Office of National Marine Sanctuaries
National Oceanic and Atmospheric Administration

Addendum to "Climate Change Vulnerability Assessment for the North-central California Coast and Ocean"

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U.S. Department of Commerce
Gina Raimondo, Secretary

National Oceanic and Atmospheric Administration
Richard W. Spinrad, Ph.D., Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator

National Ocean Service
Nicole LeBoeuf, Assistant Administrator

Office of National Marine Sanctuaries
John Armor, Director

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Cover photo: (left) Sea Palm; (top): North-central California coastline; (bottom, center): black oystercatcher; (bottom, right): California hydrocoral

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Acknowledgements

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Glossary of Acronyms

BML: Bodega Marine Lab
CBNMS: Cordell Bank National Marine Sanctuary
CDFW: California Department of Fish and Wildlife
CSUMB: California State University, Monterey Bay
CVA: Climate Vulnerability Assessment
GFA: Greater Farallones Association
GFNMS: Greater Farallones National Marine Sanctuary
MBNMS: Monterey Bay National Marine Sanctuary
MHR: Maritime Heritage Resources
MHW: Marine Heat Wave
MLML: Moss Landing Marine Labs
NERR: National Estuarine Research Reserve
NMFS: National Marine Fisheries Service
NPS: National Park Service
NOAA: National Oceanic and Atmospheric Administration
ONMS: Office of National Marine Sanctuaries
SCCWRP: Southern California Coastal Water Research Project
UCB: University of California, Berkeley
UCD: University of California, Davis
UCSC: University of California, Santa Cruz
USFWS: United States Fish and Wildlife Service
USGS: United States Geological Survey

Executive Summary

This addendum to the report *Climate Change Vulnerability Assessment for the North-central California Coast and Ocean* (Hutto et al., 2015) provides updated information for 25 of the 40 resources assessed in 2014, and presents first-time assessments for three maritime heritage resource (MHR) categories. This addendum provides the latest climate vulnerability information for key species, habitats, ecosystem services, and MHR of the north-central California coast and ocean (Figure 1), including Greater Farallones and Cordell Bank National Marine Sanctuaries, as well as the northern portion of Monterey Bay National Marine Sanctuary (sanctuaries), and should be referenced alongside the 2015 report. Of the 40 resource assessments conducted in 2014, 35 were reviewed by subject matter experts to determine if a revision was required based on continued changing ecological conditions and improved scientific understanding since the 2015 publication. Of these, 25 were identified by experts as requiring revision, which included modifications to the vulnerability scores and new information for the narrative descriptions based on experts' current understanding of the resource's exposure to climate change, sensitivity to climate change, and/or its capacity to adapt to these changes.

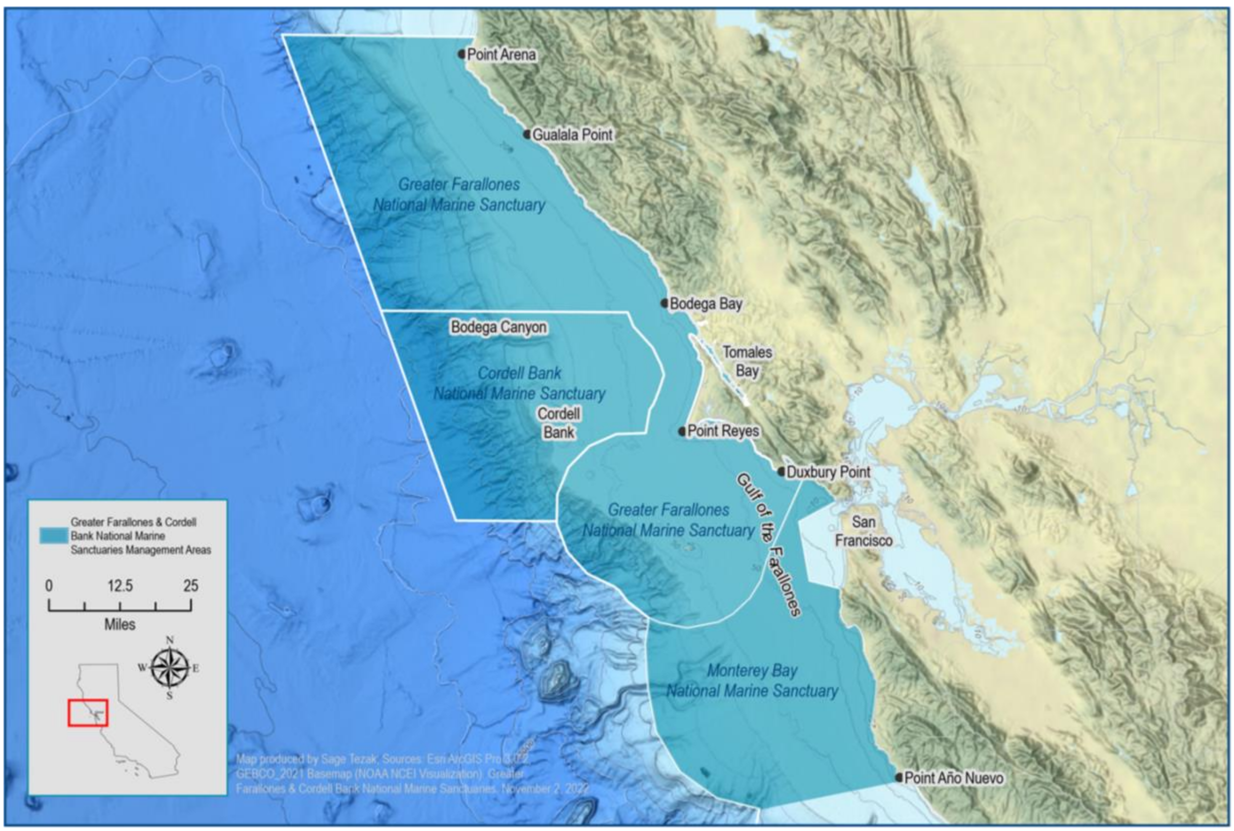

Figure 1. Map of the study region, which includes Greater Farallones and Cordell Bank National Marine Sanctuaries, as well as the northern portion of Monterey Bay National Marine Sanctuary.

These revisions resulted in increased vulnerability scores for 17 species and six habitats, and decreased vulnerability scores for one species group and two ecosystem services. One species assessment was modified and corrected, but no changes were made to its score. The primary driving factor for increased vulnerability is increased exposure and sensitivity to elevated water temperatures due to the increasing frequency and severity of marine heatwaves (MHW). The sanctuaries experienced profound and severe impacts to species abundance and health, community composition, and ecosystem function from the 2014-2016 MHW and subsequent MHW events (Auth et al., 2018; Elliott et al., 2022; Rogers-Bennett and Catton, 2019; Sanford et al., 2019), and models suggest MHWs will become more frequent and severe in a changing climate (Frölicher et al., 2018). Of these revisions, which on average resulted in a two-point increase to vulnerability, a few resources in particular stand out as having high increases in vulnerability to climate change since the 2015 report, including approximately a three-point increase for rocky intertidal habitat, red abalone, blue whale, pteropod and krill species, and over a four-point increase for kelp forest habitat. Some of these increases in vulnerability are due, in part, to a methodological change that increased the contribution of exposure to the vulnerability score. Though the most vulnerable resources are still largely those in coastal areas, offshore oceanographic processes and drivers of change are now a much greater relative concern. The 2014-2016 MHW had unprecedented impacts on nearly all resources in the sanctuaries; it is clear that sea surface temperature, driven both by discrete events like El Niño and other MHW events, as well as persistent ocean warming, will be an ongoing concern and stressor on sanctuary health and resilience, and impacts to resources from this stressor must be prioritized to ensure ecological function persists across all habitats.

Figure 2. Bull kelp forest received the greatest increase in vulnerability. Photo: NOAA

Three tangible MHR categories—doghole ports, nearshore shipwrecks and offshore shipwrecks—were also assessed. These resources were not included in the 2014 assessment and, as such, a full assessment was conducted and is presented separately from the other resources described in this addendum, on pages 67-85. The potential impact of climate change, which for MHR is defined only as the exposure and sensitivity to climate and non-climate stressors, was rated as high for both nearshore shipwrecks and doghole ports, and low for offshore shipwrecks.

Methods

From June 2022 to February 2023, Office of National Marine Sanctuary staff initiated an expedited but thorough update of the 2015 report (Hutto et al., 2015). First, a single subject-matter expert (Appendix 1) was identified for 35 of the original 40 resources in the 2015 report and was asked to complete a revision survey. Five of the 40 original assessments were not surveyed and are thus excluded from this addendum, either because the expertise to do so was not available (ecosystem service assessments of food production, water quality and recreation and tourism) or because the resource was outside sanctuaries' management area and authority (gaper clam and American dune grass, included in the 2015 assessment at the request of National Parks Service). For the remaining 35 assessments, subject-matter experts were asked to: 1) review the 2015 assessment, updated climate trends for the region (Appendix 2), information that was compiled for the draft condition reports for GFNMS for the years 2010-2022 and CBNMS for the years 2009-2021, and 2) complete a survey (Appendix 3) indicating whether revisions are needed in light of any new information since the assessments were conducted in 2014. Based on the survey results, it was determined that 10 of the assessments remained accurate and did not need an update: beach/dune habitat, cliff habitat, black oystercatcher, black rail, cavity-nesting birds, copepods, mole crab, surface-nesting birds, tidewater goby, widow rockfish. For the 25 assessments that did require an update, extensive literature review and expert elicitation (via email and phone conversations) were conducted to draft revision summaries, which included proposed changes to the original vulnerability scores[1], using the below equation, confidence in those scores, and narrative justification.

Vulnerability = (Exposure + Sensitivity) - Adaptive Capacity

Based on the score revisions, new categorical ratings (very low, low, moderate, high, very high) were assigned when the revision resulted in the score falling into a different rating category than in the previous assessment. Each draft revision summary was then distributed to two to three additional experts, termed reviewers (Appendix 1), for review and further modification. Following this review period, a vulnerability revision workshop was held with 24 regional experts to review and confirm the revisions, and incorporate any additional information, for each of the 25 revised assessments.

In addition to the score revisions based on this expert input, a methodological revision was also applied to the 35 surveyed resource assessments to remove the half-weighting previously assigned to the exposure score. In the 2015 report, exposure was weighted 50% less than sensitivity and adaptive capacity because of the uncertainty and variability that was observed at the time in the climate projections for the region. However, in 2023, experts agreed that confidence in climate models increased sufficiently to apply equal weighting to exposure, sensitivity, and adaptive capacity. Comparing the original 2015 scores (exposure half-weighted) to the new 2023 scores (exposure fully weighted) resulted in an across-the-board increase in vulnerability in 2023, which over-inflates the actual increases in vulnerability. Therefore, the

[1] For information on the vulnerability assessment model and scoring methodology, reference pages 17-26 of the 2015 Climate Vulnerability Assessment Report: https://sanctuaries.noaa.gov/science/conservation/vulnerability-assessment-gfnms.html

2015 scores were adjusted using the 2023 formula (removing the half-weighting for exposure) to allow for a more direct comparison of resources' vulnerabilities in 2015 vs. 2023. This removed large increases in vulnerability that were a result of methodological modifications alone (e.g., pteropod, krill) and retained those that were a result of actual changes in the understanding of resource climate vulnerability (e.g., kelp, red abalone; see Appendix 4 for original and adjusted scores for all 40 original resource assessments).

Results and Discussion

Habitats

Figure 3. Beaches and dunes in the study region ranked as the most vulnerable habitat. Photo: NOAA.

Of the eight habitats assessed, the ranking of the three most vulnerable habitats (Table 1) have not changed since 2015. Beaches and dunes still have the highest vulnerability score, followed by estuaries, then rocky intertidal. However, kelp forest habitat went from the lowest vulnerability score (eight out of eight) in the 2015 assessment to the fourth most vulnerable in this revision. The significant increase in the climate vulnerability score of bull kelp as the primary canopy-forming species in the sanctuary represents the most significant and unexpected change in our understanding of climate vulnerability since 2015, and exemplifies how much our understanding of a resource's vulnerability can change as novel ecological conditions arise. During the 2014 vulnerability workshop, kelp ecologists and phycologists agreed that kelp is highly resilient and well adapted to oceanographic variability and large swings in its relative abundance. While this assessment was accurate based on the best available scientific information at the time, the severe and unprecedented decline and persistent lack of recruitment since 2014 changed the scientific community's perception of kelp's vulnerability, which is reflected in these results. This exemplifies the difficulty facing marine resource managers under increasingly uncertain and unprecedented climatological conditions. The other major change in habitat vulnerability rankings is that cliffs were ranked as the fourth most vulnerable in 2015 and are now ranked as the least vulnerable in 2023; this is largely due to the vulnerability scores for nearshore, pelagic, and offshore habitats increasing more than that of cliff habitat, due in part to the 2014-2016 MHW, and does not indicate that cliffs are perceived to be any less vulnerable to climate change than they were in 2015.

Table 1. The calculated scores, rounded to the nearest tenth, for overall vulnerability, sensitivity, exposure, and adaptive capacity for the eight habitats surveyed, ordered by decreasing vulnerability score.

Habitats	Overall Vulnerability	Sensitivity	Exposure	Adaptive Capacity
Beaches and Dunes	5.3 High	3.9 High	4.5 Very High	3.1 Moderate
Estuaries	5.0 High	4.1 High	4.6 Very High	3.6 High
Rocky Intertidal	4.7 High	4.0 High	4.2 High	3.5 High
Kelp Forest	4.7 High	4.1 High	3.9 High	3.3 Moderate
Nearshore	3.7 Moderate	2.9 Moderate	4.2 High	3.3 Moderate
Pelagic Water Column	3.2 Moderate	2.7 Moderate	4.1 High	3.7 High
Offshore Rocky Reefs	2.9 Moderate	2.5 Low	3.0 Moderate	2.7 Moderate
Cliffs	2.6 Moderate	3.2 Moderate	2.3 Low	2.8 Moderate

Species

Figure 4. Pteropods, black oystercatchers, and Western snowy plovers now rank as the 3 most vulnerable species in the study region. Photos: NOAA

Nearly all species vulnerability scores increased since the 2015 assessment, with the exception of the California hydrocoral and white-lobed sponge (assessed together), which declined negligibly due to a very slight decrease in the sensitivity score. The greatest increase in vulnerability score was for red abalone, which went from being ranked as the 11th most vulnerable species to the fifth most vulnerable due to impacts from the MHW and subsequent loss of kelp. Other significant increases in vulnerability scores within the top 10 species are due both to increases in sensitivity scores, as well as the increased weighting of exposure (see Methods), and includes pteropod (from third to most vulnerable), blue whale (from eighth to fifth), Olympia oyster (from 10th to seventh), and copepod (from 17th to 10th). When compared with the original 2015 assessment scores, all 28 species vulnerability scores increased, and though some vulnerability score increases are due to the methodological change of removing the half-weighting for exposure, this is still a notable outcome of this revision as it reflects our understanding of the increasing importance of and confidence in exposure to climate stressors for a resource's climate vulnerability.

Table 2. The calculated scores, rounded to the nearest tenth, for overall vulnerability, sensitivity, exposure, and adaptive capacity for the twenty-eight species surveyed, ordered by decreasing vulnerability score.

Species	Overall Vulnerability	Sensitivity	Exposure	Adaptive Capacity
Pteropod	6.4 High	4.0 High	5.0 Very High	2.6 Low
Black oystercatcher	6.3 High	4.6 Very High	4.6 Very High	2.9 Moderate
Western snowy plover	5.5 High	4.0 High	4.3 Very High	2.8 Moderate
Blue whale	5.3 High	4.1 High	5.0 Very High	3.8 High
Red abalone	5.2 High	3.8 High	3.8 High	2.4 Low
Sea palm	5.0 High	3.6 High	4.0 High	2.7 Moderate
Olympia oyster	4.5 High	3.2 Moderate	4.3 Very High	2.9 Moderate
Black rail	4.3 High	3.8 High	2.5 Low	2.0 Low
Ashy storm petrel	4.1 Moderate	3.4 Moderate	2.5 Low	1.8 Very Low
Copepod	4.1 Moderate	2.0 Low	5.0 Very High	2.9 Moderate
Southern sea otter	4.1 Moderate	2.9 Moderate	3.6 High	2.5 Low
Cassin’s auklet	4.0 Moderate	3.5 High	3.4 Moderate	2.9 Moderate
Tidewater goby	4.0 Moderate	3.0 Moderate	3.0 Moderate	2.0 Low
Pacific herring	3.9 Moderate	2.8 Moderate	4.0 High	2.9 Moderate
California mussel	3.9 Moderate	3.3 Moderate	4.1 High	3.5 High
Ochre sea star	3.7 Moderate	3.0 Moderate	4.1 High	3.3 Moderate
Pacific sardine	3.5 Moderate	3.2 Moderate	3.7 High	3.4 Moderate
Mole crab	3.4 Moderate	2.0 Moderate	4.8 Very High	3.4 Moderate
Red urchin	3.3 Moderate	3.6 High	3.2 Moderate	3.5 High
Coralline algae	3.3 Moderate	2.9 Moderate	3.0 Moderate	2.6 Low
Purple urchin	3.2 Moderate	3.6 High	3.2 Moderate	3.5 High
Brandt’s cormorant, Common murre	3.1 Moderate	3.5 High	2.6 Low	3.0 Moderate
California hydrocoral, White lobe sponge	3.1 Moderate	3.1 Moderate	3.1 Moderate	3.2 Moderate
Northern anchovy	2.9 Moderate	2.9 Moderate	3.6 High	3.5 High
Krill	2.8 Moderate	1.8 Very Low	5.0 Very High	4.0 High
Pigeon Guillemot, Tufted puffin	2.8 Moderate	3.4 Moderate	2.5 Low	3.2 Moderate
Widow rockfish	2.7 Moderate	3.0 Moderate	3.2 Moderate	3.5 High
Blue rockfish	2.1 Moderate	3.0 Moderate	2.8 Moderate	3.7 High

Ecosystem Services

Figure 5. Tidal marsh, pictured here in Bolinas Lagoon, provides carbon storage and sequestration and flood and erosion protection services, both of which are considered highly vulnerable to climate change. Photo: NOAA.

Only two of the five ecosystem services from the 2015 report were included in this assessment, and both saw a slight decrease in vulnerability scores when compared with adjusted 2015 scores (Table 3). This decrease is driven by higher scores for adaptive capacity based on new understanding of how valued these services are to people and people's willingness to change their behavior to protect and maintain these services. However, this score change is negligible, and both ecosystem services remain rated as having high vulnerability.

Table 3. The calculated scores, rounded to the nearest tenth, for overall vulnerability, sensitivity, exposure and adaptive capacity for the two ecosystem services surveyed, ordered by decreasing vulnerability.

Ecosystem services	Overall Vulnerability	Sensitivity	Exposure	Adaptive Capacity
Flood and erosion protection	5.6 High	4.8 Very High	5.0 Very High	4.3 Very High
Carbon storage and sequestration	5.5 High	3.5 High	5.0 Very High	3.0 Moderate

Components of Vulnerability

To illustrate differences in the component scores (sensitivity, exposure, adaptive capacity), and the impact those differences have on the overall vulnerability scores, resources were grouped by high sensitivity scores, high exposure scores, and low adaptive capacity scores (Figure 6, Foden et al., 2013). This illustrates which resources are vulnerable because they are highly sensitive (a score >3.41, e.g. Brandt's cormorant), highly exposed (a score >3.41, e.g. California mussel), or non-adaptive (a score <3.0, e.g. Ashy storm petrel), which can better inform subsequent adaptation or management measures. Some resources have a combination of these characteristics, such as black rail, which is both highly sensitive and non-adaptive; these species are projected to have low to moderate future exposure to climate stressors and therefore may not currently be at risk but have high latent risk. Other focal resources, such as copepods, are highly exposed and non-adaptive, but not highly sensitive, and therefore characterized as "potential persisters" and may not be at risk. Resources such as the ecosystem services of flood and erosion protection and carbon storage and sequestration are highly sensitive and highly exposed, but have moderate to high adaptive capacity and are characterized as "potential adapters". Finally, resources that have a combination of high sensitivity, high exposure, and are non-adaptive are the most vulnerable resources—black oystercatcher, pteropod, red abalone, sea palm, and Western snowy plover. These resources are also in the top 10 most vulnerable species, and should be prioritized for management action. Resources whose scores do not qualify for any portion of the Venn diagram (Figure 6) may be considered "not currently at risk;" that includes blue and widow rockfish, hydrocoral and sponge, pigeon guillemot and tufted puffin.

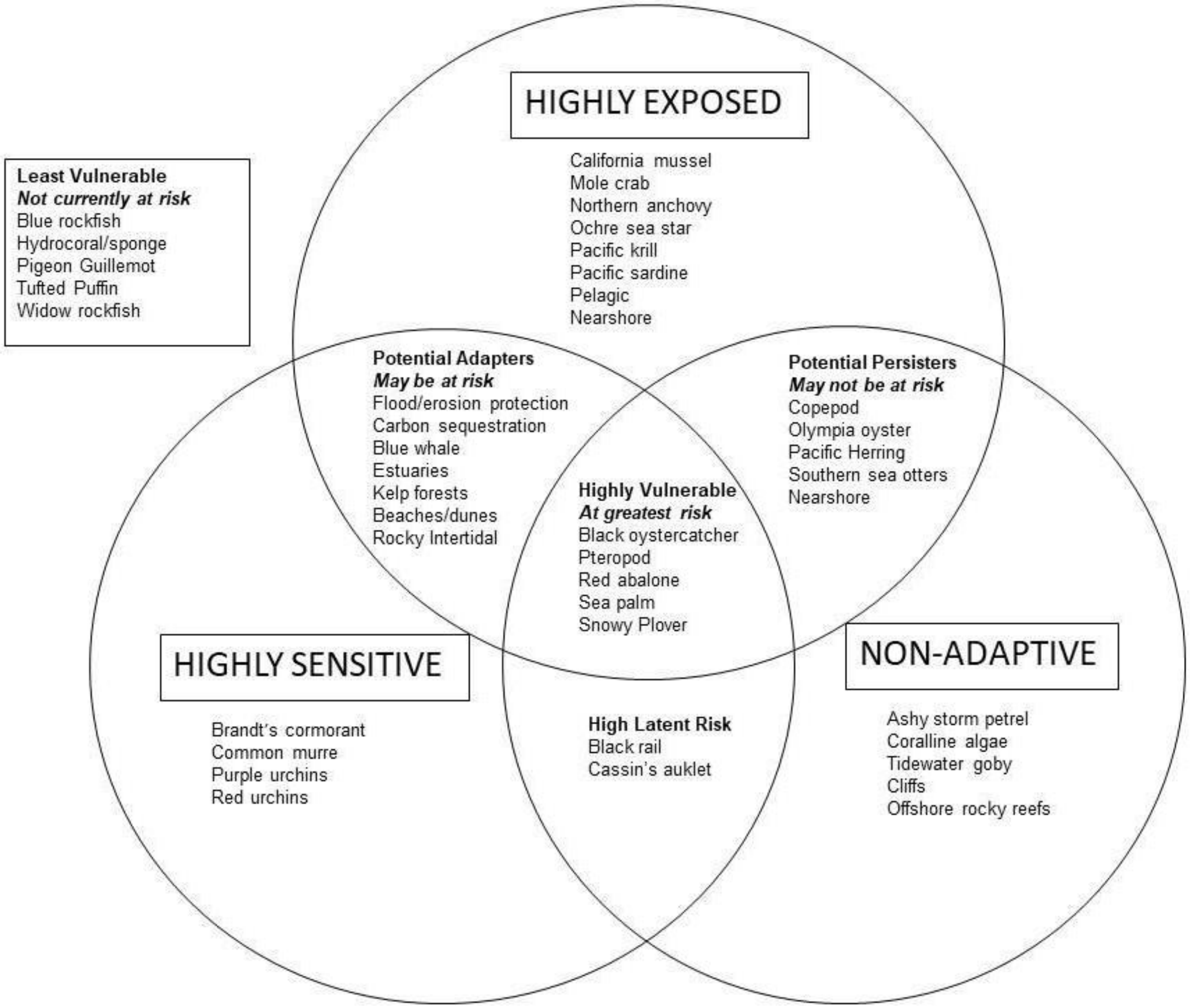

Figure 6. Venn diagram (Foden et al., 2013) of all 35 resources, organized by component vulnerability scores.

Drivers of Vulnerability

In analyzing the primary climate and non-climate stressors that contribute to resource sensitivity (Tables 4,5), it is clear that sea surface temperature and ocean conditions (currents, mixing, and stratification) are greater concerns than they were in 2015. These two climate stressors are currently ranked second (SST) and fourth (ocean conditions) for their average sensitivity score across all resources; in 2015, these stressors were ranked ninth and seventh, respectively. Other changes in the relative importance of individual climate stressors include increased sensitivity scores for pH, dissolved oxygen, coastal erosion, sea level rise, and air temperature, and slightly decreased sensitivity scores for salinity and wave action based on new information on how habitats and species are impacted by these stressors. In 2015 the top three climate stressors for resource sensitivity were 1) storm severity and frequency, 2) coastal erosion, and 3) wave action, and in 2023 the top three climate stressors are 1) storm severity and frequency, 2) sea surface temperature, and 3) coastal erosion. It is worth noting that sea surface temperature has the highest average sensitivity score for the greatest number of resources (n=27). The leading non-climate stressors driving resource vulnerability have not changed significantly since 2015; roads/armoring, invasive species, and aircraft/vessels still hold the top three spots. There were very few changes to the non-climate average sensitivity scores, with increases to land use change and harvest and a very slight increase to pollution/poisons.

Table 4. Climate stressors, listed by decreasing revised average sensitivity score for those species and habitats that identified the stressor as a sensitivity. The change in score from 2015 is noted.

Climate stressor	**Number of resources**	**2023 average sensitivity score**	**Change from 2015 score**
Storm severity/frequency	6	4.67	0.00
Sea surface temperature	27	3.71	+0.67
Coastal erosion	24	3.45	+0.20
Currents/mixing/stratification	29	3.39	+0.25
Wave action	22	3.32	-0.18
pH	30	3.31	+0.11
Oxygen	24	3.19	+0.11
Salinity	26	3.19	-0.04
Sedimentation	4	3.17	0.00
Sea level rise	18	3.13	+0.19
Air temperature	21	3.05	+0.24
Precipitation	26	2.64	+0.10

Table 5. Non-climate stressors, listed by decreasing revised average sensitivity score for those species and habitats that identified the stressor as a sensitivity. The change in score from 2015 is noted.

Non-climate stressor	Number of resources	2023 average sensitivity score	Change from 2015 score
Roads/armoring	8	3.88	0.00
Invasive & other problematic species	17	3.73	-0.05
Aircraft/vessels	3	3.67	0.00
Land use change	14	3.57	+0.24
Recreation	13	3.54	0.00
Pollution and poisons	31	3.48	+0.05
Harvest	20	3.33	+0.26
Overwater/underwater structures	4	3.25	0.00
Energy production	6	2.00	0.00

Conclusions and Next Steps

This climate vulnerability revision generated two major findings. First, while the most vulnerable resources are still largely in the coastal region, offshore oceanographic processes and drivers of change are now a much greater concern, relative to 2015, for species in both offshore and coastal habitats. This is reflected in this revision via increased vulnerability scores for pelagic and offshore species (e.g. pteropod), and the increased sensitivity scores, averaged across all resources, for sea surface temperature and dynamic ocean conditions (currents/mixing/stratification). The second major finding is that the 2014-2016 and subsequent MHWs had unprecedented impacts that reached from the rocky intertidal (Sanford et al., 2019) and kelp forests (Lonhart et al., 2019; Rogers-Bennet and Catton, 2019) to the offshore environments in the sanctuaries (Elliott et al., 2022). Very few resources were not impacted by the MHWs, and in particular, kelp forest-associated species were adversely affected. It is clear that sea surface temperature, driven both by discrete events like El Niño and other MHW events as well as persistent ocean warming, will be an ongoing physical stressor on sanctuary health and resilience and a primary management concern. Impacts to resources from this stressor must be prioritized to ensure ecological function persists across all habitats.

Moving forward, the sanctuaries should incorporate this information into a thorough update of the 2016 Climate Adaptation Plan (Hutto, 2016), and highlight the increased urgency of addressing warming ocean waters in the current Management Plan Review process. Ideally, in the next Management Plan, the sanctuaries will develop climate adaptation strategies and actions that target the key vulnerabilities identified in this addendum to ensure sanctuary resources can persist and thrive into the future. Uncertainties persist regarding the timing and severity of change, but continued long-term monitoring of climate indicators through sanctuary efforts, such as the Applied California Current Ecosystem Studies project and the Beach Watch project, will contribute to documentation of both climate and non-climate stressors and their impacts. Monitoring projects such as these, and those that are conducted by partners and external agencies, are increasingly critical to provide the foundational information that informs these assessments. We recommend that the sanctuaries continue to invest in monitoring indicators of change, and plan to conduct a completely new Climate Vulnerability Assessment by the year 2035, or just prior to the Sanctuaries' next management plan review process.

Revision Summaries

The following section presents CVA revision summaries for the 25 resources whose scores were revised. The remaining 15 original summaries can be viewed in the original report[2]. Summaries are listed in alphabetical order within resource categories, with habitat summaries presented first, followed by species, and then ecosystem services. Three summaries combine information for multiple species due to the similarities in most aspects of vulnerability: Northern anchovy and Pacific sardine, purple and red urchins, and California hydrocoral and white-lobed sponge. Each summary includes the reference pages for the original 2015 vulnerability assessment report (Hutto et al., 2015), which should be reviewed alongside this addendum.

Each individual revision summary is formatted in the same manner, with an introductory statement providing brief context for the revision, followed by score tables that present the revised scores and category descriptors for each component of vulnerability, the confidence in the revised scores, and the numerical change in the scores from the 2015 assessment. Note that the change is calculated using adjusted 2015 scores based on the methodological revision of removing the reduced exposure weighting (see Methods). Following the score tables, the details of the revisions are provided, including justification with relevant references from the literature and/or expert opinion. Finally, corrections to the 2015 assessment that did not change any scores are provided. Literature cited is included for each individual revision summary, for easy reference. The resulting revisions represent an evaluation of vulnerability scores based on existing scientific information and expert input. These revisions are intended to help sanctuary management develop and prioritize adaptation strategies to conserve these resources in the face of climate change, and are intended to be living documents that can be revised and expanded upon as new information becomes available.

[2] https://sanctuaries.noaa.gov/science/conservation/vulnerability-assessment-gfnms.html

Habitats

Estuaries

**reference pages 56-63 of the 2015 Assessment Report (Hutto et al., 2015)

Dissolved oxygen was underestimated in the 2015 assessment as a significant stressor for estuaries; slight revisions and corrections were made for this assessment.

Estuaries	Revised Score	Confidence	Change
Sensitivity	4.1 High	High	+0.04
Exposure	4.6 Very High	High	+0.2
Adaptive Capacity	3.6 High	High	-
Vulnerability	5.0 High	High	+0.3

Sensitivity: One score revised. Very slight increase in sensitivity score.

1. Dissolved oxygen: Increased from 3 (moderate) to 5 (very high) as dissolved oxygen is a significant and increasing threat in estuaries, especially as temperature increases (E. D. Grosholz/UCD, personal communication, September 30, 2022). The duration and severity of hypoxia were negatively correlated with fish survival and oyster growth, with lethal and sub-lethal effects even on stress-tolerant organisms in the estuary (Jeppeson et al., 2015)

Exposure: One score revised. Slight increase in exposure score.

1. Reduced dissolved oxygen: Increased from 3 (moderate) to 5 (very high); exposure to this stressor is expected to increase with increasing water temperature in estuaries (E. D. Grosholz/UCD, personal communication, September 30, 2022).

Corrections to 2015 CVA Summary:
Invasive species (page 59): Invasive species both out-compete *and consume* native species and decrease native species diversity and abundance. Consumption of native species is likely to have a more significant impact due to invasive species, such as the European green crab and the eastern oyster drill, *Urosalpinx cinerea*.

References:

- Jeppeson, R., Rodriguez, M., Rinde, J., Haskins, J., Hughes, B., Mehner, L., & Wasson, K. (2016). Effects of Hypoxia on Fish Survival and Oyster Growth in a Highly Eutrophic Estuary. *Estuaries and Coasts*, *41*, 89-98. DOI: 10.1007/s12237-016-0169-y

Kelp Forest

**reference pages 64-71 of the 2015 Assessment Report (Hutto et al., 2015)

Beginning in 2013, the nearshore area of the northern California coastline underwent a drastic loss (>90%) of kelp forest habitat due to a prolonged MHW compounded by a strong El Niño, loss of important urchin predators, and a boom in urchin (kelp grazer) populations (Rogers-Bennett and Catton, 2019). The scale of this kelp loss is unprecedented based on 35 years of Landsat data, and has resulted in the formation of a persistent urchin barren ecosystem state (McPherson et al., 2021), with little to no recovery of kelp in the region as of 2022 (R. Hohman/GFA, personal communication, October 19, 2022). Significant revisions to the 2015 assessment are warranted, both because of new information but also because of incorrect initial ratings.

Kelp forest	Revised Score	Confidence	Change
Sensitivity	4.1 High	High	+1.2
Exposure	3.9 Mod	High	+1.3
Adaptive Capacity	3.3 Mod	High	-0.6
Vulnerability	4.7 High	High	+3.1

Sensitivity[3]: Four scores revised, two scores added, five scores removed. Large increase in sensitivity score and overall rating increased to high.

1. Sea surface temperature: Increased from 4 (high) to 5 (very high) due to documented cascading impacts of the MHW, including ecosystem transition and subsequent severe loss of kelp as both habitat and food (Rogers-Bennett and Catton, 2019; McPherson et al., 2021; Rogers-Bennett and Catton, 2022).
2. Salinity and oxygen: Decreased from 5 (very high) to 3 (moderate), as these are not critical, driving stressors for kelp.
3. Turbidity: Added as 4 (high), as this is a known stressor for kelp recruitment (e.g., Devinny and Volse, 1978; Watanabe et al., 2016), growth and resilience (Tait, 2019), and productivity (Blain et al., 2021). In addition, Kiest (1993) documented kelp forest community consequences due to landslides and sediment deposition and transport.
4. Disturbance regimes:
   . Sensitivity to disease increased from 2 (low) to 4 (high) due to indirect impact of seastar wasting (over-grazing from urchins that were released from predation, which may have led to the transition to urchin barrens)
   a. Sensitivity to MHW added as a 5 (very high)
5. Sensitivity and current exposure to harvest were removed from the overall sensitivity score, as there is currently in place a temporary (2023-2026) closure of commercial harvest of bull kelp and recreational harvest is presumed to be negligible (not reported).

[3] The original sensitivity scoring included very low scores for stressors that are likely not a driver of change for kelp forests (i.e. sea level rise, air temperature) or whose impacts were redundant with other stressors (i.e. coastal erosion with turbidity, precipitation with salinity). These scores were either artificially reducing the overall sensitivity score or were emphasizing the impact of some stressors, and have been removed from the final average to ensure a more representative final rating of climate sensitivity for kelp forests.

Exposure[4]: Two scores revised, one score added, five scores removed. Large increase in exposure score and overall rating increased to high.

1. Sea surface temperature: Changed from 1 (very low) to 4 (high) based on 2014-2016 MHW (and subsequent heatwave events), and projections that MHWs will increase in severity and frequency (Frölicher et al., 2018).
2. Changes in salinity increased from 1 (very low) to 3 (moderate) due to projections of increased precipitation variability (Swain et al., 2018) and extreme precipitation events (Huang and Swain, 2022).
3. Turbidity added: 4 (high) due to projected increase in the severity of precipitation events (Huang and Swain, 2022), resulting impacts to coastal erosion, and storm-driven waves.

Adaptive capacity: Three scores revised. Decrease in adaptive capacity score and overall rating decreased to moderate.

1. Structural and functional integrity: Decreased from 4 (near pristine) to 1 (degraded) due to 90% loss that occurred in 2014 (Rogers-Bennett and Catton, 2019), and the little to no recovery documented since that time (R. Hohman/GFA, personal communication, October 19, 2022). This has led to degradation of the commercial urchin and recreational abalone fisheries, as well as cascading social impacts to local users of sanctuary resources.
2. Habitat recovery: Decreased from 4 (high) to 2 (low); since bull kelp has an annual life history and little is known about the persistence of spores, populations exhibit little adaptive capacity and recovery is inhibited by high rates of herbivory by purple urchins, which can persist at high densities for many years despite limited food availability (Dudley et al., 2021)
3. Functional group diversity: Decreased from 5 (very high) to 3 (moderate) because the kelp forest habitat in the sanctuary is completely reliant on a single canopy-forming algal species, bull kelp, which has been severely impacted by MHW and urchin grazing. Historically (pre-decline), there was relatively high diversity in invertebrates, fish, and important understory kelp species, and there are indications that these groups have also declined (R. Hohman/GFA, personal communication, October 19, 2022).

References

- Blain, C. O., Hansen, S. C., & Shears, N. T. (2021). Coastal darkening substantially limits the contribution of kelp to coastal carbon cycles. *Global Change Biology*, *27,* 5547–5563. DOI: 10.1111/gcb.15837.
- Devinny, J. S., & Volse, L. A. (1978). Effects of Sediments on the Development of *Macrocystis Pyrifera* Gametophytes. *Marine Biology, 48*, 343–348. DOI: 10.1007/BF00391638.
- Dudley, P. N., Rogers, T. L., Morales, M. M., Stoltz, A. D., Sheridan, C. J., Beulke, A. K., Pomeroy, C., & Carr, M. H. (2021). A more comprehensive climate vulnerability assessment framework for fisheries social-ecological systems. *Frontiers in Marine Science*, *8*, 678099. DOI: 10.3389/fmars.2021.678099
- Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine Heatwaves Under Global Warming. *Nature*, *560*, 360–364. DOI: 10.1038/s41586-018-0383-9

[4] The original exposure scoring included scores for stressors that are likely not a driver of change for kelp forests (i.e. sea level rise) or whose impacts were redundant with other stressors (i.e. El Niño with increased SST, precipitation with salinity, coastal erosion with turbidity). These scores were either artificially reducing the overall exposure score or were emphasizing the impact of some stressors, and have been removed from the final average to ensure a more representative final rating of climate exposure for kelp forests.

- Huang, X., & Swain, D. L. (2022). Climate change is increasing the risk of a California megaflood. *Science Advances*, *8*, eabq0995. DOI:10.1126/sciadv.abq0995
- Kiest, K. (1993). *The influence of sediment from landslide plumes on sessile kelp forest assemblages* (Order No. 1354149) [Masters thesis, San Jose State University].ProQuest Dissertations Publishing.
- Rogers-Bennett, L. & Catton, C. A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, *9*, 15050. DOI: 10.1038/s41598-019-51114-y
- Swain, D. L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change 8*, 427–433. DOI: 10.1038/s41558-018-0140-y
- Tait, L. W. (2019). Giant kelp forests at critical light thresholds show compromised ecological resilience to environmental and biological drivers. *Estuarine, Coastal and Shelf Science*, *219*, 231–241. DOI: 10.1016/j.ecss.2019.02.026
- Watanabe, H., Ito, M., Matsumoto, A., & Arakawaa, H. (2016). Effects of sediment influx on the settlement and survival of canopy-forming macrophytes. *Scientific Reports 6*, 18677. DOI: 10.1038/srep18677

Nearshore Soft-bottom

**reference pages 72-79 of the 2015 Assessment Report (Hutto et al., 2015)

Since 2015, our understanding of the interactive effects between extreme fires and extreme precipitation events that lead to large-scale debris flows warrants slight revisions to this assessment.

Nearshore	Revised Score	Confidence	Change
Sensitivity	2.9 Mod	High	+0.05
Exposure	4.2 High	High	+0.2
Adaptive Capacity	3.3 Mod	High	-
Vulnerability	3.7 Mod	High	+0.2

Sensitivity: Two scores added. Very slight increase to sensitivity score.

1. Disturbance regimes: Two new scores added to the disturbance regime score to account for debris flows and MHWs (4, high). Debris flows were added because of the increasing impact of fires followed by extreme rain events leading to debris flows that can smother and negatively impact the nearshore environment. New research indicates an increasing likelihood of large-scale debris flows/landslides in the region, such as the one that occurred from the Big Sur river in 2017, that can cause excessive sediment discharge and burial of the nearshore environment (Warrick et al., 2019). MHWs were added under the assumption that nearshore communities are likely impacted by increased water temperature, lower oxygen levels, and increased stratification/reduced mixing associated with MHWs.

Exposure: One score added, one score revised. Slight increase to exposure score.

1. Debris flows: New score added (4, high). Both extreme fire events and extreme rainfall events have increased in California since 1980, and fire followed by rainfall is projected to continue to increase in frequency, with a 100% increase by 2100 (Touma et al., 2022).
2. Exposure to altered currents and mixing: increased from 2 (low) to 3 (moderate) due to observed increased stratification and altered nutrient availability during the 2014-2016 MHW (Dudley et al., 2021).

References

- Dudley, P. N., Rogers, T. L., Morales, M. M., Stoltz, A. D., Sheridan, C. J., Beulke, A. K., Pomeroy, C., & Carr, M. H. (2021). A more comprehensive climate vulnerability assessment framework for fisheries social-ecological systems. *Frontiers in Marine Science*, *8*, 678099. DOI: 10.3389/fmars.2021.678099
- Touma, D., Stevenson, S., Swain, D. L., Singh, D., Kalashnikov, D. A., & Huang, X. (2022). Climate change increases risk of extreme rainfall following wildfire in the western United States. *Science Advances*, *8*, eabm0320. DOI: 10.1126/sciadv.abm0320
- Warrick, J. A., Ritchie, A. C., Schmidt, K. M., Reid, M. E., & Logan, J. (2019). Characterizing the catastrophic 2017 Mud Creek landslide, California, using repeat structure-from-motion (SfM) photogrammetry. *Landslides*, *16*, 1201–1219. DOI: 10.1007/s10346-019-01160-4

Offshore Rocky Reefs

**reference pages 80-85 of the 2015 Assessment Report (Hutto et al., 2015)

Since 2014, sanctuary staff have developed a better understanding of the impacts to offshore rocky reefs (e.g., Cordell Bank, Rittenburg Bank) from various stressors, as well as increased knowledge around how climate-related stressors are changing and impacting reefs. Some scores for both sensitivity and exposure have therefore been revised.

Offshore	Revised Score	Confidence	Change
Sensitivity	2.5 Low	Moderate	+0.5
Exposure	3.0 Mod	Moderate	+0.8
Adaptive Capacity	2.7 Mod	High	-
Vulnerability	2.9 Mod	High	+1.3

Sensitivity: Five scores revised. Increase in sensitivity score.

1. Sensitivity to water temperature: Increased from 1 (very low) to 3 (moderate). Though not yet documented, we can assume warmer water temperatures may result in range shifts of key reef species. For example, Cordell Bank represents an important intersection of the range distribution of hydrocoral species *Stylaster californicus* (the more southerly species) and *S. venustus* (the more northerly species). Knowing that both the southerly and northerly *Stylaster* species occur on Cordell Bank provides the opportunity to monitor abundance and distribution shifts for these two indicator species (Etherington et al., 2011).
2. Sensitivity to dissolved oxygen: Decreased from 5 (very high) to 3 (moderate), because there is no indication that the rocky reef assemblage would be highly sensitive to changes in dissolved oxygen; a moderate rating is more appropriate (K. Graiff and D. Lipski/ONMS, personal communication, November 18, 2022).
3. Sensitivity to currents/mixing: Increased from 3 (moderate) to 4 (high) as the rocky reef assemblage is highly dependent on the delivery of particulate matter as food for reef organisms (K. Graiff and D. Lipski/ONMS, personal communication, November 18, 2022).
4. Sensitivity to pollution: increased from 1 (very low) to 3 (moderate); though exposure remains 1 (low), an oil spill occurring in the vicinity of one of these reefs could have moderate impacts (K. Graiff and D. Lipski/ONMS, personal communication, November 18, 2022).
5. Sensitivity to gear from harvest: Increased from 1 (very low) to 3 (moderate). Though current exposure remains low, it is known from previous surveys that derelict fishing gear such as gillnets, longlines, and monofilament lines can cause damage to Cordell Bank. Therefore, although the risk of gear impacts is low, if this habitat is impacted by gear the damage could be significant (Graiff et al., 2019; Delta submersible surveys on Cordell Bank 2002-2005, unpublished data).

Exposure: Two scores revised. Increase in exposure score and overall rating to moderate.

1. Exposure to altered currents and mixing: Increased from 2 (low) to 3 (moderate) due to stratification documented during the 2014-2016 MHW and likelihood of changes to the timing and intensity of upwelling (Pozo-Buil et al., 2021).
2. Exposure to changes in water temperature: Increased from 1 (very low) to 3 (moderate), as the Cordell Bank Condition Report notes that the period 2009-2021 experienced some of the highest variability in the long-term temperature data, and temperature increases

during the MHW reached at least to 100m depth. Bottom temperatures are projected to increase between 1 and 2°C by 2100 (Siedlecki et al., 2021).

References:

- Etherington, L., Van der Leeden, P., Graiff, K., & Nickel, B. (2011). D*eep-sea coral patterns and habitat modeling results from Cordell Bank, CA*.National Oceanic and Atmospheric Administration - Cordell Bank National Marine Sanctuary. https://nmscordellbank.blob.core.windows.net/cordellbank-prod/media/archive/science/cbcoralfnl11.pdf
- Graiff, K., Lipski, D., Howard D., & Carver, M. (2019). Benthic community characterization of the mid-water reefs of Cordell Bank. NOAA Cordell Bank National Marine Sanctuary, 38 pp. https://nmscordellbank.blob.core.windows.net/cordellbank-prod/media/docs/2017-cb-benthic-community.pdf
- Pozo-Buil, M., Jacox, M. G., Fiechter, J., Alexander, M. A.., Bograd, S. J., Curchitser, E. N., Edwards, C. A., Rykaczewski, R. R., &Stock, C. A. (2021). A Dynamically Downscaled Ensemble of Future Projections for the California Current System. *Frontiers in Marine Science*, *8*, 612874. DOI: 10.3389/fmars.2021.612874
- Siedlecki, S. A., Pilcher, D., Howard, E. M., Deutsch, C., MacCready, P., Norton, E. L., Frenzel, H., Newton, J., Feely, R. A., Alin, S. R., & Klinger, T. (2021). Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences*, *18*, 2871–2890. DOI: 10.5194/bg-18-2871-2021

Pelagic

**reference pages 86-93 of the 2015 Assessment Report (Hutto et al., 2015)

Due to new research publications and observations of the impacts of various oceanographic changes on the pelagic environment since 2014, there is more information to be included in this update, as well as a few scores that warrant revision. It should be noted that there will likely be an increased exacerbative and negative effect of increased pH, decreased dissolved oxygen, and increased temperature on the pelagic environment, with frequency and duration of occurrence expected to increase.

Pelagic	Revised Score	Confidence	Change
Sensitivity	2.7 Mod	High	+0.1
Exposure	4.1 High	High	-
Adaptive Capacity	3.7 High	High	-
Vulnerability	3.2 Mod	High	+0.1

Sensitivity: Two scores revised, one score added. Slight increase in sensitivity score.

1. pH and shoaling of aragonite saturation state: Increased from 4 (high) to 5 (very high) due to severe impacts to key species in this system, including increased mortality of pteropods, habitat reduction, and impacts to larval stages of many species, including Dungeness crab, who are susceptible to internal and external exoskeleton carapace dissolution (Bednaršek et al., 2020).
2. Dissolved oxygen: Increased from 4 (high) to 5 (very high). Cold water retains dissolved oxygen more readily than warmer waters, so the increase in temperature of our ocean is leading to a decline in dissolved oxygen. As the ocean warms (particularly surface waters) and becomes more stratified, mixing between different ocean layers is reduced, and deeper waters do not receive the oxygen from the surface layers (IPCC, 2019). Low dissolved oxygen can lead to decreased biodiversity and the functioning of ocean ecosystems, species distribution shifts, reduced fish for fisheries, and expanded algal blooms (which can lead to dead zones; IUCN, 2019).
3. Disturbance regimes: New score added (5, very high) for MHWs. The 2014-2016 MHW showed increases in gelatinous species (Elliott et al., 2022) and undersaturated waters were observed throughout the water column. Impacts to species distribution vary with the extent of warm water: when warming occurs primarily in surface water (e.g. 2005-2006), krill are pushed down to where Cassin's auklets cannot forage them; when water warms throughout the water column (e.g. 2014-2016 MHW), everything is pushed offshore (M. Elliott/Point Blue, personal communication, October 4, 2022).

Corrections and additions to 2015 CVA Summary:
Potential benefit (page 86): The mention of increased upwelling potentially benefiting the pelagic environment assumes that increased upwelling will lead to increased upwelling of nutrients, which should stimulate primary production; however, some of the more recent research doesn't support this assumption. There needs to be relaxation events interspersed with upwelling; too much upwelling is too turbulent for primary production to occur (M. Elliott/Point Blue, personal communication, October 4, 2022).
Climate sensitivities (page 87): Stronger upwelling conditions were related to the increased abundance of boreal copepod species, which are larger and contain more lipid content than other copepod species in the region (Fontana et al., 2016). Meroplankton species, such as decapods, rely on upwelling as a transport mechanism; regional upwelling also impacts primary production, the main food source for larval decapods (Hameed et al., 2018). Upwelling brings

cold, CO_2-rich waters to the surface during spring and summer, while MHWs produce different conditions for the pelagic environment. When considering aragonite, undersaturated conditions were deeper during warm water events (e.g., summers of 2014 and 2015), while undersaturated waters were found in shallower waters during La Niña years (Davis et al., 2018). Another problem is when El Niño and MHW are followed by the upwelling event with insufficient relaxation event between them (Bednaršek et al., 2018, 2022), exposing populations to continuous stress. Strong upwelling conditions were associated with a shoaling of the aragonite saturation horizon, and a higher proportion of the water column was observed to have undersaturated aragonite conditions during strong upwelling events (Anderson et al., 2022). *Keystone and foundational species* (page 90): In addition to krill, copepods, rockfish, pteropods and northern anchovy are also key species in the pelagic system.

References:

- Anderson, R. J., Hines, E., Mazzini, P. L. F., Elliott, M., Largier, J. L., & Jahncke, J. (2022). Spatial patterns in aragonite saturation horizon over the northern California shelf. *Regional Studies in Marine Science*, *52*, 102286. DOI: 10.1016/j.rsma.2022.102286
- Bednaršek, N., Feely, R. A., Beck, M. W., Alin, S. R., Siedlecki, S. A., Calosi, P., Norton, E. L., Saenger, ., Strus, J., Greeley, D., Nezlin, N. P., Roethler, M., & Spicer, J. I. (2020). Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. *Science of The Total Environment*, *716*, 136610. DOI: 10.1016/j.scitotenv.2020.136610
- Davis, C. V., Hewett, K., Hill, T. M., Largier, J. L., Gaylord, B., & Jahncke, J. (2018). Reconstructing aragonite saturation state based on an empirical relationship for Northern California. *Estuaries and Coasts*, *41* , 2056-2069. DOI: 10.1007/s12237-018-0372-0
- Elliott, M., Lipski, D., Roletto, J., Warzybok, P., & Jahncke, J. (2022). *Ocean Climate Indicators Status Report: 2021*. [Unpublished Report]. Point Blue Conservation Science (Contribution No. 2422), Petaluma, CA.
- Fontana, R. E., Elliott, M. L., Largier, J. L., & Jahncke, J. (2016). Temporal variation in copepod abundance and composition in a strong, persistent coastal upwelling zone. *Progress in Oceanography*, *142*, 1-16. DOI: 10.1016/j.pocean.2016.01.004
- Hameed, S. O., Elliott, M. L., Morgan, S. G., & Jahncke, J. (2018). Interannual variation and spatial distribution of decapod larvae in a region of persistent coastal upwelling. *Marine Ecology Progress Series*, *587*, 55-71. DOI: 10.3354/meps12408
- IPCC (2019, September 25). *Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)*. [Press Release]. https://www.ipcc.ch/site/assets/uploads/sites/3/2019/09/SROCC_PressRelease_EN.pdf
- IUCN. (2022, December 6). *Ocean deoxygenation* (Issue Brief No. 1). International Union for the Conservation of Nature. . https://www.iucn.org/resources/issues-brief/ocean-deoxygenation.

Rocky Intertidal

**reference pages 94-102 of the 2015 Assessment Report (Hutto et al., 2015)

The rocky intertidal habitats in the sanctuary have experienced significant impacts and dramatic community changes since the 2015 assessment, primarily due to the 2014-2016 MHW, but also due to persistent change in the system. Multiple revisions are warranted based on new information that indicates cascading impacts in changes to key species (sea stars, intertidal kelp, urchins) due to sea star wasting combined with prolonged marine heating.

Rocky intertidal	Revised Score	Confidence	Change
Sensitivity	4.0 High	Moderate	+0.1
Exposure	4.2 High	Moderate	+0.1
Adaptive Capacity	3.5 High	Moderate	-0.5
Vulnerability	4.7 High	Moderate	+0.7

Sensitivity: Three scores revised, one note. Slight increase in sensitivity score.

1. Sea surface temperature: Increased from 3 (moderate) to 4 (high) due to impacts to habitat, structure, diversity, and abundance from both persistent heating and the 2014-2016 MHW (K. Lindquist/GFA, personal communication, November 29, 2022)
2. Sea level rise: Increased from 3 (moderate) to 4 (high); the 2015 assessment noted that this habitat was only moderately sensitive, "as long as there is room to migrate"; however, most rocky intertidal benches in the sanctuary are backed by cliffs and/or development, and do not have room to migrate (K. Lindquist/GFA, personal communication, November 29, 2022).
3. Disturbance regimes: Sensitivity to MHWs was not included in the 2015 assessment, though disease (sea star wasting) was scored as 5 (very high). Many more impacts to the rocky intertidal were documented during the MHW, including shifts in species composition (Sanford et al., 2019) and slowed recovery rates following disturbance (Menge et al., 2021)
4. Recreation: Sensitivity to recreation was previously scored as 4 (high) with localized high current exposure. While these scores are still accurate, it is important to note that in the most visited rocky intertidal sites (e.g., Duxbury reef, Fitzgerald Marine Reserve), visitation has increased since the start of the pandemic and seems to be continuing (based on preliminary beach watch use data).

Exposure: One score added. Slight increase in exposure score.

1. Debris flows: New score added (4, high). Both extreme fire events and extreme rainfall events have increased in California since 1980, and fire followed by rainfall is projected to continue to increase in frequency, with a 100% increase by 2100 (Touma et al., 2022). New research indicates an increasing likelihood of large-scale debris flows/landslides in the region, such as the one that occurred from the Big Sur river in 2016, that can cause excessive sediment discharge and burial of the nearshore environment (Warrick et al., 2019).

Adaptive Capacity: Three scores revised. Decrease in adaptive capacity score.

1. Structural and functional integrity: Decreased from 5 (very high) to 4 (high), due to documented impacts following MHW events that have altered community composition and structure (Sanford et al., 2019) including sea star loss and urchin barren increase, with severe degradation at some sites in the northern portion of the sanctuary (K. Lindquist/GFA, personal communication, November 29, 2022).

2. Ability of habitat to recover from disturbance: Decreased from 5 (very high) to 3 (moderate) due to long-term studies that indicate reduced resilience and slowed recovery rates over the last decade (Menge et al., 2021; Corey Garza/CSUMB, personal communication, January 5, 2023).
3. Species and functional group diversity: Decreased from 5 (very high) to 4 (high) due to MHW impacts on community composition (Sanford et al., 2019), algal diversity (Fales and Smith, 2022), and seastar loss from seastar wasting.

References:

- Fales, R. J., & Smith, J. R. (2022). Long-term change in a high-intertidal rockweed (*Pelvetiopsis californica*) and community-level consequences. *Marine Biology*, *169*, 34. DOI: 10.1007/s00227-022-04022-1
- Menge, B. A., Gravem, S. A., Johnson, A., Robinson, J. W., & Poirson, B. N. (2022). Increasing instability of a rocky intertidal meta-ecosystem. *Proceedings of the National Academy of Sciences*, *119*, e2114257119. DOI: 10.1073/pnas.2114257119
- Sanford, E., Sones, J. L., Garcia-Reyes, M., Goddard, J. H. R., & Largier, J. L. (2019). Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. *Nature*, *9*, 4216. DOI: 10.1038/s41598-019-40784-3
- Touma, D., Stevenson, S., Swain, D. L., Singh, D., Kalashnikov, D. A., & Huang, X. (2022). Climate change increases risk of extreme rainfall following wildfire in the western United States. *Science Advances*, *8*, eabm0320. DOI: 10.1126/sciadv.abm0320
- Warrick, J. A., Ritchie, A. C., Schmidt, K. M., Reid, M .E., & Logan, J. (2019). Characterizing the catastrophic 2017 Mud Creek landslide, California, using repeat structure-from-motion (SfM) photogrammetry. *Landslides*, *16*, 1201–1219. DOI: 10.1007/s10346-019-01160-4

Species

Blue Rockfish

**reference pages 131-138 of the 2015 Assessment Report (Hutto et al., 2015)

Though the 2014-2016 MHW had unprecedented impacts on shallow rocky reef and kelp forest-associated species, blue rockfish continue to demonstrate moderate vulnerability to climate impacts, largely because the species is relatively well adapted to change (long larval duration, highly mobile, and wide-ranging). However, revisions were warranted due to new impacts and a number of inconsistencies and inaccuracies in the original 2015 CVA.

Blue rockfish	Revised Score	Confidence	Change
Sensitivity	3.0 Mod	High	-0.04
Exposure	2.8 Mod	High	+0.2
Adaptive Capacity	3.7 High	High	-
Vulnerability	2.1 Mod	High	+0.1

Sensitivity: Three scores revised, one additional stressor to note. Very slight decrease in sensitivity score.

1. pH: Decreased from 4 (high) to 3 (moderate); since the 2014 assessment, new research on the effects of ocean acidification on multiple life stages of various rockfish species indicate that blue rockfish are more tolerant than other species to low pH (Hamilton et al., 2017; Cline et al., 2019; Saksa, 2021). The 2014 assessment relied on studies of other fish species, so the score is revised to more accurately reflect current scientific understanding.
2. Dissolved oxygen: Decreased from 5 (very high) to 4 (high); similar to the revised pH score, both juvenile and adult blue rockfish have been found to be relatively more tolerant to reduced dissolved oxygen than other rockfish species (Mattiason et al., 2020; Saksa, 2021).
3. Disturbance regimes: Decreased from 4 (high) to 3 (moderate) because MHWs were not considered in the 2014 assessment, and the rating of 4 (high) was found to be too high for the combined impact of storms and MHWs. Blue rockfish recruitment numbers were not impacted by the 2014-2016 MHW, with 2014 and 2016 average years and 2015 slightly below average but not as low as would be expected if this disturbance regime was a major driver (T. Laidig/NMFS and S. Hamilton/MLML, personal communication, December 9, 2022; Ziegler et al., *in revision*). Additionally, blue rockfish can and do move to deeper waters during disturbance events, which can ameliorate these impacts (M. Carr/UCSC, personal communication, December 22, 2022). Disease is not a current or projected impact.
4. Energy production: Not considered in the 2015 CVA is larval and juvenile entrainment and impingement in once-through cooling systems of coastal power plants and future desalination plants (M. Carr/UCSC, personal communication, December 22, 2022). Though not currently a stressor present in GFNMS and CBNMS, it is an important potential stressor to the species.

Exposure: One score revised. Slight increase in exposure score.

1. Sea surface temperature: Increased from 2 (low) to 3 (moderate) based on 2014-2016 MHW, which resulted in unprecedented impacts to the shallow, nearshore environment in the sanctuary, and will continue to do so periodically, with increased severity and frequency (Frölicher et al., 2018).

Corrections to 2015 CVA Summary:

Geographic extent (page 131): The executive summary of the 2015 assessment incorrectly states that blue rockfish have a transcontinental geographic extent; rather, transboundary is the intended term, to describe that the species ranges from the Bering Sea to Baja California. However, recent genetic analyses have determined that blue rockfish is actually two distinct species: deacon rockfish, which occur from Morro Bay up to Alaska, and blue rockfish which occur from Newport, Oregon to Punta Santo Tomas, Baja California (Frable et al., 2015). The fact that blue rockfish are two distinct species was not factored in the score revisions, as any stressors are likely relevant for both species.

Dispersal (pages 131 and 135): The executive summary incorrectly states that both the larval and adult stages have high dispersal; rather the larval and pelagic juvenile stages have high dispersal and the adult stage is not nearly as dispersive (M. Carr/UCSC, personal communication, December 22, 2022). The description of dispersal capability on page 5 should be clarified as: Larval and pelagic juvenile dispersal potential is high based on the long pelagic duration (3-4 mo). Adult movement and home range is more limited (< 2 km; Freiwald, 2012; Green et al., 2014).

Impact of harvest (page 131): To clarify the intent of the last sentence of the executive summary, climate change impacts are very likely to outweigh harvest impacts, but harvest may need to be adaptively managed so as not to exacerbate climate impacts.

Sensitivity to pH (page 132): The Munday et al. (2009) study has received criticism from the scientific community and is focused on a different species from a different region, and therefore should not be relied upon to make any inferences about the impact of pH on blue rockfish.

Sensitivity to storms (page 132): Blue rockfish recruit to rocky reef habitat, not kelp. Increased storm energy and frequency will directly impact all life stages of blue rockfish through (i) physical disturbance, (ii) possible increase in sedimentation that reduces the availability of rocky substratum, and (iii) increased water turbidity that can reduce foraging efficiency of planktivores (M. Carr/UCSC, personal communication, December 22, 2022).

Dependencies (pages 132/133): The 2015 CVA incorrectly states that blue rockfish are highly dependent upon kelp forest. Rather, adult fish and recruitment are dependent upon high relief, shallow rocky reefs (habitat specialist, Carr, 1991). Kelp forest, while likely not a strong influence, does provide some value by extending habitat up into the water column (M. Carr/UCSC, personal communication, December 22, 2022). In recent years in areas with little to no kelp, rockfish recruitment has remained average or above average, with 2020 as the best year for recruitment in reefs along the Monterey peninsula in 20 years (T. Laidig/NOAA, personal communication, December 9, 2022). Rockfish are less dependent on specific food sources (prey generalist, Hallacher and Roberts, 1985).

Fecundity (page 136): The 2015 CVA incorrectly states that blue rockfish produce relatively few offspring; rather, though the species is viviparous and long-lived, females have high fecundity, expelling large numbers of larvae in each reproductive season (Love et al., 2002).

References:

- Carr, M. H.(1991). Habitat selection and recruitment of an assemblage of temperate zone reef fishes. *Journal of Experimental Marine Biology and Ecology*, *146*, 113-137. DOI: 10.1016/0022-0981(91)90257-W
- Cline, A. J., Hamilton, S. L., & Logan, C. A. (2019). Effects of multiple climate change stressors on gene expression in blue rockfish (*Sebastes mystinus*). *Comparative Biochemistry and Physiology, Part A: Molecular and Integrative Physiology*, *239*, 110580. DOI: 10.1016/j.cbpa.2019.110580
- Freiwald, J. (2012). Movement of adult temperate reef fishes off the west coast of North America. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*, 1362-1374. DOI: 10.1139/f2012-068
- Frable, B. W., Wagman, D. W., Frierson, T. N., Aquilar, A., & Sidlauskas, B. L.. (2015). A new species of Sebastes (*Scorpaeniformes: Sebastidae*) from the northeastern Pacific, with a redescription of the blue rockfish, *S. mystinus* (Jordan and Gilbert, 1881). *Fishery Bulletin*, *113*, 355–377. DOI: 10.7755/FB.113.4.1
- Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). MHWs under global warming. *Nature*, *560*, 360–364. DOI: 10.1038/s41586-018-0383-9
- Green, K. M., Greenley, A. P., & Starr, R.M. (2014). Movements of Blue rockfish (*Sebastes mystinus*) off Central California with comparisons to similar species. *PLoS One*, *9*, e98976. DOI: 10.1371/journal.pone.0098976
- Hamilton, S. L., Logan, C., Fennie, W., Sogard, S., Barry, J., Makukhov, A., Tobosa, L., Boyer, K., Lovera, C., & Bernardi, G. (2017). Species-specific responses of juvenile rockfish to ocean acidification: from behavior to genomics. *PLoS One*, *12*, e0169670. DOI: 10.1371/journal.pone.0169670
- Hallacher, L. E., & Roberts, D.A. (1985). Differential utilization of space and food by the inshore rockfishes (*Scorpaenidae: Sebastes*) of Carmel Bay, California. *Environmental Biology of Fishes*, *12*, 91-110. DOI: 10.1007/BF00002762
- Love, M. S., Yoklavich, M., & Thorsteinson, L.K. (2002). *The Rockfishes of the Northeast Pacific*. Univ of California Press.
- Mattiasen, E. G., Kashef, N. S., Stafford, D. M., Logan, C. A., Sogard, S. M., Bjorkstedt, E. P., & Hamilton, S. L. (2020). Effects of hypoxia on the behavior and physiology of juvenile rockfishes. *Global Change Biology*, *26*, 3498–3511. DOI: 10.1111/gcb.15076
- Munday, P. L, Dixson, D. L., Donelson, J. M., Jones, G. P., Pratchett, M. S., Devitsina, G. V., & Døving, K. B. (2009). Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences*, *106*, 1848-1852. DOI: 10.1073/pnas.0809996106
- Saksa, K. (2021). *Effects of climate change induced ocean acidification and low oxygen on larval rockfish* (Publication No. 1217) [Masters thesis, California State University Monterey Bay]. CSUMB Digital Commons..
- Ziegler, S .L., Johnson, J. M., Brooks, R. O., Johnson, E. M., Mohay, J. L., Ruttenberg, B. I., Starr, R. M., Waltz, G. T., Wendt, D. E., & Hamilton, S. L. (2023). Marine protected areas, marine heatwaves, and the resiliency of nearshore fish communities. *Scientific Reports*, 13, 1405. DOI: 10.1038/s41598-023-28507-1

Blue Whale

**reference pages 124-130 of the 2015 Assessment Report (Hutto et al. 2015)

New science and literature are available regarding changes in timing, response to ocean climate and impacts of human activities, warranting slight revisions and some additional information. Blue whale arrival to the Gulf of the Farallones region is earlier now than in the early 1990s due to changes in climate (Ingman et al., 2021).

Blue whale	Revised Score	Confidence	Change
Sensitivity	4.1 High	High	+0.2
Exposure	5.0 Very High	High	-
Adaptive Capacity	3.8 High	High	-
Vulnerability	5.3 High	High	+0.2

Sensitivity: One score revised, one new score added. Slight increase in sensitivity score.

1. Dynamic ocean conditions (currents, mixing, stratification): increased from 2 (low) to 3 (moderate) due to the sensitivity of blue whale's primary prey, krill, as well as new research that indicates blue whale observations are significantly related with upwelling indices (Rockwood et al., 2020).
2. Salinity: new score added as 3 (moderate) due to new research that indicates blue whale observations are significantly related with midwater salinity (Rockwood et al., 2020).

Corrections and additions to 2015 CVA Summary:
Climate stressors (page 124, bottom): Though blue whales are more directly sensitive to non-climate stressors (e.g., ship strikes), climate-related changes are having indirect impacts on whales due to their primary prey, krill. Krill are more closely linked to climate-driven changes; krill abundance in the Gulf of the Farallones region was associated with climate variables (PDO, NPGO, SOI), upwelling indices, and midwater oceanographic variables. In addition, krill were associated with the continental shelf break, which were also blue whale hotspots (Rockwood et al., 2020).

Sea surface temperature (page 125): While less productive conditions (e.g., positive PDO, negative NPGO) as those observed in 2005-06 and 2014-16 were associated with low blue whale sightings, improved conditions do not always result in increased blue whale densities; this species is more closely associated with dense krill populations than with specific ocean/climate variables (Elliott et al., 2022).

Human interaction (page 126): The statement that 4 blue whales are killed by vessel strike every year is not accurate; rather, *up to* 4 blue whales are recorded killed by vessel strike each year, though this number is likely higher due to unreported or unknown collisions. Conservative model results estimate that total ship strike fatalities on blue whales is approximately 4 times the current Potential Biological Removal value for this species (Rockwood et al., 2017; NMFS Stock Assessment Reports, 2021).

Management potential (page 128): Modeling efforts have shown that most blue whale ship strike mortality occurs in only 10% of the study area, suggesting that management efforts (e.g., vessel speed reductions) in this area could have a big impact on saving blue whales (Rockwood et al., 2017).

References:

- Elliott, M. L., Lipski, D., Roletto, J., Warzybok, P., & Jahncke, J. (2022). Ocean Climate Indicators Status Report: 2021. Unpublished report. Point Blue Conservation Science (Contribution No. 2422), Petaluma, CA.
- Ingman, K., Hines, E., Mazzini, P. L. F., Rockwood, R. C., Nur, N., & Jahncke, J. (2021). Modeling changes in baleen whale seasonal abundance, timing of migration, and environmental variables to explain the sudden rise in entanglements in California. *PLoS One*, *16*, e0248557. DOI: 10.1371/journal.pone.0248557
- Rockwood, R. C., Elliott, M. L., Saenz, B., Nur, N., & Jahncke, J. (2020). Modeling predator and prey hotspots: Management implications of baleen whale co-occurrence with krill in Central California. *PLoS One*, *15*, e0235603. DOI: 10.1371/journal.pone.0235603
- Rockwood, R. C., Calambokidis, J., & Jahncke, J. (2017). High mortality of blue, humpback and fin whales from modeling of vessel collisions on the U.S. West Coast suggests population impacts and insufficient protection. *PLoS One*, *12*, e0183052. DOI: 10.1371/journal.pone.0183052

California Hydrocoral and White Lobed Sponge

**reference pages 139-144 of the 2015 Assessment Report (Hutto et al., 2015)

For this assessment update, scores were revised based on increased understanding of climate sensitivities to hydrocorals and sponges generally, using the white lobed sponge as a representative structure forming sponge. White lobed sponge (*Xestospongia* spp.*)* replaces red sponge because it is more commonly encountered on offshore reefs in the Sanctuaries, particularly *Xestospongia edapha* on Cordell Bank. Red sponge extends to the intertidal and likely has very different exposure and sensitivity; also, as an encrusting sponge, it's not easily identifiable and is not quantified in video analyses from benthic surveys. The species selected as indicators in this assessment are at the shallow end of the range of corals and sponges in CBNMS and GFNMS; deeper species may respond differently (e.g., lower exposure to changing temperatures but higher sensitivity).

Hydrocoral/Sponge	Revised Score	Confidence	Change
Sensitivity	3.1 Mod	Moderate	-0.06
Exposure	3.1 Mod	High	-
Adaptive Capacity	3.2 Mod	Moderate	-
Vulnerability	3.1 Mod	Moderate	-0.06

Sensitivity: Four scores revised, one added. Very slight decrease in sensitivity score.

1. Sensitivity to dissolved oxygen: Increased from 3 (moderate) to 4 (high), as corals and sponges are sensitive to hypoxia and cannot escape low DO waters (K. Graiff and D. Lipski/ONMS, personal communication, November 18, 2022).
2. Sensitivity to pH: Increased from 3 (moderate) to 4 (high) for hydrocoral only, because of the sensitivity of its calcium carbonate structure (K. Graiff and D. Lipski/ONMS, personal communication, November 18, 2022).
3. Sensitivity to invasive species: Decrease from 5 (very high) to 4 (high); the presence of an unknown species of encrusting tunicate that resembles the colonial tunicate, *Didemnum vexillum*, a species that has smothered areas of George's Bank in the Gulf of Maine and has been documented in the San Francisco Bay area (Bullard et al., 2007). There is no direct evidence that the impacts of the encrusting tunicate in the Sanctuaries is serious enough to warrant the highest rating (K. Graiff and D. Lipski/ONMS, personal communication, November 18, 2022; Graiff et al., 2019). Current exposure to the invasive tunicate, *Didemnum vexillum,* remains low.
4. Sensitivity to pollution: Decrease from 4 (high) to 3 (moderate); while corals and sponges are known to be sensitive to poor water quality and oil spills, this threat is more moderate in nature compared to other stressors. Current exposure to this stressor remains low.
5. Sensitivity to water temperature: This stressor was added as 3 (moderate), as it was not previously included in the 2015 assessment, and as a cold-water species, the hydrocoral may be affected by water temperature variability directly at depth and indirectly if warm water temperatures have a negative impact to their planktonic food sources in surface waters (K. Graiff and D. Lipski/ONMS, personal communication, November 18, 2022). Impacts are also suspected for sponges, though there is no direct evidence for deep-water sponges (Clark et al., 2017).

Adaptive capacity: No score revisions; 2 additions to the narrative.

1. Population status: Although there are concerns about climate stressors to corals, data from the region does not indicate major increases or decreases in hydrocorals or sponges since 2010 (Graiff et al., 2019; Graiff and Lipski, 2020; Graiff and Lipski, in review).
2. Species diversity: Cordell Bank is a transition zone of the northern species *S. venustus* and the southern species *S. californica*, although they cannot be distinguished unless collected. Climate change may result in range shifts of these two species, which could alter the species composition of hydrocorals on rocky reefs in the region. It is not expected that this would alter ecosystem dynamics, as the two species are expected to have similar ecosystem function.

References:

- Bullard, S. G., Lambert, G., Carman, M. R., Byrnes, J., Whitlatch, R. B., Ruiz, G., Miller, R. J., Harris, L., Valentine, P. C., Collie, J. S., Pederson, J., McNaught, D. C., Cohen, A. N., Asch, R. G., Dijkstra, J., & Heinonen, K. (2007). The colonial ascidian Didemnum sp. A: Current distribution, basic biology and potential threat to marine communities of the northeast and west coasts of North America. *Journal of Experimental Marine Biology and Ecology*, *342*, 99-108. DOI: 10.1016/j.jembe.2006.10.020
- Clarke, M. E., Whitmire, C. E., Yoklavich, M. M. (2017). State of Deep-Sea Coral and Sponge Ecosystems of the U.S. West Coast. In: Hourigan, T. F., Etnoyer, P. J., Cairns, S. D. (eds.). The State of Deep-Sea Coral and Sponge Ecosystems of the United States. NOAA Technical Memorandum NMFS-OHC-4, Silver Spring, MD. 44 p. Available online: http://deepseacoraldata.noaa.gov/library.
- Graiff, K., Lipski, D., Howard D., & Carver, M. (2019). Benthic community characterization of the mid-water reefs of Cordell Bank. NOAA Cordell Bank National Marine Sanctuary, 38 pp. https://nmscordellbank.blob.core.windows.net/cordellbank-prod/media/docs/2017-cb-benthic-community.pdf
- Graiff, K., & Lipski, D. (2020). Characterization of Cordell Bank, and Continental Shelf and Slope: 2018 ROV Surveys. NOAA Cordell Bank National Marine Sanctuary. 33 pp. https://nmscordellbank.blob.core.windows.net/cordellbank-prod/media/docs/20200709-characterization-of-cordell-bank-and-continental-shelf-and-slope.pdf
- Graiff, K., & Lipski, D. (in review). Characterization of Cordell Bank, and Continental Shelf and Slope: 2021 ROV Surveys. NOAA Cordell Bank National Marine Sanctuary. 36 pp.

California Mussel

**reference pages 145-152 of the 2015 Assessment Report (Hutto et al., 2015)

Due to some inconsistencies and assumptions in the 2015 assessment of this species, multiple revisions and corrections were provided, though there were no resulting changes to overall ratings.

California mussel	Revised Score	Confidence	Change
Sensitivity	3.3 Mod	High	+0.2
Exposure	4.1 High	Moderate	-
Adaptive Capacity	3.5 Mod	Moderate	+0.1
Vulnerability	3.9 Mod	High	+0.1

Sensitivity: One score removed, one score with important notes (but not changed), two scores revised. Slight increase in sensitivity score.

1. Sea surface temperature: Increased from 3 (moderate) to 4 (high).
2. Wave action: Decreased from 5 (very high) to 3 (moderate). Not only are mussels highly adapted to wave energy, but there is some evidence that mussel beds are more expansive in wave swept areas because predation rates decrease under those conditions (Robles and Desharnais, 2002; Robles et al., 2010). This stressor, therefore, is not likely to drive declines in the species and the score was revised.
3. Invasive species: Score removed from overall sensitivity assessment. There is no evidence of direct impact of invasive species on the California mussel.
4. Harvest: Score to remain at 3 (moderate), though it is important to note that this may change in the future and is a stressor to monitor as an increase in recreational harvest was noted during the pandemic, especially in southern California (M. Miner/UCSC, personal communication, January 5, 2023).
5. Dependency on sensitive habitat: Increase from 1 (very low) to 3 (moderate) due to the sensitivity of the species' primary habitat, the rocky intertidal.
6. Disturbance regimes: Sensitivity to MHWs was not included in the 2015 assessment, and was added as 5 (very high) with no impact to overall disturbance regime score, which was already scored as high.

Adaptive Capacity: Two scores revised. No change to adaptive capacity score.

1. Population status: Decreased from 5 to 4 (1 = endangered, 5 = robust) due to substantial loss in Southern California, and evidence of slower and more variable recovery of mussel beds following disturbance, compared to algal and barnacle-dominated assemblages (Conway-Cranos, 2012). Additionally, a mass mortality event of mussels occurred in June 2019 during a significant heat wave that may have negatively impacted the population.
2. Species value: Increased from 3 (moderate) to 5 (very high) due to increasing recognition that this species is a key foundation species in the rocky intertidal, supporting hundreds of other species.

Corrections to 2015 CVA Summary:
Adaptive capacity (page 151, bottom): Mussel beds are largely restricted to the mid-intertidal zone by predation from the Ochre sea star along the lower edge of the mussel bed. Any negative impacts on the sea star due to climate change (i.e. increased virulence and sea star wasting (SSW) events) could result in the expansion of mussels into the lower intertidal zone.

References:

- Conway-Cranos, L. L. (2012). Geographic variation in resilience: an experimental evaluation of four rocky intertidal assemblages. *Marine Ecology Progress Series*, *457*, 67-83. DOI: 10.3354/meps09715
- Robles, C. D., Desharnais, R. A. (2002). History and current development of a paradigm of predation in rocky intertidal communities. *Ecology*, *83*, 1521–1537. DOI: 10.1890/0012-9658(2002)083[1521:HACDOA]2.0.CO;2
- Robles, C. D., Garza, C., Desharnais, R. A., Donahue, M. J. (2010). Landscape patterns in boundary intensity: a case study of mussel beds. *Landscape Ecology*, *25*, 745-759. DOI: 10.1007/s10980-010-9450-9

Cassin's Auklet

**reference pages 153-160 of the 2015 Assessment Report(Hutto et al., 2015)

The 2014-2016 MHW led to a mass mortality event of Cassin's Auklets from California to British Columbia; in light of these impacts as well as updated climate projections for the region for several key climate stressors, this assessment required revisions.

Cassin's auklet	Revised Score	Confidence	Change
Sensitivity	3.5 High	High	+0.1
Exposure	3.4 Mod	High	+0.8
Adaptive Capacity	2.9 Mod	High	-
Vulnerability	4.0 Mod	High	+0.9

Sensitivity: Two scores revised, one score added. Slight increase in sensitivity score.

1. Air temperature: Increased from 1 (very low) to 3 (moderate). Though auklets aren't necessarily inherently sensitive to air temperature in their natural habitat, in the region of the sanctuaries, much of the population is dependent on artificial habitat (wooden nest boxes). These boxes can become superheated on extreme hot days, which increases the species' sensitivity to extreme heat events, with documented impacts including breeding failure and adult breeding bird mortality (P. Warzybok/Point Blue, personal communication, November 30, 2022).
2. Sea surface temperature: Increased from 3 (moderate) to 4 (high) due to the massive mortality event related to the 2014-16 MHW and persistent declines globally due to increasing water temperatures (Jones et al., 2017).
3. Disturbance regimes: Added MHW as a significant disturbance event (rated 5, very high) due the documented mass mortality event caused by starvation following the shift in zooplankton composition associated with the MHW (Jones et al., 2017).

Exposure: Six scores revised. Increase in exposure score, and an increase in the overall rating to moderate.

1. Increased air and sea surface temperatures: Increased from 3 (moderate) to 5 (very high) (Howard et al., 2020)
2. Decreased pH: Increased from 3 (moderate) to 4 (high) (Gruber et al., 2021)
3. Changes in precipitation: Increased from 2 (low) to 3 (moderate) (Warner et al., 2015)
4. Increased coastal erosion and run-off, increased flooding, and increased storminess: Increased from 2 (low) to 3 (moderate) (Huang et al., 2020; Huang and Swain, 2022).

References:

- Howard, E. M., Penn, J. L., Frenzel, H., Seibel, B. A., Bianchi, D., Renault, L., Kessouri, F., Sutula, M. A., McWilliams, J. C., & Deutsch, C. (2020). Climate-driven aerobic habitat loss in the California current system. *Science Advances*, *6*, 1-11. DOI: 10.1126/sciadv.aay3188
- Gruber, N., Hauri, C., Lachkar, Z., Loher, D., Frölicher, T. L., Plattner, G.-K. (2012). Rapid progression of ocean acidification in the California Current System. *Science*, *337*, 220–223. DOI: 10.1126/science.1216773
- Huang, X., Swain D. L., Hall, A. D. (2020). Future precipitation increase from very high resolution ensemble downscaling of extreme atmospheric river storms in California. *Science Advances*, *6*, eaba1323. DOI: 10.1126/sciadv.aba1323
- Huang, X., & Swain, D. L. (2022). Climate change is increasing the risk of a California megaflood. *Science Advances*, *8*, eabq0995. DOI: 10.1126/sciadv.abq099

- Jones, T., Parrish, J. K., Peterson, W. T., Bjorkstedt, E. P., Bond, N. A., Ballance, L. T., ... & Harvey, J.. (2018). Massive mortality of a planktivorous seabird in response to a marine heatwave. *Geophysical Research Letters*, *45*, 3193-3202. DOI: 10.1002/2017GL076164
- Warner, M. D., Mass, C. F., & Salathe, Jr., E. P. (2015). Changes in Winter Atmospheric Rivers along the North American West Coast in CMIP5 Climate Models. *Journal of Hydrometeorology*, *16*, 118-128. DOI: 10.1175/JHM-D-14-0080.1

Coralline Algae

**reference pages 178-183 of the 2015 Assessment Report (Hutto et al., 2015)

Due to inconsistencies in the 2015 assessment of this species group and a robust body of literature since that time, revisions were warranted. It is important to note that this assessment and review were conducted for coralline algae as a species complex, as species identification can be challenging. It is quite likely that values for individual species would vary, with some being more susceptible to impacts of climate change, and some less. In some cases, this variable response has been documented (McCoy and Pfister, 2014 documented varying responses of coralline algae species to OA). Additionally, it is very likely that species range shifts into and out of the sanctuaries and species loss from climate change will be missed.

Coralline algae	Revised Score	Confidence	Change
Sensitivity	2.9 Mod	High	+0.6
Exposure	3.0 Mod	Moderate	-
Adaptive Capacity	2.6 Low	High	+0.2
Vulnerability	3.3 Mod	High	+0.4

Sensitivity: Two scores revised, one score added. Increase in sensitivity score and overall rating increased to moderate.

1. Sea surface temperature: Increased from 4 (high) to 5 (very high). Mesocosm experiments with *C. tuberculosm* (a species present throughout the California Current System), show a significant reduction of both calcification and growth under warming and reduced pH conditions, with an antagonistic effect and a stronger impact from warming than OA (Donham et al., 2022). Additional research supports high sensitivity to OA (i.e. McCoy and Kamenos, 2015; McCoy and Kamenos, 2018; Pena et al., 2021), and very high sensitivity to warming (i.e. Huggett et al., 2018; Cornwall et al., 2019; Page and Diaz-Pulido, 2020).
2. Disturbance regimes: Added a new score for MHW as 4 (high). The 2015 CVA did not identify any significant sensitivities to disturbance regimes, and literature cited above indicate strong sensitivity to ocean warming. Coralline algae can bleach during short-term disturbance events, but can also recover relatively quickly (M. Miner/UCSC, personal communication, January 5, 2023).
3. Urchin overgrazing: New score added as 4 (high) for documented impact of urchin overgrazing due to extreme increases in urchin densities (L. Rogers-Bennett/CDFW, personal communication, January 25, 2023), which has also been documented in East Africa (O'Leary and McClanahan, 2010).

Adaptive capacity: One score revised, one score added. Slight increase in adaptive capacity score.

1. Phenotypic plasticity: Increased from 2 (low) to 4 (high). As indicated in the 2015 summary, and confirmed via expert elicitation (M. Miner/UCSC, personal communication, January 5, 2023) and supporting literature (i.e. diversity in morphology and reproductive strategies, Miklasz, 2012; Steneck et al., 1986), the initial rating by workshop participants was too low, and high plasticity is much more representative of this group of algae.
2. Other adaptive capacity: New score added (2, low) to reflect the slow-growing nature of this species complex, and slow recovery from disturbance (L. Rogers-Bennett/CDFW, personal communication, January 25, 2023).

Corrections to 2015 CVA Summary:
Species sensitivity (page 178): The reference to Miklasz (2012) suggesting that coralline algae could benefit from climate impacts due to decreased competition is inconsistent with much of the literature. Rather, studies suggest that coralline algae could suffer under future climate scenarios due not only to direct impacts from warming and OA (see references above), but also increased competition from species, such as fleshy seaweeds, that may be less impacted by changing ocean chemistry (Kuffner et al., 2008; Koch et al., 2013; M. Miner/UCSC, personal communication, January 5, 2023).

Species dependence (page 179): Text regarding dependence on sensitive habitats incorrectly states that coralline algae are dependent upon kelp forest habitat. Rather, most species are dependent on availability of bare rock, both within and outside of kelp forests.

References:

- Cornwall, C., Diaz-Pulido, G., & Comeau, S. (2019). Impacts of Ocean Warming on Coralline Algal Calcification: Meta-Analysis, Knowledge Gaps, and Key Recommendations for Future Research. *Frontiers in Marine Science*, *6*, 186. DOI: 10.3389/fmars.2019.00186.
- Donham, E. M., Hamilton, S. L., Aiello, I., Price, N. N., & Smith, J. E. (2022). Consequences of Warming and Acidification for the Temperate Articulated Coralline Alga, Calliarthron Tuberculosum (*Florideophyceae, Rhodophyta*). *Journal of Phycology*,l *58*, 517-529. DOI: 10.1111/jpy.13272
- Huggett, M. J., McMahon, K., & Bernascone, R. (2018). Future warming and acidification result in multiple ecological impacts to a temperate coralline alga. *Environmental Microbiology*, *20*, 2769-2782. DOI: 10.1111/1462-2920.14113
- Kuffner, I. B., Andersson, A. J., Jokiel, P. L., Rodgers, K. S., & MacKenzie, F. (2008). Decreased abundance of crustose coralline algae due to ocean acidification. *Nature Geoscience*, *1*, 114-117. DOI: 10.1038/ngeo100
- Koch, M., Bowes, G., Ross, C., & Zhang, X. H. (2013). Climate change and ocean acidification effects on seagrasses and marine macroalgae. *Global Change Biology*, *19*, 103-32. DOI: 10.1111/j.1365-2486.2012.02791
- McCoy, S. J., & Kamenos, N. A. (2015). Coralline algae (Rhodophyta) in a changing world: integrating ecological, physiological, and geochemical responses to global change. *Journal of Phycology*, *51*, 6-24. DOI: 10.1111/jpy.12262
- McCoy, S. J., & Kamenos, N. A. (2018). Coralline algal skeletal mineralogy affects grazer impacts. *Global Change Biology*, 24, 4775-4783. DOI: 10.1111/gcb.14370
- McCoy, S. J., & Pfister, C.A. (2014). Historical comparisons reveal altered competitive interactions in a guild of crustose coralline algae. *Ecology Letters*, 17, 475-83. DOI: 10.1111/ele.12247
- Page, T. M., & Diaz-Pulido, G. (2020). Plasticity of adult coralline algae to prolonged increased temperature and pCO2 exposure but reduced survival in their first generation. *PLoS One*, *15*, e0235125. DOI: 10.1371/journal.pone.0235125
- Peña, V., Harvey, B., Agostini, S., Porzio, L., Milazzo, M., Horta, P., Gall, L., & Hall-Spencer, J. (2021). Major loss of coralline algal diversity in response to ocean acidification. *Global Change Biology*, *27*, 4785-4798. DOI: 10.1111/gcb.15757

Krill

**reference pages 192-197 of the 2015 Assessment Report (Hutto et al., 2015)

New information is available regarding the influence of large-scale oceanographic processes as well as local conditions on euphausiid biomass and abundance that warrants revision of some scores.

Krill	Revised Score	Confidence	Change
Sensitivity	1.8 Very Low	High	+0.15
Exposure	5.0 Very High	High	-
Adaptive Capacity	4.0 High	Moderate	-
Vulnerability	2.8 Mod	High	+0.15

Sensitivity: Two scores revised, one score added. Slight increase in sensitivity rating.

1. Dynamic ocean conditions: Increased from 3 (moderate) to 5 (very high). Higher euphausiid densities were found in periods of increased upwelling and more productive ocean conditions, as well as in conditions consistent with stratified, mature upwelled waters (Rockwood et al., 2020). Euphausiid biomass was associated with both large scale (i.e., Southern Oscillation Index, PDO) and local processes and conditions (i.e., regional upwelling index; surface values of temperature, salinity, and fluorescence; Manugian et al., 2015).
2. Sea surface temperature: Increased from 3 (moderate) to 5 (very high). Related to comments above regarding dynamic ocean conditions, euphausiid biomass was associated with sea surface temperature, with higher biomass associated with colder water temperatures (Manugian et al., 2015).
3. pH: Score added as 3 (moderate), as there is some indication that krill abundance decreases in aragonite-undersaturated conditions (Anderson, 2019).

Exposure: One score added. No change to exposure score or overall rating.

1. pH: score added as 5 (very high), the same score provided for pelagic habitat, as pH is expected to continue to decline.

Adaptive Capacity: No revisions to scores, but important to note the following:

1. Update on krill population dynamics and latest biomass information based on the latest Ocean Climate Indicators Status Report (Elliott et al., 2022): Euphausiid biomass in the region, measured by acoustics, peaked in June 2021, and adult krill, which are larger and higher in lipid content than juveniles, dominate the zooplankton samples during cold water years, including 2021. Cold ocean conditions result in larger adult euphausiids compared to periods with warm conditions.

References:

- Anderson, R. J. (2019). *Spatial patterns in aragonite saturation for the north central California shelf* (Publication No. AS36 2019 MARSC .A53) [Masters thesis, San Francisco State University]. ScholarWorks.
- Elliott, M .L., Lipski, D., Roletto, J., Warzybok, P., & Jahncke, J. (2022). Ocean Climate Indicators Status Report: 2021. Unpublished report. Point Blue Conservation Science (Contribution No. 2422), Petaluma, CA.
- Manugian, S., Elliott, M. L., Bradley, R., Howar, J., Karnovsky, N., Saenz, B., Studwell, A., Warzybok, P., Nur, N., & Jahncke, J. (2015). Spatial distribution and temporal

patterns of Cassin's auklet foraging and their euphausiid prey in a variable ocean environment. *PLoS One*, *10*, e0144232. DOI: 10.1371/journal.pone.0144232

- Rockwood, R. C., Elliott, M. L., Saenz, B., Nur, N., & Jahncke, J. (2020). Modeling predator and prey hotspots: Management implications of baleen whale co-occurrence with krill in Central California. *PLoS One*, *15*, e0235603. DOI: 10.1371/journal.pone.0235603

Northern Anchovy and Pacific Sardine

**reference pages 206-213 of the 2015 Assessment Report (Hutto et al., 2015)

Climate projections for the region have improved over the last 7-8 years, and new studies have been published that evaluate likely or plausible climate change impacts on both Pacific sardine and northern anchovy. Thus, revisions to the assessments for both species is warranted. It should be noted, however, that significant uncertainties remain regarding the mechanisms driving recruitment and population dynamics for these species. The prior working paradigm, that anchovy are more abundant in cold water years and sardine are more abundant in warm water years (Chavez, 2003; cited in 2015 assessment report on page 207), is no longer holding true, as anchovy have, in the last 20 years, experienced high recruitment in warm water years, and sardine have experienced persistent recruitment failure since the mid-2000s (A. Thompson/NMFS, personal communication, January 10, 2023). There is some indication that anchovy may be more resilient to population collapse (McClatchie et al., 2017).

Northern anchovy	Revised Score	Confidence	Change
Sensitivity	2.9 Mod	High	-
Exposure	3.6 High	High	+0.3
Adaptive Capacity	3.5 High	High	+0.1
Vulnerability	2.9 Mod	High	+0.1

Pacific sardine	Revised Score	Confidence	Change
Sensitivity	3.2 Mod	High	+0.1
Exposure	3.7 High	High	+0.3
Adaptive Capacity	3.4 Mod	High	-0.4
Vulnerability	3.5 Mod	High	+0.9

Sensitivity: One score added for sardine only. Slight increase in sensitivity score.

1. Disturbance regimes: MHWs were not included in the 2015 assessment, and were added as a 5 (very high) for sardine only. The 2014-2016 MHW was associated with earlier sardine spawning and an unprecedented northern shift of the sardine spawning area (Auth et al., 2018; McClatchie et al., 2016). In contrast, during this time, anchovy had several strong recruitment classes that resulted in historically high adult abundances by 2021 (Thompson et al., 2022 a,b).
2. New research predicts a northward shift of Pacific Sardine (500-800 km in the 21st century, depending on the rate of warming, Fiechter et al., 2021) and decreased landings (30-70%) in the coming decades due to reduced habitat suitability in the region of the Sanctuary (Smith et al., 2021; Smith et al., 2023). This finding is consistent with a robust body of literature that suggests both species undergo orders of magnitude fluctuations in abundance and productivity in response to ocean condition over both short (interannual) and longer (interdecadal) time scales (Checkley et al., 2009; Lindegren et al., 2013; McClatchie et al., 2017). While both species were rated as having high sensitivity to climate-driven changes, the overall sensitivity score remains at moderate (3) due to other components of sensitivity that are rated very low to moderate (e.g. very low sensitivity to pollution, moderate dependency on specific prey, very low current harvest).

Exposure: YTwo scores revised. Slight increase in exposure score and increase in overall rating from moderate to high.

1. Decreased dissolved oxygen: Increased from 4 (high) to 5 (very high). The metabolic index, a measure of the environment's capacity to meet temperature-dependent oxygen demand, is projected to decrease below critical levels in 30-50% of anchovies' present range by 2100, with a complete loss of aerobic habitat in the southern region of the California Current System (Howard et al., 2020). It is assumed that sardine will have similar exposure.
2. Altered currents and mixing: Increased from 2 (low) to 3 (moderate) due to observed increased stratification and altered nutrient availability during the 2014-2016 MHW (Dudley et al., 2021).

Adaptive Capacity: One score revised, one new score added. Overall rating for anchovy increased to high; overall rating for sardine decreased to moderate.

1. Population status: Populations of both species have changed dramatically in recent years (consistent with the strong sensitivity of these populations to climate forcing). Pacific sardine abundance has declined very steeply since the 2015 assessment, and the stock is now considered overfished (Kuriyama et al., 2021) - the score for population status has therefore decreased from 3 to 2 (1 = endangered, 5 = robust). By contrast, the northern anchovy stock was recently assessed for the first time in over 30 years, and found to be at very high abundance levels (Kuriyama et al., 2022) - the score for population status has therefore increased from 3 to 4 (1 = endangered, 5 = robust).
2. Resilience and recovery: New adaptive capacity scores added to the rating as 4 (high) for anchovy and 2 (low) for sardine based on paleo and modern studies of varying population responses of the two species. Though "collapse" of these populations is a normal state repeatedly experienced by anchovy and sardine throughout history, paleo data for years 1000 to 1500 indicate anchovy were in a boom state much more than sardine and the mean recovery time was 8 years, about a third that of sardine (22 years, McClatchie et al., 2017). Since 1951, anchovy have been abundant much more than sardine, from 1960-1990, 2003-2005, and 2015-present while sardine were high only from the mid 1990s to about 2009 (A. Thompson/NMFS, personal communication, January 10, 2023).

References:

- Auth, T. D., Daly, E. A., Brodeur, R. D., & Fisher, J. L. (2018). Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. *Global Change Biology*, *24*, 259-272. DOI: 10.1111/gcb.13872
- Checkley, D. M., Alheit, J., & Oozeki, Y. (Eds). (2009). Climate change and small pelagic fish. Cambridge: Cambridge University Press.
- Dudley, P. N., Rogers, T. L., Morales, M. M., Stoltz, A. D., Sheridan, C. J., Beulke, A .K., Pomeroy, C., & Carr, M. H. (2021). A more comprehensive climate vulnerability assessment framework for fisheries social-ecological systems. *Frontiers in Marine Science*, *8*, 678099. DOI: 10.3389/fmars.2021.678099
- Fiechter, J., Pozo Buil, M., Jacox, M .G., Alexander, M. A., & Rose, K. A. (2021). Projected Shifts in 21st Century Sardine Distribution and Catch in the California Current. *Frontiers in Marine Science*, *8*, 685241. DOI: 10.3389/fmars.2021.685241
- Howard, E. M., Penn, J. L., Frenzel, H., Seibel, B. A., Bianchi, D., Renault, L., Kessouri, F., Sutula, M. A., McWilliams, J. C., & Deutsch, C. (2020). Climate-driven aerobic habitat loss in the California Current System. *Science Advances*, *6*, eaay3188. DOI: 10.1126/sciadv.aay3188
- Jacox, M. G., Alexander, M. A., Stock, C. A., & Hervieux, G. (2019). On the skill of seasonal sea surface temperature forecasts in the California Current System and its

connection to ENSO variability. *Climate Dynamics*, *53*, 7519-7533. DOI: 10.1007/s00382-017-3608-y

- Kuriyama, P. T., Zwolinski J. P., Hill, K. T., & Crone, P. R. (2020). Assessment of the Pacific sardine resource in 2020 for U.S. management in 2020-2021. Pacific Fishery Management Council: Portland, OR. Available from https://media.fisheries.noaa.gov/dam-migration/kuriyama_et_al_2020_sardine_assessment.pdf
- Kuriyama, P. T., Zwolinski J. P., Teo, S. L. H., & Hill, K. T. (2021). Assessment of the Northern anchovy (Engrualis mordax) central subpopulation in 2021 for U.S. management. Pacific Fishery Management Council, Portland, OR. Available from https://www.pcouncil.org/documents/2022/07/assessment-of-the-northern-anchovy-engraulis-mordax-central-subpopulation-in-2021-for-u-s-management-june-2022.pdf/
- Lindegren, M., Checkley Jr, D. M., Rouyer, T., MacCall, A. D., & Stenseth, N. C. (2013). Climate, fishing, and fluctuations of sardine and anchovy in the California Current. *Proceedings of the National Academy of Sciences*, *110*, 13672-13677. DOI: 10.1073/pnas.1305733110
- Lluch-Belda, D. R. J. M., Crawford, R. J., Kawasaki, T., MacCall, A. D., Parrish, R. H., Schwartzlose, R. A., & Smith, P. E. (1989). World-wide fluctuations of sardine and anchovy stocks: the regime problem. *South African Journal of Marine Science*, *8*, 195-205.
- McClatchie, S., Goericke, R., Leising, A., Auth, T. D., Bjorkstedt, E., Robertson, R. R., Brodeur, R. D., Du, X., Daly, E. A., Morgan, C. A., Chavez, F. P., Debich, A. J., Hildebrand, J., Field, J., Sakuma, K., Jacox, M. G., Kahru, M., Kudela, R., Anderson, C., Lavaniegos, B. E., ... & Jahncke, J. (2016). State of the California Current 2015–16: Comparisons with the 1997–98 El Niño. *California Cooperative Oceanic Fisheries Investigations Reports*, *57*, 1– 57.
- McClatchie, S., Hendy, I. L., Thompson, A. R., & Watson, W. (2017). Collapse and recovery of forage fish populations prior to commercial exploitation. *Geophysical Research Letters*,, *44*, 1877-1885. doi:10.1002/2016GL071751
- Pozo Buil, M., Jacox, M. G., Fiechter, J., Alexander, M. A., Bograd, S. J., Curchitser, E. N., Edwards, C. A., Rykaczewski, R. R., &Stock, C. A. (2021). A dynamically downscaled ensemble of future projections for the California current system. *Frontiers in Marine Science*, *8*, 612874. DOI: 10.3389/fmars.2021.612874
- Smith, J. A., Muhling, B., Sweeney, J., Tommasi, D., Pozo Buil, M., Fiechter, J., & Jacox, M. G. (2021). The potential impact of a shifting Pacific sardine distribution on US West Coast landings. *Fisheries Oceanography*, *30*, 437-454. DOI: 10.1111/fog.12529
- Smith, J. A., Pozo Buil, M., Muhling, B., Tommasi, D., Brodie, S., Frawley, T. H., ... & Jacox, M. (2023). Projecting climate change impacts from physics to fisheries: A view from three California Current fisheries. *Progress in Oceanography*, *211*, 102973. DOI: 10.1016/j.pocean.2023.102973
- Thompson A. R., Ben-Aderet N. J., Bowlin N. M., Kacev D., Swalethorp R., Watson W. (2022). Putting the pacific marine heatwave into perspective: The response of larval fish off southern California to unprecedented warming in 2014–2016 relative to the previous 65 years. *Global Change Biology*, *28*, 1766–1785. DOI: 10.1111/gcb.16010
- Thompson, A. R., Bjorkstedt, E. P., Bograd, S. J., Fisher, J. L., Hazen, E. L., Leising, A., ... & Weber, E. D.. (2022). State of the California Current Ecosystem in 2021: Winter is coming? *Frontiers in Marine Science*, *9*, 958727. DOI: 10.3389/fmars.2022.958727

Ochre Sea Star

**reference pages 214-219 of the 2015 Assessment Report (Hutto et al., 2015)

In 2014, when the initial assessment was undertaken, little was known about Sea Star Wasting disease (SSW), its long-term impacts and the capacity of the ochre sea star to recover and adapt. While the cause of SSW is still not known, we now have more information about the impact of the disease on ochre stars and their surrounding community. Coast-wide, ochre star populations remain depressed compared to pre-SSW levels and low levels of sick stars persist, but many areas, including some within the sanctuary, are showing signs of recovery (but note that recovery rates are highly variable; Miner et al., 2018). This additional knowledge, along with corrections to some assumptions made regarding other stressors, warrants multiple revisions for this species assessment.

Ochre sea star	Revised Score	Confidence	Change
Sensitivity	3.0 Mod	High	-
Exposure	4.1 High	Moderate	-
Adaptive Capacity	3.3 Mod	High	-0.2
Vulnerability	3.7 Mod	Moderate	+0.2

Sensitivity: Three scores revised. No change to sensitivity score.

1. Sea surface temperature: Increased from 3 (moderate) to 4 (high). Association of elevated water temperatures with the current (2013-present) SSW event has been mixed (see Miner et al., 2018 for discussion of various findings and literature), but prior SSW events have been strongly correlated with warm water events (e.g., Eckert et al., 1999).
2. Wave action: Decreased from 5 (very high) to 3 (moderate). Ochre sea stars are highly adapted to wave action, and there is no indication that the species is particularly sensitive (M. Miner/UCSC, personal communication, January 5, 2023).
3. Precipitation: Increased from 2 (low) to 3 (moderate). The original rating considered only the direct impacts of precipitation on the species, and did not include impacts from debris flows caused by fire and extreme precipitation, leading to sedimentation and burial of the nearshore environment (Warrick et al., 2019).
4. Disturbance regimes: No score revision (already scored as 5, very high), but it should be noted that a 2011 harmful algal bloom was documented to coincide with a significant mortality event of multiple invertebrate species, including the ochre sea star (Rogers-Bennett et al., 2012).

Adaptive capacity: One score revised. Slight decrease in adaptive capacity score and overall rating decreased to moderate.

1. Population status: Decreased from 5 to 3 (1 = endangered, 5 = robust). Sea stars have experienced massive die-offs since 2010 due to SSW. SSW continues to persist in the system and to impact ochre stars at low levels with some sites in the sanctuary trending toward recovery, while others have shown very little sign of recovery (M. Miner/UCSC and E. Sanford/BML, personal communication, January 5, 2023).

References:

- Eckert, G. L., Engle, J. M., & Kushner, D.J. (1999). Sea star disease and population declines at the Channel Islands. *Proceedings of the fifth California Islands symposium 5*, 390–393. DOI:
- Miner, C. M., Burnaford, J. L., Ambrose, R. F., Antrim, L., Bohlmann, H., Blanchette, C. A., ... & Raimondi, P. T. (2018). Large-scale impacts of sea star wasting disease (SSWD)

on intertidal sea stars and implications for recovery. *PLoS One*, *13*, e0192870. DOI: 10.1371/journal.pone.0192870

- Rogers-Bennett, L. Kudela, R., Nielsen, K., Paquin, A., O'Kelly, C. Langlois, G., Crane, D., & Moore, J. (2012). Dinoflagellate bloom coincides with marine invertebrate mortalities in northern California. *Harmful Algae News*, *46*, 10-11.
- Warrick, J. A., Ritchie, A. C., Schmidt, K. M., Reid, M. E., & Logan, J. (2019). Characterizing the catastrophic 2017 Mud Creek landslide, California, using repeat structure-from-motion (SfM) photogrammetry. *Landslides*, *16*, 1201–1219. DOI: 10.1007/s10346-019-01160-4

Olympia Oyster

**reference pages 220-226 of the 2015 Assessment Report (Hutto et al., 2015)

No revisions were made, but there are a number of corrections and recent studies of Olympia oysters in Tomales Bay to document in this revision, as we now have a much more robust body of literature confirming many of the scores from the 2015 assessment.

Olympia oyster	Revised Score	Confidence	Change
Sensitivity	3.2 Mod	High	-
Exposure	4.3 Very High	High	-
Adaptive Capacity	2.9 Mod	High	-
Vulnerability	4.5 High	High	No change

Though no changes to the 2015 scores are proposed, there are a number of new studies of Olympia oysters that are important to note in this update, which vastly improves our understanding of climate impacts to the species as well as the species distribution within GFNMS.

- There is clear evidence of Olympia oyster presence in Tomales Bay, with improved abundance and distribution data for the species which was not available for the 2015 summary (Kornbluth et al., 2022; Olympia and Pacific Oyster Data Portal: https://arcg.is/0Dai4O).
- Different climate-related stressors impact oyster health at different times of the year; in winter, salinity, nutrients, and alkalinity driven by run-off are driving forces, whereas temperature, pH, and dissolved oxygen are dominant in summer (Hollarsmith et al., 2020).
- The spatio-temporal variation in oyster recruitment and adult growth and mortality is based on a number of factors, including predation by non-native oyster drills. In Tomales Bay, adult oyster mortality is highest in the inner bay, where predators are abundant, and lowest in the middle bay, where oysters experience greatest growth. Juvenile mortality is constant throughout the bay, and recruitment is highest in the inner bay (Kimbro et al., 2019).
- Low salinity and high air temperature have synergistic negative effects on Olympia oyster mortality, suggesting temporal variation in climate-driven stressors will likely drive impacts to oysters (Bible et al., 2017).
- A near 100% mass mortality event of Olympia oysters occurred in northern San Francisco Bay immediately following a series of atmospheric rivers that led to extreme freshwater discharge and sustained extremely low salinities (below 6.3 psu for eight consecutive days; Cheng et al., 2017).

Corrections to 2015 CVA Summary:
Invasive species (page 222): The following sentence is incorrect because Pacific oysters are not naturalized in any estuaries in GFNMS (E. D. Grosholz/UCD, personal communication, September 30, 2022): "Finally, the Olympia oyster is directly displaced by larger non-native oysters, including the Pacific oyster (Pacific Biodiversity Institute, Trimble et al., 2009)." This paper by Trimble refers to Olympia oysters in Washington state only.

Adaptive capacity (page 224): The reference at the top of the page (Cheng, NERRS Science Collaborative, unpublished data) is incorrect, and should read "Chang", not "Cheng". The trace element work was conducted by Andy Chang at the Smithsonian Environmental Research Center.

References:

- Bible, J. M., Cheng, B. S., Chang, A .L., Ferner, M. C., Wasson, K., Zabin, C. J., Latta, M., Sanford, E., Deck, A., & Grosholz, E. D. (2017). Timing of stressors alters interactive effects on a coastal foundation species. *Ecology*, *98*, 2468-2478. DOI: 10.1002/ecy.1943
- Cheng, B. S., Chang, A. L., Deck, A., &Ferner, M. C. (2022). Atmospheric rivers and the mass mortality of wild oysters: insight into an extreme future? *Proceedings of the Royal Society B-Biological Sciences*, *283*, 20161462. DOI: 10.1098/rspb.2016.1462
- Hollarsmith, J. A., Sadowski, J. S., Picard, M. M., Cheng, B., Farlin, J., Russell, A., Grosholz, E. D. (2020). Effects of seasonal upwelling and runoff on water chemistry and growth and survival of native and commercial oysters. *Limnology and Oceanography*, *65*, 224-235. DOI: 10.1002/lno.11293
- Kimbro, D. L., White, J. W., & Grosholz, E. D. (2018). The dynamics of open populations: integration of top–down, bottom–up and supply–side influences on intertidal oysters. *Oikos*, *128*, 584-595. DOI: 10.1111/oik.05892
- Kornbluth, A., Perog, B. D., Crippen, S., Zacherl, D., Quintana, B., Grosholz, E. D., & Wasson, K. (2022). Mapping oysters on the Pacific coast of North America: A coast-wide collaboration to inform enhanced conservation. *PLoS One*, *17*, e0263998. DOI: 10.1371/journal.pone.0263998
- Trimble, A. C., Ruesink, J. L., & Dumbauld, B. R. (2009). Factors preventing the recovery of a historically overexploited shellfish species, *Ostrea lurida* Carpenter 1864. *Journal of Shellfish Research*, *28*, 97-106. DOI: 10.2983/035.028.0116

Pacific Herring

**reference pages 227-233 of the 2015 Assessment Report (Hutto et al., 2015)

The status of the local stock in San Francisco Bay has changed since the information in the 2015 report was provided, and our understanding of the linkages between population trends and environmental indicators has improved.

Pacific herring	Revised Score	Confidence	Change
Sensitivity	2.8 Mod	High	+0.3
Exposure	4.0 High	High	+0.3
Adaptive Capacity	2.9 Mod	High	-
Vulnerability	3.9 Mod	High	+0.6

Sensitivity: Three scores revised, one score added. Slight increase in sensitivity score and overall rating increased to moderate.

1. Sea surface temperature and salinity: Increased from 3 (moderate) to 4 (high). Standing stock biomass (SSB) was significantly correlated with Sacramento River outflow, offshore SST, and in-bay salinity (Sydeman et al., 2018). Herring are sensitive to run-off and salinity in the bays, and sensitive to temperature associated with changing ocean conditions (which also affects their prey).
2. Disturbance regimes: Added MHW and drought as 4 (high). Drought and MHW were not included in the 2015 assessment, and Sydeman et al. (2018) indicates sensitivity to SST and salinity, both driven in part by these disturbance regimes. The 2019 Fisheries Management Plan (FMP) indicates that oceanographic conditions are becoming more variable, which is impacting herring SSB, and that herring have become more sensitive to environmental variation since 1990 compared to prior to 1990 (Hare and Mantua, 2000)
3. Harvest: Sensitivity to harvest increased from 1 (very low) to 2 (low), while current exposure to harvest remains a 1 (very low). The 2019 FMP proposes a precautionary management approach to reduce impacts of harvest to the SSB of Pacific herring, including catch limits, size limits, and spatial and temporal closures, suggesting that herring are sensitive to harvest.

Exposure: Two scores revised. Slight increase in exposure score.

1. Precipitation variability and coastal run-off: Both scores increased from 3 (moderate) to 4 (high) due to projections of increased precipitation variability (Swain et al., 2018) and extreme precipitation events (Huang and Swain, 2022), which will likely exacerbate run-off.

Adaptive capacity: Two scores revised. No change to adaptive capacity score.

1. Population status: Decreased from 3 to 2 (1 = endangered, 5 = robust). Most recent and available data indicates that SSB is low (the past 6 years have been well below the average biomass) and the population has been in decline since the 2015 assessment (CDFW Season Summaries). Biomass has not been estimated since the 2019–2020 season due to decreased fishery effort and a tiered management system under the 2019 Herring Fishery Management Plan that scales management effort to fishery effort. Anecdotal reports of good spawning in Tomales some years and annual surveys in SF bay indicate fair to good spawning quality (A. Weltz/CDFW, personal communication, October 17, 2022)

2. Species value: Increased from 1 (very low value) to 2 (low value), as recreational birders and other outdoor consumptive and non-consumptive recreational users are well aware of the occurrence and value of herring spawns in the winter (A. Weltz/CDFW, personal communication, October 17, 2022)

Corrections to 2015 CVA Summary:
Biomass estimates (pages 227 and 230) are incorrectly attributed to commercial fishery data, when they are actually based on spawn deposition (A. Weltz/CDFW, personal communication, October 17, 2022; Herring FMP, 2019).
SST (page 228): A 1956 reference is used to support the SST exposure of herring (46-50° F); temperatures are certainly higher 70 years later, with nearshore temperatures 60–70° F during MHW events, and routinely in SF bay even in 'normal' years (A. Weltz/CDFW, personal communication, October 17, 2022).

References:

- California Pacific Herring Fishery Management Plan. (2019). *California Department of Fish and Wildlife*. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=184122&inline.
- CDFW Pacific herring season summaries. *California Department of Fish and Wildlife*. https://wildlife.ca.gov/Fishing/Commercial/Herring/Season-Summaries.
- Huang, X., & Swain, D. L. (2022). Climate change is increasing the risk of a California megaflood. *Science Advances*, *8*, eabq0995. DOI: 10.1126/sciadv.abq0995.
- Hare, S. R., & Mantua, N.J. (2000). Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography*, *47*, 103-145. DOI: 10.1016/S0079-6611(00)00033-1
- Swain, D .L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, *8*, 427–433. DOI: 10.1038/s41558-018-0140-y
- Sydeman, W. J., García-Reyes, M., Szoboszlai, A. I., Thompson, S. A., & Thayer, J. A. (2018) Forecasting herring biomass using environmental and population parameters. *Fisheries Research*, *205*, 141-148. DOI: 10.1016/j.fishres.2018.04.020

Pteropod

**reference pages 234-238 of the 2015 Assessment Report (Hutto et al., 2015)

New information is available regarding the impact of multiple ocean condition parameters on pteropod survival and abundance that warrants revision of some scores. Overall, because of high expected future exposure to unfavorable conditions combined with high sensitivity and low adaptive capacity, pteropods are under high risk due to the impact of OA in combination with multiple stressors (see also Bednaršek et al., 2021).

Pteropod	Revised Score	Confidence	Change
Sensitivity	4.0 High	High	+0.4
Exposure	5.0 Very High	High	-
Adaptive Capacity	2.6 Low	High	-0.1
Vulnerability	6.4 High	High	+0.5

Sensitivity: One new score added, two scores revised, one note. Slight increase in sensitivity score.

1. Sea surface temperature: Score added as 5 (very high). Pteropods are sensitive to warm ocean temperatures, and the two stressors of high temperature and low aragonite saturation state have been shown to create conditions of high mortality in this species (Bednaršek et al., 2022).
2. Dynamic ocean conditions: Increased from 4 (high) to 5 (very high). A relationship using easily-measured water properties (e.g., temperature, salinity, and dissolved oxygen) to estimate aragonite saturation state specific to Northern California was created in order to monitor ocean acidification in this region; the aragonite saturation horizon was deeper and surface aragonite saturation state estimates were higher during anomalously warm conditions (i.e., marine heat waves; e.g., summers of 2014 and 2015; Davis et al., 2018) or El Niños (e.g., 2016). Another study showed similar results, with a shoaling aragonite saturation horizon in strong upwelling conditions, and a higher proportion of the water column was observed to have undersaturated aragonite conditions during strong upwelling events (Anderson et al., 2022). Pteropods have been shown to be very sensitive to combined effects of MHW or El Niño, which are preceded by upwelling (low aragonite), increasing the impact on population dynamics (Bednaršek et al., 2018; 2022), and in general, multi-stressor exposure is expected to negatively impact the species (Bednaršek et al., 2016).
3. Dependence on sensitive habitat: Increased from 2 (low) to 3 (moderate) due to the species dependence on pelagic water conditions, specifically pH and temperature dependencies.
4. pH: Though no change to the score is made (scored as 5, very high), it is worth noting recent studies that continue to demonstrate the severe impact of ocean acidification on pteropods, including reduced calcification (Mekkes et al., 2021; Bednaršek et al., 2017; 2021), severe dissolution (Bednaršek et al., 2014; 2017), reduced survival (Bednaršek et al., 2017a) and increase in stress status (Bednaršek et al., 2018; Engstroem-Ost et al., 2019). The sensitivity of these impacts matches the magnitude of thresholds in aragonite saturation state that have been selected in the meta-analyses study (Bednaršek et al., 2019), further supporting experimental results.

Exposure: One score added, no change to score.

1. Increased sea surface temperature: new score added as 5 (very high), the same score provided for pelagic habitat, as sea surface temperature is predicted to continue to increase in the study region (Howard et al., 2020; Siedlecki et al., 2021).

Adaptive capacity: One score revised. Slight decrease in adaptive capacity score, and a decrease in the overall rating to low.

1. Genetic diversity: Decreased from 3 (moderate) to 2 (low). Two studies focusing on pteropod genetic structure across the California Current Ecosystem and northwards into the eastern North Pacific (Bednaršek et al., 2021; Mekkes et al., 2020) both show similar results, where the genetic analyses based on mitochondrial haplotypes identified all individuals of the dominant species (*Limacina helicina*) as a single species with no genetic differentiation between them. This genetic uniformity within the most abundant and dominant species indicates relatively low genetic adaptive capacity.

<u>References</u>:

- Anderson, R. J., Hines, E., Mazzini, P. L. F., Elliott, M., Largier, J. L., & Jahncke, J. (2022). Spatial patterns in aragonite saturation horizon over the northern California shelf. *Regional Studies in Marine Science*, *52*, 102286. DOI: 10.1016/j.rsma.2022.102286
- Bednaršek, N., Feely, R. A., Reum, J. C. P., Peterson, B., Menkel, J., Alin, S. R., & Hales, B. (2014). *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proceedings of the Royal Society B: Biological Sciences, 281*, 20140123. DOI: 10.1098/rspb.2014.0123
- Bednaršek, N., Harvey, C. J., Kaplan, I. C., Feely, R. A., & Možina, J. (2016). Pteropods on the edge: Cumulative effects of ocean acidification, warming, and deoxygenation. *Progress in Oceanography*, *145*, 1-24. DOI: 10.1016/j.pocean.2016.04.002
- Bednaršek, N., Feely, R. A., Tolimieri, N., Hermann, A. J., Siedlecki, S. A., Waldbusser, G. G., McElhany, P., Alin, S. R., Klinger, T., Moore-Maley, B., & Pörtner, H. O. (2017). Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. *Scientific Reports*, *7*, 1-12. DOI: 10.1038/s41598-017-03934-z
- Bednaršek, N., Klinger, T., Harvey, C. J., Weisberg, S., McCabe, R. M., Feely, R. A., Newton, J., & Tolimieri, N. (2017). New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. *Ecological Indicators*, *76*, 240-244. DOI: 10.1016/j.ecolind.2017.01.025
- Bednaršek, N., Feely, R. A., Beck, M. W., Glippa, O., Kanerva, M., & Engström-Öst, J. (2018). El Niño-related thermal stress coupled with upwelling-related ocean acidification negatively impacts cellular to population-level responses in pteropods along the California current system with implications for increased bioenergetic costs. *Frontiers in Marine Science*, *5*, 486. DOI: 10.3389/fmars.2018.00486
- Bednaršek, N., Feely, R. A., Howes, E. L., Hunt, B. P., Kessouri, F., León, P., Lischka, S., Maas, A. E., McLaughlin, K., Nezlin, N. P., & Sutula, M. (2019). Systematic review and meta-analysis toward synthesis of thresholds of ocean acidification impacts on calcifying pteropods and interactions with warming. *Frontiers in Marine Science*, *6*, 227. DOI: 10.3389/fmars.2019.00227
- Bednaršek, N., Newton, J. A., Beck, M. W., Alin, S .R., Feely, R. A., Christman, N. R., & Klinger, T. (2021). Severe biological effects under present-day estuarine acidification in the seasonally variable Salish Sea. *Science of The Total Environment*, *765*, 142689. DOI: 10.1016/j.scitotenv.2020.142689

- Bednaršek, N., Carter, B. R., McCabe, R. M., Feely, R .A., Howard, E., Chavez, F. P., Elliott, M., Fisher, J. L., Jahncke, J., & Siegrist, Z. (2022). Pelagic calcifiers face increased mortality and habitat loss with warming and ocean acidification. *Ecological Applications*, 32, e2674. DOI: 10.1002/eap.2674
- Davis, C. V., Hewett, K., Hill, T. M., Largier, J. L., Gaylord, B., & Jahncke, J. (2018). Reconstructing aragonite saturation state based on an empirical relationship for Northern California. *Estuaries and Coasts*, *41*, 2056-2069. DOI: 10.1007/s12237-018-0372-0
- Elliott, M. L., Lipski, D., Roletto, J., Warzybok, P., & Jahncke, J. (2022). Ocean Climate Indicators Status Report: 2021. Unpublished report, Point Blue Conservation Science (Contribution No. 2422). Petaluma, CA.
- Engström-Öst, J., Glippa, O., Feely, R. A., Kanerva, M., Keister, J. E., Alin, S. R., Carter, B. R., McLaskey, A. K., Vuori, K. A., & Bednaršek, N. (2019). Eco-physiological responses of copepods and pteropods to ocean warming and acidification. *Scientific reports*, *9*, 1-13. DOI: 10.1038/s41598-019-41213-1
- Feely, R. A., Alin, S. R., Carter, B., Bednaršek, N., Hales, B., Chan, F., Hill, T. M., Gaylord, B., Sanford, E., Byrne, R. H., & Sabine, C. L. (2016). Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal and Shelf Science*, *183*, 260-270. DOI: 10.1016/j.ecss.2016.08.043
- Howard, E. M., Penn, J. L., Frenzel, H., Seibel, B. A., Bianchi, D., Renault, L., Kessouri, F., Sutula, M. A., McWilliams, J. C., & Deutsch, C. (2020). Climate-driven aerobic habitat loss in the California current system. *Science Advances*, *6*, 1-11. DOI: 10.1126/sciadv.aay3188
- Mekkes, L., Renema, W., Bednaršek, N., Alin, S. R., Feely, R. A., Huisman, J., Roessingh, P., & Peijnenburg, K. T. (2021). Pteropods make thinner shells in the upwelling region of the California Current Ecosystem. *Scientific reports*, *11*, 1-11. DOI: 10.1038/s41598-021-81131-9
- Niemi, A., Bednaršek, N., Michel, C., Feely, R. A., Williams, W., Azetsu-Scott, K., Walkusz, W., & Reist, J. D. (2021). Biological impact of ocean acidification in the Canadian Arctic: widespread severe pteropod shell dissolution in Amundsen Gulf. *Frontiers in Marine Science*, *8*, 600184. DOI: 10.3389/fmars.2021.600184
- Siedlecki, S. A., Pilcher, D., Howard, E. M., Deutsch, C., MacCready, P., Norton, E. L., Frenzel, H., Newton, J., Feely, R. A., Alin, S. R., & Klinger, T. (2021). Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences*, *18*, 2871–2890. DOI: 10.5194/bg-18-2871-2021

Purple and Red Urchins

**reference pages 246-252 of the 2015 Assessment Report (Hutto et al., 2015)

The 2014-2016 MHW, and subsequent MHW events, resulted in dramatic changes to the nearshore environment, with unprecedented impacts on shallow rocky reef and kelp forest-associated species, including both purple and red urchins. The MHW resulted in two big ecological shifts: 1) sea star wasting syndrome removed an important urchin predator and resulted in a trophic release of both red and purple urchins; 2) kelp loss resulted in a significant reduction of drift algae which is the urchins' main food source (Dudley et al., 2021). Purple urchins responded by shifting from passive detritivores to active grazers of live kelp, removing almost all macroalgae from reefs (Rogers-Bennett and Catton, 2019; McPherson et al., 2021), effectively out-competing red urchins. Though the commercial red sea urchin fishery has collapsed due to starvation conditions leading to poor gonad production and unmarketable sea urchins (Rogers-Bennett and Catton, 2019), some of the population has persisted by moving to deeper waters to avoid competition with purple urchins (M. Carr/UCSC, personal communication, December 22, 2022) and during times of starvation (Ebert, 1967; Dudley et al., 2021). Once kelp recovers, it is presumed that red urchins will redistribute to shallower depths and both species will reallocate energy to gonad development. Multiple scores were revised to reflect these indirect effects of increased water temperatures.

Purple urchin	Revised Score	Confidence	Change
Sensitivity	3.6 High	High	+0.4
Exposure	3.2 Mod	High	+0.8
Adaptive Capacity	3.5 High	High	+0.4
Vulnerability	3.2 Mod	High	+0.8

Red urchin	Revised Score	Confidence	Change
Sensitivity	3.6 High	High	+0.4
Exposure	3.2 Mod	High	+0.8
Adaptive Capacity	3.4 High	High	+0.3
Vulnerability	3.3 Mod	High	+0.9

Sensitivity: Three scores revised, one score added. Increase in sensitivity score, and overall rating increased to high.

1. Sea surface temperature: Increased from 3 (moderate) to 4 (high) due to indirect effects of MHW-driven kelp loss on reproduction and gonad health (Rogers-Bennett and Catton, 2019). However, it should be noted that it is not SST per se that influences the reduced productivity of macroalgae, rather the lower nutrient levels associated with increased SST (M. Carr/UCSC, personal communication, December 22, 2022; Garcia-Reyes et al., 2014).
2. Disturbance regimes: Added MHW as a new score (5, very high), which increased rating from 4 (moderate) to 5 (very high).
3. Dependence on forage: Increased from 1 (very low) to 4 (high) due to the observed decline in body condition and reproduction following the loss of its prime forage, kelp (Rogers-Bennett and Catton, 2019; Dudley et al., 2021).
4. Other sensitivities (reds only): Sensitivity to competition added to red urchins (4, high). Purple urchins have out-competed red urchins following the loss of kelp as both habitat and food source, and have driven red urchins to deeper waters in search of alternative food sources (M. Carr/UCSC, personal communication, December 22, 2022).

Exposure: Two scores revised. Increase in exposure score and overall rating increased to moderate.

1. Increased sea surface temperature: Increase from 1 (very low) to 4 (high) based on 2014-2016 MHW, and projections that MHWs will increase in severity and frequency (Frölicher et al., 2018).
2. Altered currents and mixing: Increase from 1 (very low) to 3 (moderate) due to increased stratification from MHW, which led to low nutrient availability and reduced kelp productivity (Dudley et al., 2021)

Adaptive Capacity: Two scores revised. Increase in adaptive capacity score, and overall rating increased to high.

1. Population status: Red urchins remain at 4; purple urchins increase to 5 (1 = endangered, 5 = robust). Urchin density data at Fort Ross, collected by Reef Check California, shows moderate increases in red urchins since 2014, and very significant increases in purple urchins (R. Hohman/GFA, personal communication, October 19, 2022). Data from the southern end of the species range (from Monterey south to Cambria, outside this study region) indicate populations for both species are higher post-2015 (D. Malone/UCSC, personal communication, December 23, 2022)
2. Behavioral plasticity: Increase from 2 (low-moderate) to 4 (moderate-high). Evidenced by their persistent high numbers through and after the MHW, both species have shown the ability to persist during times of starvation, and to change their foraging behavior (passive to active grazer) to track food availability across depth zones (Smith and Tinker, 2022).

<u>Corrections to 2015 CVA Summary:</u>
Harvest (page 248): Red urchin is fished in many areas within its range, not throughout its entire range, as the species is not harvested in central California
Dispersal (page 249): Clarification that the maximum dispersal distance of 100km is for urchin larvae, not adults or juveniles.

<u>References</u>:

- Dudley, P. N., Rogers, T. L., Morales, M. M., Stoltz, A. D., Sheridan, C. J., Beulke, A. K., Pomeroy, C., & Carr, M. H. (2021). A more comprehensive climate vulnerability assessment framework for fisheries social-ecological systems. *Frontiers in Marine Science*, *8*, 678099. DOI: 10.3389/fmars.2021.678099
- Ebeling, A. W., Laur, D. R., & Rowley, R. J. (1985). Severe storm disturbances and reversal of community structure in a southern California kelp forest. *Marine Biology*, *84*, 287-294. DOI: 10.1007/BF00392498
- Ebert, T. A. (1967). Negative Growth and Longevity in the Purple Sea Urchin *Strongylocentrotus purpuratus* (Stimpson). *Science*, *157*, 557-55. DOI: 10.1126/science.157.3788.557.
- Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine Heatwaves Under Global Warming. *Nature*, *560*, 360–364. DOI: 10.1038/s41586-018-0383-9
- McPherson, M. L., Finger, D. J. I., Houskeeper, H. F., Bell, T. W., Carr, M. H., Rogers-Bennett, L., & R.M. Kudela. (2021). Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave. *Communications Biology*, *4*, 1-9. DOI: 10.1038/s42003-021-01827-6
- Rogers-Bennett, L., & Catton, C .A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, *9*, 15050. DOI: 10.1038/s41598-019-51114-y

- Smith, J. G., & Tinker, M. T. (2022). Alternations in the foraging behaviour of a primary consumer drive patch transition dynamics in a temperate rocky reef ecosystem. *Ecology Letters*, *25*, 1827-1838. DOI: 10.1111/ele.14064

Red Abalone

**reference pages 239-245 of the 2015 Assessment Report (Hutto et al., 2015)

The 2014-2016 MHW resulted in dramatic changes to the nearshore environment, with unprecedented impacts on shallow rocky reef and kelp forest-associated species. Red abalone are now at extremely low abundances and survivors have poor reproduction, the recreational fishery for red abalone has collapsed, and surviving populations are not recovering.

Red abalone	Revised Score	Confidence	Change
Sensitivity	3.8 High	High	+0.2
Exposure	3.8 High	High	+0.8
Adaptive Capacity	2.4 Low	High	-0.3
Vulnerability	5.2 High	High	+1.4

Sensitivity: Two scores revised, one score added, one note. Slight increase in sensitivity score.

1. Sea surface temperature (SST): Increased from 4 (high) to 5 (very high) due to documented cascading impacts of the MHW, including ecosystem transition and subsequent severe loss of kelp as both habitat and food (Rogers-Bennett and Catton, 2019; McPherson et al., 2021; Rogers-Bennett and Catton, 2022). The 2015 score for SST reflected only the direct impact of SST; this increase is due to the many other indirect impacts that have been documented and are now well understood.
2. Disturbance regimes: Though the 2015 score was already the highest rating possible (5, very high), MHW were not a part of the score. The 2014-2016 MHW was a major disturbance event, from which red abalone have not recovered (Rogers-Bennett and Catton 2022; L. Rogers-Bennett/CDFW, personal communication, January 25, 202).
3. Dependence on prey or forage: Increased from 2 (low) to 4 (high) due to current impact of kelp loss on red abalone body condition and reproduction, indicating a very strong dependence on forage (Rogers-Bennett et al., 2021).
4. Harvest: No change in score (remains 5, very high), but a note that the recreational fishery was closed in 2018 as a result of the MHW-driven kelp loss, and will remain closed until 2026.

Exposure: One score revised. Increase in exposure score and overall rating increased to high.

1. Sea surface temperature: Increased from 1 (low) to 4 (high) due to projected increase in frequency and severity of MHW (Frölicher et al., 2018).

Adaptive Capacity: Two scores revised. Decrease in rating to low.

1. Population status: Decreased from 3 to 1 based on recent losses (1 = endangered, 5 = robust). Abalone are now at extremely low abundances and survivors have poor body condition and reproduction (Rogers-Bennett et al., 2021; Rogers-Bennett and Catton, 2022).
2. Likelihood of managing or alleviating impacts: Decreased from 3 (moderate) to 2 (low) due to the extreme impacts resulting from kelp loss and ecosystem transition that is difficult to manage directly. Managing impacts to red abalone will require flexible management strategies, significant intervention, and novel restoration tools (Rogers-Bennett et al., 2022).

References:

- Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine Heatwaves Under Global Warming. *Nature*, *560*, 360–364. DOI: 10.1038/s41586-018-0383-9

- McPherson, M. L., Finger, D. J. I., Houskeeper, H. F., Bell, T. W., Carr, M. H., Rogers-Bennett, L., & Kudela, R. M. (2021). Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave. *Communications Biology, 4*, 298. DOI: 10.1038/s42003-021-01827-6
- Rogers-Bennett, L., & Catton, C. A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, *9*,: 15050. DOI: doi.org/10.1038/s41598-019-51114-y
- Rogers-Bennett, L., &. Catton, C. A. (2022). Cascading Impacts of a Climate-Driven Ecosystem Transition Intensifies Population Vulnerabilities and Fishery Collapse. *Frontiers in Climate*, *4*, 908708. DOI: 10.3389/fclim.2022.908708
- Rogers-Bennett, L., Klamt, R., & Catton, C. A. (2021). Survivors of climate driven abalone mass mortality exhibit declines in health and reproduction following kelp forest collapse. *Frontiers in Marine Science*, *8*, 725134. DOI: 10.3389/fmars.2021.725134
- Rogers-Bennett, L., Yang, G., & Mann, J. A. (2022). Using the Resist-Accept-Direct management framework to respond to climate driven transitions in marine ecosystems. *Fisheries Management and Ecology*, *29*, 409-422. DOI: 10.1111/fme.12539

Sea Palm

**reference pages 253-259 of the 2015 Assessment Report (Hutto et al., 2015)

Since the 2015 CVA, the impacts of warm water on this species have become much more apparent, with documented declines state-wide and local extirpation in its southern range. Scores have been revised to reflect this increased knowledge, though with no impact to overall vulnerability, due to the already relatively high scores for this species.

Sea palm	Revised Score	Confidence	Change
Sensitivity	3.6 High	High	+0.1
Exposure	4.0 High	Moderate	-
Adaptive Capacity	2.7 Mod	High	-0.2
Vulnerability	5.0 High	High	+0.4

Sensitivity: Two scores revised. Slight increase in sensitivity score.

1. Sea surface temperature: Increased from 3 (moderate) to 5 (very high) due to long-term monitoring data collected by the Multi-Agency Rocky Intertidal Network (MARINe) showing a strong correlation between *Postelsia* decline and warm water events (M. Miner/UCSC, personal communication, January 5, 2023).
2. Disturbance regimes: Added new score for MHW and ENSOs, as they were not considered in the initial rating of disturbance regimes; however, this rating was already a 5 (very high), so inclusion of these additional disturbance regimes does not impact the score.
3. Harvest: Though sensitivity to harvest remains at 5 (very high), the score for current exposure was increased from 2 (low) to 3 (moderate). The 2015 to 2021 average annual reported commercial sea palm harvest in the study region, Alder Creek, Mendocino County to Point Año Nuevo, San Mateo County, was 211 lbs wet weight whereas the average annual sea palm reported harvest statewide for the same time frame was 12,999 lbs (Data source: CDFW Commercial Edible Seaweed/Agarweed Aquatic Plant Harvester's Monthly Reports).

Adaptive Capacity: One score revised. Slight decrease in adaptive capacity score.

1. Population status: Decreased from 5 to 3 (1 = endangered, 5 = robust), due to local extirpation at the southern end of the species' range associated with prolonged warm water events, as well as ongoing state-wide decline in density since 2015 (unpublished MARINe long-term monitoring data).

Corrections to 2015 CVA Summary:
Managing Impacts (page 258): In the description regarding the likelihood of managing impacts to this species, harvest is described as "very low". However, CDFW estimates 10,000-20,000 pounds wet weight are harvested commercially each year (Flores-Miller, presentation to Marine Resources Committee, 2022), there are no limits on the number of licenses available for sale and no harvest limits or seasonal closures for sea palm, and Thompson et al. (2010) suggest the species is highly sensitive to harvest. Regulating the timing and scale of harvest would likely be a very impactful management option, and CDFW is, in fact, currently reviewing commercial harvest of sea palm in response to species decline (Committee Staff Summary for March 2022 Marine Resources Committee meeting).

References:

- Marine Resources Committee meeting (2022, March 24). Agenda item. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=199392&inline
- Marine Resources Committee meeting (2022, March 24). Meeting summary. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=200700&inline

Southern Sea Otter

**reference pages 260-266 of the 2015 Assessment Report (Hutto et al., 2015)

With the recent release of the 2022 USFWS Feasibility Assessment: Sea Otter Reintroduction to the Pacific Coast, new information regarding the effect of the 2014-2016 MHW and related climate impacts warrants revision of this assessment. Many corrections to the 2014 summary were also noted.

Southern sea otter	Revised Score	Confidence	Change
Sensitivity	2.9 Mod	High	+0.4
Exposure	3.6 High	Moderate	+0.1
Adaptive Capacity	2.5 Low	Moderate	-
Vulnerability	4.1 Mod	Moderate	+0.5

Sensitivity: One score revised, one score added, one stressor to note. Increase in sensitivity score and overall rating increased to moderate.

1. Sea surface temperature: Increased from 1 (very low) to 3 (moderate), due to significant indirect effects that were not considered in the original assessment. Following the 2014 MHW, subsequent loss of kelp canopy in the region is believed to have made sea otters more exposed to white shark bites (Nicholson et al., 2018). In addition to this increased exposure, shark-bite mortality is likely to increase in the region as waters warm, which increases the spatial and temporal overlap between juvenile white sharks and sea otters (Tinker et al., 2016; Moxley et al., 2019; Tanaka et al., 2021). Shark bite mortality has changed from being largely seasonal to a year-round threat (Miller et al., 2020) and has been recognized as a major factor limiting sea otter range expansion and abundance in California (Tinker et al., 2016; Tinker et al., 2021). Increased sea surface temperatures are also expected to cause harmful algal and cyanobacterial blooms, which produce biotoxins such as domoic acid (SIMoN, 2014; Preece et al., 2017; Trainer et al., 2020), with documented impacts on sea otters (Miller et al., 2020; Moriarty et al., 2021).
2. Disturbance regimes: Added 4 (high) sensitivity to MHW based on observed impacts following 2014-2016 MHW.
3. pH (no score change): The 2015 assessment accurately recognizes that ocean acidification could affect sea otter prey; this effect could be devastating, by impacting a broad range of calcifying marine organisms (USFWS, 2022). However, ecological interactions could mean that some beneficial effects could occur alongside the mostly negative effects (Marshall et al., 2017). There remains great uncertainty regarding the food web dynamics in response to changing ocean conditions, such as acidification.

Exposure: One score added. Slight increase in exposure score.

1. Increased sea surface temperature: Added as 4 (high) in light of the 2015-2016 MHW and likelihood for MHWs to be more frequent and severe in the future (Frölicher et al., 2018).

Corrections to 2015 CVA Summary:
Sensitivity to climate (page 260): The 2015 climate assessment states that increasing SST may expand the range of suitable habitat for the sea otter. While this may be true for the northern sea otter subspecies because it inhabits areas adjacent to those where the loss of sea ice may increase available habitat, this is not applicable to the southern subspecies (L. Carswell/USFWS, personal communication, January 5, 2023).

Sensitivity to precipitation (page 261): While many otters are infected with *Toxoplasma gondii*, this parasite causes very little disease or death; rather, *Sarcocystis neurona*, another terrestrial-derived protozoal parasite, was found to be responsible for 5x more sea otter deaths than *Toxoplasma* in the most recent mortality study (Miller et al., 2020).

Sensitivity to disease (page 262): From 1998 to 2012, infectious disease was a primary or contributing cause of death for 63% (n=354/560) of otters examined (Miller et al., 2020). In that study, infectious disease was not identified as a risk factor for other causes of death such as shark bite or boat strike, as previously suggested. The most significant infectious disease affecting sea otters during that timeframe was acanthocephalan peritonitis, which is caused by trans-intestinal parasite migration by the acanthocephalan *Profilicollis* sp. (Mayer et al., 2003), a thorny-headed worm transmitted to otters by the ingestion of marine crustaceans. The protozoal parasites *Toxoplasma gondii* and *Sarcocystis neurona* were also important causes of death (Miller et al., 2020); these parasites have feline (VanWormer et al., 2016) and opossum (Rejmanek et al., 2010) terrestrial definitive hosts and enter the marine environment through freshwater runoff. Other diseases that affect sea otters include cardiomyopathy and domoic acid toxicosis (Miller et al., 2020).

Population range and status (page 263): The Southern sea otter ranges from Pigeon Point to Gaviota, and now numbers around 2,962 individuals (Hatfield et al., 2019).

Dispersal distance (page 263): Sea otters exhibit strong site fidelity, with adult females rarely dispersing more than 20 km within a 1-year period (Riedman and Estes, 1990; Tinker et al., 2019), and an average home range of 8.6 km (Tarjan and Tinker, 2016). Males may disperse further to new areas, but range expansion relies on females establishing a breeding population which may take years to occur following male dispersal (Lafferty and Tinker, 2014).

Life history (page 264): Females have a pup roughly every one year with a pup dependency period of approximately six months (Riedman et al., 1994).

<u>References</u>:

- Hatfield, B. B., Yee, J. L., Kenner, M. C., & Tomoleoni, J. A. (2019) California sea otter (*Enhydra lutris nereis*) census results, spring 2019. *U.S. Geological Survey Data Series*, *1118*, 12. DOI: 10.3133/ds1118
- Lafferty, K. D., & Tinker, M. T. (2014). Sea otters are recolonizing southern California in fits and starts. *Ecosphere*, *5*, 1-11. DOI: 10.1890/ES13-00394.1
- Marshall, K. N., Kaplan, I. C., Hodgson, E. E., Hermann, A., Busch, D. S., McElhany, P., Essington, T. E., Harvey, C. J., & Fulton, E. A. (2017). Risks of ocean acidification in the California Current food web and fisheries: ecosystem model projections. *Global Change Biology*, *23*, 1525-1539. DOI: 10.1111/gcb.13594
- Mayer, K. A., Dailey, M. D., & Miller, M. A. (2003). Helminth parasites of the southern sea otter Enhydra lutris nereis in central California: abundance, distribution and pathology. *Disease of Aquatic Organisms*, *53*, 77-88. DOI: 10.3354/dao053077
- Miller, M. A., Moriarty, M. E., Henkel, L., Tinker, M. T., Burgess, T. L., Batac, F. I., Dodd, E., Young, C., Harris, M. D., Jessup, D. A. Ames, J., Conrad, P. A., Packham, A. E., & Johnson, C. K.. (2020). Predators, Disease, and Environmental Change in the Nearshore Ecosystem: Mortality in Southern Sea Otters (*Enhydra lutris nereis*) From 1998–2012. *Frontiers in Marine Science*, *7*, 582. DOI: 10.3389/fmars.2020.00582
- Moriarty, M. E., Tinker, M. T., Miller, M. A., Tomoleoni, J. A., Staedler, M. M., Fujii, J. A., Batac, F. I., Dodd, E. M., Kudela, R. M., Zubkousky-White, V., & Johnson, C. K.

(2021). Exposure to domoic acid is an ecological driver of cardiac disease in southern sea otters. *Harmful Algae*, *101*, 101973. DOI: 10.1016/j.hal.2020.101973

- Moxley, J. H., Nicholson, T. E., Van Houtan, K. S., & Jorgensen, S. J. (2019). Non-trophic impacts from white sharks complicate population recovery for sea otters. *Ecology and Evolution*, *9*, 6378-6388. DOI: 10.1002/ece3.5209
- Nicholson, T. E., Mayer, K. A., Staedler, M. M., Fujii, J. A., Murray, M. J., Johnson, A. B., Tinker, M. T., & Van Houtan, K. S. (2018). Gaps in kelp cover may threaten the recovery of California sea otters. *Ecography*, *41*, 1751–1762. DOI: 10.1111/ecog.03561
- Preece, E. P., Hardy, F. J., Moore, B. C., & Bryan, M. (2017). A review of microcystin detections in Estuarine and Marine waters: Environmental implications and human health risk. *Harmful Algae*, 61, 31-45. DOI: 10.1016/j.hal.2016.11.006
- Rejmanek, D., Miller, M.A., Grigg, M.E., Crosbie, P.R., & Conrada, P.A. (2010). Molecular characterization of Sarcocystis neurona strains from opossums (*Didelphis virginiana*) and intermediate hosts from Central California. *Veterinary Parasitology*, *170*, 20-29. DOI: 10.1016/j.vetpar.2009.12.045
- Riedman, M., & Estes, J. A. (1991). *The sea otter (Enhydra lutris): behavior, ecology, and natural history* (Vol. 90, No. 14). US Department of the Interior, Fish and Wildlife Service.
- Riedman, M. L., Estes, J. A., Staedler, M. M. Giles, A. A., & Carlson, D. R. (1994). Breeding patterns and reproductive success of California sea otters. *The Journal of Wildlife Management*, *58*, 391–399. DOI: 10.2307/3809308
- Tinker, M. T. (2021). *Population and Demographic Considerations*. Elakha Alliance Draft Feasibility Study.
- Tinker, M. T., Hatfield, B. B., Harris, M. D., & Ames, J. A. (2016). Dramatic increase in sea otter mortality from white sharks in California. *Marine Mammal Science*, *32*, 309-326. DOI: 10.1111/mms.12261
- Tinker, M. T., Tomoleoni, J. A., Weitzman, B. P., Staedler, M., Jessup, D., Murray, M. J., ... & Conrad, P. (2019). *Southern sea otter (Enhydra lutris nereis) population biology at Big Sur and Monterey, California--Investigating the consequences of resource abundance and anthropogenic stressors for sea otter recovery* (No. 2019-1022). US Geological Survey..
- Tanaka, K. R., Van Houtan, K. S., Mailander, E., Dias, B. S., Galginaitis, C., O'Sullivan, K., Lowe, C. G., &Jorgensen, S. J. (2021). North Pacific warming shifts the juvenile range of a marine apex predator. *Scientific Reports*, *11*, 3373. DOI: 10.1038/s41598-021-82424-9
- Tarjan, L. M., & Tinker, M. T. (2016). Permissible home range estimation (PHRE) in restricted habitats: A new algorithm and an evaluation for sea otters. *PLoS One*, *11*, e0150547. DOI: 10.1371/journal.pone.0150547
- Trainer, V. L., Kudela, R. M., Hunter, M. V., Adams, N. G., & McCabe, R. M. (2020). Climate Extreme Seeds a New Domoic Acid Hotspot on the US West Coast. *Frontiers in Climate*, *2*, 571836. DOI: 10.3389/fclim.2020.571836
- US Fish and Wildlife Service. (2022). Feasibility assessment: sea otter reintroduction to the Pacific coast. In: *Report to Congress Prepared by the US Fish and Wildlife Service. Sacramento, California*.
- VanWormer, E., Carpenter, T. E., Singh, P., Shapiro, K., Wallender, W. W., Conrad, P. A., Largier, J. L., Maneta, M.P., & Mazet, J. A. K. (2016). Coastal development and precipitation drive pathogen flow from land to sea: evidence from a *Toxoplasma gondii* and felid host system. *Scientific Reports*, *6*, 29252. DOI: 10.1038/srep29252

Western Snowy Plover

Updated scientific name*: Charadrius nivosus nivosus*
**reference pages 282-288 of the 2015 Assessment Report (Hutto et al., 2015)

The 2015 assessment is largely still accurate, with minor revisions related to precipitation impacts.

Western snowy plover	Revised Score	Confidence	Change
Sensitivity	4.0 High	High	+0.2
Exposure	4.3 Very High	High	+0.3
Adaptive Capacity	2.8 Mod	High	-
Vulnerability	5.5 High	High	+0.5

Sensitivity: One score revised, one score removed. Slight increase in sensitivity score.

1. Precipitation: Increased from 2 (low) to 3 (moderate) due to flooding of nesting areas, especially if precipitation occurs later in the spring season when chicks hatch (K. Lindquist/GFA, personal communication, November 29, 2022).
2. pH: Sensitivity score was removed entirely from the assessment, as pH has no documented impact on Snowy Plovers, and should not be included (K. Lindquist/GFA, personal communication, November 29, 2022).

Exposure: One score revised, one score removed. Slight increase in exposure score.

1. Changes in precipitation: Increase from 2 (low) to 3 (moderate) due to wetter wet years and drier dry years already being observed and projected to intensify (Warner et al., 2015). The likelihood of extreme precipitation is projected to increase (Swain et al., 2018).
2. pH: Exposure score was removed entirely from the assessment, as pH has no documented impact on Snowy Plovers, and should not be included (K. Lindquist/GFA, personal communication, November 29, 2022).

Adaptive Capacity: no revision, but important to note the following:

1. Point Reyes National Seashore recently recorded the highest fledge rate since 2012 and the highest total number of fledged chicks since 1997. This success is likely due to park managers working quickly to find and protect nests with mini-enclosures within the park, to protect the nests from predation. However, not all nesting sites throughout the Sanctuary are so closely managed, and the adaptive capacity of this species is likely highly dependent on these management interventions.

References:

- Swain, D. L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, *8*, 427–433. DOI: 10.1038/s41558-018-0140-y
- Warner, M. D., Mass, C. F., & Salathe, Jr., E. P. (2015). Changes in Winter Atmospheric Rivers along the North American West Coast in CMIP5 Climate Models. *Journal of Hydrometeorology*, *16*, 118-128. DOI: 10.1175/JHM-D-14-0080.1

Ecosystem Services

Carbon Storage and Sequestration

**reference pages 297-303 of the 2015 Assessment Report (Hutto et al., 2015)

The 2015 assessment of the ecosystem service "carbon storage and sequestration" focused solely on the provisioning of this service by saltmarsh and eelgrass plants. Based on findings from the Blue Carbon in MPAs report series (Hutto et al., 2021), this addendum revises the findings and scores of the original assessment to incorporate the provisioning of this service by the sanctuary's bull kelp, large baleen whales, and phytoplankton. These processes are known to contribute to carbon sequestration in marine environments via carbon export to the deep sea, where carbon may be stored in seabed sediments for millennia (Hutto et al., 2021). Though there are myriad additional pathways for carbon sequestration in the marine environment (i.e. mesopelagic fish, zooplankton), this update is limited to those species/processes for which we have sufficient information to assess.

Carbon storage and sequestration	Revised Score	Confidence	Change
Sensitivity	3.5 High	Moderate	+0.5
Exposure	5.0 Very High	High	-
Adaptive Capacity	3.0 Mod	Moderate	+0.7
Vulnerability	5.5 High	High	-0.2

Sensitivity: One score revised. Increase in sensitivity score and of overall sensitivity rating to high.

1. Climate stressors: Overall sensitivity to climate stressors increased from 2 (low) to 4 (high) for the following reasons:
    a. The high sensitivity of the sanctuary's bull kelp to sea surface temperature, as evidenced during the 2014-2016 MHW, and the resulting decline in carbon export (Hutto et al., 2021).
    b. The documented shift in dominant phytoplankton taxa from larger species to smaller species during the MHW (Cavole et al., 2016), which will likely impact carbon export and sequestration (Bolanos et al., 2020).
    c. The moderate sensitivity of blue whales to climate stressors, including dynamic ocean conditions due to impacts to prey (krill).
2. Non-climate stressors: The 2015 assessment rated sensitivity to land-use change, roads/armoring, invasives, pollution, recreation, aquaculture, and dredging as moderate-high. Though this addendum does not propose changing this component of the overall sensitivity rating, the following should be noted:
    a. Pollution, and its impacts on water quality, was rated as a high sensitivity for kelp.
    b. There are additional non-climate stressors to consider for whales, including ship strikes, entanglements, and noise, which were rated as high in the blue whale assessment.
    c. There are potential sensitivities for the seabed carbon sink, such as trawling and incidental disturbance events.

Adaptive Capacity: Two scores revised. Increase in adaptive capacity score and of overall rating to moderate.

1. Service value: increased from 2 (low) to 3 (moderate) due to rapidly increasing interest in blue carbon in recent years, as well as increased awareness by the general public,

policy-makers, funders, and sanctuary managers. A search of the Web of Knowledge database found that only 28 papers were published with the term "blue carbon" in their titles prior to 2015 while, since that time, 357 such papers have been published. Anecdotally, requests from media, funders and educational groups have increased significantly for sanctuary staff.

2. Willingness to change behavior: Increased from 1 (very low) to 2 (low): Desire to better protect carbon sequestration processes and sinks has increased, as well as knowledge of the best management practices to protect and maintain the service (Hutto et al., 2021).

References:

- Bolaños, L. M., Karp-Boss, L., Choi, C. J., Worden, A. Z., Graff, J. R., Haëntjens, N., ... & Giovannoni, S. J. (2020). Small phytoplankton dominate western North Atlantic biomass. *The ISME Journal*, *14*, 1663-1674. DOI: 10.1038/s41396-020-0636-0
- Cavole, L. M., Demko, A. M., Diner, R. E., Giddings, A., Koester, I., Pagniello, C. M., ... & Franks, P. J. (2016). Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: winners, losers, and the future. *Oceanography*, *29*, 273-285. DOI: 10.5670/oceanog.2016.32
- Hutto, S. H., Brown, M., & Francis, E. (2021). Blue carbon in marine protected areas: Part 1; A guide to understanding and increasing protection of blue carbon. *National Marine Sanctuaries Conservation Science Series ONMS-21-07*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries.
- Hutto, S. H., Hohman, R., & Tezak, S. (2021). Blue carbon in marine protected areas: Part 2; A blue carbon assessment of Greater Farallones National Marine Sanctuary. *National Marine Sanctuaries Conservation Series ONMS-21-10*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries.

Flood and Erosion Protection

**reference pages 304-311 of the 2015 Assessment Report (Hutto et al., 2015)

Though there have been significant scientific advances in local climate science predictions in the last 15 years that impact and worsen predictions of coastal erosion (Thorne et al., 2016), the 2015 scores for sensitivity and exposure were so high, that no further modification can be made to further increase these scores. However, there have been improvements in the potential to manage for these impacts, which this revision notes.

Flood and erosion protection	Revised Score	Confidence	Change
Sensitivity	4.8 Very High	High	-
Exposure	5.0 Very High	High	-
Adaptive Capacity	4.3 Very High	High	+0.9
Vulnerability	5.6 High	High	-0.9

Adaptive Capacity: One score revised. Increase in adaptive capacity score, but no change to overall rating.

1. Willingness to change behavior: Increased from 2 (low) to 4 (high), as public and agency awareness of the issue of coastal protection has gained attention and there is increased local, state, and national interest and funding in using natural and nature-based solutions to mitigate impacts (Newkirk et al., 2018; California Coastal Commission, 2018).

References:

- California Coastal Commission (2018). *California Coastal Commission Sea Level Rise Policy Guidance*. Adopted by the California Coastal Commission on 7 November 2018. Sacramento, CA. 307 pp.
- Newkirk, S., Veloz, S., Hayden, M., Heady, W., Leo, K., Judge, J., Battalio, R., Cheng, T., Ursell, T., & Small, M. (2018). *Toward Natural Infrastructure to Manage Shoreline Change in California* (California's Fourth Climate Change Assessment Publication No. CCCA4-CNRA-2018-011). California Natural Resources Agency.
- Thorne, K. M., MacDonald, G. M., Ambrose, R. F., Buffington, K. J., Freeman,C. M., Janousek, C. N., Brown, L. N., Holmquist, J. R., Gutenspergen, G. R., Powelson, K. W., Barnard, P. L., & Takekawa., J. Y. (2016). *Effects of climate change on tidal marshes along a latitudinal gradient in California* (No. 2016-1125). US Geological Survey. DOI: 10.3133/ofr20161125

Climate Vulnerability Assessment for Maritime Heritage Resources

As part of the revision to the 2015 Climate Vulnerability Assessment presented in this addendum, three new maritime heritage resource categories were assessed for the first time: doghole ports, nearshore shipwrecks, and offshore shipwrecks. This is the first assessment of climate vulnerability for tangible maritime heritage resources (MHRs) in GFNMS, CBNMS, and the northern portion of MBNMS, and is modeled after similar assessments undertaken at Olympic Coast NMS. These resources were assessed internally by ONMS staff, using the same climate vulnerability model from the 2015 assessment for the exposure and sensitivity components[5] (Hutto et al., 2015). However, as is general practice among heritage resource managers, adaptive capacity was not included because non-renewable resources such as heritage resources are non-adaptive and thus cannot be scored for adaptive capacity. In addition, heritage resources retain a high degree of significance based on their historical association with events, individuals, distinctive characteristics of a construction method or period, and/or their ability to yield information on the past. As this historical association is reliant on site integrity (i.e. location, design, setting, materials, workmanship, feeling, and association), modifying heritage resources through external management actions (e.g. adding stabilization braces or reburying visible materials to prevent further degradation) reduces resource integrity and significance. Thus, adaptive capacity of tangible heritage is not assessed. The vulnerability of the resource category, therefore, is the same as the potential impact that resource category is likely to experience and is simply a combination of exposure and sensitivity. In place of adaptive capacity, however, this assessment does include qualitative descriptions of other important considerations, including resource value and significance and data management potential. While this information does not factor into the vulnerability score, it supports a broader discussion on resource management in a changing climate.

Across the three MHR categories of resources assessed, exposure and sensitivity to climate-driven changes was rated as highest for doghole ports and lowest for offshore shipwrecks. This is due to the significant disturbances expected in coastal and nearshore areas from increased wave action and erosion, increased sedimentation, and inundation. These stressors are much less of a concern for deeper water shipwrecks further offshore. Dissolved oxygen and pH are concerns common across the three resource categories, with moderate to high sensitivity and very high exposure. It should be noted that confidence in future climate exposure was much lower for offshore shipwrecks due to the uncertainty of climate-driven processes at depth. Sensitivity to non-climate stressors was similar across the three resource categories, with artifact movement and biochemical degradation sensitivity rated as very high, though current exposure to these stressors is variable across resource categories: high for doghole ports, moderate for nearshore shipwrecks, and low for offshore shipwrecks. The potential impact of climate change (Table 5), which is defined as the exposure and sensitivity to climate and non-climate stressors, is high for both nearshore shipwrecks and doghole ports, and low for offshore shipwrecks.

[5] Reference pages 18-22 of the 2015 Climate Vulnerability Assessment Report (Hutto et al., 2015) for a full description of the CVA model and methodology applied here.

Table 5. The mean exposure and sensitivity scores for each MHR category, as well as the expert confidence in those scores. Potential impact is the calculated projected impact of climate change based on exposure and sensitivity.

Resource Category	Exposure	Confidence	Sensitivity	Confidence	Potential Impact
Doghole Ports	4.3 Very High	High	3.3 Mod	High	High
Nearshore Shipwrecks	3.7 High	High	3.0 Mod	Moderate	High
Offshore Shipwrecks	2.7 Mod	Low	2.6 Low	Moderate	Low

Recognizing that heritage resources cannot adapt to changing conditions, the most likely course of action in response to this assessment is to document and commemorate these resources so the intangible values can persist through stories and educational opportunities, even as the resources themselves inevitably degrade. Mitigating data loss and preserving the memories and stories of these resources should be the priority for sanctuaries moving forward. In addition, sanctuaries should investigate management opportunities where site modification could be considered a net-positive management action when weighed against resource degradation and, when applicable, implement these measures before further degradation occurs.

Recommendations, which should be considered for inclusion in the upcoming GF/CBNMS management plan review and update process, include:

- To fill knowledge gaps, develop an overall plan for continued assessment of the presence and condition of maritime heritage resources within GFNMS, CBNMS and northern MBNMS, including initial prioritization of sites for management actions.
- As a part of the maritime heritage resources assessment plan, develop and include climate-related variables among those intended to track changes in the resources' condition.
- Integrate maritime heritage historical research and field research into planning for and implementing biological/ecological field research projects; this may require an organizational shift.
- Management actions that depend on acquiring data at the locations (sites) of historic or potentially historic resources will be impacted by climate change (e.g., mapping, site recording, remote sensing) because of the physical changes that will affect both accessing the sites and the data to be gathered. Therefore, documenting maritime heritage resources should be a high priority for sanctuaries, so this information can be captured before complete degradation occurs.
- Interpretation and outreach should be conducted to maintain the intangible value of these resources, and to increase public support for documenting these maritime heritage sites and resources.

The following reports for the three assessed heritage resource categories are evaluations (represented as scores) and comments from an internal expert-elicitation workshop on the exposure and sensitivity to climate and non-climate stressors. Supporting information was either gathered from Roth (2021)[6], or was provided by workshop participants.

[6] Roth, M. (2021). Draft Climate Change Impacts to Maritime Heritage Resources: Gap Analysis. Department of Commerce, NOAA, Office of National Marine Sanctuaries. Unpublished internal agency document.

Doghole Ports

Figure 7. Trough chutes at Stewart's Point Landing and unknown schooner loading tanbark. Photo: San Francisco Maritime National Historical Park SAFR 21374.

Doghole ports are archaeological sites along the rugged and largely inaccessible north-central and northern coasts of California. These sites are small embayments where the lumber industry of the 19th and 20th centuries transferred lumber as well as produce, other products, and people from shore to ship through extensive networks of wharves, wire chutes, rail lines, and steam winches. There are 24 such sites within GFNMS boundaries, but only the 14 sites in Sonoma County have been surveyed by federal and state partners. Various archaeological evidence has been documented at these sites, including remnants of chutes and associated maritime infrastructure including anchor chains and mooring bolts. The sites were submitted in a multiple property listing for inclusion in the National Register of Historic Places (listed April 11, 2022). Two Landing Historical and Archaeological District sites were listed to the Register: Fort Ross on April 7, 2023 and Salt Point on April 11, 2022.

With the archaeological remnants of these sites spanning from the coastal bluffs (outside GFNMS boundaries) down to the subtidal submerged environment, these sites will be exposed to climate and non-climate impacts occurring with variable intensity and timing. Overall, future exposure of the remnants within GFNMS to climate change is expected to be very high, with the sensitivity of the sites to both climate and non-climate impacts rated as moderate. These sites are expected to be more sensitive to climate impacts than non-climate impacts, such as wave action, erosion, inundation and sedimentation; though there may be some benefit realized through increased concretion and reduced degradation of fully submerged artifacts. This MHR category is expected to experience the greatest potential impact from climate change in comparison with the other MHR categories assessed.

Sensitivity to climate and climate-driven stressors

Climate Stressor	**Sensitivity (score, rating**[7]**)**	**Confidence**[8]
Air temperature	1, very low	moderate
Sea temperature	3, moderate	moderate
Precipitation	1, very low	moderate
Salinity	3, moderate	moderate
Dissolved oxygen	4, high	moderate
pH	3, moderate	moderate
Increased water depth (SLR)	5, very high	high
Wave/tidal action	5, very high	high
Water flow velocity	3, moderate	moderate
Site erosion	5, very high	high
Sedimentation	5, very high	high
Storm surge/inundation	5, very high	high
Overall sensitivity	**4, high**	**moderate**

Many of these stressors will have variable impacts on doghole port remnants based on the location and condition, with greater impacts expected on those materials that are higher in the intertidal zone, and fewer impacts on those materials already submerged in the subtidal environment.

- Impacts from reduced pH may be variable; a loss of calcifying colonizers will destabilize concretion processes, but adverse impacts on wood-boring bivalves may reduce degradation.
- Decreased dissolved oxygen content may slow material corrosion rates.
- Increased water depth (SLR) may result in inundation and flooding of intertidal portions of the doghole port sites
- Coastal erosion will be exacerbated through destabilization of the sediment and vegetation matrix. The potential for novel site discovery is increased as is the risk of looting and movement of artifacts.

[7] Stressors were scored on a scale of 1-5, with 5 indicating very high sensitivity and 1 indicating very low sensitivity.
[8] Confidence level indicated by workshop participants.

- Storm surge and currents will physically alter site structure and may disperse materials.

Climate-driven stressors that may benefit the resource: Sedimentation, dissolved oxygen, pH, increased water depth

- Sedimentation could benefit doghole port remnants if burial protects against degradation.
- Dissolved oxygen is projected to decrease and, as the main driver of colonization and concretion, may result in slower degradation rates.
- pH may have negative impacts on calcifying organisms, such as *Teredo* spp. (marine wood-boring bivalves) and invasive mussels that cause resource degradation; any negative effects on these species may benefit the resource.
- Increasing water levels could benefit resources that are intertidal and cycle between water and air, as being fully inundated may result in less degradation over time.

Exposure to climate-driven stressors

Climate Stressor	**Exposure (score, rating[9])**	**Confidence[10]**
Air temperature	2, low	low
Sea temperature	5, very high	high
Precipitation	2, low	moderate
Salinity	5, very high	high
Dissolved oxygen	5, very high	high
pH	5, very high	high
Increased water depth (SLR)	3, moderate	moderate
Wave/tidal action	5, very high	high
Water flow velocity	3, moderate	moderate
Site erosion	5, very high	high
Sedimentation	5, very high	high
Storm surge/inundation	5, very high	high
Overall sensitivity	**5, very high**	**high**

[9] Stressors were scored on a scale of 1-5, with 5 indicating very high sensitivity and 1 indicating very low sensitivity.
[10] Confidence level indicated by workshop participants.

Some scores were considered as averages across intertidal and subtidal remnants; for resources that are intertidal and already exposed, future air temperature and precipitation exposure can be considered very high. Exposure to increased water depth also varies between shallow and deep resources.

Sensitivity and current exposure to non-climate stressors

Non-climate Stressor	**Sensitivity (score[11], rating[12])**	**Confidence**	**Current exposure (score, rating)**	**Confidence**
Artifact movement	5, very high	high	4, high	high
Biochemical degradation	5, very high	high	4, high	high
Neglect	3, moderate	high	3, moderate	high
Pollution/run-off	2, low	low	1, very low	high
Research	4, high	moderate	2, low	high
Visitation	2, low	low	1, very low	moderate
Algal growth	1, very low	low	3, moderate	low
Overall	**3, moderate**	**moderate**	**3, moderate**	**high**

Fishing is a potential non-climate stressor, but impacts have not been documented in the region, nor has it been documented at specific doghole port sites in GFNMS and was therefore omitted from the list, but should be considered if data becomes available. *Teredo* spp. are of specific concern when it comes to biological degradation. The rating for "neglect" refers to The National Historic Preservation Act of 1966 (NHPA) which states that sanctuaries have a responsibility to manage these resources, and are currently doing so in a very limited capacity. Visitation is rated as low because it is only possible at a few sites, and most are difficult to access by land.

Heritage significance

Maritime heritage resources with high structural integrity often hold greater archaeological or historical value, and therefore greater significance to constituents. The perception of adverse impacts from climate change on these resources may be greater if they are damaged or lost; however, they may also garner better public support for management actions.

<u>How much do people value this resource category:</u> Low

- Confidence of workshop participants: High

[11] Stressors were scored on a scale of 1-5, with 5 indicating very high sensitivity and 1 indicating very low sensitivity.
[12] Confidence level indicated by workshop participants.

The doghole port resource category is relatively little known by the public compared to shipwrecks, as they are not one single structure but specific locations with closely associated multiple features. Only relatively recently, after the GFNMS boundaries were expanded by NOAA in 2015, have publications and web information been released about them. There is great historical, aesthetic, educational, and recreational value, with some diving and snorkeling around doghole ports. The National Register of Historic Places evaluation for the majority of locations is in process, and this implies there is great historical value for these resources. This low rating applies to the general public, but there is much greater value for the maritime heritage community and the broader sanctuary community.

Likelihood of maintaining resource significance under a changing climate: High

- Confidence of workshop participants: High

There is a high likelihood of maintaining intangible values, though resources will continue to physically degrade. The difficulty of visiting sites will continue and may worsen. Diving may become more difficult due to changing ocean conditions. However, there is great opportunity and potential to increase this resource category's educational value. The doghole port site at Fort Ross is a great example of historical and educational value, and the California Department of Parks and Recreation (California State Parks) is a critical partner in education and recognition.

Data management potential

Current restrictions in assessing or conducting research on the resource category: Regulations, permits, funding, reduced accessibility.

- It is best practice to leave maritime heritage resources in place. While this assists managers in retaining integrity of place and setting, it creates limitations in the preservation of archaeological remnants. *In-situ* preservation is the preferred treatment for archaeological resources; however, it remains time, energy, and resource intensive for effective management.
- Sanctuary regulations prohibit possessing, moving, removing, or injuring, or attempting to possess, move, remove or injure, a sanctuary historical resource (15CFR922.82(a)(9); 15CFR922.112(a)(7); and 15CFR922.132(a)(3)).[13]
- National Marine Sanctuary permits may be issued for activities that would otherwise be prohibited, without a permit, by sanctuary regulations (15CFR922.30 - 922.35). Activities that are not prohibited by the regulations do not require a National Marine Sanctuary permit, though they may require permits or other approvals by other agencies.
- Funding is a restriction, as the research required is often expensive.
- Safe access to some sites is a restriction due to ocean conditions. Some sites may not ever be able to be assessed due to environmental conditions.
- Reduced accessibility to conduct research due to private land ownership upland of some sites may also be a restriction.

[13] The MBNMS prohibition does not apply to, moving, removing, or injury resulting incidentally from kelp harvesting, aquaculture, or lawful fishing activities.

Likelihood of managing data loss due to climate impacts: Very Low

- Confidence of workshop participants: High

Likelihood of managing or alleviating climate impacts: Very Low

- Confidence of workshop participants: High

In just the last decade this resource category has been recognized as being historically significant. There is opportunity to continue to capitalize on the novelty of this heritage resource and focus messaging in a strategic way to educate communities.

Nearshore Shipwrecks

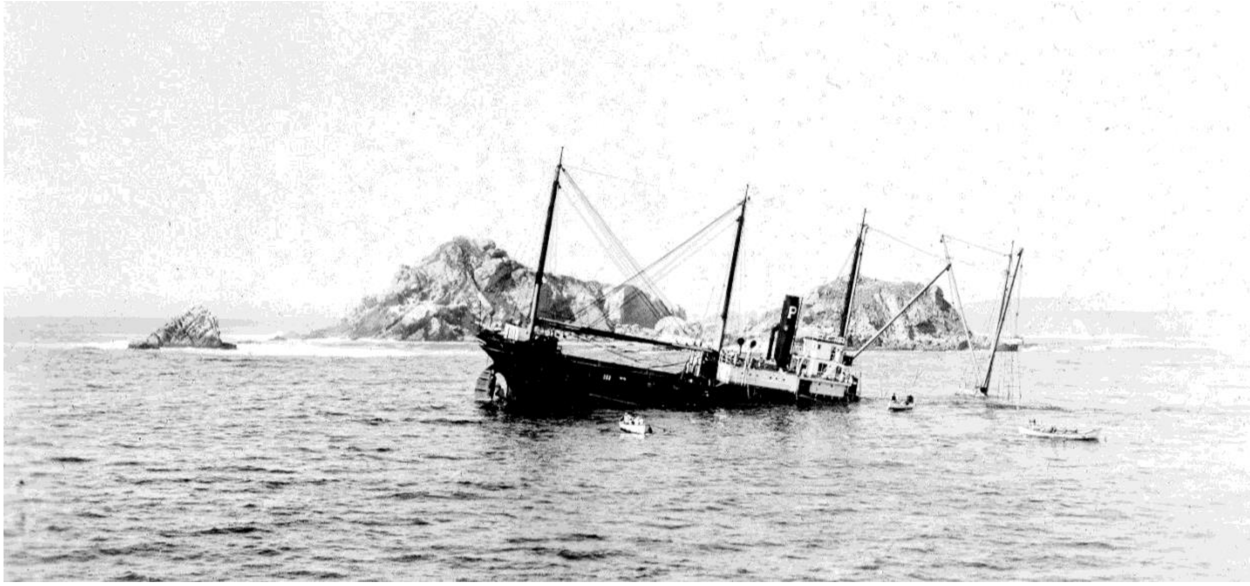

Figure 8. SS Dorothy Wintermote, lost in 1938, in Greater Farallones National Marine Sanctuary. Photo: San Francisco Maritime National Historic Park.

Nearshore shipwrecks are defined as those that are shallower than 30 meters[14]. There are 24 nearshore shipwrecks known to exist in GFNMS, none in CBNMS, and 8 in the northern portion of MBNMS. Loss records indicate that there could be more nearshore shipwrecks within the sanctuaries yet to be discovered. Sixteen shipwrecks were formally documented by federal, state, or private sector partners. Summary findings of the condition of 13 wrecks (7 of which are nearshore wrecks) have been made, and all 13 were found to have experienced physical degradation. These wrecks are composed of a variety of materials, including wood, iron and steel.

For nearshore shipwrecks, future exposure to climate change is expected to be high (less than that of doghole ports, but greater than offshore wrecks), with the sensitivity of these resources to both climate and non-climate impacts rated as moderate. These sites are expected to be slightly more sensitive to climate impacts than non-climate impacts, including dissolved oxygen, wave action, erosion and sedimentation; though there may be some benefit realized through reduced degradation of artifacts protected by sedimentation. This resource category is projected to experience high potential impact from climate change, slightly less than that of doghole ports but greater than offshore wrecks.

[14] This is consistent with the Climate Vulnerability Assessment (Hutto et al.,2015), which defines the nearshore environment as less than 30 m; however, is different from that of the GFNMS Condition Report (ONMS 2010) in which it is defined as less than 20 m.

Sensitivity to climate-driven stressors

Climate Stressor	Sensitivity (score, rating[15])	Confidence[16]
Sea temperature	3, moderate	moderate
Salinity	3, moderate	moderate
Dissolved oxygen	4, high	moderate
pH	3, moderate	moderate
Increased water depth (SLR)	1, very low	low
Wave/tidal action	4, high	high
Water flow velocity	2, low	moderate
Site erosion	5, very high	high
Sedimentation	5, very high	high
Overall sensitivity	**4, high**	**moderate**

The nearshore environment is highly dynamic, and there are likely impacts from storms due to water and sediment movement, and erosion and sedimentation from the coastal environment. Depth of the resource is a driving degradation factor; shallow resources are likely to be more exposed to these impacts. For example, part of the *Tennessee* shipwreck sits above the water line and, as such, is subject to terrestrial and submerged degradative forces. In addition to continual processes, seasonal storm activity that removes sediment from beaches may uncover previously covered shallow nearshore wrecks, possibly resulting in an increase in visitation and looting. Though sea level rise may not generally be a concern for nearshore wrecks, there is not enough information to know how much sea level rise may impact resources due to the changing gas content of seawater with depth. Workshop participants expressed a higher confidence in the physical processes such as direct damage, and lower confidence in oceanographic processes and impacts.

- Dissolved oxygen is a main driver of corrosion; anaerobic environments are important and decreased dissolved oxygen content may slow material corrosion rates.
- Wave and tidal action can lead to currents, scouring, and changes to gas diffusion (the rate that water passes over differential membranes and impacts corrosion). Storm surge and currents will physically alter site structure and may disperse materials.
- Erosion at the site could undermine, encapsulate, and/or scatter materials.
- Sedimentation could cause increased scouring, or could actually protect the resource (depends on the type of resource, type of encapsulation). High energy shallow water areas

[15] Stressors were scored on a scale of 1-5, with 5 indicating very high sensitivity and 1 indicating very low sensitivity.
[16] Confidence level indicated by workshop participants.

may experience increased erosion and sediment loss, while low energy shallow environments may experience enhanced protection from sedimentation.
- Warming ocean waters could increase the abundance of *Teredo* shipworm species.

Climate-driven stressors that may benefit the resource: Sedimentation, dissolved oxygen, pH.
- Sedimentation could benefit nearshore shipwrecks if burial protects against degradation.
- pH may have negative impacts on calcifying organisms, such as *Teredo* and invasive mussels that cause resource degradation; any negative effects on these species may benefit the resource.
- Dissolved oxygen is projected to decrease and, as the main driver of colonization and concretion, may slow these processes and prolong total resource loss.

Exposure to climate-driven stressors

Climate Stressor	**Exposure (score, rating[17])**	**Confidence [18]**
Sea temperature	5, very high	high
Salinity	5, very high	high
Dissolved oxygen	5, very high	high
pH	5, very high	high
Increased water depth (SLR)	1, very low	moderate
Wave/tidal action	4, high	high
Water flow velocity	2, low	moderate
Site erosion	3, moderate	high
Sedimentation	3, moderate	high
Overall sensitivity	**4, high**	**high**

Sensitivity and current exposure to non-climate stressors

Non-climate Stressor	**Sensitivity (score, rating[17])**	**Confidence[18]**	**Current exposure (score, rating)**	**Confidence**
Artifact movement	5, very high	high	3, moderate	low
Biochemical degradation	5, very high	high	4, high	high

[17] Stressors were scored on a scale of 1-5, with 5 indicating very high sensitivity and 1 indicating very low sensitivity.
[18] Confidence level indicated by workshop participants.

Non-climate Stressor	Sensitivity (score, rating[17])	Confidence[18]	Current exposure (score, rating)	Confidence
Fishing	5, very high	high	2, low	low
Hazardous materials (cargo, bunker fuel)	2, low	moderate	2, low	low
Neglect	3, moderate	high	5, very high	high
Pollution/run-off	2, low	low	1, very low	high
Research	2, low	low	3, moderate	high
Visitation	2, low	moderate	1, very low	high
Algal growth	1, very low	low	3, moderate	low
Overall	**3, moderate**	**moderate**	**3, moderate**	**moderate**

There are a number of data and assessment gaps. While evidence of past looting has been documented for several shipwrecks in the sanctuaries (e.g., SS *Klamath*, SS *Pomona*), it is not clear if this is a current stressor. Similarly, two offshore wrecks (TV *Puerto Rican*, SS *Selja*) have derelict fishing gear on parts of the wrecks (actual impacts on the wrecks not assessed), but it is not known how prevalent an impact fishing or derelict gear may be on resource quality. While research activities are occurring in these areas, their impacts on nearshore shipwrecks are not assessed.

Heritage significance

Maritime heritage resources with high structural integrity often hold greater archaeological or historical value, and therefore greater significance to constituents. The perception of adverse impacts from climate change on these resources may be greater if they are damaged or lost; however, they may also garner better public support for management actions.

<u>How much do people value this resource category:</u> Moderate

- Confidence of workshop participants: Low

The value of nearshore shipwrecks includes consideration of aesthetic, archaeological, commercial, educational, historical, recreational, and traditional values. Resources listed on the National Register of Historic Places include the *Norlina* and the SS *Pomona* in GFNMS, and the SS *Tennessee* in the northern portion of MBNMS. There is also great interest in the historical and archaeological value of nearshore shipwrecks. Some recreational diving occurs, and there is educational value.

<u>Likelihood of maintaining resource significance under a changing climate:</u> Moderate

- Confidence of workshop participants: High

The likelihood of maintaining resource integrity and therefore significance is lower than offshore shipwrecks due to relatively higher disturbance and degradation. Many of these resources still have intangible resource significance, including education, and stories that can be maintained. Some place names are based on shipwrecks, which leaves a lasting legacy. Different ratings could be given for tangible vs intangible resource significance. Historic listings are contingent on a strong degree of integrity (of materials and form) and there is a possibility that resources will become ineligible as they degrade. Effort should focus, therefore, on documenting resources *in situ* and improved understanding of degradation rates.

Data management potential

Maritime heritage resource management potential is based on current resource condition and the potential to conduct research. The ability to conduct research and better understand the MHR category is one means of reducing the impacts of climate change. For nearshore shipwrecks, partnerships are critical for recognition, awareness, research and education.

<u>Current restrictions in assessing or conducting research on the resource category:</u> Regulations, permits, funding.

- It is best practice to leave maritime heritage resources in place. While this assists managers in retaining integrity of place and setting, it creates limitations in the preservation of archaeological remnants. *In-situ* preservation is the preferred treatment for archaeological resources; however, it remains time, energy, and resource intensive for effective management.
- Regulations for the sanctuaries prohibit possessing, moving, removing, or injuring, or attempting to possess, move, remove or injure, a sanctuary historical resource (15CFR922.82(a)(9); 15CFR922.112(a)(7); and 15CFR922.132(a)(3)).
- National Marine Sanctuary permits may be issued for activities that would otherwise be prohibited, without a permit, by sanctuary regulations (15CFR922.30 - 922.35). Activities that are not prohibited by the regulations do not require a National Marine Sanctuary permit, though they may require permits or other approvals by other agencies.
- Funding is a restriction, as the research required is often expensive.
- Safe access to some sites is a restriction due to ocean conditions. Some sites may not ever be able to be assessed.

<u>Likelihood of managing data loss due to climate impacts</u>: Very Low

- Confidence of workshop participants: High

<u>Likelihood of managing or alleviating climate impacts</u>: Very Low

- Confidence of workshop participants: High

With funding, staffing, more robust partnerships, and prioritization from management, there could be increased management potential.

Offshore Shipwrecks

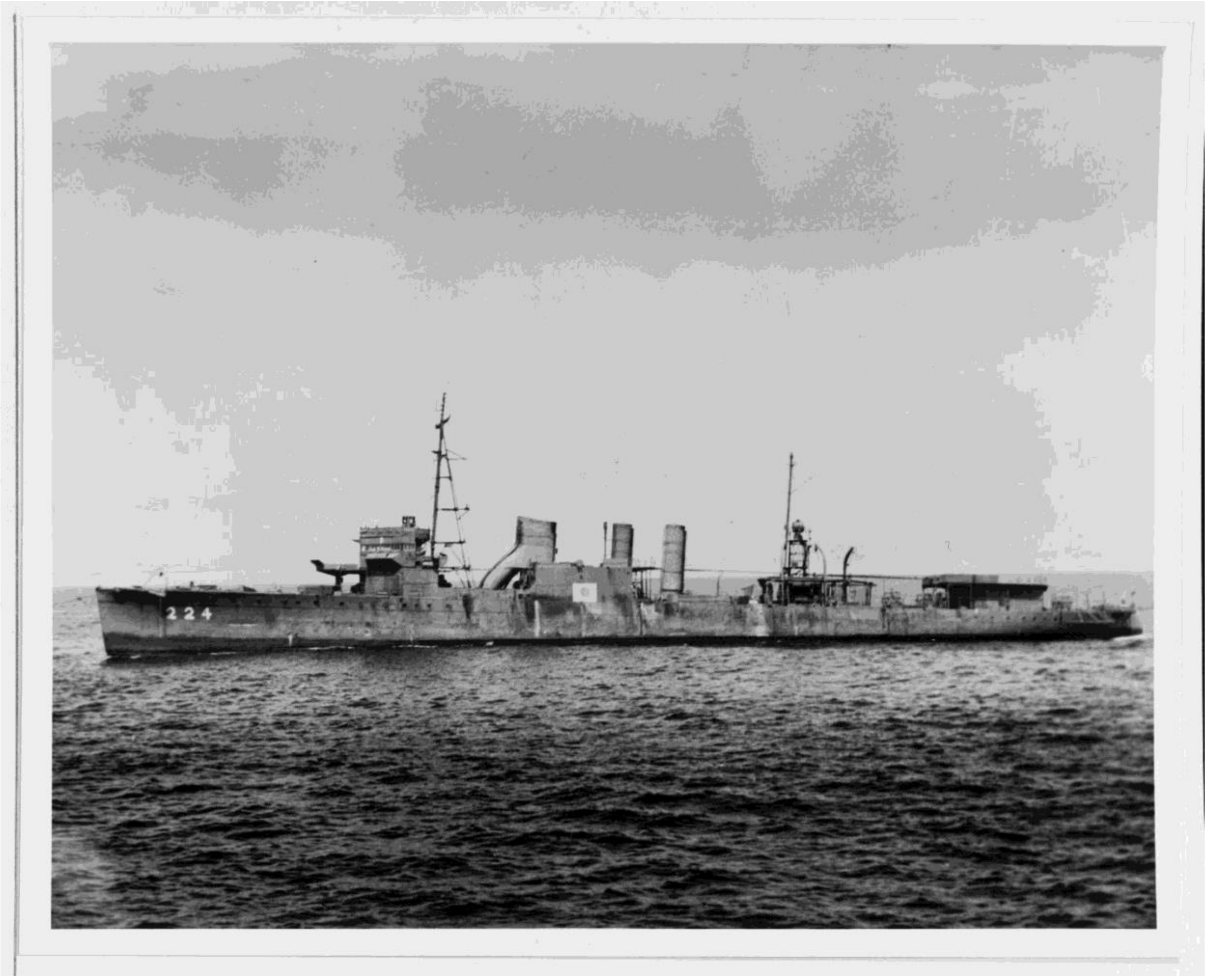

Figure 9. Ex-USS Stewart (DD-224) on May 24, 1946, just before being sunk. Photo: Official U.S. Navy Photograph, National Archives and Records Administration.

Offshore shipwrecks are defined as those that are deeper than 30 meters[19]. There are 10 offshore shipwrecks known to exist in GFNMS, one in CBNMS, and one in the northern portion of MBNMS. Loss records indicate that there could be more offshore shipwrecks yet to be discovered. Sixteen shipwrecks were formally documented by federal, state, or private sector partners. Summary findings of the condition of 13 wrecks (6 of which are offshore wrecks) indicate all have experienced physical degradation. These wrecks are composed of a variety of materials, including wood, iron and steel.

For offshore shipwrecks, future exposure to climate change is expected to be moderate, which is less than that of doghole ports and nearshore wrecks, with the sensitivity of these resources to both climate and non-climate impacts rated as low. These sites are expected to be slightly more

[19] This is consistent with the Climate Vulnerability Assessment (Hutto et al., 2015), which defines the offshore environment as greater than 30 m; however, is different from that of the GFNMS Condition Report (ONMS 2010) in which it is defined as greater than 20 m.

sensitive to non-climate impacts than to climate impacts due to possible artifact movement and biochemical degradation. However, it should be noted that the climate sensitivity of offshore wrecks is highly uncertain, with the lowest confidence rating in this MHR assessment. This resource category is projected to experience low potential impact from climate change, much less than that of doghole ports and nearshore shipwrecks.

Sensitivity to climate-driven stressors

Climate Stressor	**Sensitivity (score, rating[20])**	**Confidence[21]**
Sea temperature	3, moderate	moderate
Salinity	3, moderate	moderate
Dissolved oxygen	4, high	moderate
pH	3, moderate	moderate
Water flow velocity	1, very low	moderate
Site erosion	2, low	moderate
Sedimentation	3, moderate	moderate
Storm surge/inundation	5, very high	high
Overall sensitivity	**3, moderate**	**low**

Effects of salinity are largely unknown, and there are data gaps on the effects of deep currents and upwelling.

<u>Climate-driven stressors that may benefit the resource</u>: Sedimentation, seawater temperature, dissolved oxygen, pH

- Sedimentation could benefit offshore wrecks if it protects against degradation.
- pH may have negative impacts on calcifying organisms, such as *Teredo* and invasive mussels that cause resource degradation; any negative effects on these species may benefit the resource.
- Dissolved oxygen is projected to decrease and as the main driver of colonization and concretion, two processes affecting the rate of degradation, may prolong time until the resource is lost.

[20] Stressors were scored on a scale of 1-5, with 5 indicating very high sensitivity and 1 indicating very low sensitivity.
[21] Confidence level indicated by workshop participants.

Exposure to climate stressors

Climate Stressor	Exposure (score, rating[22])	Confidence [23]
Sea temperature	3, moderate	moderate
Salinity	2, low	low
Dissolved oxygen	3, moderate	moderate
pH	5, very high	high
Water flow velocity	2, low	low
Site erosion	2, low	low
Sedimentation	2, low	low
Overall sensitivity	**3, moderate**	**low**

Sensitivity and current exposure to non-climate stressors

Non-climate Stressor	Sensitivity (score, rating[22])	Confidence[23]	Current exposure (score, rating)	Confidence
Artifact movement	5, very high	high	2, low	low
Biochemical degradation	5, very high	moderate	3, moderate	low
Fishing/trawling	4, high	moderate	2, low	low
Hazardous materials (cargo, bunker fuelt)	2, low	moderate	2, low	moderate
Neglect	3, moderate	high	5, very high	moderate
Pollution/run-off	2, low	low	1, very low	high
Research	2, low	low	3, moderate	high
Visitation	2, low	low	1, very low	high
Algal growth	1, very low	low	1, very low	low
Overall	**3, moderate**	**moderate**	**2, low**	**moderate**

[22] Stressors were scored on a scale of 1-5, with 5 indicating very high sensitivity and 1 indicating very low sensitivity.
[23] Confidence level indicated by workshop participants.

There are a number of data and assessment gaps. Evidence of past looting is less prevalent at deep-water shipwreck sites than nearshore sites due to the required effort to access deeper sites and their associated artifact assemblages; it is not clear if this is a current stressor. Two offshore wrecks (TV *Puerto Rican*, SS *Selja*), have derelict fishing gear on parts of the wrecks (actual impacts on the wrecks not assessed). Without more intensive study of offshore sites, the impact of fishing gear cannot be quantified and it is not known how prevalent an impact fishing or derelict gear may be on resource quality. Future seafloor use, including offshore energy development, carbon sequestration, and materials mining is of concern; however, there are few metrics to delineate potential future impacts. Similarly, while research activities are occurring in these areas, their impacts on offshore shipwrecks are not assessed.

Heritage significance

Maritime heritage resources with high structural integrity often hold greater archaeological or historical value, and therefore greater significance to constituents. The perception of adverse impacts from climate change on these resources may be greater if they are damaged or lost; however, they may also garner better public support for management actions.

<u>How much do people value this resource category:</u> Moderate

- Confidence of workshop participants: Low

The value of offshore shipwrecks includes consideration of aesthetic, archaeological, commercial, educational, historical, recreational, and traditional values. Several wrecks are listed on the National Register of Historic Places. A very minor amount of recreational diving takes place on these deeper wrecks (less than nearshore wrecks). The USS *Conestoga*, in GFNMS, is a military grave site, a remnant of human history and American heritage and is listed on the National Register of Historic Places. Along with the SS *Ituna*, these two wrecks received much public and media attention, resulting in exposure to a broader audience. The significance of these sites may be enhanced due to this media attention, although the metrics for understanding significance have not been tracked. Overall, offshore wrecks experience less disturbance, and a higher structural integrity may increase their aesthetic and engagement value. The ex-USS *Independence*, an aircraft carrier that was intentionally sunk, holds value for those still alive who served on the vessel in World War II, and serves as a legacy of that time in US history. This is also applicable to the ex-USS *Stewart* (DD-224), also intentionally sunk, which is the only known maritime heritage resource in CBNMS.

<u>Likelihood of maintaining resource significance under a changing climate:</u> High

- Confidence of workshop participants: High

Though a lower rating could be justified because we know that climate change will accelerate degradation, the likelihood of maintaining resource significance is higher than nearshore shipwrecks due to relatively lower disturbance and degradation. Many of these resources still have intangible resource significance, including education, and stories that can be maintained. Emphasis on historical research may result in maintaining significance and cultural value.

Data management potential

Maritime heritage resource management potential is based on current resource condition and the potential to conduct research. The ability to conduct research and better understand the MHR category is one means of reducing the impacts of climate change.

Current restrictions in assessing or conducting research on the resource category: Regulations, permits, funding.

- It is best practice to leave maritime heritage resources in place. While this assists managers in retaining integrity of place and setting, it creates limitations in the preservation of archaeological remnants. *In-situ* preservation is the preferred treatment for archaeological resources; however, it remains time, energy, and resource intensive for effective management.
- Regulations for the sanctuaries prohibit possessing, moving, removing, or injuring, or attempting to possess, move, remove or injure, a sanctuary historical resource (15CFR922.82(a)(9); 15CFR922.112(a)(7); and 15CFR922.132(a)(3)).
- National Marine Sanctuary permits may be issued for activities that would otherwise be prohibited, without a permit, by sanctuary regulations (15CFR922.30 - 922.35). Activities that are not prohibited by the regulations do not require a National Marine Sanctuary permit, though they may require permits or other approvals by other agencies.
- As these resources are more difficult to access due to geographic location and water depth, funding is a severe restriction due to technological requirements.
- Safe access to some sites is a restriction due to ocean conditions. Some sites may not ever be able to be assessed due to the physical conditions at the site.

Likelihood of managing data loss due to climate impacts: Low

- Confidence of workshop participants: High

The likelihood of managing data loss is even lower than that of the nearshore shipwrecks. But with funding, staffing, partners, and management priority, there could be increased management potential. This is a critical priority because these are non-renewable resources.

Likelihood of managing or alleviating climate impacts: Low

- Confidence of workshop participants: High

References

Auth, T. D., Daly, E. A., Brodeur, R. D., & Fisher, J. L. (2018). Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. *Global Change Biology*, *24*, 259– 272. DOI: 10.1111/gcb.13872

Elliott, M. L., Lipski, D., Roletto, J., Warzybok, P., & Jahncke, J. (2022). Ocean Climate Indicators Status Report: 2021. Unpublished report. Point Blue Conservation Science (Contribution No. 2422), Petaluma, CA.

Foden, W. B., Butchart, S. H. M., Stuart, S. N., Vié, J. -C., Akçakaya, H. R., Angulo, A., ... & Mace, G. M. (2013). Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. *PLoS One*, 8, e65427. DOI: 10.1371/journal.pone.0065427

Frölicher, T. L., Fischer, E. M., Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, *560*, 360–364. DOI: 10.1038/s41586-018-0383-9

Hutto, S. V., Higgason, K. D., Kershner, J. M., Reynier, W. A., & Gregg, D. S. (2015). Climate Change Vulnerability Assessment for the North-central California Coast and Ocean. *Marine Sanctuaries Conservation Series ONMS-15-02*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 473 pp.

Hutto, S.V. (2016). Climate Adaptation Plan. Report of the Greater Farallones National Marine Sanctuary. NOAA. San Francisco, CA. 19 pp.

Largier, J.L, Cheng, B.S., and Higgason, K.D., editors. (2010). Climate Change Impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries. Report of a Joint Working Group of the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries Advisory Councils. Marine Sanctuaries Conservation Series ONMS-11-04. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 121 pp.

Lonhart, S. I., Jeppesen, R., Beas-Luna, R., Crooks, J. A., & Lorda, J. (2019). Shifts in the distribution and abundance of coastal marine species along the eastern Pacific Ocean during marine heatwaves from 2013 to 2018. *Marine Biodiversity Records*, *12*, 1-15. DOI: 10.1186/s41200-019-0171-8.

Office of National Marine Sanctuaries. 2010. Gulf of the Farallones National Marine Sanctuary Condition Report 2010. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 97 pp.

Rogers-Bennett, L., & Catton, C. A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, 9, 15050. DOI: 10.1038/s41598-019-51114-y

Sanford, E., Sones, J. L., Garcia-Reyes, M., Goddard, J. H. R., & Largier, J. L. (2019). Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. *Nature*, *9*, 4216. DOI: 10.1038/s41598-019-40784-3

Appendix A: Assessment Revision Experts, Reviewers, and Workshop Attendees

Resource	**Subject-matter expert**	**Reviewers**
Black Oystercatcher	Kirsten Lindquist, GFA	n/a, not revised
Black Rail	Julian Wood, Point Blue	n/a, not revised
Blue Rockfish	Mark Carr, UCSC	Scott Hamilton, MLML; Tom Laidig, NOAA
Blue Whale	Meredith Elliott, Point Blue	Jaime Jahncke, Point Blue
California Mussel	Melissa Miner, UCSC	Eric Sanford, BML; Corey Garza, CSUMB; Kathy Ann Miller, UCB; Laura Rogers-Bennett, CDFW
Cassin's Auklet	Kirsten Lindquist, GFA	Pete Warzybok, Point Blue
Cavity Nesters (Ashy Storm Petrel, Tufted Puffin, PIGU)	Pete Warzybok, Point Blue	n/a, not revised
Copepod	Jaime Jahncke and Meredith Elliott, Point Blue	n/a, not revised
Coralline Algae	Melissa Miner, UCSC	Eric Sanford, BML; Kathy Ann Miller, UCB; Laura Rogers-Bennett, CDFW
Hydrocoral/Sponge	Dani Lipski, GF/CBNMS	Kaitlin Graiff, ONMS; Tom Laidig, NOAA
Krill	Meredith Elliott, Point Blue	Jaime Jahncke, Point Blue
Mole Crab	Kirsten Lindquist and Jaclyn Schneider, GFA	n/a, not revised
Northern Anchovy/Pacific Sardine	John Field, NOAA	Andrew Thompson, NMFS
Ochre Sea Star	Melissa Miner, UCSC	Eric Sanford, BML; Laura Rogers-Bennett, CDFW
Olympia Oyster	Edwin D. Grosholz, UCD	Kerstin Wasson, Elkhorn Slough NERR
Pacific Herring	Andrew Weltz, CDFW	

Resource	Subject-matter expert	Reviewers
Pteropod	Meredith Elliott, Point Blue	Jaime Jahncke, Point Blue; Nina Bednarsek, SCCWRP
Red Abalone	Laura Rogers-Bennett, CDFW	Mike Kenner, USGS; Mark Carr, UCSC
Sea Otter	Lilian Carswell, USFWS	Colleen Young, CDFW; Mike Kenner, USGS
Sea Palm	Melissa Miner, UCSC	Eric Sanford, BML; Kathy Ann Miller, UCB; Rebecca Flores-Miller, CDFW
Sea Urchins	Mark Carr, UCSC	Rietta Hohman, GFA; Mike Kenner, USGS; Laura Rogers-Bennett, CDFW
Snowy Plover	Kirsten Lindquist, GFA	Matt Lau, NPS; Edwin D. Grosholz, UCD
Surface Nesters (Brandt's Cormorant, Common Murre)	Kirsten Lindquist, GFA	n/a, not revised
Tidewater Goby	Darren Fong, NPS	n/a, not revised
Widow Rockfish	Tom Laidig, NMFS	n/a, not revised
Beaches and Dunes	Kirsten Lindquist, GFA	n/a, not revised
Cliffs	Pete Warzybok, Point Blue	n/a, not revised
Estuaries	Edwin D. Grosholz, UCD	Kerstin Wasson, Elkhorn Slough NERR
Kelp Forest	Rietta Hohman, GFA	Mike Kenner, USGS; Kristen Elsmore, CDFW
Nearshore soft bottom	Steve Lonhart, MBNMS	Scott Hamilton, MLML; Tom Laidig, NOAA
Offshore rocky reefs	Dani Lipski, GF/CBNMS	Kaitlin Graiff, ONMS; Tom Laidig, NOAA
Pelagic	Meredith Elliott, Point Blue	Jaime Jahncke, Point Blue; Nina Bednarsek, SCCWRP
Rocky Intertidal	Kirsten Lindquist and Jaclyn Schneider, GFA	Melissa Miner, UCSC; Eric Sanford, BML; Corey Garza, CSUMB
Carbon Storage and Sequestration	Sara Hutto, GFA	Doug George, NOAA; Wendy Kordesch, GFA
Flood and Erosion Protection	Wendy Kordesch, GFA	Doug George, NOAA; Sara Hutto, GFA

Workshop attendees: Sara Hutto (GFA), Monisha Sugla (GF/CBNMS), Dani Lipski (GF/CBNMS), Kaitlin Graiff, Jan Roletto (GF/CBNMS), Maria Brown (GF/CBNMS), Kirsten Lindquist (GFA), Steve Lonhart (MBNMS), Zac Cannizzo (ONMS), Jaime Jahncke (Point Blue), Melissa Miner (UCSC), Corey Garza (CSUMB), Meredith Elliot (Point Blue), Douglas George (NOAA OCM), John Field (NOAA), Rebecca Flores Miller (CDFW), Edwin Grosholz (BML), Colleen Young (CDFW), Tom Laidig (NOAA), Keighley Lane (CINMS), Jordan Gorostiza (GFA), Gina Contolini (GFA), Angela Zepp (GFA), Brian Johnson (GF/CBNMS), Carol Preston (GF/CBNMS).

Maritime Heritage Resource assessments

Resource experts: Madilyn Roth (ONMS), Hans Van Tilburg (ONMS), Robert Schwemmer (ONMS West Coast Region), Lilli Ferguson (GF/ CBNMS), Erica Burton (MBNMS).
Note-taker: Grace Kumaishi (ONMS West Coast Region)
Facilitator: Sara Hutto (GF/CBNMS)

Appendix B. Updated Climate Projections for the North-central California Coast and Ocean

The Greater Farallones 2010 Climate Change Impacts Report (Largier et al., 2010) informed the 2015 climate vulnerability assessment and identified 11 major climate impacts and trends. In the intervening decade, our understanding of climate change has advanced and predictions have been refined. While some trends identified in the 2010 report remain the same, many are accelerating faster than initially expected. The below table summarizes each of the major climate trends from the 2010 report, in addition to ocean deoxygenation, and provides information on how our understanding of those trends has changed since that report.

Climate Hazard	Trend from 2010 report	Change in projected trend since 2010	Explanation of change in projection	Supporting Literature
Sea Level Rise	Up to 75 inches by 2100	No meaningful change in projection	The most recent (2022) NOAA sea level rise projections predict up to 57 (intermediate high) to 78 inches (high scenario) of sea level rise by 2100.	Sweet et al. 2022 NOAA SLR viewer
Coastal Erosion	Increase due to rising sea levels and increased wave and storm intensity	Likely to be greater change than previously projected	A number of recent studies suggest a higher incidence of extreme precipitation and flood events than previously predicted as well as an increase in storm strength (see below). While no studies project erosion, it is likely that these effects will accelerate coastal erosion beyond previous estimates.	See precipitation and extreme events below
Spring Runoff	Decreases due to decreased Sierra snowpack	Greater projected change than previous projections	Studies suggest a more rapid shift in Sierra precipitation towards rainfall, leading to decreased snowpack and spring runoff by 2100. Spring runoff is projected to decrease and occur earlier.	Schwartz et al. 2017 Sun et al. 2019

Climate Hazard	Trend from 2010 report	Change in projected trend since 2010	Explanation of change in projection	Supporting Literature
Precipitation	Increased variability with drier dry years and wetter wet years	Previously projected change already being observed. Greater projected change than previous projections.	Wetter wet years and drier dry years are already being observed. Projected increases in the frequency and intensity of both extreme wet and extreme dry events. Projected 25-100% increase in extreme dry-to-wet precipitation events. Projected increase in rapid transitions from very wet to very dry years and vice-versa.	Warner et al. 2015 Wehner et al. 2017 Swain et al. 2018
Water Temperature	Increase offshore and over continental shelf	Greater projected change than previous projections	Sea surface temperatures in the sanctuary could increase between 1.5 and 3 ^{o}C by 2100. Bottom water temperatures in the sanctuary could increase between 1 and 2 ^{o}C by 2100. These changes may be partially mitigated by increasing upwelling intensity.	Howard et al. 2020 Siedlecki et al. 2021 Pozo-Buil et al. 2021
Upwelling	Enhanced upwelling due to increasing alongshore winds	Greater uncertainty than previous projections	Upwelling timing and intensity are projected to change across the region over the next century. Projected increase in spring upwelling intensity, some decrease in summer upwelling. Overall, a likely increase in upwelling intensity in Greater Farallones and Cordell Bank, with greater uncertainty in trend towards the southern end of the Sanctuaries.	Howard et al. 2020 Pozo-Buil et al. 2021

Climate Hazard	Trend from 2010 report	Change in projected trend since 2010	Explanation of change in projection	Supporting Literature
Extreme Events	Increase in frequency and intensity	Greater projected change than previous projections	MHWs are expected to increase in frequency and intensity. Total number of non-atmospheric river storms may decrease. Storms, including atmospheric river events, are expected to increase in intensity with greater likelihood for extreme precipitation events.	Wang et al. 2017 Frölicher et al. 2018 Knutson et al. 2019 Huang et al. 2020 Corringham et al. 2022 Huang and Swain 2022
Ocean Acidification	Decrease in pH, increase in pCO_2	Greater projected change than previous projections	The acidity of California waters has increased by 60% (decrease of 0.21 pH) since 1895, a faster rate than previously thought. pH of California waters could decrease an additional 40% below 1995 levels by 2050.	Gruber et al. 2012 Osborne et al. 2020
Species Range Shifts	Expected northward shift of key species	Previously projected change already being observed. Greater projected change than previous projections.	Species have been observed moving generally northward and deeper, more quickly than previously anticipated. MHWs led to unprecedented rapid and extreme shifts.	Poloczanska et al. 2013 Sandford et al. 2019 Lonhart et al. 2019 Pinsky et al. 2020
Phytoplankton Community	Shift in dominant taxa from larger species to smaller species	Previously projected change already being observed. Greater projected change than previous projections.	A shift in the phytoplankton community towards smaller species was observed during the 2013-2016 heatwave and is seen as a possible glimpse into future conditions. Shifts towards domination of the zooplankton community by smaller species has also been observed and is expected under future conditions.	Fisher et al. 2015 Cavole et al. 2016 Sandford et al. 2019

Climate Hazard	Trend from 2010 report	Change in projected trend since 2010	Explanation of change in projection	Supporting Literature
Human impacts	Climate impacts will be compounded by human impacts	Previously projected change already being observed. Likely to be greater change than previously projected.	Expected to continue and likely to increase. Sharp example is the record whale entanglement within Monterey Bay in 2016 resulting from an intersection of heatwave-driven impacts on upwelling, a HAB triggered by the heatwave, and the Dungeness crab fishery.	Santora et al. 2020
Deoxygenation	Not included in 2010 report as this was not a widely-known climate impact at the time		Oxygen concentrations in deep waters off California have dropped by 20% since 1980. Oxygen levels in deep waters could drop below the range of natural variability between 2030 and 2060. Expected to be exacerbated by upwelled water that is progressively lower in oxygen due to climate-driven changes in oxygen supplies to deep waters globally.	Bograd et al. 2015 Long et al. 2016 Ito et al. 2017 Breitburg et al. 2018 Howard et al. 2020 Pozo-Buli et al. 2021

Bograd, S.J., Pozo Buil, M., Di Lorenzo, E., Castro, C.G., Schroeder, I.D., Goericke, R., Anderson, C.R., Benitez-Nelson, C., & Whitney, F.A. (2015). Changes in source waters to the Southern California Bight. *Deep Sea Research Part II: Topical Studies in Oceanography, 112*, 42-52. DOI: 10.1016/j.dsr2.2014.04.009.

Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., ... & Zhang, J. (2018). Declining oxygen in the global ocean and coastal waters. *Science*, *359*(6371), eaam7240. DOI:10.1126/science.aam7240.

Cavole, L.M., Demko, A.M., Diner, R.E., Giddings, A., Koester, I., Pagniello, C.M.L.S., Paulsen, M., Ramirez-Valdez, A., Schwenck, S.M., Yen, N.K., Zill, M.E., & Franks, P. (2016) Biological impacts of the 2013-2016 warm-water anomaly in the northeast Pacific: Winners, losers, and the future. *Oceanography, 29*(2), 273-285.

Corringham, T. W., McCarthy, J., Shulgina, T., Gershunov, A., Cayan, D. R., & Ralph, F. M. (2022). Climate change contributions to future atmospheric river flood damages in the western United States. *Scientific reports*, *12*(1), 13747. DOI:10.1038/s41598-022-15474-2

Fisher, J.L., Peterson, W.T., & Rykaczewski, R.R. (2015). The impact of El Niño events on the pelagic food chain in the northern California Current. *Global Change Biology, 21*(12): 4401-4414.

Frölicher, T.L., Fischer, E.M., & Gruber, N. (2018) Marine heatwaves under global warming. *Nature, 560*, 360–364.

Gruber, N., Hauri, C., Lachkar, Z., Loher, D., Frölicher, T. L., & Plattner, G. K. (2012). Rapid progression of ocean acidification in the California Current System. *Science*, *337*(6091), 220-223.

Howard E.M., Frenzel H., Kessouri F., Renault L., Bianchi D., McWilliams, J.C., & Deutsch, C. (2020). Attributing causes of future climate change in the California Current System with multimodel downscaling. *Global Biogeochemical Cycles 34:6646*. DOI: 10.1029/2020GB006646

Huang, X., & Swain, D. L. (2022). Climate change is increasing the risk of a California megaflood. *Science Advances, 8*, eabq0995. DOI:10.1126/sciadv.abq0995

Huang, X., Swain D. L., & Hall, A. D. (2020). Future precipitation increase from very high resolution ensemble downscaling of extreme atmospheric river storms in California. *Science Advances, 6*, eaba1323. DOI: 10.1126/sciadv.aba1323

Ito, T., Minobe, S., Deutsch, C., & Long, M.C. (2017). Upper ocean O2 trends: 1958–2015. *Geophysical Research Letters, 44*(9). DOI: 10.1002/2017GL073613

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., & Wu, L. (2019) Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society, 100*(10), 1987-2007. DOI: 10.1175/BAMS-D-18-0189.1

Long, M.C., Deutsch, C., & Ito, T. (2016). Finding forced trends in oceanic oxygen. *Global Biogeochemical Cycles, 30*(2), 381-397. DOI: 10.1002/2015GB005310

Lonhart, S.I., Jeppesen, R., Beas-Luna, R., Crooks, J.A., & Lorda, J. (2019). Shifts in the distribution and abundance of coastal marine species along the eastern Pacific Ocean during marine heatwaves from 2013 to 2018. *Marine Biodiversity Records 12*,13. DOI: 10.1186/s41200-019-0171-8

Osborne, E. B., Thunell, R. C., Gruber, N., Feely, R. A., & Benitez-Nelson, C. R. (2020). Decadal variability in twentieth-century ocean acidification in the California Current Ecosystem. *Nature Geoscience*, *13*(1), 43-49.

Pinsky, M.L., Selden, R.L. & Kitchel, Z.J. (2020). Climate-Driven Shifts in Marine Species Ranges: Scaling from Organisms to Communities. *Annual Review of Marine Science 12*:1, 153-179. DOI: 10.1146/annurev-marine-010419-010916

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., ... & Richardson, A. J. (2013). Global imprint of climate change on marine life. *Nature Climate Change*, *3*(10), 919-925.

Pozo Buil, M., Jacox, M. G., Fiechter, J., Alexander, M. A., Bograd, S. J., Curchitser, E. N., Edwards, C.A., & Stock, C.A. (2021). A dynamically downscaled ensemble of future projections for the California current system. *Frontiers in Marine Science*, *8*. DOI: 10.3389/fmars.2021.612874

Sanford, E., Sones, J.L., & García-Reyes, M. (2019). Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. *Science Reports 9*, 4216. DOI: 10.1038/s41598-019-40784-3

Santora, J.A., Mantua, N.J., & Schroeder, I.D. (2020). Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications, 11*, 536. DOI: 10.1038/s41467-019-14215-w

Schwartz, M., Hall, A., Sun, F., Berg, N., & Walton, D. (2017). Significant and Inevitable End-of-Twenty-First-Century Advances in Surface Runoff Timing in California's Sierra Nevada. *Journal of Hydrometeorology 18*(12), 3181-3197. DOI: 10.1175/JHM-D-16-0257.1

Siedlecki, S. A., Pilcher, D., Howard, E. M., Deutsch, C., MacCready, P., Norton, E. L., Frenzel, H., Newton, J., Feely, R. A., Alin, S. R., & Klinger, T. (2021). Coastal processes modify projections of some climate-driven stressors in the California Current System. *Biogeosciences*, *18*, 2871–2890, https://doi.org/10.5194/bg-18-2871-2021.

Sun, F., Berg, N., Hall, A., Schwartz, M., & Walton, D. (2019). Understanding end-of-century snowpack changes over California's Sierra Nevada. *Geophysical Research Letters, 46*(2), 933-943. DOI: 10.1029/2018GL080362

Swain, D. L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change, 8*, 427–433. DOI: 10.1038/s41558-018-0140-y

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, & C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf

Wang, J., Kim, H., & Chang, E.K.M. (2017). Changes in northern hemisphere winter storm tracks under the background of Arctic amplification. *Journal of Climate, 30*, 3705-3724. DOI:10.1175/JCLI-D-16-0650.1

Warner, M.D., Mass, C.F., & Salathe, E.P. (2015). Changes in atmospheric rivers along the North American west coast in CMIP5 climate models. *Journal of Hydrometeorology 16*(1), 128-138. DOI: 10.1175/JHM-D-14-0080.1

Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, & A.N. LeGrande. (2017). Droughts, floods, and wildfires. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 231-256 doi: 10.7930/J0CJ8BNN.

Appendix C. Climate Vulnerability Revision Survey

Q1: Using your expert opinion, the 2022 climate science update, and any other supporting literature, have climate projections and projected impacts to your resource changed significantly enough in the past 15 years to warrant a revision of the 2015 assessment?

Q2: Using your expert opinion, the summarized Status and Trend information from the Sanctuary Condition Reports and any other supporting literature, has the condition of the resource changed sufficiently enough since 2010 to warrant a revision of the 2015 assessment?

Q3: In your expert opinion, and in light of your responses to Q1 and Q2, do the overall rankings of vulnerability (available at the top of your resource's 2015 vulnerability assessment) need to be revised to reflect the current available knowledge? (i.e. has new research been conducted or information come to light that changes our perception of the resource's vulnerability?)

Q4: How confident are you in your responses to this survey on a scale from 1-5?

Appendix D. Vulnerability scores for all resources

Species	2014 Score	2014 Adjusted[24]	2023 Score	Change
American Dune Grass	3.77	6.27	N/A	N/A
Ashy Storm Petrel	2.86	4.13	4.13	0.00
Black Rail	3.05	4.30	4.30	0.00
Blue Rockfish	0.65	1.99	2.11	0.13
Blue Whale	2.56	5.06	5.28	0.23
Brandt's Cormorant and Common Murre	1.81	3.12	3.12	0.00
California Mussel	1.71	3.76	3.87	0.12
Cassin's Auklet	1.83	3.10	4.00	0.90
Copepod	1.60	4.10	4.10	0.00
Coralline Algae	1.41	2.91	3.31	0.40
Gaper Clam	2.25	4.31	N/A	N/A
Hydrocoral/Sponge	1.56	3.13	3.07	-0.06
Krill	0.14	2.64	2.79	0.15
Mole Crab	1.02	3.41	3.41	0.00
Northern Anchovy	1.10	2.74	3.04	0.30
Ochre Seastar	1.50	3.55	3.75	0.20
Olympia Oyster	2.39	4.52	4.52	0.00
Oyster Catcher	4.02	6.32	6.32	0.00
Pacific Herring	1.48	3.32	3.91	0.59
Pacific Sardine	1.20	2.87	3.59	0.72
Pigeon Guillemot, Tufted Puffin	1.51	2.78	2.78	0.00
Pteropod	3.43	5.93	6.40	0.48
Purple Urchin	1.24	2.41	3.25	0.84
Red Abalone	2.26	3.76	5.16	1.40
Red Urchin	1.24	2.41	3.34	0.93

[24] The 2014 scores were adjusted by removing the 0.5 weighting for exposure, in order to compare with the newly revised 2023 scores.

Species	2014 Score	2014 Adjusted[24]	2023 Score	Change
Sea Palm	2.62	4.62	4.98	0.36
Southern Sea Otter	1.87	3.62	4.08	0.45
Tidewater Goby	2.50	4.00	4.00	0.00
Western Snowy Plover	2.98	4.98	5.48	0.50
Widow Rockfish	1.13	2.73	2.73	0.00

Habitats	2014 Score	2014 Adjusted[25]	2023 Score	Change
Beaches/Dunes	3.08	5.33	5.33	0.00
Coastal Cliffs	1.50	2.64	2.64	0.00
Estuaries	2.62	4.78	5.04	0.26
Kelp Forest	0.28	1.55	4.69	3.14
Nearshore soft bottom	1.50	3.50	3.72	0.22
Offshore rocky reefs	0.46	1.58	2.86	1.28
Pelagic	1.05	3.11	3.18	0.06
Rocky Intertidal	2.02	4.06	4.73	0.67

Ecosystem services	2014 Score	2014 Adjusted[26]	2023 Score	Change
Carbon Storage	3.17	5.67	5.50	-0.17
Flood and Erosion Protection	3.97	6.47	5.55	-0.92
Food Production	2.05	4.05	N/A	N/A
Recreation and Tourism	1.20	3.20	N/A	N/A
Water Quality	2.55	4.55	N/A	N/A

[25] The 2014 scores were adjusted by removing the 0.5 weighting for exposure, in order to compare with the newly revised 2023 scores.
[26] The 2014 scores were adjusted by removing the 0.5 weighting for exposure, in order to compare with the newly revised 2023 scores.

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