Integrated ocean observing systems for assessing marine protected areas across California

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CENTRAL & NORTHERN CALIFORNIA OCEAN OBSERVING SYSTEM
SOUTHERN CALIFORNIA COASTAL OCEAN OBSERVING SYSTEM

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I. Introduction

Spatial and temporal variability in California's marine ecosystems occurs both from environmental variation and from human impacts including fisheries. Environmental variability spans many different spatiotemporal scales, which presents challenges for interpreting ecosystem changes in relation to marine protected area (MPA) implementation and other management actions. For example, *How can changes in MPA condition be attributed to MPA management and/or other phenomena such as regional climate change?* Moreover, such management assessments require an integrative approach to data, including standardization, processing, analysis, and visualization of data from a diversity of sources. Some of these data processes are time-consuming and complex, especially for diverse environmental habitat and indicator data. *How can data from various investigators, locations, habitats, and methods be integrated to produce robust assessments of change in key indicators that are useful for MPA management?* Contemporary ocean observing systems are working to overcome these challenges in part by providing information across a wide range of scales and a broad array of variables. This includes streamlining data management and building cyberinfrastructures that allow for more timely and repeatable analysis.

We have used the Integrated Ocean Observing System (IOOS) framework in the Central and Northern California Ocean Observing System (CeNCOOS) and Southern California Coastal Ocean Observing System (SCCOOS) to develop and curate collections of MPA-relevant datasets and data visualization and exploration tools. These tools are supported by replicable and documented data streams and processes, allowing MPA researchers and managers to address these challenges and thereby improve their ability to attribute observed changes to natural and/or human drivers. We prioritized the specification and capabilities of the tools and data in order to address specific goals of the California Marine Life Protection Act (MLPA) and the MPA Monitoring Action Plan, including via consultations with MPA Monitoring Program investigators, the California Department of Fish and Wildlife (CDFW), and the Ocean Protection Council (OPC). Our report covers advances made as part of the recently completed OPC-funded project *Integrated ocean observing systems for assessing marine protected areas across California*, which produced the following:

- Streamlined access to curated sets of environmental and ecological MPA data, generated through documented and replicable data processes;
- Customized visualizations of the datasets via the interactive *California MPA Dashboard* application;
- High-resolution models of MPA connectivity data for MPAs and coastal regions within the greater Monterey Bay area;
- Detailed estimates of ecosystem-level variation and harmful algal bloom (HAB) risk across bioregions and MPAs;
- Integrated multi-scale assessments of environmental variation and change over the past two decades, at MPA and bioregion scales;
- Detailed estimates of climate change risk for bioregions and MPAs.

Below we highlight our methods for addressing the above objectives, our detailed research questions and analytical approaches, results from these activities to date and discussion placing these results in the context of the Marine Life Protection Act and MPA Action Plan goals and questions.

II. Highlights and Key Findings

1. Streamlined access to MPA data in integrated formats for expert assessments.

Assembling and using easily accessible and robust datasets for MPA assessment by many independent teams is time consuming and adds risk of incompatibility in later analysis and results. As part of our work since 2019, we:

- Curated a collection of datasets and data products specific to California MPAs, including oceanographic, climatological, and ecological data;
- Created documented, replicable data processing scripts and metadata through a central cloud-based project management and data analysis platform to verify, summarize, and standardize the data, such that future updates to the source datasets can also be efficiently processed;
- Made these datasets and data products discoverable and accessible via multiple use points. These represent significant investments into data quality, standardization, visualization, and replicable information streams to enable effective identification, access, and use of datasets in current and future MPA analyses and assessments.

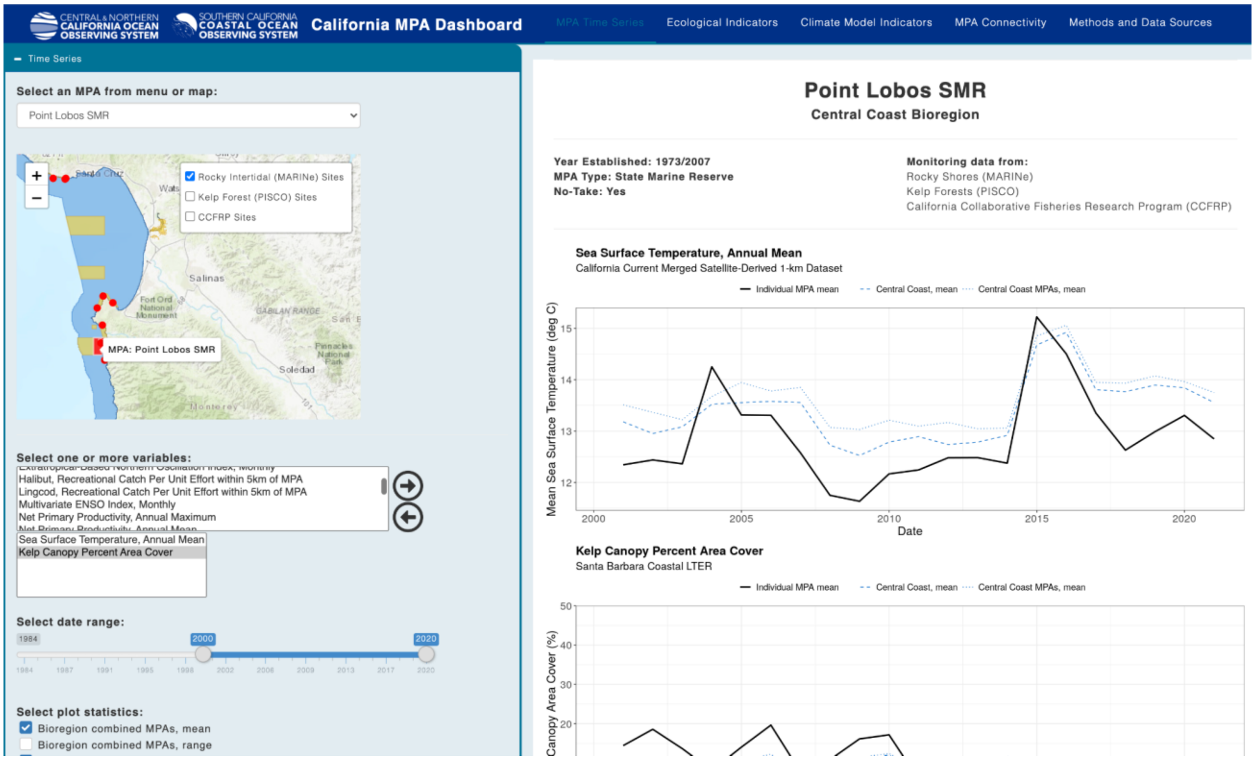
Oceanographic and climatological data were obtained from various publicly available datasets, quality-checked, and, where applicable, used to generate monthly and annual summary variables at the spatial scale of each individual MPA, combined (aggregated) MPAs, and the reference bioregion. These integrated data with common time and space formatting are publicly available through DataONE and California IOOS data systems at weekly and monthly timescales wherever available. Long-term ecological monitoring datasets were obtained from different habitat monitoring groups within and outside the California MPA Monitoring Program. We worked closely with representatives from these groups to understand how each dataset was collected and conducted verification and quality checks for inaccuracies or inconsistencies in the data. This process was especially important to ensure the long-term interpretation and utility of these datasets, which have complex sampling and observing methods, data and formatting. Once these datasets were quality checked, we worked to standardize the data using the Darwin Core standard (dwc.tdwg.org) and made them accessible and discoverable through a variety of endpoints, including the new California Ocean Observing Data Portal (data.caloos.org), the Marine Biodiversity Observation Network (MBON) data portal, the Ocean Biodiversity Information System (OBIS), and the Global Biodiversity Information Facility (GBIF). Over time we continue to facilitate the progression of data from the Program into State, national and international domains making the data findable, accessible, interoperable and reusable (FAIR, **Table A1**). Researchers, managers, and others can thereby use common sets of up-to-date information for understanding and assessment.

2. Streamlined access to MPA data via the California MPA Dashboard

Identifying and processing datasets that are relevant to MPA assessments is time consuming and may lead to less efficient use of available data in MPA assessments and research by different research and management groups. We developed a *California MPA Dashboard* application that provides easy access to data and visualizations of a curated collection of datasets from a variety of sources, which have been identified and processed specifically to be useful for answering questions about MPAs, including research and assessment interests highlighted in the MPA Monitoring Action Plan. Relevant data can be easily explored and visualized through a public website interface. Datasets of interest can either be downloaded directly from the MPA Dashboard, or users can identify the data source from the

MPA Dashboard and obtain data for further analysis. Researchers, managers, and other stakeholders can easily locate and explore data relevant to MPA assessments and research questions. See **Table A2** for the current complete list of datasets. Sources and methods can be found at: mpa-dashboard.caloos.org/methods. This collection of datasets will be regularly updated as the underlying datasets are updated, and expanded as additional relevant datasets become available. The Dashboard consists of four main tools, which address MLPA goals and MPA Monitoring Action Plan questions including:

1. MPA Time Series tool (**Fig. 1**), which creates user-customizable visualizations of oceanographic, climatological, and ecological time series data for individual MPAs and bioregions, based on datasets described in Section 1. This allows for visualizations and comparisons of abundance timeseries for ecologically and economically important species from multiple monitoring programs, alongside timeseries of oceanographic and climatological variables to provide environmental context, in order to address MPA Monitoring Action Plan Questions relevant to MLPA Goals 1 and 2.
    - MLPA Goal 1: Protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems.
        - Do focal and/or protected species inside of MPAs differ in size, numbers, and biomass relative to reference sites?
        - Do the abundance, size/age structure, and/or diversity of predator and prey species differ inside MPAs, or outside areas of comparable habitat?
    - MLPA Goal 2: Help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted.
        - Question: How do species differ in their rate of response to MPA implementation?



Select an MPA from menu or map: Point Lobos SMR

☑ Rocky Intertidal (MARINe) Sites
☐ Kelp Forest (PISCO) Sites
☐ CCFRP Sites

Select one or more variables:

Extratropical-Based Northern Oscillation Index, Monthly
Halibut, Recreational Catch Per Unit Effort within 5km of MPA
Lingcod, Recreational Catch Per Unit Effort within 5km of MPA
Multivariate ENSO Index, Monthly
Net Primary Productivity, Annual Maximum
Net Primary Productivity, Annual Mean

Sea Surface Temperature, Annual Mean
Kelp Canopy Percent Area Cover

Select date range: 1984 2000 2020

Select plot statistics:
☑ Bioregion combined MPAs, mean
☐ Bioregion combined MPAs, range

Point Lobos SMR
Central Coast Bioregion

Year Established: 1973/2007
MPA Type: State Marine Reserve
No-Take: Yes

Monitoring data from:
Rocky Shores (MARINe)
Kelp Forests (PISCO)
California Collaborative Fisheries Research Program (CCFRP)

Sea Surface Temperature, Annual Mean
California Current Merged Satellite-Derived 1-km Dataset

Kelp Canopy Percent Area Cover
Santa Barbara Coastal LTER

Fig. 1. Screenshot of the MPA Time Series Tool in the California MPA Dashboard - showing user menus and visualized data from Point Lobos SMR across selected variables and times.

2. Ecological Model Outputs tool, which visualizes data on ecosystem-level variation via “Dynamic Seascapes,” assessments of harmful algal bloom (HAB) risk, and predicted likelihood of vulnerable species encountering HAB exposures in California MPAs and bioregions (see Section 4 and 5). This allows for assessments of the diversity of ocean habitats and their change over time within MPAs, and assessments of an important stressor, HABs, in MPAs, to address MPA Monitoring Action Plan Questions relevant to MLPA Goals 4 and 6.
    - MLPA Goal 4: To protect marine natural heritage, including protection of representative and unique marine life habitats in California waters for their intrinsic value.
        - Have unique habitats been adequately represented and protected by the current distribution and designation of MPAs?
    - MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network
        - How do other stressors impact the management of MPAs over time (e.g., water quality, oil spills, desalination plants, ocean acidification, sea level rise)?
3. MPA Connectivity tool, which visualizes modeled connectivity and larval dispersal patterns for 11 MPAs and non-MPA nearshore habitat within the greater Monterey Bay region (see Section 3). This allows for assessments of MPA connectivity under different conditions, to address MPA Monitoring Action Plan Questions relevant to MLPA Goal 6.
    - MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network.
        - What are the demographic effects of siting MPAs in larval source or sink locations, and how do demographic responses to MPAs contribute to larval production and connectivity of MPAs in the network?
        - How does the distance and larval contribution between a source MPA and sink MPA influence the ecosystem response inside the sink MPA?
        - How does the level of connectivity and larval supply from an MPA to areas outside of MPAs affect fisheries?
4. Climate Model Indicators tool, visualizing climate variable projections across all California MPAs (see Section 7). This allows for addressing of priority research questions from the OPC Science Advisory Team’s report on Climate Resilience and California’s MPA Network.
    - What is the spatial distribution of MPAs relative to historic and current stressor exposures, and how are those stressors likely to evolve in the future?
    - What are physical, ecological, and biological characteristics of climate refugia? Do MPAs include or promote these conditions? Will climate refugia persist into the future?

3. Improved realism and timeliness of MPA connectivity data

Modeling connectivity of organisms by ocean currents between MPA regions and between MPA and non-MPA regions provides quantitative information concerning how MPA regions function as a network beyond the sum of their parts. We statistically analyzed realistic virtual larval or propagule transport trajectories generated from state-of-the-science ocean circulation models (NOAA’s West Coast Operational Forecast System; WCOFS) coupled to larval transport models including different types of larval behaviors in the water column and a range of different pelagic larval durations, for MPA and non-MPA regions in the greater Monterey Bay area between March 2020 and September 2021 (**Fig. A1**). This circulation and connectivity model for the greater Monterey Bay region can be considered a prototype for similar implementations extending to other regions of the California coast, for more comprehensive analyses of connectivity throughout the broader MPA network.

This work, and potential follow on work, can address MLPA Goal 6: To ensure that the MPAs are designed and managed, to the extent possible, as a component of a statewide network. MPA Monitoring Action Plan questions include: How does the distance and larval contribution between a source MPA and sink MPA influence the ecosystem response inside the sink MPA? And, How does the level of connectivity and larval supply from an MPA to areas outside of MPAs affect fisheries? This work has resulted in an assessment of source and sink dynamics for MPA and non-MPA coastal locations for the greater Monterey Bay Area.

During the year and a half of trajectories analyzed, all MPAs studied showed connectivity with amplitudes that varied with pelagic larval duration, time of year released, and organismal behavior. Some MPAs experienced generally greater transport to and from multiple other MPAs, with general trends of higher local retention under shorter pelagic larval durations, and higher between-MPA connectivity, particularly from south to north, under longer pelagic larval durations (**Fig. A2**). Spillover effects from MPAs to non-MPA nearshore zones also resulted from ocean circulation (**Fig. 2).**

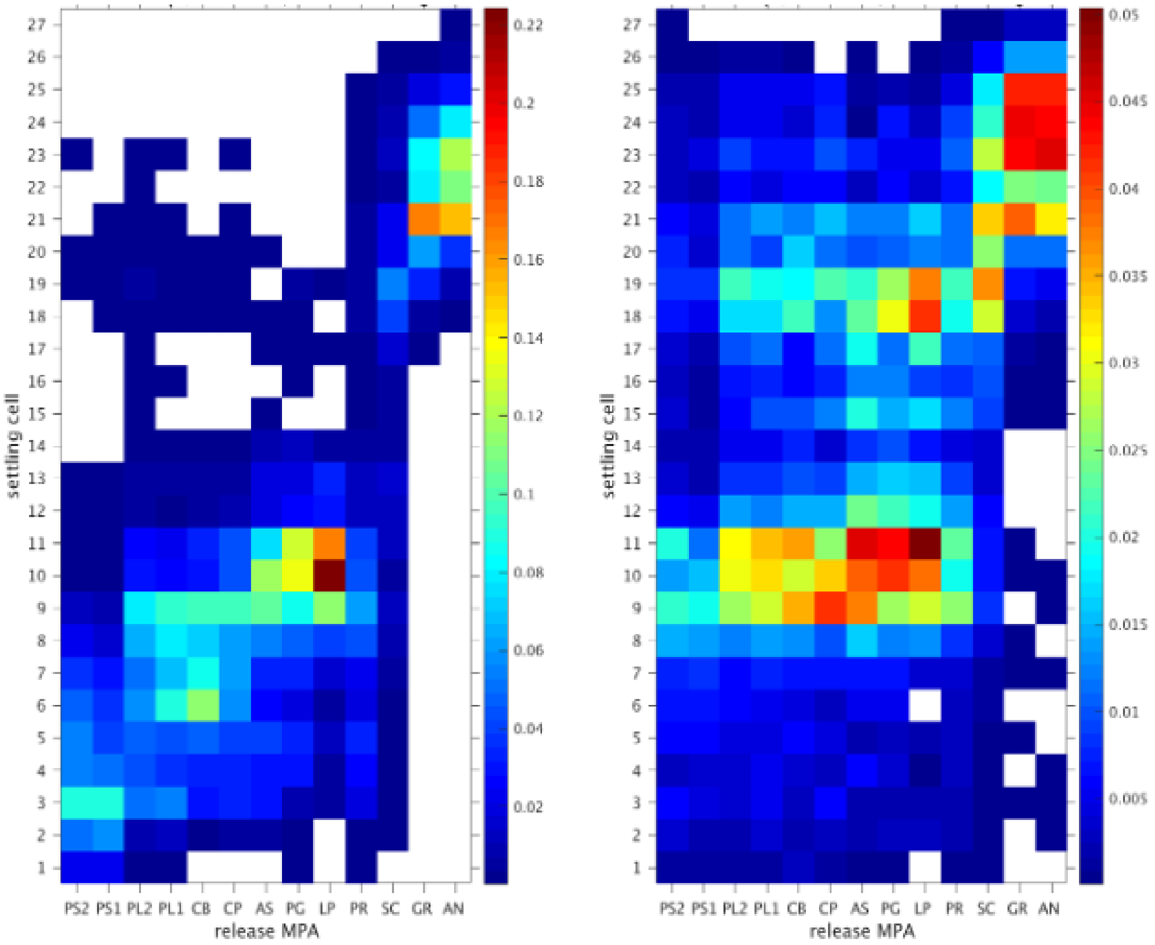


Fig. 2. Connectivity matrices showing the probability that a float released from an MPA designated on the x-axis in April 2020 could potentially settle in a nearshore coastal region on the y-axis for the scenarios of neutral larval behavior and pelagic larval durations of (left) 7-9.5 days and (right) 30-45 days. All horizontal rows contain at least one non-zero value, indicating spillover of modeled larvae into each non-MPA location from at least one MPA. The key for MPA initials and nearshore coastal areas is given in Fig. A1. Note differing color scales in each plot.

Across all three of these scenarios, all nearshore cells received modeled larvae from at least one of the MPA locations within the greater Monterey Bay area. This suggests that MPAs were sufficiently spaced that protected regions experienced larval exchange dependent on pelagic larval duration, time of release, and larval behavior. While this approach is among the most advanced and high-resolution methods available, limitations include errors in the ocean circulation model and the simplification of larval and propagule behaviors into the trajectory and connectivity estimates.

4. Detailed estimates of ecosystem-level variation across bioregions and MPAs

Understanding the connections between ocean conditions, biodiversity, and indicator species variation can aid our understanding of marine ecosystem dynamics and inform adaptive management strategies. We used a classification model with inputs of remotely sensed physical, chemical, and biological data to characterize ocean conditions within California MPAs and bioregions into distinct categories of “Dynamic Seascapes”, at the landscape scale.

Overall, California’s marine bioregions experience similar ocean conditions characterized by 12 unique Seascape categories (**Table A3**), but the South Coast and Channel Islands bioregions experience a more diverse set of Seascape conditions on an overall and annual basis (**Fig. A3**). Aberrant ocean conditions were also detected using Seascape classifications, including the 2015 marine heat wave (“The Blob”), which related to changes in Seascapes extending from Southern California MPAs north to Campus Point SMCA (**Fig. 3**). We see high mean kelp biomass associated with Seascapes with “Tropical/Subtropical Upwelling” (Seascape 11), and “Hypersaline Eutrophic” (Seascape 27), while “Tropical Seas” (Seascape 15) had the lowest mean kelp biomass. These findings show that Seascape state-space classifications can be summarized at the spatial scales of MPAs, and provide wider- and longer-scale estimates of variability among California’s marine waters.

5. Detailed estimates of harmful algal bloom risk for California bioregions and MPAs

Using high frequency nowcasts of harmful algal bloom (HAB) predictions from the California-Harmful Algae Risk Mapping (C-HARM) model and projected distributions of vulnerable bycatch species (leatherback sea turtles, sea lions, and blue sharks) from the EcoCast species distribution models, we found spatial and temporal patterns of potential exposure of a key stressor, HABs, and risk for vulnerable species, in California MPAs and bioregions.

C-HARM temporal patterns from 2018-2021 show that the risks of exceeding key thresholds for cellular domoic acid, particulate domoic acid, and *Pseudo-nitzschia* spp. blooms were already high in all bioregions (**Fig. A4-A5**). The EcoCast and C-HARM risk maps suggest a potential increasing frequency, persistence and spatial extent of HABs in recent years, but the contiguous record is still only a few years long. These areas of risk coincide with ecologically important migrating species, posing a risk of these species suffering adverse effects due to domoic acid and HABs. This was especially true for MPAs in the Central and North Coast bioregions (**Fig. A6**).

6. Integrated multi-scale assessments of variation and change over the past two decades

To assess how dynamic ocean conditions at different spatial and temporal scales can influence conditions in California MPAs and bioregions, we examined data from global to regional climate indices that focus on various mechanisms and scales of change. There was a notable El Niño-Southern Oscillation (ENSO) event around December 2009.

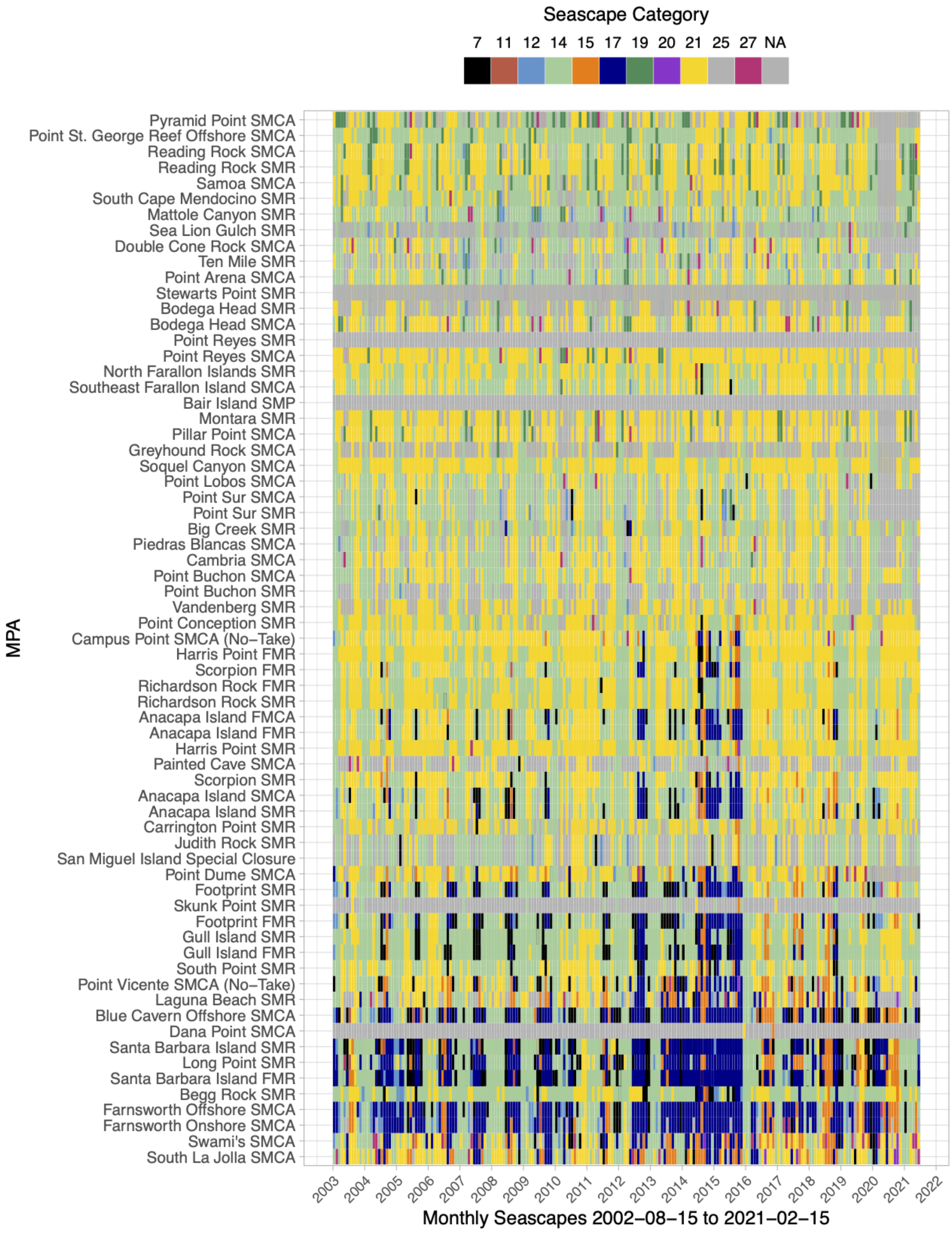


Fig. 3. Time series of monthly Seascapes within California MPAs, ordered by latitude. Seascapes are dynamic classifications of water masses based on oceanographic properties derived from satellite imagery.

The spatial and temporal evolution of the warming event in 2015 was nonetheless the most prominent interannual signal in climate and Seascapes variation observed during the period 2003 to 2021.The unusual conditions that dominated that period, even into 2018, have since dissipated. This is evident in the time series of the California Multivariate Ocean Climate Indicator (MOCI), Seascapes ocean habitat classifications and other ocean climate indicators (e.g. **Fig. A7**). For example, the MOCI index was negative for much of 2011 to 2013 and was negative again in late 2020 across the state. While conditions over the last decade have been variable, long-term, multi-decadal changes associated with climate change are becoming clearer, such as with kelp loss, new records in ocean temperatures, and ongoing ocean acidification.

We also assessed how individual MPAs differed from their bioregions with respect to environmental conditions on a year-to-year basis and across an 18-year timeseries. This work enabled us to address key questions including: How have conditions changed over time from basin to California MPA bioregion scales? How has the similarity of oceanographic conditions in individual MPAs changed over time relative to their bioregion? Which MPAs have exhibited the greatest differences in variation from their bioregion, and when?

MPAs that were most divergent from their bioregions tended to be located near the latitudinal boundaries of the bioregion, but we also identified divergent areas that were not located at latitudinal boundaries, e.g., Point Sur SMR (**Table A4**). The differences between MPAs and their bioregion builds understanding regarding the degree to which they represent unique areas, and conversely, the degree to which they are representative of regional-scale variations. This can contribute to understanding of how important regional oceanographic conditions are for determining regional MPA performance relative to the protection measures designated by a given MPA.

7. Detailed estimates of climate change risk for California bioregions and MPAs

To understand the role that MPAs may play in supporting ecosystem resilience and providing societal benefits in the face of climate change, it is necessary to understand how key environmental variables are projected to change in California's state waters and in MPAs. We extracted summaries of projected change in key oceanographic variables from a California Current Regional Ocean Modeling System model (ROMS-NEMUCSC), coupled to downscaled versions of different Earth Systems Models. We assessed differences between environmental conditions in each MPA and bioregion between past (1980-2009) and future (2070-2099) periods. We identified potential 'climate refugia' as areas projected to experience the least (bottom 10th percentile) change across multiple oceanographic variables and mapped these areas relative to the location of MPAs.

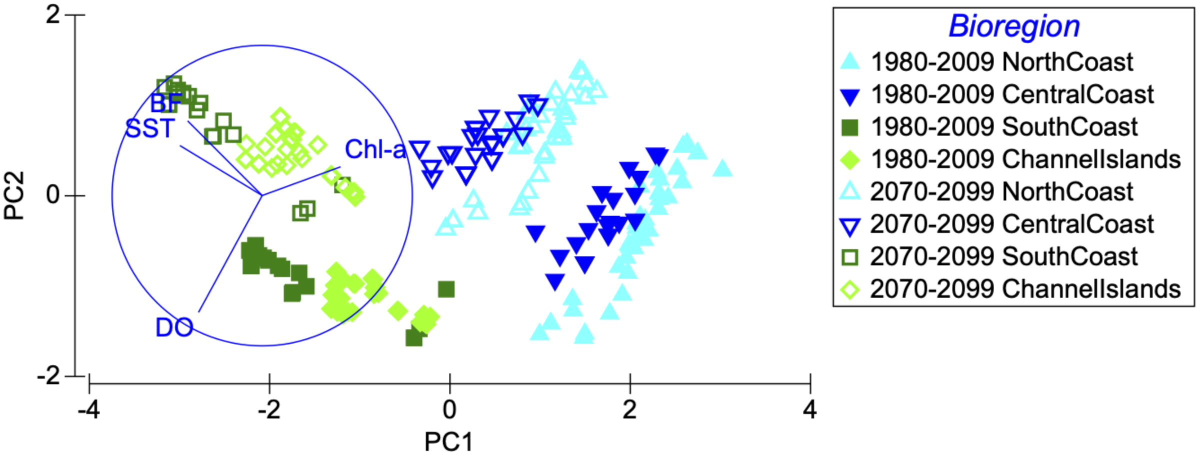


Fig. 4. Principal component analysis of climate change illustrating the multivariate similarity of MPAs during the past (1980-2009) and future (2070-2099) periods within and across bioregions. The relative contributions of the multiple environmental variables to each of the principal component axes (PC1 and PC2) are also plotted. These include SST, buoyancy frequency (BF) as a measure of stratification, chlorophyll-a (chl-a), and dissolved oxygen (DO).

Bioregions were statistically distinct from each other in both past and future periods, and there were also no overlaps between past and future MPA conditions, both within and across bioregions (**Fig. 4**). This suggests that no environmental analogs of current MPAs may exist for the 2070-2099 time period, even when comparing past lower-latitude sites with future higher-latitude sites. Coastal marine species in California may be unlikely to be able to migrate poleward to find fully analogous environmental conditions on a large scale. We find that the current MPA network protects a greater percentage of these potential environmental refugia from 1980-2099, compared to the percentage protection of all state waters (**Fig. A8**), but refugia were often not spatially persistent through different time periods.

8. Contributions from other projects that facilitated this work

Resources and capabilities from several other projects were useful in this work. These included from the following projects:

- *The CeNCOOS MBON: Integrating remote sensing,* in situ *data and models to understand central California ecosystem responses to environmental change* (National Aeronautics and Space Administration (NASA)),awarded through the National Ocean Partnership Program (NOPP). NOPP includes contributions from NASA, the Bureau of Ocean Energy Management (BOEM), Office of Naval Research (ONR), and NOAA.
- *National Marine Sanctuaries as Sentinel Sites for a Demonstration Marine Biodiversity Observation Network* (Sanctuaries MBON, NASA)
- *CeNCOOS: Integrating Marine Observations for Decision Makers and the General Public* (NOAA)
- *Integrated Ocean Observing System Implementation: Southern California Coastal Ocean Observing System* (SCCOOS, NOAA)
- Additional data resources came from the NOAA CoastWatch, the NOAA Center for Operational Oceanographic Products and Services (CO-OPS), the NOAA National Centers for Environmental Information (NCEI), the NOAA Southwest Fisheries Science Center and others.

III. Challenges

The conditions of remote working over the last two years have placed limitations on in person structured and informal dialogue that often results in finding and socializing resolving issues. We have worked to mitigate this through a series of virtual engagements. However these were often focused on specific tasks, and cross-project engagement ultimately limited progress. Field and laboratory work that underpins some of the data we integrated was also limited in the past two years, slowing the integration of some datasets. The other major challenge in our work and with the assessments overall has been the varied time and space structuring of observations and sampling, including for MPAs as well as reference areas. Although our work sought to reduce this issue through bringing data into common time and space domains, this variance in data availability also limits interpretive capability.

IV. Knowledge Gaps and Recommendations

Continued Data Integration and Visualization - This work is ongoing. CeNCOOS and SCCOOS will work with CDFW, OPC and data providers and others to prioritize working with data as it becomes available in support of the Decadal Management Assessment and onward MPA management needs.

Connectivity Modeling Roadmap - The high-resolution circulation and connectivity model only represents a portion of the California MPA network, and can be considered as a prototype for similar operational implementations extending to other regions of the California coast. The current model covers about 10% of the total coastline. There are two potential ways to achieve full coverage of high-resolution connectivity modeling that are assimilative of observations, similar to weather forecast models. One involves constructing an additional set of nine nest domains at 160 m grid cell resolution, with approximately three intermediate nests at 800 m resolution that bridge between the native WCOFS resolution and the 160 m grid cells. Alternatively, new work could only focus on the intermediate scale with associated efficiencies. Our connectivity results for the intermediate and inner nests are quantitatively different but qualitatively quite similar, which suggest that using solely the intermediate scale nests will be practical and useful.

The modeled connectivity metrics for MPAs and coastal areas can be used in the future to study demographic effects based on pelagic larval duration (PLD), larval behavior and time-of-release. Multi-generational demographic effects can be assessed by propagating connectivity matrices through multiple generations and including additional effects (e.g., habitat, larval mortality, larval production).

Climate change risk assessment - These analyses of projected climate change in California MPAs and bioregions are based on projected variables from an implementation of a ROMS-NEMUCSC model coupled to downscaled climate change models. This model is best suited to assessing change on long term (30-year) time scales and is limited in its usefulness for shorter-term predictions of oceanographic change. Additional work will be needed to understand nearshore areas not well represented in this model format, such as estuaries and changes in interannual phenomena such as ENSO. Other key oceanographic variables (e.g., pH and carbonate chemistry) from the model are still being worked on by the modeling team and will be incorporated into the climate change analyses when they are made available.

V. Conclusion

Work to date has enabled us to conduct integrated assessments of change across scales and into the future. This work marks major advancements in the ways in which MPA analytical workflows are developed, documented, and managed, and supports higher quality assessments being delivered more efficiently now and into the future. This includes the assessments addressing the MPA Monitoring Action Plan goals, with emphasis on providing data to understand the context of change across a wide range of scales including for habitat monitoring project data that also includes diversity and abundance of marine life, and the structure, function and integrity of marine ecosystems. Along with other program teams, we quantified the environmental and water quality context of change in marine life populations, including fisheries of economic value, thus providing information for possible rebuilding of stocks that are depleted. The data provided are bringing understanding of how long-term change might influence perceptions of what constitutes baseline conditions (e.g., potential shifting baselines). This understanding is a critical requirement to meet the criteria laid out in the 2021 Ocean Protection Council report on Climate Resilience and California’s MPA Network. Information from this project helps evaluate if MPAs are achieving objectives in the context of climate variability and secular change. This enables assessments at the scale of individual MPAs, the North, Central, and South Coast bioregions, with the Channel Islands assessed independently, and the degree to which individual MPAs may be experiencing similar conditions to the bioregions in which they are located.

VI. Appendix

Tables

Table 1. MPA data integration tracking tool highlighting the current stages of data integration. Importantly, this has expanded to include additional datasets and extends the integration from use in the California MPA Dashboard to onward availability in the IOOS portal systems and globally via OBIS and GBIF.

Dataset	On DataONE	DwC conversion scripts complete	On IOOS portal	On OBIS	On MPA dashboard	Latest year
Reef Check – fish transects	Yes	Yes	N/A	Yes	No	2019
Reef Check – invertebrate transects	Yes	Yes	N/A	Yes	No	2019
Reef Check – algae transects	Yes	Yes	N/A	Yes	No	2019
Reef Check – UPC data	Yes	Yes	N/A	Yes	No	2019
Reef Check – invasive algae surveys	Yes	Yes	N/A	N/A	No	2019
Reef Check – urchin size data	Yes	Yes	N/A	N/A	No	2019
Reef Check – abalone size data	Yes	Yes	N/A	N/A	No	2019
CCFRP – fish abundance and CPUE	Yes	Yes	N/A	N/A	Yes	2020
MARINe – LTM sea star and Katharina counts	Yes	Yes	In progress	Yes	Yes	2021
MARINe – LTM intertidal species abundance, photoplot and transect data	Yes	Yes	In progress	Yes	Yes	2021
MARINe – CBS intertidal species abundance, swath data	Yes	In progress	No	No	No	2021
MARINe – CBS intertidal species abundance, quadrat data	Yes	In progress	No	No	No	2021
MARINe – CBS intertidal species abundance, point contact data	Yes	In progress	No	No	No	2021
PISCO – fish transects	Yes	Yes	No	No	Yes	2020
PISCO – swath transects	Yes	Yes	No	No	Yes	2020
PISCO – size frequency data	Yes	Yes	No	No	No	2020
Sandy beaches – wrack cover and composition	Yes (baseline only, private)	No	No	No	No	2020
Sandy beaches – kelp and seabird abundance*	Yes (baseline only, private)	No	No	No	No	N/A
Sandy beaches – physical characteristics	Yes (baseline only, private)	N/A	No	N/A	No	2020
Sandy beaches – surf zone fish abundance*	No*	No	No	No	No	N/A
CRFS – recreational catch	N/A	N/A	N/A	N/A	Yes	2019
Ecotrust – NC spatial fishing data§	Yes (samples of post-MPA only)	N/A	N/A	N/A	No	N/A
Ecotrust – NCC spatial fishing data	Yes (samples of pre-MPA only)	N/A	N/A	N/A	No	N/A
Ecotrust – SC spatial fishing data	Yes (samples of post-MPA only)	N/A	N/A	N/A	No	N/A
North coast swath transects and size frequency data	In progress	Partially	No	No	No	2019
Estuaries – vegetation survey data	No	No	No	No	No	N/A
Estuaries – beach seine and cast net survey data	No	No	No	No	No	N/A
Mid-depth and deep survey data	No	No	No	No	No	N/A

Table A2. Datasets and summary variables presently available in the MPA dashboard, including the time range of available data. Datasets that are labeled with (A): Oceanographic and Climatological Datasets; datasets that are labeled with (B): Ecological Monitoring Datasets; data sets that are labeled with (C): Ecological Model and Indicator Outputs. Sources and methods can be found here: https://mpa-dashboard.caloos.org/methods/.

MPA DASHBOARD DATASETS	Years Data is Available
(A) Multivariate ENSO Index • Monthly Index	**1988 - 2020**
(A) Extratropical-Based Northern Oscillation Index • Monthly Index	**1988 - 2020**
(A) Pacific Decadal Oscillation Index • Monthly Index	**1988 - 2020**
(A) Biologically Effective Upwelling Transport Index (BEUTI) • Monthly Index	**1988 - 2020**
(A) Coastal Upwelling Transport Index (CUTI) • Monthly Index	**1988 - 2020**
(A) Sea Surface Temperature • Annual Mean, Maximum • Monthly Mean, Maximum	**2000 - 2020**
(A) Net Primary Productivity • Annual Mean, Maximum • Monthly Mean	**1996 - 2020**
(A) Attenuation of Downwelling Light at 490nm (Turbidity) • Annual Mean • Monthly Mean	**1996 - 2020**
(A) Significant Wave Height • Annual Mean, Maximum, 95th Percentile • Monthly Mean, Maximum, 95th Percentile	**2000 - 2020**
(A) Wave Orbital Velocity • Annual Mean, Maximum, 95th Percentile • Monthly Mean, Maximum, 95th Percentile	**2000 - 2020**
(A) Surface Aragonite Saturation • Annual Mean • Monthly Mean	**1988 - 2010**
(A) Bottom Aragonite Saturation • Annual Mean • Monthly Mean	**1988 - 2010**
(B) California Collaborative Fisheries Research Program (CCFRP) Angler Surveys • Combined fish counts • Combined fish CPUE	**2007 - 2020**
(B) Multi-Agency Intertidal Network (MARINe) Rocky Intertidal Surveys • Barnacle percent cover • Mussel percent cover • Sea star density • Black chiton density	**2000 - 2020**

MPA DASHBOARD DATASETS	Years Data is Available
(B) Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) Kelp Forest Diver Surveys • Combined finfish density • Combined rockfish (*Sebastes* spp.) density • Combined basses (*Paralabrax* spp.) density • California sheephead density • Combined benthic invertebrate density • Combined abalone (*Haliotis* spp.) density • California spiny lobster density • Sea urchin (*Strongylocentrotus* and *Mesocentrotus* spp.) density • Combined crab density	**2000 - 2020**
(B) Reef Check California Kelp Forest Diver Surveys • Combined finfish density • Combined rockfish (*Sebastes* spp.) density • Combined basses (*Paralabrax* spp.) density • California sheephead density • Lingcod density • Combined benthic invertebrate density • Combined abalone (*Haliotis* spp.) density • Sea urchin (*Strongylocentrotus* and *Mesocentrotus* spp.) density • Combined crab density	**2007 - 2020**
(B) California Recreational Fisheries Survey (CRFS) Angler Surveys • Red abalone CPUE within 5km of MPA • Dungeness crab CPUE within 5km of MPA • California sheephead CPUE within 5km of MPA • Lingcod CPUE within 5km of MPA • California spiny lobster CPUE within 5km of MPA	**2013 - 2020**
(B) Kelp Canopy Satellite Data • Annual Mean	**1988 - 2020**
(C) Seascapes	**2002 - 2020**
(C) EcoCAST	**2017 - 2020**
(C) California Harmful Algal Risk Mapping (C-HARM)	**2014 - 2020**

Table A3. List of all Seascape categories that have occurred in California waters during the model year range of 2002-2021. Note that because Seascapes were categorized and named using a global model for water masses of similar biochemical function, the nominal names of some Seascapes may not be particularly intuitive for a California-specific context, e.g., Seascape 12 “Subpolar”.

Seascape	Seascape Nominal Descriptor
7	Temperate Transition
11	Tropical Subtropical Upwelling
12	Subpolar
14	Temperate Blooms Upwelling
15	Tropical
17	Subtropical Transition Low Nutrient Stress
19	Arctic Subpolar Shelves
20	Subtropical Fresh Influenced Coastal
21	Warm Blooms High Nutrients
22	Arctic Late Summer
23	Freshwater Influenced Polar Subpolar Shelves
27	Hypersaline Eutrophic

Table A4. Table showing the average of annual Euclidean distance, as a measure of difference with respect to multiple environmental variables, between each listed MPA and its bioregion. North Coast, Central Coast, and South Coast variables: NPP, Turbidity, SST, Wave height, Wave power, BEUTI, CUTI; Channel Island variables: NPP, Turbidity, SST

Bioregion	MPA	Euclidean Distance
North Coast	Sea Lion Gulch SMR	3.80
North Coast	Point Reyes SMR	3.51
North Coast	MacKerricher SMCA	2.73
North Coast	Big Flat SMCA	2.73
North Coast	Point Arena SMR	2.68
North Coast	Saunders Reef SMCA	2.58
North Coast	Stewarts Point SMR	2.07
North Coast	Double Cone Rock SMCA	1.84
North Coast	Ten Mile SMR	1.79
North Coast	**NORTH COAST MPAs AVERAGE**	**2.64**
Central Coast	Vandenberg SMR	3.72
Central Coast	Point Sur SMR	3.46
Central Coast	Montara SMR	3.18
Central Coast	Pillar Point SMCA	2.75
Central Coast	Point Lobos SMR	2.40
Central Coast	Piedras Blancas SMR	2.06
Central Coast	Año Nuevo SMR	2.05
Central Coast	Big Creek SMR	2.04
Central Coast	Greyhound Rock SMCA	1.95
Central Coast	Point Buchon SMR	1.77
Central Coast	**CENTRAL COAST MPAs AVERAGE**	**2.54**
South Coast	South La Jolla SMR	3.82
South Coast	Point Conception SMR	3.10
South Coast	Swami's SMCA	2.85
South Coast	Abalone Cove SMCA	2.63
South Coast	Point Vicente SMCA (No-Take)	2.53
South Coast	Campus Point SMCA (No-Take)	2.26
South Coast	Point Dume SMCA	2.11
South Coast	Laguna Beach SMR	2.06
South Coast	**SOUTH COAST MPAs AVERAGE**	**2.67**
Channel Islands	Carrington Point SMR	3.47
Channel Islands	Judith Rock SMR	2.95
Channel Islands	Harris Point SMR	2.87
Channel Islands	Richardson Rock SMR	2.66
Channel Islands	Blue Cavern Onshore SMCA (No-Take)	2.51
Channel Islands	Santa Barbara Island SMR	2.24
Channel Islands	Scorpion SMR	2.07
Channel Islands	Anacapa Island Special Closure	1.82
Channel Islands	Anacapa Island SMCA	1.80

Channel Islands	Anacapa Island SMR	1.72
Channel Islands	South Point SMR	1.55
Channel Islands	Gull Island SMR	1.50
Channel Islands	**CHANNEL ISLANDS MPAs AVERAGE**	**2.26**

Figures

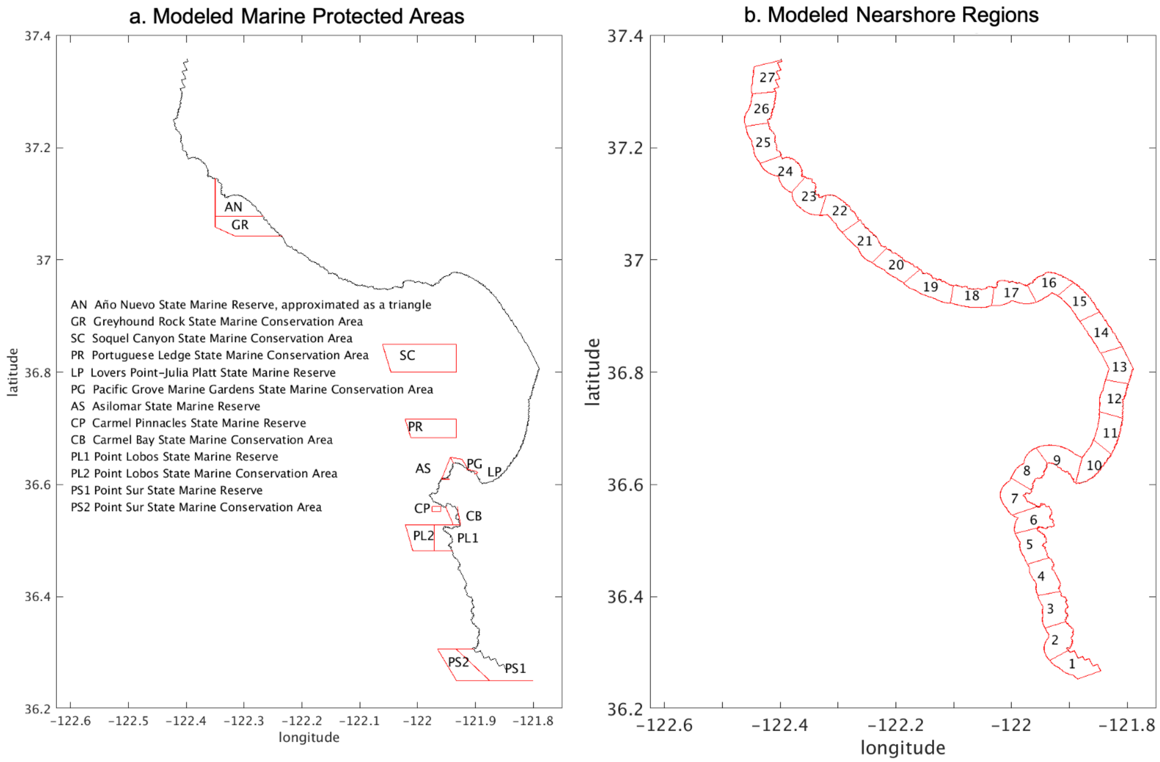


Fig. A1. Modeled release and settlement regions for larval connectivity in the greater Monterey Bay area: (a) MPAs; and (b) nearshore coastal cells, along with distinguishing notation

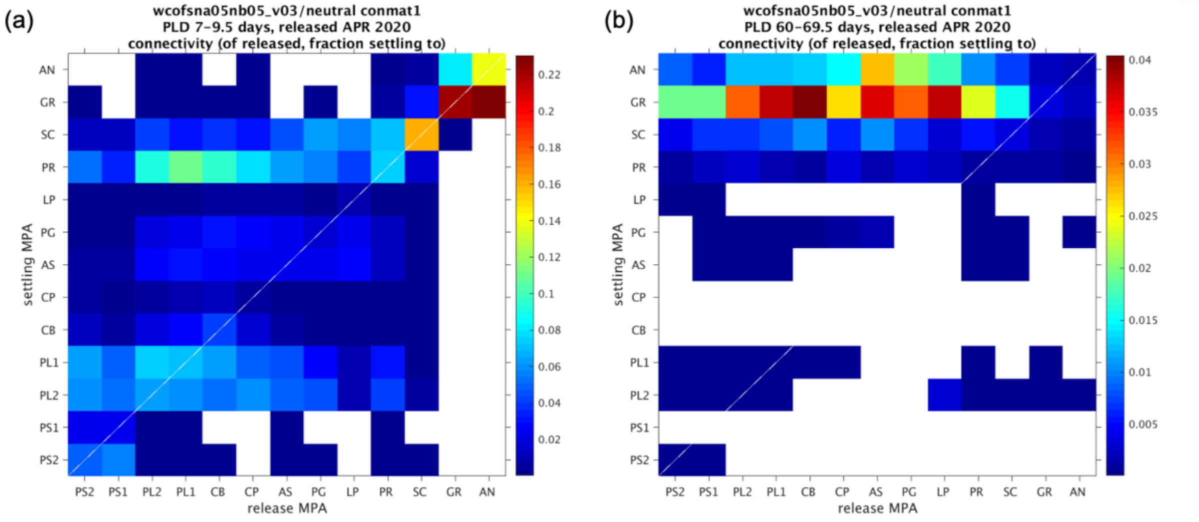


Fig A2. Connectivity matrices showing the probability that a float released from an MPA designated on the x-axis in April 2020 could potentially settle in an MPA on the y-axis, for the scenarios of neutral larval behavior and pelagic larval durations of (a) 7-9.5 days; (b) 60-69.5 days. The key for MPA initials and nearshore coastal subdomains is given in Fig. A1.

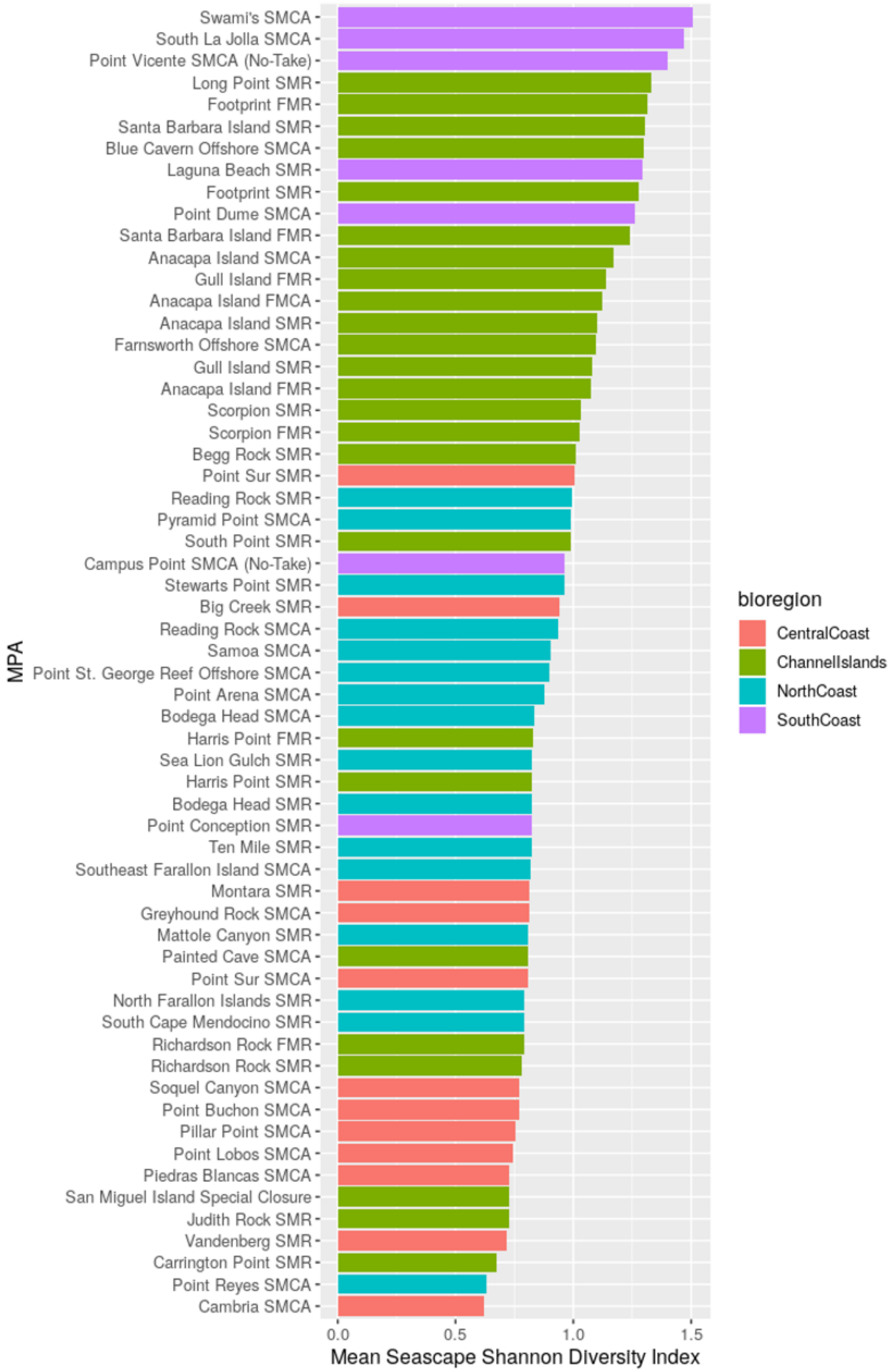


Fig. A3. Mean Shannon Diversity Indices of Seascape classes for all of Seascape data for MPAs from 2002-08-15 to 2021-02-15. Shannon Diversity Indices were calculated using monthly Seascape da

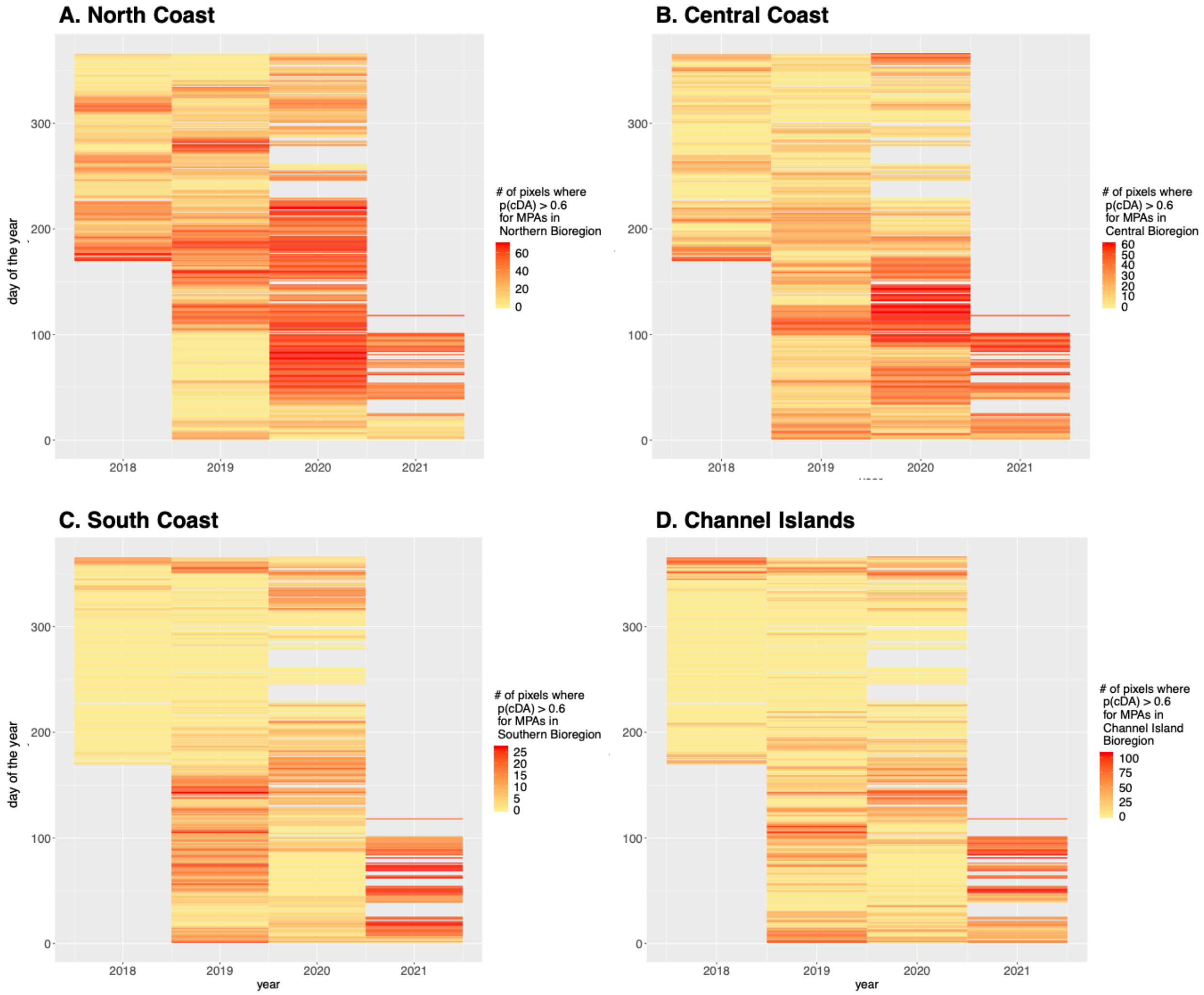


Fig. A4. Plots showing the spatial extent (number of 3 x 3 km resolution pixels) for which there was a high probability of cellular domoic acid (cDA) concentrations exceeding the threshold of 10 picograms/cell, for each day of the year from 2018-06-18 to 2021-02-10 for MPAs in each bioregion. The gray areas indicate no data.

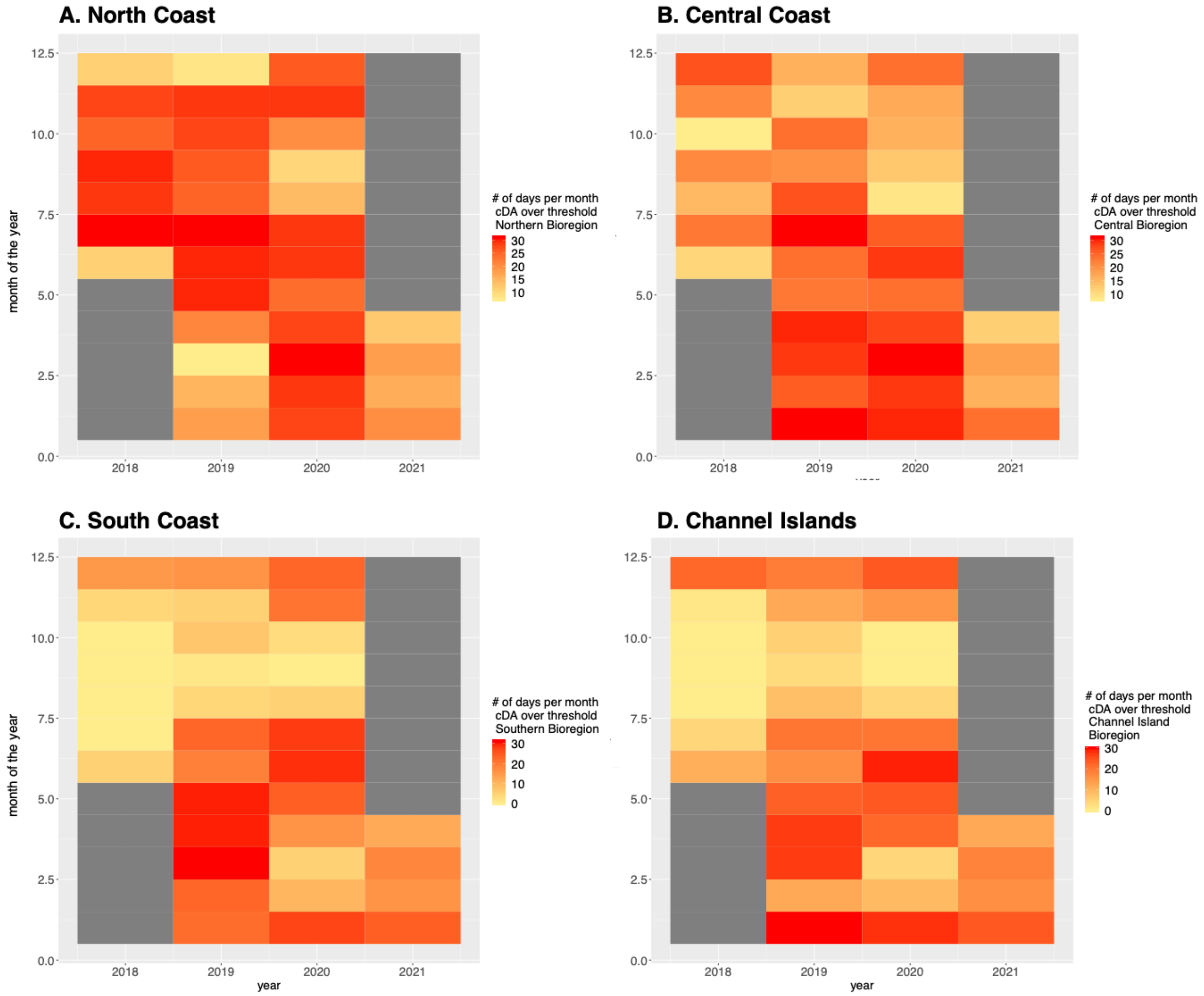


Fig. A5. Plots showing the number of days of each month from 2018-06-18 to 2021-02-10, where at least one location in the aggregated MPAs had a high (>0.6) probability of cellular domoic acid (cDA) concentrations exceeding the threshold of 10 picograms per cell.

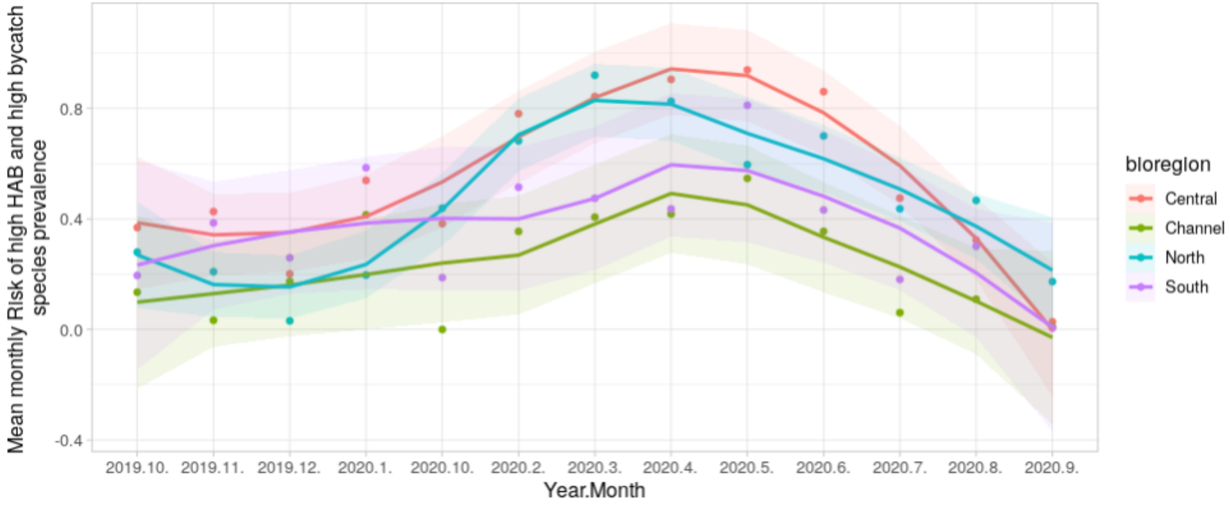


Fig. A6. Spatial overlap between high harmful algal bloom risk and high probability of vulnerable species (leatherback sea turtles, sea lions, and blue sharks) occurrence. This is expressed as the proportion of the total MPA area for each bioregion, with the shaded area representing 95% confidence intervals.

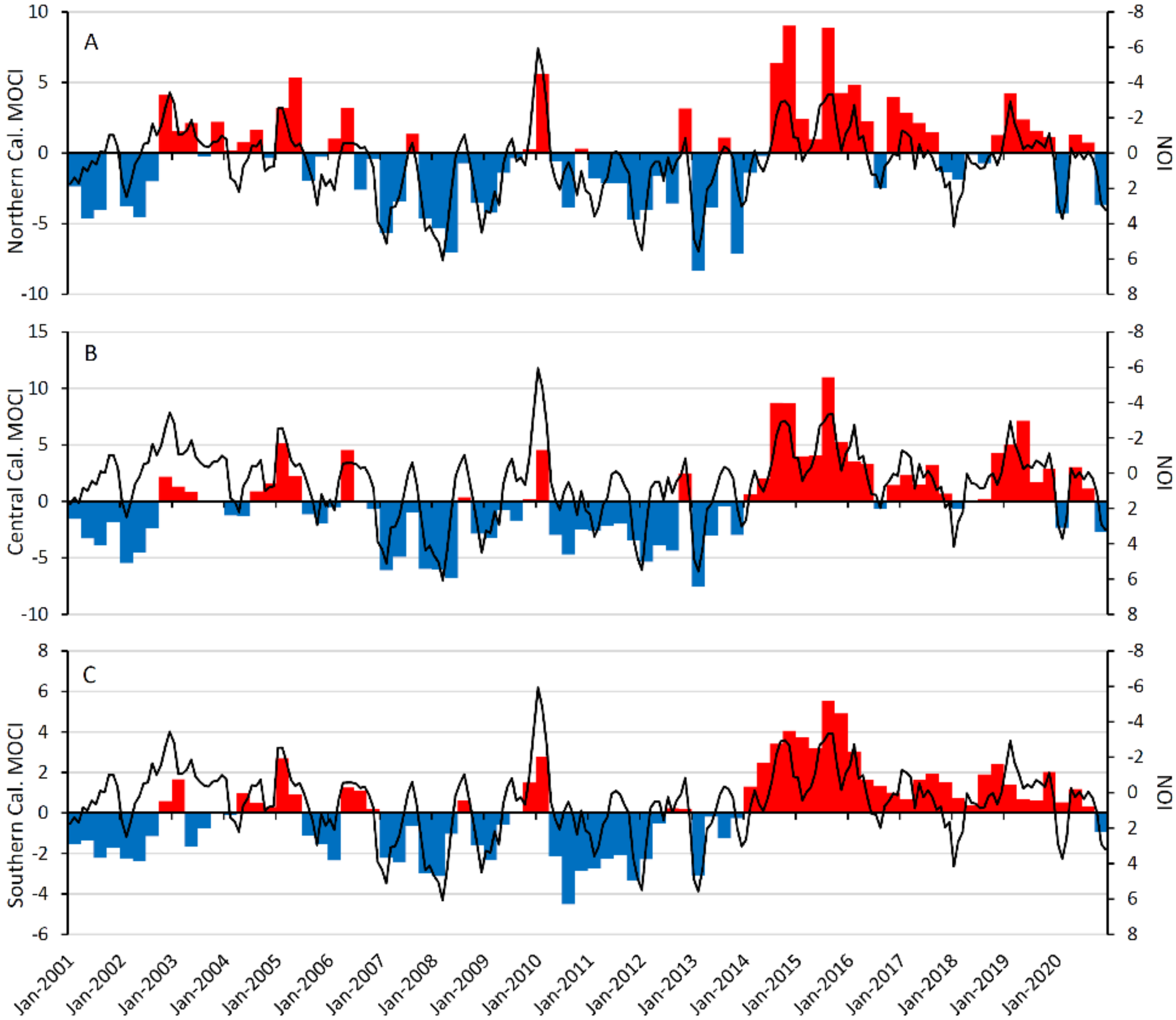


Fig. A7. Timeseries of the California Multivariate Ocean Climate Indicator (MOCI), which is calculated as seasonal values across the A) Northern (38-42°N), B) Central (34.5-38°N), and C) Southern (32-34.5°N) bioregions (red and blue bars). Also shown with each is the Northern Oscillation Index (NOI) with a 3-month seasonal running mean (black line).

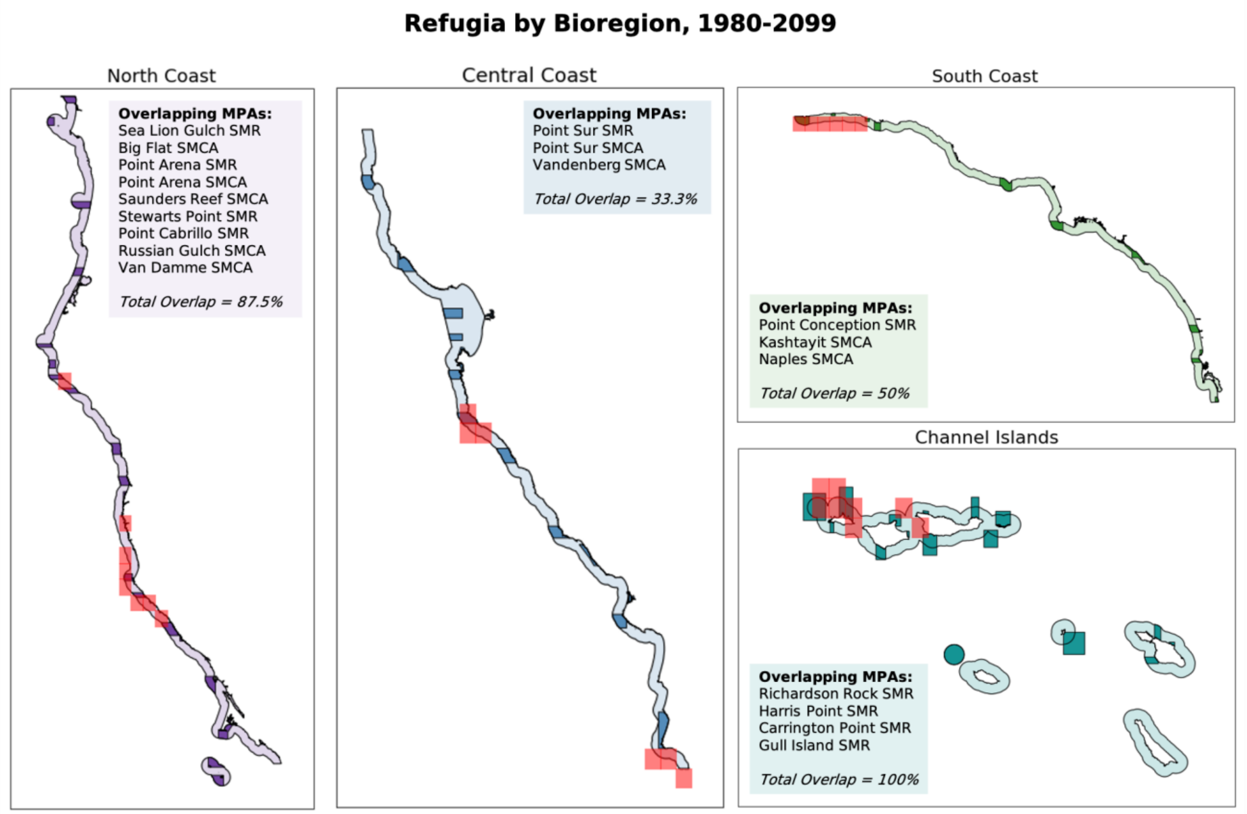


Fig. A8. Maps of California state waters for each bioregion. Potential climate refugia, i.e., areas projected to experience the least (bottom 10%) amount of change across 5 combined climate variables (Sea Surface Temperature, Chlorophyll a, Dissolved Oxygen, Buoyancy Frequency) from 1980-2099 are indicated with red pixels. Darker polygons indicate Marine Protected Areas. The inset boxes list the names of the MPAs that overlap these potential climate refugia, and the total percentage of potential refugia that overlap MPAs.