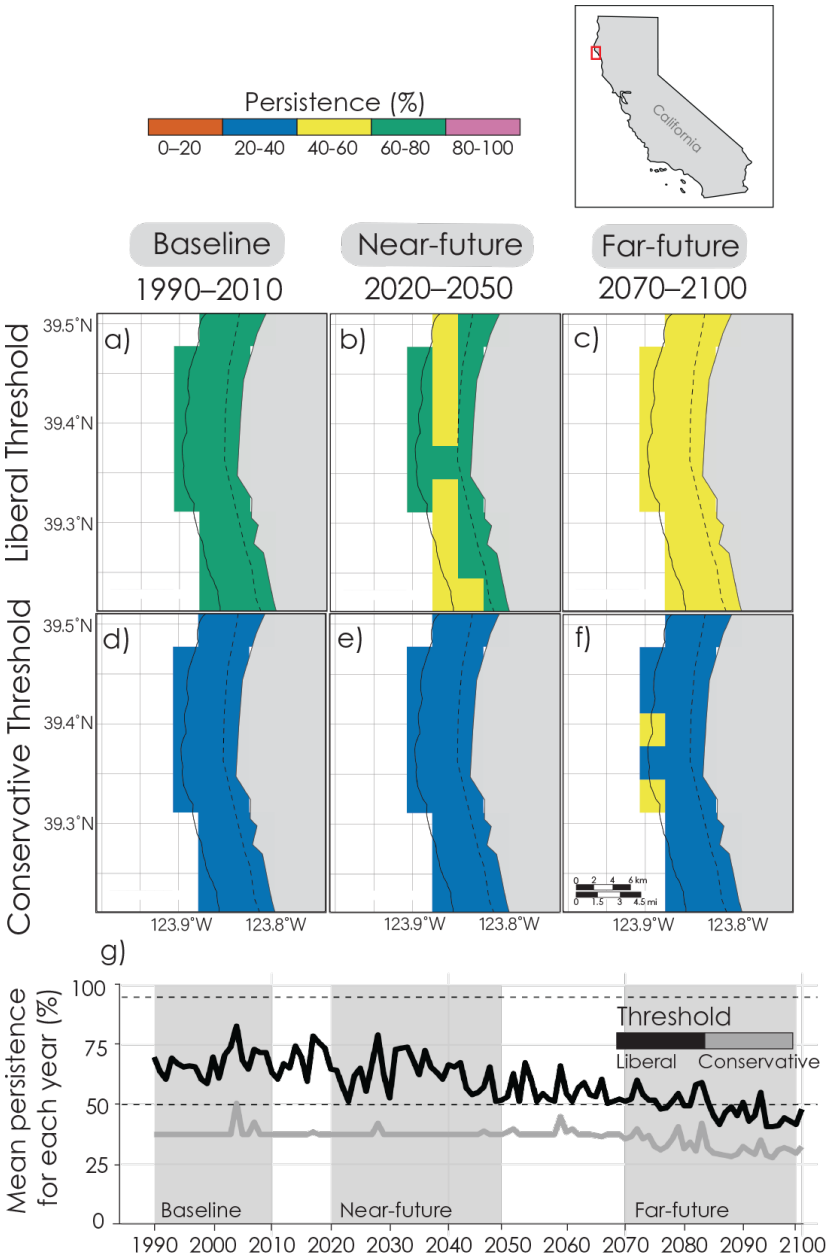


Figure 10: Projected refugia persistence for the Mendocino coast. See caption for Figure 9 for further information.

Projected persistence of climate refugia for the Gaviota coast

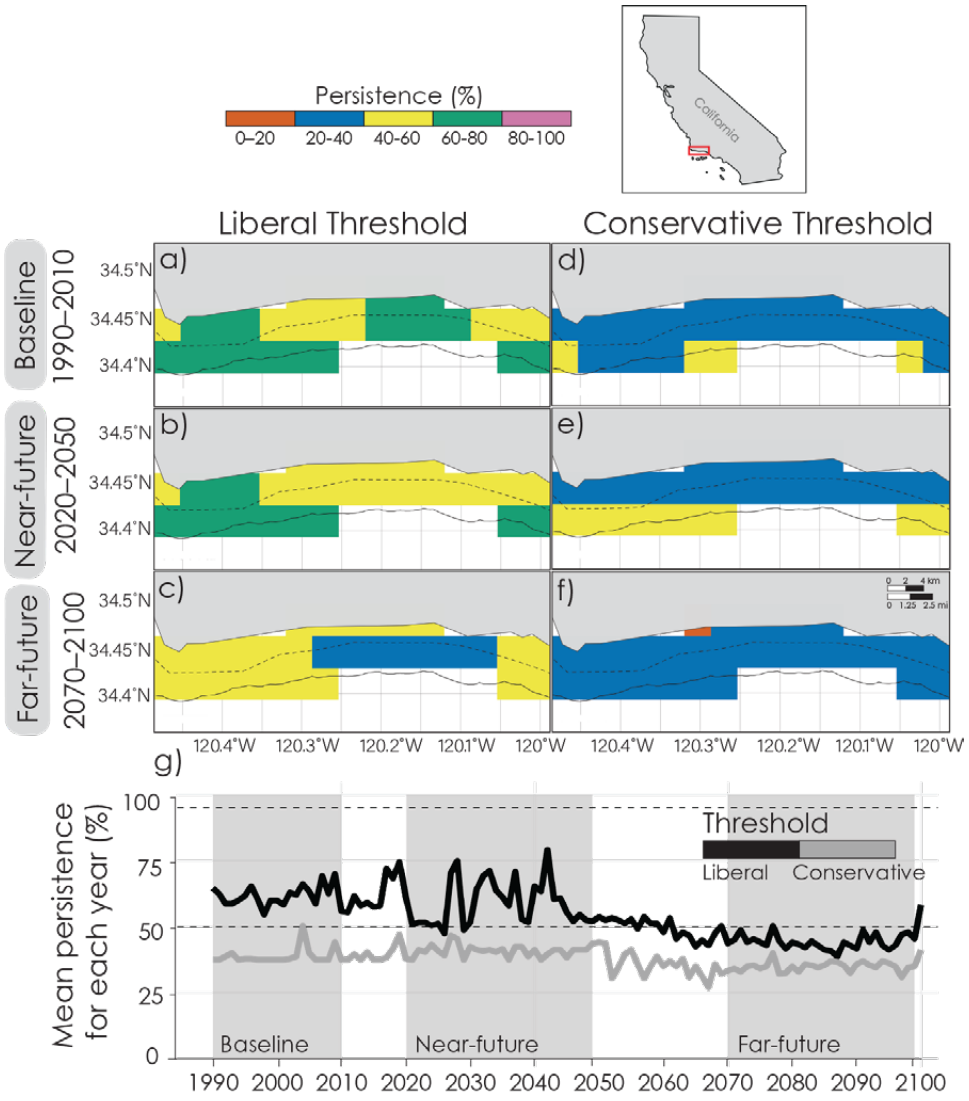


Figure 11: Projected refugia persistence for the Gaviota coast. See caption for Figure 9 for further information.

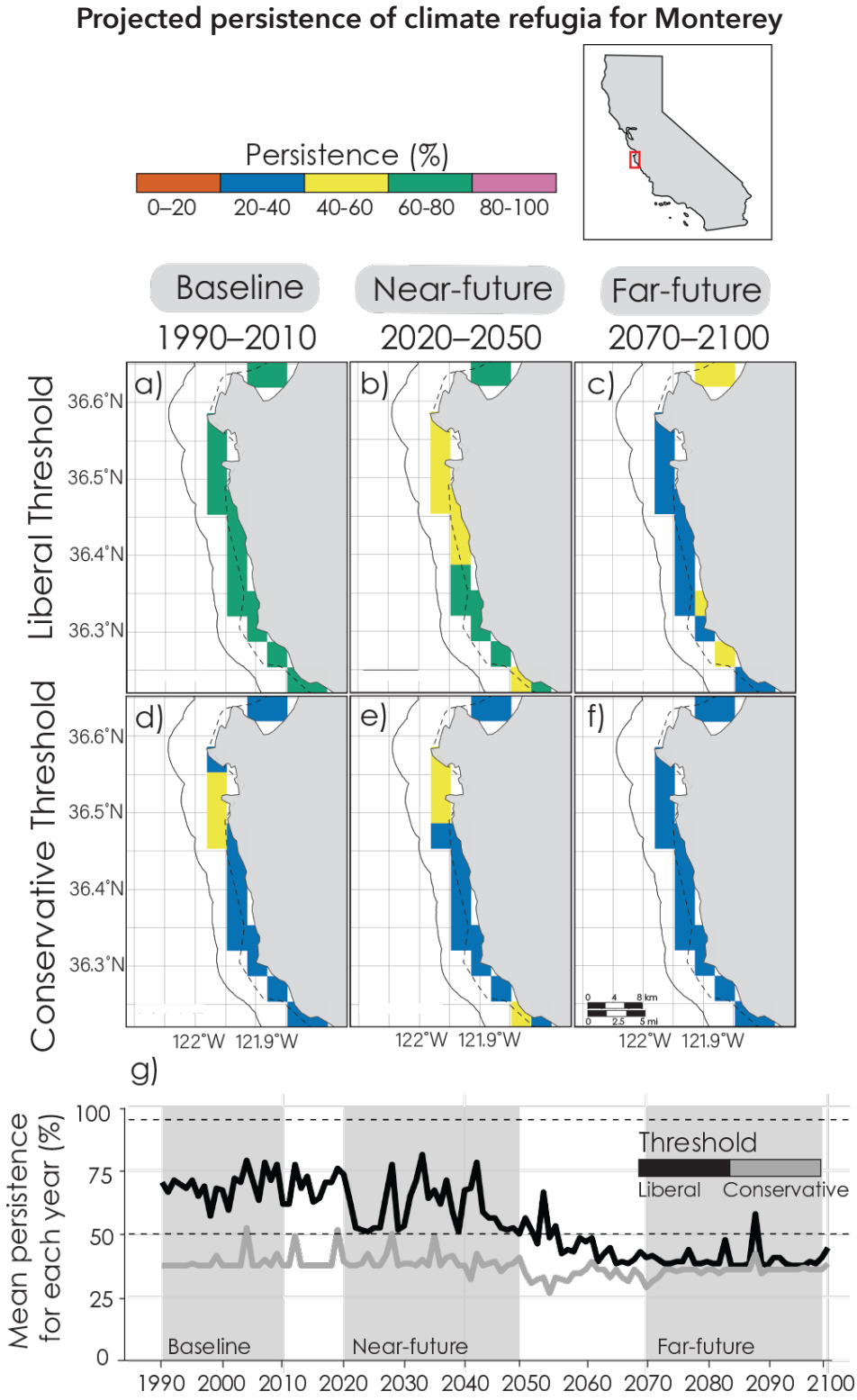


Figure 12: Projected refugia persistence for the Monterey region. See caption for Figure 9 for further information.

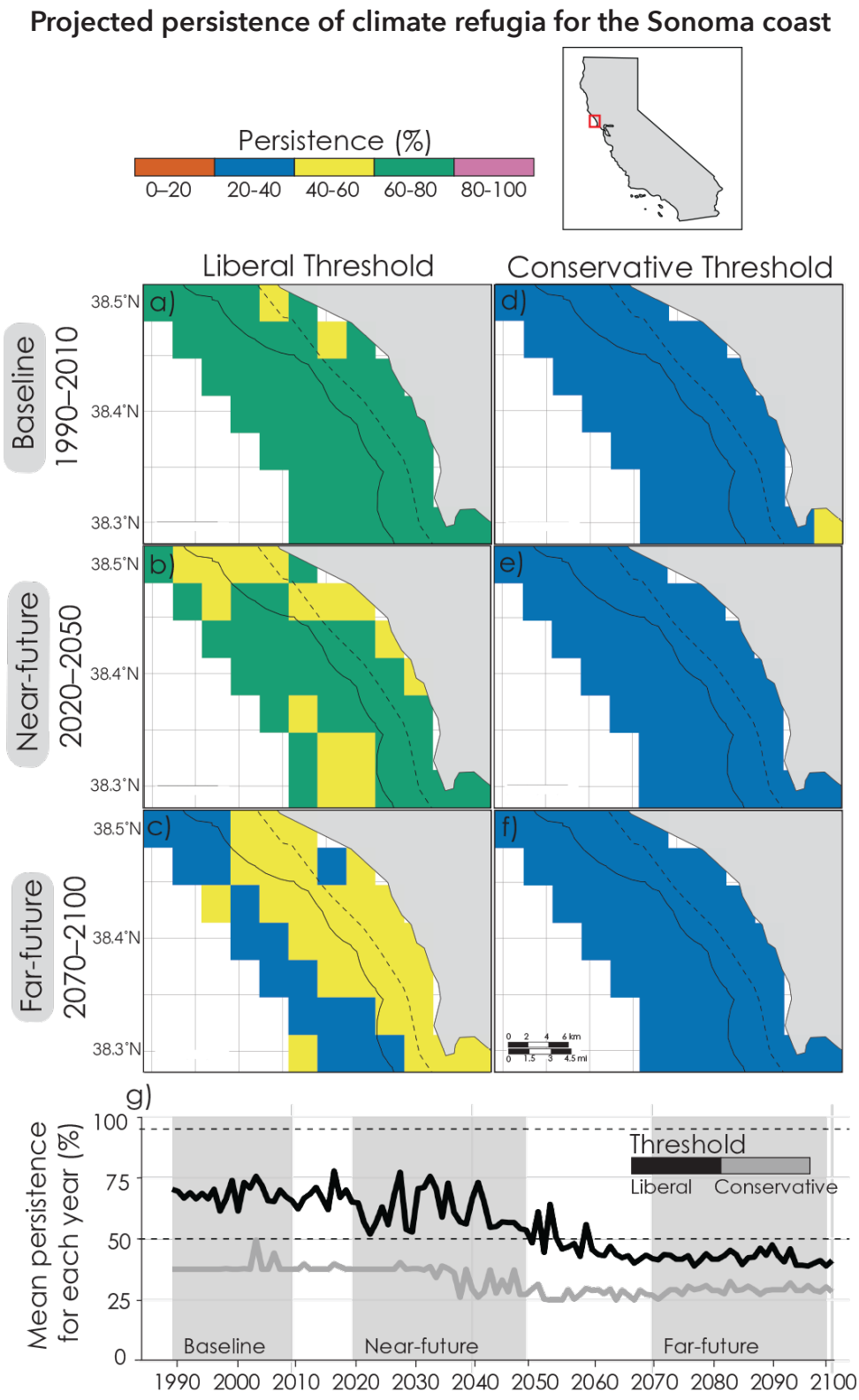


Figure 13: Projected refugia persistence for the Sonoma coast. See caption for Figure 9 for further information.

3.3.2 Channel Islands Focus

We are particularly interested in the Channel Islands due to their historical and ecological importance for red abalone populations, as well as their status as a site of active kelp forest restoration. In this region, projections indicate a notable increase in climate refugia—up to 30%—relative to the historical baseline (1990–2010), across both conservative and liberal thresholds. This increase is particularly pronounced under the conservative threshold, which requires suitable conditions for more than 95% of the year (Figure 14).

By the end of the century, under the conservative threshold, we observe a small, isolated increase in refugia along the northeastern shore of Santa Rosa Island, while the remainder of the area shows declines of up to 15%. In contrast, projections using the liberal threshold reveal a widespread decrease in refugia across the region, with reductions reaching up to 40% compared to the historical baseline (Figure 14).

Change in persistence of refugia in the Channel Islands relative to the baseline period (1990–2010)

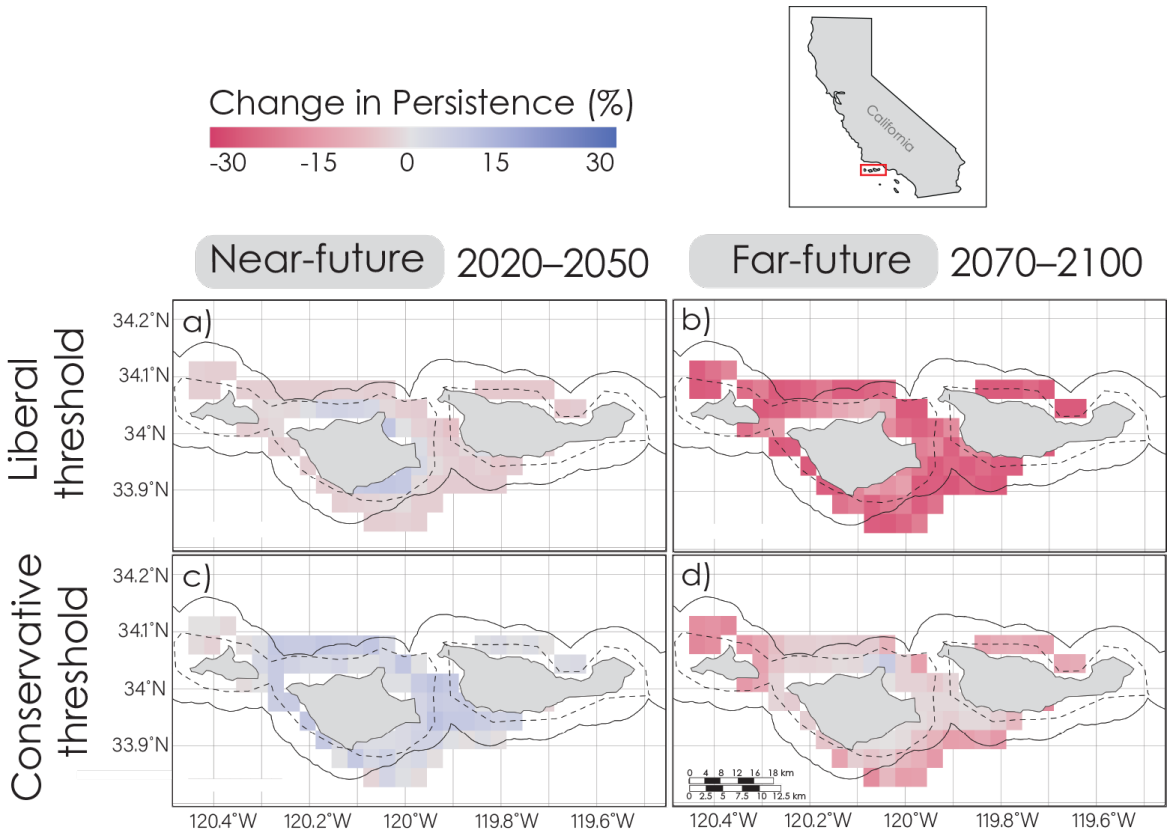


Figure 14: The percentage change (i.e., delta change) in projected refugia compared to the 1990–2010 baseline. Two temporal thresholds are applied: a conservative threshold (conditions met ≥95% of the time) and a liberal threshold (conditions met ≥50% of the time). Refugia projections are aggregated across all eight definitions.

3.3.3 Historical Fishing Analysis

We used commercial fish ticket data from the California Department of Fish and Wildlife (CDFW) to identify the main ports where red abalone were landed between 1991 and 1997—before the fishery was closed. We defined "high-use" ports as those with landings exceeding 1,500 pounds in any single year. Most ports reported minimal commercial harvests, whereas a small subset, specifically Santa Barbara, Ventura, Oxnard, and Half Moon Bay (Figures 15–16), consistently recorded landings several orders of magnitude higher (ranging from tens to hundreds of thousands of pounds annually). The 1,500-pound cutoff therefore served as a practical breakpoint distinguishing these primary centers of commercial activity from low-volume or incidental landing sites.

Our analysis shows that historical red abalone fishing grounds are projected to experience varying levels of climate refugia persistence in the coming decades. While Santa Barbara's fishing footprint may retain some refugia through mid-century (+1.8%), both it and Half Moon Bay's footprint are likely to see significant declines in suitable habitat by the end of the century (-8% and -26.5% respectively).

Core fishing blocks associated with high-use red abalone ports between 1991–1997.

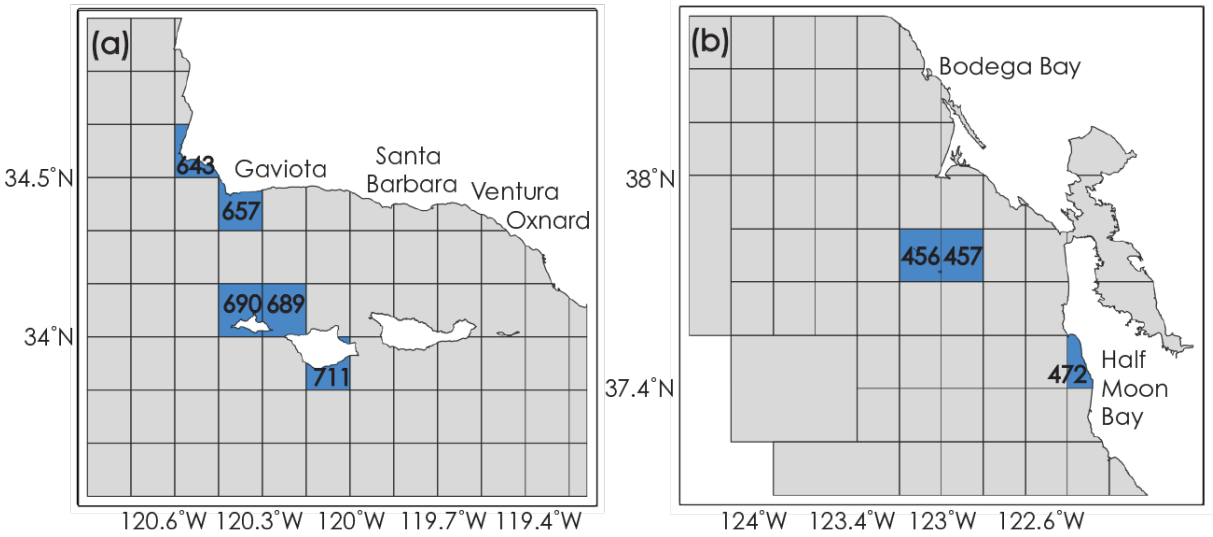


Figure 15: (a) Core fishing blocks for the Santa Barbara/Ventura/Oxnard ports and (b) core fishing blocks for the Princeton/Half Moon Bay ports. Map grids are CDFW fishing blocks in California, with high-use blocks indicated by block identifier.

Identification of "high-use" historical red abalone fishing ports in California

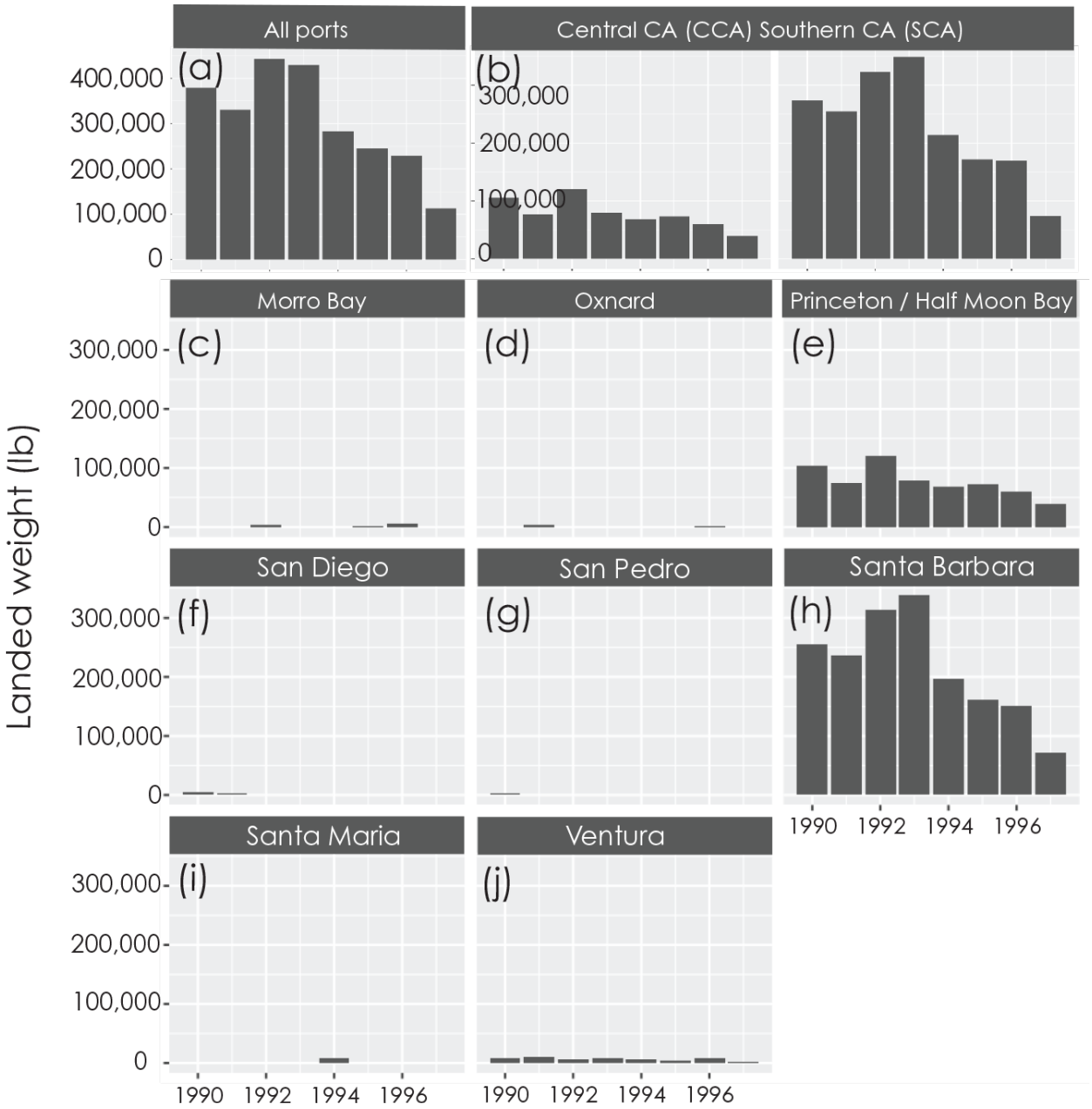


Figure 16: (a) Total red abalone landings (lb) reported across all California ports from 1991 to 1997. (b) Regional breakdown of landings in Central and Southern California (CCA and SCA, respectively). CCA represents the ports of Princeton/Half Moon Bay, and SCA represents the ports of Santa Barbara and Ventura. (c–j) Top 10 ports with annual landings exceeding 1,500 lb in any year during the 1991–1997 period. Data sourced from CDFW Pacfin fish ticket data.

3.4 Implications

Our study suggests that climate refugia for red abalone are likely to contract across California's coastline under future climate scenarios, indicating widespread loss of suitable habitat by the end of the century. Despite this overall decline, small but important pockets of potential refugia—especially around the Channel Islands—are expected to persist until mid-century, offering critical areas for targeted conservation and management in the near-term.

These refugia may persist largely because of localized oceanographic features, including strong coastal upwelling, complex bathymetry, and cooler subsurface waters that buffer temperature extremes and sustain oxygen and pH conditions more favorable to abalone physiology. In contrast, other coastal areas are projected to experience compounded stressors, such as thermal extremes, deoxygenation, and ocean acidification, that exceed physiological thresholds for growth and survival. This mechanistic understanding clarifies why refugia are concentrated in regions like the Channel Islands: these areas are maintained by the same dynamic physical processes that have historically supported high biodiversity and productive kelp ecosystems.

The Channel Islands also represent the cultural and ancestral homeland of the Chumash peoples and fall within the newly designated Chumash Heritage National Marine Sanctuary (CHNMS). This sanctuary creates a crucial ecological and cultural continuum between the Monterey Bay and Channel Islands National Marine Sanctuaries. Protecting red abalone refugia in this region therefore has dual significance by supporting both biodiversity resilience and the intergenerational cultural connections of Indigenous communities whose stewardship has long sustained these ecosystems.

These findings emphasize the urgency of prioritizing these refugia in adaptation strategies to support red abalone populations as ocean conditions continue to change. The projected habitat losses highlight the need for intensive restoration efforts, particularly kelp forest restoration, in areas where refugia are expected to persist. Collaboration with agencies such as CDFW, Ocean Protection Council, and the National Oceanic and Atmospheric Administration, as well as Tribal governments, will be key to translating these findings into actionable spatial priorities for habitat restoration and climate adaptation.

4: Environmental Projections and Modeling Framework

4.1 Dynamically Downscaled Ocean Projections

This project leverages high-resolution (3-km) ocean projections from the Regional Ocean Modeling System (ROMS) configured for the central California Current System. The ROMS domain covers 32–44°N and offshore to 126°W, with 42 terrain-following vertical levels. This central California Current System model is forced by an outer domain for the broader California Current System (30–48°N, 115–134°W) at 10-km resolution with physical data assimilation.

ROMS is coupled to a biogeochemical model called NEMUCSC—a California Current System-specific version of the North Pacific Ecosystem Model for Understanding Regional Oceanography. NEMUCSC includes three limiting macro-nutrients, two phytoplankton groups, three zooplankton groups, three detritus pools, and oxygen and carbon cycling.

4.2 Climate Model Ensemble

We use projections forced by output from three CMIP5 Earth system models (ESMs) under the Representative Concentration Pathway (RCP) 8.5 scenario (high emissions): GFDL-ESM2M, HadGEM2-ES, and IPSL-CM5A-MR. These models were chosen to span the range of physical and biogeochemical change in the California Current System projected by the CMIP5 ensemble. Prior to downscaling, the output of the ESMs is bias-corrected using a time-varying approach that allows for temporally evolving ocean conditions needed to study future ecosystem states.

4.3 Projected Environmental Changes

Surface temperature in the central California Current System is projected to increase by the end of the century, with the ensemble average changes of approximately 3°C, particularly in offshore waters, and smaller changes along the coast. Northern California is projected to reach surface temperatures of around 16°C, compared to approximately 22°C in the Southern California Bight (Figure 17).

Surface chlorophyll—a proxy for primary productivity—is projected to decline. Declines are especially concentrated in coastal waters near San Francisco and Humboldt Bay. Zooplankton biomass is projected to increase in coastal regions where historical primary productivity has been highest, while decreasing elsewhere, particularly in offshore waters of central California and along the coast of the Southern California Bight (Figure 17).

Bottom temperature is projected to gradually increase through the end of the century, with the ensemble average changes of approximately 1°C by mid-century and reaching up to 2.5°C by the end of the century (Figure 18). The largest warming is projected in the San Francisco and Monterey Bay regions. Bottom oxygen shows the most significant declines along Humboldt Bay, the Southern California Bight, and around the Channel Islands, where decreases may reach as much as -16 mmol/m³ by the end of the century. Bottom pH is expected to decline by approximately -0.1 by mid-century and up to -0.3 in offshore waters near San Francisco Bay, the Channel Islands, and Humboldt Bay (Figure 18).

Projected changes for environmental variables used in sardine models

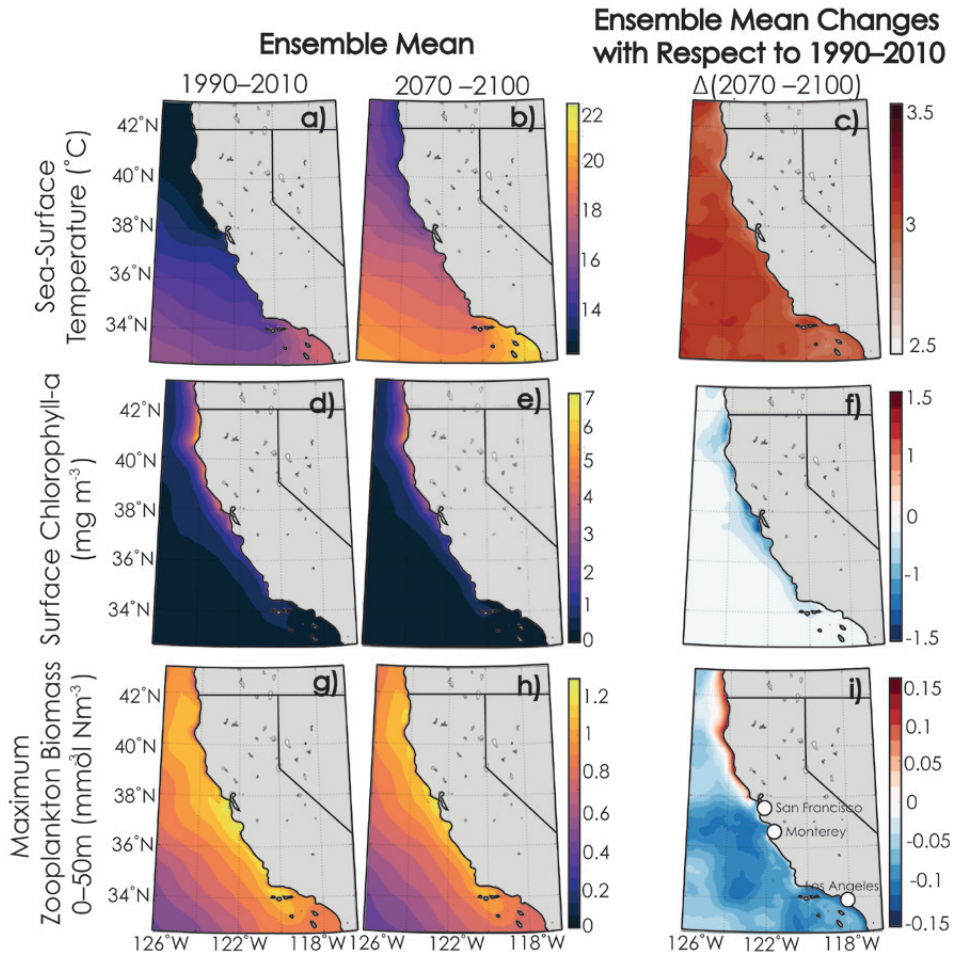


Figure 17: Spatial annual mean and future changes (relative to historical) for the environmental variables used for sardine projections along the California coast. Rows show (a–c) sea surface temperature (°C), (d–f) sea surface chlorophyll a (mg m-3), and (g–i) maximum zooplankton biomass from (0-50 mmol N m-3). Columns show (a, d, g) ensemble mean historical values, (b, e, h) ensemble mean end-of-century values, and (c, f, i) end-of-century changes relative to historical (2070–2100 vs. 1990–2010).

Projected changes for environmental variables used for abalone refugia

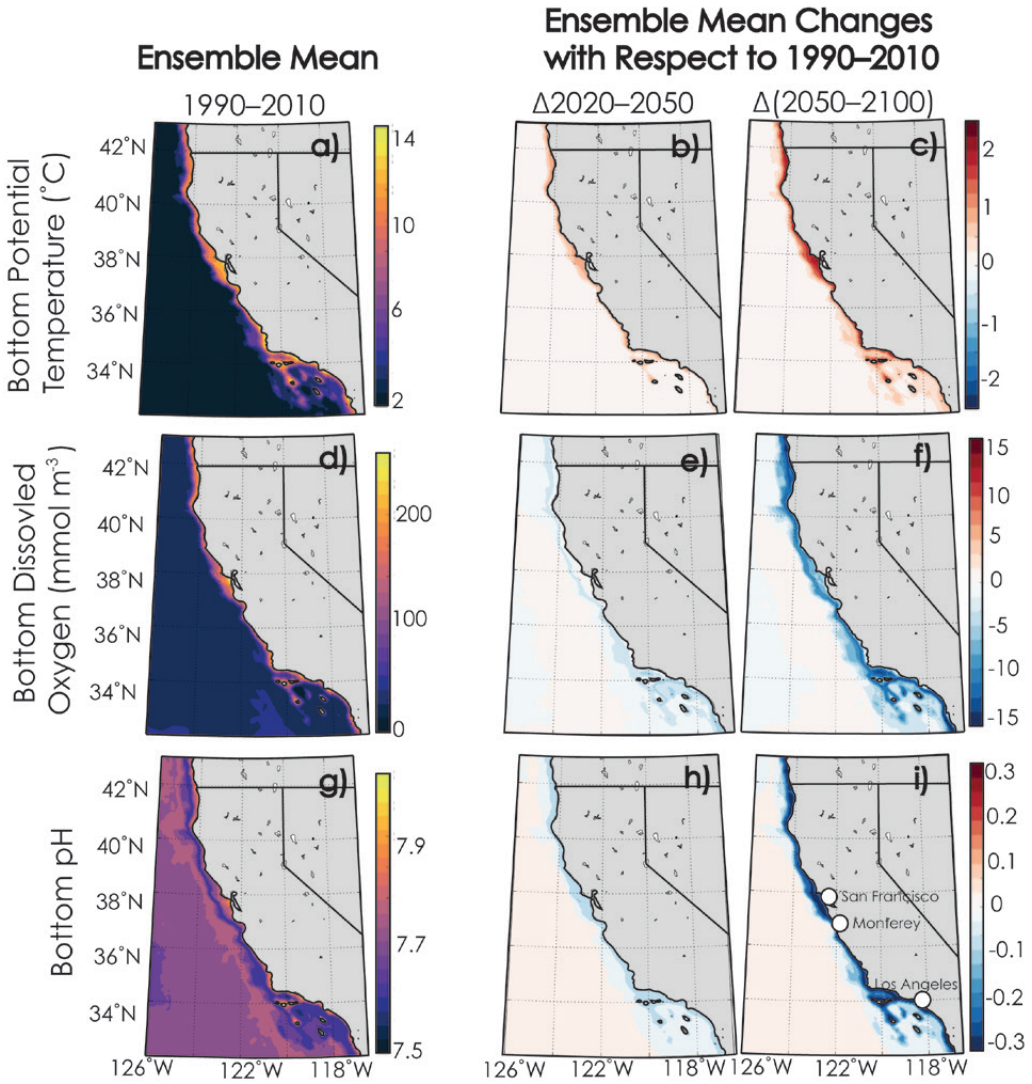


Figure 18: Spatial annual mean and future changes (relative to historical) for the environmental variables used to identify abalone refugia along the California coast. Rows show (a–c) bottom temperature, (d–f) bottom dissolved oxygen, and (g–i) pH. Columns show: (a, d, g) ensemble mean historical values (1990–2010), (b, e, h) ensemble mid-of-century changes (2020–2050 relative to historical), and (c, f, i) ensemble end-of-century changes (2050–2100 relative to historical).

5: Conclusions and Future Directions

5.1 Synthesis of Key Findings

This study reveals contrasting futures for two iconic California marine species under climate change. Pacific sardine climate refugia are generally projected to expand across California waters, particularly in the Southern California Bight, while red abalone refugia are projected to contract across all coastal regions. These divergent trajectories reflect fundamental differences in species biology, habitat requirements, and vulnerability to multiple climate stressors.

The expansion of sardine refugia, supported by both statistical and mechanistic modeling approaches, indicates that this economically important species may benefit from climate change in California waters. The projected southward shift in habitat center of gravity suggests that fisheries management and infrastructure may need adaptation, but the overall prognosis for sardine habitat availability is positive.
In contrast, the widespread contraction of red abalone refugia across multiple definitions and climate models indicates heightened vulnerability that demands urgent conservation action. The identification of small refugia pockets, particularly around the Channel Islands during the mid-century, provides critical targets for restoration and protection efforts.

5.2 Management Implications

5.2.1 Fisheries Management

For Pacific sardine, our findings support forward-looking management that anticipates habitat shifts and prepares fishing communities for changing distributions. The persistence and expansion of suitable habitat provide optimism for eventual stock recovery and fishery reopening, though managers should consider the southward habitat shift in planning future fishing opportunities.
For red abalone, the severe projected habitat contractions emphasize the need for intensive restoration efforts focused on the identified refugia areas. Kelp forest restoration should be prioritized in regions where abalone refugia are projected to persist, as these areas offer the best prospects for supporting viable populations through the climate transition.

5.2.2 Marine Protected Area Effectiveness

Our analysis of refugia overlap within California's Marine Protected Area (MPA) network reveals important considerations for climate-adaptive management. Areas where refugia coincide with existing protected areas represent high-value targets for enhanced protection and monitoring, while refugia outside the current MPA network may warrant consideration for additional protection measures.

The recent designation of the Chumash Heritage National Marine Sanctuary (CHNMS) adds a critical new dimension to this framework. Spanning the region between the Monterey Bay and Channel Islands National Marine Sanctuaries, the CHNMS strengthens ecological connectivity along California's central coast while embedding Indigenous cultural values into marine management. The sanctuary's co-stewardship model developed collaboratively between the National Ocean and Atmospheric Administration and Chumash Tribal representatives provides a pathway for integrating Traditional Ecological Knowledge with modern conservation practices. Given that the Channel Islands are projected to serve as one of the few remaining refugia for red abalone through mid-century, the CHNMS will likely play a pivotal role in ensuring their protection. Within this sanctuary, future abalone restoration and monitoring could be guided by co-stewardship approaches that recognize both ecological function and cultural continuity. This framework offers a model for how fisheries management can evolve to include Indigenous leadership, shared governance, and the recognition of cultural ecosystem services as integral components of climate resilience.

Together, the alignment of ecological refugia, protected areas, and Indigenous stewardship offers a powerful opportunity to build a more inclusive and adaptive marine management network—one that not only preserves biodiversity but also revitalizes long-standing cultural relationships with the ocean.

5.3 Methodological Contributions

This study demonstrates the critical importance of high-resolution climate projections for species-specific management planning. The 3-km resolution of our downscaled projections reveals spatial heterogeneity in climate impacts that would be missed by coarser global models, enabling identification of localized refugia that may be essential for species persistence.

Our integration of multiple modeling approaches—statistical and mechanistic for sardine, multiple stress definitions for abalone—provides robust uncertainty quantification that strengthens confidence in management recommendations. The ensemble approach captures both climate model uncertainty and biological model uncertainty, providing a more complete picture of refugia projections.

5.4 Future Research Directions

Several research priorities emerge from this work. First, continued monitoring of both species' responses to environmental variability will help validate and refine refugia projections. Long-term datasets from research programs like the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) and California Department of Fish and Wildlife surveys will be essential for tracking how species distributions change relative to projections.

Second, expansion of the refugia framework to additional species would provide a more comprehensive view of climate impacts on California's marine ecosystems. Species with different life histories, thermal tolerances, and habitat requirements will likely show varied responses to climate change, and identifying common refugia areas could inform ecosystem-scale management approaches.

Third, integration of refugia projections with socioeconomic analysis would strengthen the policy relevance of this work. Understanding how refugia changes affect fishing communities, tourism, and other ocean-dependent sectors would provide a more complete foundation for climate adaptation planning.

Finally, development of management scenarios that incorporate refugia projections could help evaluate different adaptation strategies. Comparing the effectiveness of various conservation, restoration, and management approaches under different climate and refugia scenarios would provide decision-makers with actionable guidance for preparing California's marine resources for climate change.

5.5 Broader Implications

This work contributes to the growing field of climate refugia science by demonstrating methods for identifying marine refugia at management-relevant scales. The contrasting species responses highlight the importance of species-specific approaches to climate adaptation, while the high-resolution projections reveal the spatial complexity of climate impacts in dynamic coastal systems.

The identification of both expanding and contracting refugia within the same ecosystem underscores that climate change will create both challenges and opportunities for California's marine resources. Successful adaptation will require flexible management approaches that can respond to these varying trajectories while maintaining the ecological integrity and economic value of the state's marine ecosystems.

Our findings provide a foundation for climate-ready fisheries management and marine conservation that acknowledges both the threats and opportunities presented by changing ocean conditions. By identifying where climate refugia will persist, expand, or contract, this work enables proactive management that can help California's iconic marine species and the communities that depend on them navigate the challenges of a changing climate.

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Appendix A: Alternative text and metadata for figures in the report

A.1 Alternative text

Figure 1: Figure showing predictors and partial effect plots (a–e) from the hybrid sardine habitat model based on 3-km ROMS and stock assessment data. Predictors include biogeochemical variables to capture nearshore habitats: surface chlorophyll (panel b), upper 50 m zooplankton (panel c), and spawning stock biomass (panel e). Partial effects are shown as smooth curves fitted with thin-plate regression splines.

Figure 2: Figure showing predicted sardine habitat probability (ranging from 0 to 1) on August 15, 2012, using two modeling approaches. Panel (a) shows results from a generalized linear mixed model without a spatial field. Panel (b) shows results from a generalized linear mixed model with a spatial field included.

Figure 3: Figure showing ensemble mean projections of sardine habitat suitability for historical (1990–2010) and end-of-century (2070–2100) periods. The top row presents results from a correlative SDM without spatiotemporal effects, and the bottom row shows results with spatiotemporal effects. Panels (a, b, f, g) display probability of occurrence. Panels (c, d, h, i) show model uncertainty, measured as the standard deviation across three ESMs. Panels (e, j) illustrate differences between end-of-century and historical projections, where purple indicates habitat gain and red indicates habitat loss.

Figure 4: Figure showing GAM smooth plots of additive effects of fish weight (grams) and water temperature (°C) on sardine metabolic rates. Panels (a, b) show effects on routine metabolic rate, and panels (c, d) show effects on maximum metabolic rate.

Figure 5: Figure showing GAM predictions used to calculate sardine metabolic scope. Panel (a) shows predicted routine metabolic rate, panel (b) shows predicted maximum metabolic rate, and panel (c) shows predicted metabolic scope expressed as a percentage of maximum metabolic rate.

Figure 6: Figure showing projected sardine metabolic scope for September 7. Panel (a) depicts historical conditions for 1990 using the GFDL model, and panel (b) shows future conditions for 2100 using the HADL model. Values are expressed as routine metabolic rate as a percentage of maximum metabolic rate.

Figure 7: Figure showing the contribution of sardine landings from the top five California ports between 2000 and 2020. Bars are colored by region, distinguishing central from southern California. Data come from PacFIN historical fish tickets.

Figure 8: Figure showing the contribution of sardine landings from the top five California ports between 2000 and 2020. Bars are colored by region, distinguishing central from southern California. Data come from PacFIN historical fish tickets.

Figure 9: Map showing persistent climate refugia for red abalone (Haliotis rufescens) in the Channel Islands region under two future time periods. Two maps compare near-future (2020–2050) and far-future (2070–2100) changes relative to a historical baseline (1990–2010). Refugia are areas where ocean conditions (temperature, oxygen, pH) remain within species' tolerance limits ≥50% of the time. Areas of increase or loss in refugia are color-coded across the Channel Islands at ~3-km² resolution. Below the maps, a line plot tracks changes in the total extent of refugia in the Channel Islands from 1990–2100, across the liberal and conservative thresholds. Data are derived from a dynamically-downscaled California ROMS climate model using the RCP-8.5 climate scenario, and processed using R.

Figure 10: Map showing persistent climate refugia for red abalone (Haliotis rufescens) in the Mendocino region under two future time periods. Two maps compare near-future (2020–2050) and far-future (2070–2100) changes relative to a historical baseline (1990–2010). Refugia are areas where ocean conditions (temperature, oxygen, pH) remain within species' tolerance limits ≥50% of the time. Areas of increase or loss in refugia are color-coded across the Mendocino region at ~3-km² resolution. Below the maps, a line plot tracks changes in the total extent of refugia in the Mendocino region from 1990–2100, across the liberal and conservative thresholds. Data are derived from a dynamically-downscaled California ROMS climate model using the RCP-8.5 climate scenario, and processed using R.

Figure 11: Map showing persistent climate refugia for red abalone (Haliotis rufescens) in the Gaviota region under two future time periods. Two maps compare near-future (2020–2050) and far-future (2070–2100) changes relative to a historical baseline (1990–2010). Refugia are areas where ocean conditions (temperature, oxygen, pH) remain within species' tolerance limits ≥50% of the time. Areas of increase or loss in refugia are color-coded across the Gaviota region at ~3-km² resolution. Below the maps, a line plot tracks changes in the total extent of refugia in the Gaviota region from 1990–2100, across the liberal and conservative thresholds. Data are derived from a dynamically-downscaled California ROMS climate model using the RCP-8.5 climate scenario, and processed using R.

Figure 12: Map showing persistent climate refugia for red abalone (Haliotis rufescens) in the Monterey region under two future time periods. Two maps compare near-future (2020–2050) and far-future (2070–2100) changes relative to a historical baseline (1990–2010). Refugia are areas where ocean conditions (temperature, oxygen, pH) remain within species' tolerance limits ≥50% of the time. Areas of increase or loss in refugia are color-coded across the Monterey region at ~3-km² resolution. Below the maps, a line plot tracks changes in the total extent of refugia in the Monterey region from 1990–2100, across the liberal and conservative thresholds. Data are derived from a dynamically-downscaled California ROMS climate model using the RCP-8.5 climate scenario, and processed using R.

Figure 13: Map showing persistent climate refugia for red abalone (Haliotis rufescens) in the Sonoma region under two future time periods. Two maps compare near-future (2020–2050) and far-future (2070–2100) changes relative to a historical baseline (1990–2010). Refugia are areas where ocean conditions (temperature, oxygen, pH) remain within species' tolerance limits ≥50% of the time. Areas of increase or loss in refugia are color-coded across the Sonoma region at ~3-km² resolution. Below the maps, a line plot tracks changes in the total extent of refugia in the Sonoma region from 1990–2100, across the liberal and conservative thresholds. Data are derived from a dynamically-downscaled California ROMS climate model using the RCP-8.5 climate scenario, and processed using R.

Figure 14: Map showing the percent change in persistent climate refugia for red abalone (Haliotis rufescens) in the Channel Islands region under two future time periods. Two maps compare near-future (2020–2050) and far-future (2070–2100) changes relative to a historical baseline (1990–2010). Refugia are areas where ocean conditions (temperature, oxygen, pH) remain within species' tolerance limits ≥50% of the time. Areas of increase or loss in refugia are color-coded across the Channel Islands region at ~3-km² resolution. Data are derived from a dynamically-downscaled California ROMS climate model using the RCP-8.5 climate scenario, and processed using R.

Figure 15: Two maps showing core fishing blocks in California. Panel (a) highlights core fishing blocks for the Santa Barbara, Ventura, and Oxnard ports. Panel (b) shows core fishing blocks for the Princeton and Half Moon Bay ports. Maps are divided into CDFW fishing block grids, with high-use blocks labeled by block number.

Figure 16: Multi-panel figure showing red abalone landings in California from 1991–1997. Panel (a) displays total statewide landings. Panel (b) shows landings split by Central California (CCA) and Southern California (SCA). Panels (c–j) highlight the top 10 individual ports, each with at least one year of landings over 1,500 pounds. Data are sourced from CDFW Pacfin fish tickets.

Figure 17: Figure showing projected changes in environmental variables used in sardine models. Three rows display: (a–c) sea surface temperature in °C, (d–f) sea surface chlorophyll a in mg m^{-3}, and (g–i) maximum zooplankton biomass in 0–50 mmol N m^{-3}. Columns compare ensemble mean historical values (1990–2010), ensemble mean end-of-century values (2070–2100), and projected changes between the two periods.

Figure 18: Figure showing projected changes in environmental variables used to identify abalone refugia. Rows display (a–c) bottom temperature, (d–f) bottom dissolved oxygen, and (g–i) pH. Columns show ensemble mean historical values (1990–2010), mid-century changes (2020–2050 relative to historical), and end-of-century changes (2050–2100 relative to historical).

A.2 Figure Metadata

Figure 1

Title	**Partial effects of predictors used in the hybrid habitat model**
Figure ID	Figure 1
Description	Predictors and resulting partial effects (a–e) used in the hybrid sardine habitat model from the 3-km ROMS and stock assessment. We include a suite of biogeochemical predictors to better resolve nearshore habitats (i.e., panels b,c and e; surface chlorophyll, upper 50 m zooplankton, and spawning stock biomass). All partial effect smooths use a thin-plate regression spline.
Data Sources	• Environmental data: ROMS downscaled ocean model output • Spawning stock biomass from PacFin fish ticket data
Software	R ({sdmTMB}, {ggplot2})
Units	Sea-surface temperature (˚C), surface chlorophyll (mg m-3), zooplankton (mmolN/m3), distance from land (m), spawning stock biomass (tn)
Figure Author	Nerea Lezama-Ochoa (UCSC), Barb Muhling (UCSC), Jessica Bolin (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 2

Title	**Model predictions of sardine habitat probability**
Figure ID	Figure 2
Description	Model predictions of sardine habitat probability (0–1) using two modeling approaches for the August 15, 2012. (a): generalized linear mixed model without a spatial field. (b): generalized linear mixed model including a spatial field.
Data Sources	• Environmental data: ROMS downscaled ocean model output • Spawning stock
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Temporal Resolution	Daily timestep for August 15, 2012

Title	Model predictions of sardine habitat probability
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Software	R ({terra}, {tidyverse}, {sdmTMB})
Units	Sardine probability (0–1)

Figure 3

Title	Projected habitat suitability for sardine
Figure ID	Figure 3
Description	Projected habitat suitability ensemble means of sardine for the historical (1990–2010) and end-of-century (2070–2100) periods. Top row: correlative SDM without spatiotemporal effects. Bottom row: correlative SDM with spatiotemporal effects. Panels (a,b,f,g): probability of occurrence, Panels (c,d,h,i): model uncertainty (i.e., standard deviation across the three ESMs), Panels (e,j):difference between end-of-century and historical projections (i.e., purple represents gain of habitat and red loss of habitat).
Data Sources	• Environmental data: ROMS downscaled ocean model output • Spawning stock biomass from PacFin fish ticket data
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Temporal Resolution	Baseline: 1990–2010; far-future: 2070–2100
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Software	R ({terra}, {tidyverse}, {sdmTMB})
Units	Sardine probability (0–1)
Coord. Ref. System	WGS 84 (EPSG:4326)
Figure Author	Nerea Lezama-Ochoa (UCSC), Barb Muhling (UCSC), Jessica Bolin (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 4

Title	**GAM Smooths for Additive Effects on Sardine Metabolic Rates**
Figure ID	Figure 4
Description	Plots of GAM smooths for the additive effects of fish weight (grams) and water temperature (˚C) for the routine (a,b) and maximum (c,d) metabolic rates of sardine.
Data Sources	• Environmental data: ROMS downscaled ocean model output • Spawning stock biomass from PacFin fish ticket data
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Software	R ({tidyverse}, {sdmTMB})
Figure Author	Nerea Lezama-Ochoa (UCSC), Barb Muhling (UCSC), Jessica Bolin (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 5

Title	**Calculating metabolic scope using GAMs**
Figure ID	Figure 5
Description	Calculating metabolic scope using GAMs. (a) Predicted routine metabolic rate.(b) Predicted maximum metabolic rate. (c) Predicted metabolic scope (% of maximum metabolic rate).
Data Sources	• Environmental data: ROMS downscaled ocean model output
Software	R ({tidyverse}, {sdmTMB})
Figure Author	Nerea Lezama-Ochoa (UCSC), Barb Muhling (UCSC), Jessica Bolin (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 6

Title	**Projections of Metabolic Scope**
Figure ID	Figure 6
Description	Projections of metabolic scope for September 7th in the historical period (Panel a: 1990, GFDL) and future period (Panel b: 2100, HADL). Units expressed as routine metabolic rate as a % of maximum metabolic rate.
Data Sources	• Environmental data: ROMS downscaled ocean model output
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Software	R ({tidyverse}, {sdmTMB}, {terra})
Figure Author	Nerea Lezama-Ochoa (UCSC), Barb Muhling (UCSC), Jessica Bolin (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 7

Title	**Sardine Landings for High-Use California Ports**
Figure ID	Figure 7
Description	Contribution of sardine landings for the top five California ports from 2000–2020, colored by region (i.e., central or southern California). Data sourced from PacFIN historical fish tickets.
	• Environmental data: ROMS downscaled ocean model output • Landed weight from PacFin fish ticket data
Software	R ({tidyverse}, {ggplot2})
Figure Author	Nerea Lezama-Ochoa (UCSC), Barb Muhling (UCSC), Jessica Bolin (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 8

Title	**Sardine Fishing Footprints**
Figure ID	Figure 8
Description	Fishing 'footprint' associated with each port, representing a polygon around all fished CDFW blocks corresponding to the port. Blue = Monterey, green = Moss Landing, orange = Port Hueneme, red = San Pedro and purple = Terminal Island.
Data Sources	• Environmental data: ROMS downscaled ocean model output • PacFin fish ticket data
Software	R ({tidyverse}, {ggplot2}, {sf})
Figure Author	Nerea Lezama-Ochoa (UCSC), Barb Muhling (UCSC), Jessica Bolin (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
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Figure 9

Title	**Projected refugia for the Channel Islands.**
Figure ID	Figure 9
Description	Projected refugia for the Channel Islands. Plots show (a–f) spatial persistence, defined as the percentage of time a given location is classified as refugia during the time period of interest, and (g) annual time series, showing the percentage of each year that refugia conditions are met, averaged across all grid cells within the Channel Islands region. Two temporal thresholds are applied: a conservative threshold (grey line, conditions met ≥95% of the time) and a liberal threshold (black line, conditions met ≥50% of the time). Solid grey boxes indicate time periods used in the analyses (baseline: 1990–2010, near-future: 2020–2050 and long-term: 2070–2100). Refugia projections are aggregated across all eight definitions. The time series panel displays the ensemble mean across three Earth System Models.
Data Sources	• Environmental data: ROMS downscaled ocean model output (SST, DO, pH) • Refugia classification framework: Based on thresholds of environmental stability and species-specific ecophysiological tolerance ranges

Title	Projected refugia for the Channel Islands.
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Temporal Resolution	Historical baseline: 1990–2010; Near-term projection: 2020–2050; Long-term projection: 2070–2100; Threshold: ≥50% of time steps must meet criteria to be classified as persistent refugia
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Methods Summary	Refugia were identified by overlaying modeled environmental variables with red abalone ecophysiological tolerance thresholds. Temporal persistence was calculated by counting the proportion of time each location met tolerance-based criteria. Differences between historical and future periods were computed for each grid cell and then aggregated for the Channel Islands region.
Software	R ({terra}, {tidyverse}, {sf}, {tmap})
Units	Persistence of refugia area (%) Refugia defined as binary (yes/no per cell)
Coord. Ref. System	WGS 84 (EPSG:4326)
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 10

Title	Projected refugia for the Mendocino coast
Figure ID	Figure 10
Description	Projected refugia for the Mendocino coast. Plots show (a–f) spatial persistence, defined as the percentage of time a given location is classified as refugia during the time period of interest, and (g) annual time series, showing the percentage of each year that refugia conditions are met, averaged across all grid cells within the Mendocino region. Two temporal thresholds are applied: a conservative threshold (grey line, conditions met ≥95% of the time) and a liberal threshold (black line, conditions met ≥50% of the time). Solid grey boxes indicate time periods used in the analyses (baseline: 1990–2010, near-future: 2020–2050 and long-term: 2070–2100). Refugia projections are aggregated across all eight definitions. The time series panel displays the ensemble mean across three Earth System Models.

Title	Projected refugia for the Mendocino coast
Data Sources	• Environmental data: ROMS downscaled ocean model output (SST, DO, pH) • Refugia classification framework: Based on thresholds of environmental stability and species-specific ecophysiological tolerance
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Temporal Resolution	Historical baseline: 1990–2010; Near-term projection: 2020–2050; Long-term projection: 2070–2100; Threshold: ≥50% of time steps must meet criteria to be classified as persistent refugia
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Methods Summary	Refugia were identified by overlaying modeled environmental variables with red abalone ecophysiological tolerance thresholds. Temporal persistence was calculated by counting the proportion of time each location met tolerance-based criteria. Differences between historical and future periods were computed for each grid cell and then aggregated for the Mendocino region.
Software	R ({terra}, {tidyverse}, {sf}, {tmap})
Units	Persistence of refugia area (%) Refugia defined as binary (yes/no per cell)
Coord. Ref. System	WGS 84 (EPSG:4326)
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 11

Title	Projected refugia for the Gaviota coast
Figure ID	Figure 11
Description	Projected refugia for the Gaviota coast. Plots show (a–f) spatial persistence, defined as the percentage of time a given location is classified as refugia during the time period of interest, and (g) annual time series, showing the percentage of each year that refugia conditions are met, averaged across all grid cells within the Gaviota region. Two temporal thresholds are applied: a conservative threshold (grey line, conditions met ≥95% of the time) and a liberal threshold (black line, conditions met ≥50% of the time). Solid grey boxes indicate time periods used in the analyses (baseline: 1990–2010, near-future: 2020–2050 and long-term: 2070–2100). Refugia projections are aggregated across all eight definitions. The time series panel displays the ensemble mean across three Earth System Models.
Data Sources	• Environmental data: ROMS downscaled ocean model output (SST, DO, pH) • Refugia classification framework: Based on thresholds of environmental stability and species-specific ecophysiological tolerance ranges
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Temporal Resolution	Historical baseline: 1990–2010; Near-term projection: 2020–2049; Long-term projection: 2070–2099; Threshold: ≥50% of time steps must meet criteria to be classified as persistent refugia
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5

Title	Projected refugia for the Gaviota coast
Methods Summary	Refugia were identified by overlaying modeled environmental variables with red abalone ecophysiological tolerance thresholds. Temporal persistence was calculated by counting the proportion of time each location met tolerance-based criteria. Differences between historical and future periods were computed for each grid cell and then aggregated for the Gaviota region.
Software	R ({terra}, {tidyverse}, {sf}, {tmap})
Units	Persistence of refugia area (%) Refugia defined as binary (yes/no per cell)
Coord. Ref. System	WGS 84 (EPSG:4326)
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 12

Title	Projected refugia for the Monterey region
Figure ID	Figure 12
Description	Projected refugia for the Monterey region. Plots show (a–f) spatial persistence, defined as the percentage of time a given location is classified as refugia during the time period of interest, and (g) annual time series, showing the percentage of each year that refugia conditions are met, averaged across all grid cells within the Monterey region. Two temporal thresholds are applied: a conservative threshold (grey line, conditions met ≥95% of the time) and a liberal threshold (black line, conditions met ≥50% of the time). Solid grey boxes indicate time periods used in the analyses (baseline: 1990–2010, near-future: 2020–2050 and long-term: 2070–2100). Refugia projections are aggregated across all eight definitions. The time series panel displays the ensemble mean across three Earth System Models.
Data Sources	• Environmental data: ROMS downscaled ocean model output (SST, DO, pH) • Refugia classification framework: Based on thresholds of environmental stability and species-specific ecophysiological tolerance ranges
Spatial Resolution	~3-km² resolution; based on ROMS model grid

Title	Projected refugia for the Monterey region
Temporal Resolution	Historical baseline: 1990–2010; Near-term projection: 2020–2050; Long-term projection: 2070–2100; Threshold: ≥50% of time steps must meet criteria to be classified as persistent refugia
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Methods Summary	Refugia were identified by overlaying modeled environmental variables with red abalone ecophysiological tolerance thresholds. Temporal persistence was calculated by counting the proportion of time each location met tolerance-based criteria. Differences between historical and future periods were computed for each grid cell and then aggregated for the Monterey region.
Software	R ({terra}, {tidyverse}, {sf}, {tmap})
Units	Persistence of refugia area (%) Refugia defined as binary (yes/no per cell)
Coord. Ref. System	WGS 84 (EPSG:4326)
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 13

Title	Projected refugia for the Sonoma coast
Figure ID	Figure 13
Description	Projected refugia for the Sonoma coast. Plots show (a–f) spatial persistence, defined as the percentage of time a given location is classified as refugia during the time period of interest, and (g) annual time series, showing the percentage of each year that refugia conditions are met, averaged across all grid cells within the Sonoma region. Two temporal thresholds are applied: a conservative threshold (grey line, conditions met ≥95% of the time) and a liberal threshold (black line, conditions met ≥50% of the time). Solid grey boxes indicate time periods used in the analyses (baseline: 1990–2010, near-future: 2020–2050 and long-term: 2070–2100). Refugia projections are aggregated across all eight definitions. The time series panel displays the ensemble mean across three Earth System Models.

Title	Projected refugia for the Sonoma coast
Data Sources	• Environmental data: ROMS downscaled ocean model output (SST, DO, pH) • Refugia classification framework: Based on thresholds of environmental stability and species-specific ecophysiological tolerance ranges
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Temporal Resolution	Historical baseline: 1990–2010; Near-term projection: 2020–2050; Long-term projection: 2070–2100; Threshold: ≥50% of time steps must meet criteria to be classified as persistent refugia
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Methods Summary	Refugia were identified by overlaying modeled environmental variables with red abalone ecophysiological tolerance thresholds. Temporal persistence was calculated by counting the proportion of time each location met tolerance-based criteria. Differences between historical and future periods were computed for each grid cell and then aggregated for the Sonoma region.
Software	R ({terra}, {tidyverse}, {sf}, {tmap})
Units	Persistence of refugia area (%) Refugia defined as binary (yes/no per cell)
Coord. Ref. System	WGS 84 (EPSG:4326)
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
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Figure 14

Title	**Change in persistent refugia for the Channel Islands region.**
Figure ID	Figure 14
Description	Projected change in persistent refugia for the Channel Islands region. Plots show the change in spatial persistence, defined as the percentage of time a given location is classified as refugia during the time period of interest, minus the same for the historical baseline period (1990-2010). Two temporal thresholds are applied: a conservative threshold (grey line, conditions met ≥95% of the time) and a liberal threshold (black line, conditions met ≥50% of the time). Refugia projections are aggregated across all eight definitions and represent a 50% temporal threshold, where refugia conditions must be met 50% of the time.
Data Sources	• Environmental data: ROMS downscaled ocean model output (SST, DO, pH) • Refugia classification framework: Based on thresholds of environmental stability and species-specific ecophysiological tolerance ranges
Spatial Resolution	~3-km² resolution; based on ROMS model grid
Temporal Resolution	Historical baseline: 1990–2010; Near-term projection: 2020–2050; Long-term projection: 2070–2100; Threshold: ≥50% of time steps must meet criteria to be classified as persistent refugia
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Methods Summary	Refugia were identified by overlaying modeled environmental variables with red abalone ecophysiological tolerance thresholds. Temporal persistence was calculated by counting the proportion of time each location met tolerance-based criteria. Differences between historical and future periods were computed for each grid cell and then aggregated for the Sonoma region.
Software	R ({terra}, {tidyverse}, {sf}, {tmap})
Units	Percent change in refugia area (%)
Coord. Ref. System	WGS 84 (EPSG:4326)

Title	Change in persistent refugia for the Channel Islands region.
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 15

Title	Core fishing blocks for historical high-use red abalone ports
Figure ID	Figure 15
Description	Core fishing blocks for the Santa Barbara/Ventura/Oxnard port complex, and for the Princeton/Half Moon Bay port complex. Map grids are CDFW fishing blocks in California, with high-use blocks indicated by block identifier.
Data Sources	• CDFW red abalone landings data 1990–1997
Spatial Resolution	~10-km² resolution; based on CDFW fishing block grid
Temporal Resolution	1991–1997
Methods Summary	Core fishing blocks were identified by identifying high-use ports as those with landings exceeding 1,500 pounds in any single year, with the top five blocks for each port labelled as core fishing blocks.
Software	R ({tidyverse}, {sf}, {tmap})
Coord. Ref. System	WGS 84 (EPSG:4326)
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
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Figure 16

Title	Identification of "high-use" historical red abalone fishing ports in California
Figure ID	Figure 16
Description	(a) Total red abalone landings (lb) reported across all California ports from 1991 to 1997. (b) Regional breakdown of landings in Central and Southern California (CCA, SCA). (c–j) Top 10 ports with annual landings exceeding 1,500 lb in any year during the 1991–1997 period. Data sourced from CDFW Pacfin fish ticket data.
Data Sources	• CDFW Pacfin fish tickets 1991–1997

Title	**Identification of "high-use" historical red abalone fishing ports in California**
Spatial Resolution	~10-km² resolution; based on CDFW fishing block grid
Temporal Resolution	1991–1997
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Methods Summary	Refugia were identified by overlaying modeled environmental variables with red abalone ecophysiological tolerance thresholds. Temporal persistence was calculated by counting the proportion of time each location met tolerance-based criteria. Differences between historical and future periods were computed for each grid cell and then aggregated for the Sonoma region.
Software	R ({tidyverse}, {sf}, {tmap})
Units	Landed weight (lb)
Figure Author	Jessica Bolin, UC Davis, jabbolin@ucdavis.edu
Date of creation	August 2025
Licence	Internal use only

Figure 17

Title	**Projected changes for environmental variables used in sardine models**
Figure ID	Figure 17
Description	Spatial annual mean and future changes (relative to historical) for the environmental variables used for sardine projections. Rows shown: (a–c) sea surface temperature (°C), (d–f) sea surface chlorophyll a (mg m-3), and (gî) maximum zooplankton biomass from (0-50 mmol N m-3). Columns show: (a,d,g) ensemble mean historical values, (b,e,h) ensemble mean end-of-century values, and (c,f,i) end-of-century changes relative to historical (2070–2100 vs. 1990–2010).
Data Sources	• High-resolution ocean projections from the Regional Ocean Modeling System (ROMS) configured for the central California Current System.
Spatial Resolution	3-km² resolution
Temporal Resolution	Daily, 1990–2100
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5

Title	Projected changes for environmental variables used in sardine models
Units	˚C, mg m^{-3}, mmol Nm^{-3}
Figure Author	Mer Pozo Buil (UCSC) mpozobuil@seoe.sc.edu, Jessica Bolin, (UC Davis), jabbolin@ucdavis.edu
Date of creation	August 2025
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Figure 18

Title	Projected changes for environmental variables used for abalone refugia
Figure ID	Figure 18
Description	Spatial annual mean and future changes (relative to historical) for the environmental variables used to identify abalone refugia. Rows shown: (a–c) bottom temperature, (d–f) bottom dissolved oxygen, and (g–i) pH. Columns show: (a,d,g) ensemble mean historical values (1990-2010), (b,e,h) ensemble mid-of-century changes (2020–2050 relative to historical), and (c,f,i) ensemble end-of-century changes (2050–2100 relative to historical).
Data Sources	• High-resolution ocean projections from the Regional Ocean Modeling System (ROMS) configured for the central California Current System.
Spatial Resolution	3-km^2 resolution
Temporal Resolution	Daily, 1990–2100
Climate Scenarios	CMIP5 multi-model ensemble: Hadley, IPSL and GFDL; RCP5-8.5
Units	˚C, pH (unitless), mmol m^{-3}
Figure Author	Mer Pozo Buil (UCSC) mpozobuil@seoe.sc.edu, Jessica Bolin, (UC Davis), jabbolin@ucdavis.edu
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