2023 HIGHLY MIGRATORY SPECIES ANNUAL REPORT

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TABLE OF CONTENTS

The National Oceanic and Atmospheric Administration Southwest Fisheries Science Center (NOAA SWFSC) collects fishery information and conducts research on managed fisheries and fish in the Eastern Pacific Ocean (EPO). This report focuses on the work of SWFSC scientists on highly migratory species (HMS) and their fisheries. Contributions and activities of the past year, April 1, 2022 – March 31, 2023, are briefly described.

I. MONITORING U.S. HIGHLY MIGRATORY SPECIES (HMS) FISHERIES

SWFSC Fisheries Resources Division (FRD) scientists monitor U.S. HMS fisheries in the Pacific and routinely summarize the information into data products for HMS researchers, fisheries managers, and regional fishery management organizations in support of the conservation and management of HMS stocks in the Pacific. The HMS Fisheries Monitoring Group (FMG) within FRD compiles and manages information on vessels, gear, effort, catch, bycatch, protected species interactions, landings, and biological sampling collected from these HMS fisheries. FMG staff collaborate with staff from other National Marine Fisheries Service (NMFS) regional science centers, regional offices, headquarters, as well as fishery management councils, commissions, state fisheries agencies, and others to collect and share information from HMS fisheries in the Pacific.

The EPO contains a number of commercial and recreational fisheries that target various HMS. The U.S. Pacific tuna purse-seine fishery, which was historically a large vessel fleet fishing throughout the tropics, has dwindled to a few smaller coastal purse seine vessels that occasionally target tunas in southern California waters. The North Pacific albacore (*Thunnus alalunga*) troll and pole-and-line fishery is the largest commercial HMS fishery by tons landed based on the West Coast. This fishery began in the 1940s and its fishing grounds have expanded and contracted from southern California and Baja California, MX, to the international dateline (at longitude 180°) in the southern Pacific Ocean in the austral summer months (creating an entirely new fishery in 1986), and most recently back to the coastal waters off Washington and Oregon. The large-mesh drift gillnet fishery off California, which will be phased out completely at the end of 2028, targets broadbill swordfish (*Xiphias gladius*), Pacific bluefin tuna (*Thunnus orientalis*), and common thresher shark (*Alopias vulpinus*) off the coast of central and southern California. The California harpoon fishery targets swordfish mostly in the Southern California bight. Historically, a longline fishery that targeted swordfish and tunas was based out of California but most vessels have since relocated to Hawaii. The recreational fisheries that target HMS are composed of private and commercial passenger fishing vessels (CPFVs) that target albacore off of Washington, Oregon, and central California, as well as albacore, Pacific bluefin tuna, and yellowfin tuna (*Thunnus albacares*) in southern California and Mexican waters. The commercial hook and line fishery consists mostly of skiffs and smaller vessels that target tunas and, in more recent years, swordfish in offshore waters using gear similar to the recreational fishery. Table 1 shows the total catch in 2021 for the HMS fisheries monitored by the FMG. Catch and effort are down for the reported year possibly due to lingering impacts of the COVID-19 pandemic.

Table 1. Landed catch in the U.S. commercial HMS fisheries[1]. Catches cannot be reported for fisheries for which fewer than three vessels participated.

FISHERY	2021 CATCH IN METRIC TONS	NUMBER OF VESSELS
North Pacific Albacore Troll and Pole-and-line	4209	311
South Pacific Albacore Troll	657	21
Eastern Pacific Ocean Purse Seine	55	3
California Large-mesh Drift Gillnet	76	6
California Harpoon	7	11
Hook and Line	119	21

North Pacific Albacore Troll and Pole-and-Line

Logbook data from this and other HMS fisheries are required to be submitted to SWFSC under the HMS Fishery Management Plan enacted by the Pacific Fishery Management Council (PFMC) in 2005. Total annual catch of albacore from the North Pacific albacore troll and pole-and-line fishery decreased nearly 44% from 7,516 t in 2020 to 4,209 t in 2021. The number of vessels decreased from 404 vessels in 2020 to 311 vessels in 2021. The average weight of retained albacore in 2021 was 14.8 pounds, compared to 17 pounds in 2020.

[1] Numbers taken from RFMO submissions made in 2022.

South Pacific Albacore Troll

Participation in the South Pacific albacore troll fishery has decreased substantially in recent years relative to the 1980s and early 1990s, when greater than 50 vessels typically participated each season. Twenty-one vessels participated in the fishery in 2021, up from the eighteen that participated in 2020. Total catch of albacore in the 2021 fishery was 657 t, a decrease of 66% from the 1908 t landed in 2020. No fish size sampling has been done in this fishery since 2007. In recent years, vessels from this fishery have sold their catches in French Polynesia, Canada, and U.S. West Coast ports.

Eastern Pacific Ocean Purse Seine

Logbooks for the EPO purse seine fishery are collected by the Inter American Tropical Tuna Commission (IATTC) and managed by the HMS FMG at the Southwest Fisheries Science Center. This fishery was historically very large in Southern California for tunas but has decreased over the past several decades. In 2021, 3 vessels participated in the fishery landing 43 t of Pacific bluefin tuna down from 12 vessels landing 116 t in 2020.

California Large-Mesh Drift Gillnet

The California large-mesh drift gillnet fleet decreased from 12 vessels in 2020 to 6 vessels in 2021. In 2020, these vessels landed 35 t of swordfish and 28 t of Pacific bluefin tuna while in 2021, 14 t of swordfish and 55 t of Pacific bluefin tuna were caught. The FMG staff manage the gillnet logbook database (including set net and small-mesh drift gillnet) in collaboration with California Department of Fish and Wildlife (CDFW). Data editing and data entry are managed by staff from both offices. The NOAA West Coast Regional Office (WCRO) observer program monitors approximately 20% of the fishery effort and conducts on-board size sampling. Drift gillnets have been banned under both federal and California state law. All remaining state drift gillnet permits will be phased out by January 31, 2024 and federal drift gillnet permits will be phased out by the end of 2028.

California Harpoon

The California harpoon fishery decreased from 17 vessels in 2020 to 11 vessels in 2021. Six metric tons of swordfish were caught in 2020 compared with seven metric tons caught in 2021. No fish size sampling information is collected from this fishery. The logbook data from this fishery are also managed by FMG staff in cooperation with CDFW.

Longline (California-Based)

Deep-set longlining for tuna is permitted under the PFMC FMP for HMS. In 2021, three vessels were based in California, the same number as 2020, but several Hawaii-based longline vessels operated out of West Coast ports. The vessels based in California landed 9 t of Albacore and 6 t of Swordfish. These Hawaii-based vessels fished under their Hawaii longline permit. Hawaiian and West Coast longline logbook data have been consolidated since 2015 and are managed by Pacific Islands Fisheries Science Center (PIFSC).

Recreational HMS Fisheries

Several different fleets of recreational vessels target HMS along the U.S. West Coast. Both CPFVs and private vessels target albacore off the coasts of Washington and Oregon. In recent years, anglers have caught very few albacore in Southern California. The recreational catch of albacore by vessels that target albacore off the West Coast was 248 t in 2021 down from 260 t in 2020. The catch of Pacific bluefin tuna by U.S. recreational anglers was 1248 t in 2021 up from 716 t in 2020.

Commercial Hook and Line Fisheries

The hook and line fisheries primarily target tunas in Southern California waters with an emphasis on Pacific bluefin tuna in recent years. The fishery has also begun targeting swordfish in deep waters in the past several years. The hook and line catch increased to 119 t in 2021 from 88 t in 2020. The catch of Pacific bluefin tuna increased to 116 t in 2021 from 87 t in 2020.

Miscellaneous Fisheries

HMS caught incidentally in other commercial fisheries (such as set gillnet, salmon troll, etc.) are summarized from the Pacific Fisheries Information Network (PacFIN) database where state landings data from marine fisheries are maintained. These fisheries caught 3 t of Pacific bluefin tuna, 64 t of Albacore and 54 t of Swordfish in 2021.

II. SUPPORTING U.S. OBLIGATIONS OF INTERNATIONAL AGREEMENTS

North Pacific Albacore

North Pacific albacore supports the most important HMS commercial fishery on the U.S. West Coast and is an essential stock for recreational fisheries. The International Scientific Committee for Tuna and Tuna-Like Species in the North Pacific Ocean (ISC) Albacore Working Group (ALBWG) performs the stock assessments and management strategy evaluations (MSE) of North Pacific albacore (NPALB). The primary focus of the ALBWG from 2022-2023 was to prepare for and conduct a benchmark stock assessment in 2023. The ALBWG held a virtual workshop on May 9-12, 2022, to review and discuss Working Group members' progress on improving the model for the 2023 assessment. The Working Group included 16 scientists from Canada, Chinese

Taipei, Japan, USA, IATTC, and SPC. The purpose of the workshop was to review the results of the research conducted by the members of the working group, address the research recommendations identified in the 2020 assessment, and develop an albacore tuna assessment model designed for the assessment that is scheduled for use in 2023. Three working papers and two presentations were reviewed and discussed by the working group. The ALBWG held a subsequent online meeting in September 2022 to review additional working papers that were developed to inform the next stock assessment. In November 2022, the ALBWG met in Yokohama, Japan, to prepare data and further discuss potential modeling changes for the next assessment. The ALBWG subsequently met March 20-27, 2023, in La Jolla, California, to review preliminary benchmark model results and to resolve issues associated with key indices of abundance. The ALBWG is planning to have a candidate model and stock projections prepared in time for the 2023 ISC plenary session.

Pacific Bluefin Tuna

Pacific bluefin tuna supports important recreational and commercial fisheries on the U.S. West Coast. The ISC's Pacific Bluefin Tuna Working Group (PBFWG) conducts stock assessments and MSEs of Pacific bluefin tuna in support of management by the WCPFC, IATTC, and PFMC. In 2022, the PBFWG completed an updated stock assessment of the Pacific bluefin tuna. This updated assessment was reviewed and adopted by the ISC, the WCPFC, and IATTC in 2022. The 2022 stock assessment for Pacific bluefin tuna used a length-based and age-structured model (Stock Synthesis v3.30), which incorporated catch data, size compositions, and catch-per-unit of effort (CPUE)-based abundance indices from 1952 to 2021. The model included observations from 25 different fishing fleets and was fitted to input data using a likelihood-based statistical framework. The assessment model structure was similar to the 2020 assessment, but with additional data observations, model diagnostics, and the inclusion of additional model runs into the stock projections, which was a key improvement.

The report presents the results of the Pacific bluefin tuna assessment from 1952 to 2020 (fishing year, FY; July 1-June 30), which indicated fluctuations in spawning stock biomass (SSB) and total biomass. SSB declined from 1996 to 2010 but increased from 2010-2020 to the 1996 level. Fishing mortality (F%SPR) declined to 1% of SPR from 2004-2009 but returned to 30.7% of SPR from 2018-2020. The SSB in 2020 was estimated to be around 65,464 t, a 30,000t increase from 2018. An increase in young fish (0-2 years old) biomass from 2016-2020 is expected to further accelerate SSB recovery. The 2020 SSB was above the initial rebuilding target but remains below the second rebuilding target adopted by the WCPFC and IATTC. However, stock recovery is occurring at a faster rate than anticipated by managers in 2012 when the harvest strategy to foster rebuilding was implemented (WCPFC HS 2017-02). Under all projection scenarios evaluated, it is very likely that the second rebuilding target (20%SSB0 with 60% probability) will be achieved by 2029 (probabilities > 90%).

The PBFWG was tasked to complete the benchmark stock assessment by 2024 and the MSE by 2025. To meet those goals, the PBFWG held two workshops in late 2022 and early 2023 and will hold workshops in late 2023, early 2024, and late 2024.

ISC/22/Annex/13. 2022. Stock assessment of Pacific Bluefin tuna in the Pacific Ocean in 2022. Annex 13 of the 22nd meeting of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean. *https://isc.fra.go.jp/pdf/ISC22/ISC22_ANNEX13_Stock_Assessment_for_Pacific_Bluefin_Tuna.pdf*

North Pacific Blue Shark

North Pacific blue shark (*Prionace glauca*, NPO BSH) supports an important HMS commercial fishery on the West Coast of Mexico and is a bycatch species for U.S. commercial and recreational fisheries. The ISC Shark Working Group (SHARKWG) performs the stock assessments of North Pacific blue shark. The primary focus of the SHARKWG from 2021 – 2022 was on completing the North Pacific blue shark stock assessment in 2022. The SHARKWG held a stock assessment workshop in April 2022 to complete the assessment, and the assessment report was reviewed and adopted during the summer 2022 ISC Plenary. Based on the most complete fisheries and biological data ever compiled for NPO BSH and a new ensemble modeling approach, the SHARKWG developed a very thorough, rigorous, and fully integrated BSH benchmark assessment for the NPO BSH. The SHARKWG is not scheduled to provide an assessment for the ISC in 2023, but the group did meet in December 2022 to discuss general problems with NPO BSH and shortfin mako (*Isurus oxyrinchus*) life history and fisheries data.

ISC/22/Annex/12. 2022. Stock assessment and future projections of blue sharks in the North Pacific Ocean through 2020. Annex 12 of the 22nd meeting of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean. *https://isc.fra.go.jp/pdf/ISC22/ISC22_ANNEX13_Stock_Assessment_for_Pacific_Bluefin_Tuna.pdf*

III. SUPPORTING PACIFIC FISHERY MANAGEMENT COUNCIL ACTIVITIES

FRD scientists serve on the Highly Migratory Species Management Team (HMSMT), an advisory body of the PFMC. The HMSMT met several times in 2022 and early 2023, resuming in person meetings for the first time since March 2020 with the June 2022 meeting in Vancouver, WA, and continuing thereafter with a mixture of virtual and in-person meetings. The main HMS fisheries concerns which the HMSMT and the Council addressed over the past year included: (1) initiating the second phase of a review of essential fish habitat for HMS; (2) continuing to aid the Council with approving exempted fishing permits to test alternative methods of targeting swordfish; (3) suggesting biennial harvest specifications and management measures for HMS fisheries; (4) analyzing a range of alternatives for hard caps on protected species interactions in the large mesh drift gillnet fishery; (5) developing recommendations for international management activities; (6) contributing to a discussion of Council Meeting and Process Efficiencies to consider lessons learned from the pandemic experience; and (7) preparing the 2022 Stock Assessment and Fishery Evaluation (SAFE) Report.

IV. ADVANCING RESEARCH ON TUNAS, BILLFISH, AND OPAH

FRD scientists have a long history of conducting research on tunas and tuna-like species in the Pacific Ocean including, but not limited to, Pacific bluefin tuna, yellowfin tuna, albacore, swordfish, and opah studies use a range of methods and quantitative approaches to 1) examine movements and behaviors and their associated environmental drivers, 2) characterize the position of HMS in marine food webs, and 3) fill life history data gaps to improve stock assessments and support management. This information is provided to international, national, and regional fisheries management bodies having stewardship for tuna and tuna-like species. Described here are studies that have been recently completed or are ongoing. Many of these studies are collaborative and involve stakeholders and colleagues both in the United States and abroad.

North Pacific Albacore Size Data Sampling Program

Since 1961, size data have been collected from albacore landings made by the U.S. and Canadian troll fleets at ports along the U.S. Pacific coast. The SWFSC supports state fishery personnel to collect size data from albacore fishing vessels when they unload their catches in coastal ports. In 2021, 12,586 albacore averaging 66.6 cm fork length (FL) were measured at various West Coast ports.

Projecting Species Distributions

Many marine species are shifting their distributions in response to changing ocean conditions, posing significant challenges and risks for fisheries management. Species distribution models (SDMs) can be used to project future species distributions in the face of a changing climate using fishery-dependent data which is often the only type of data available for HMS. Karp et al. (2023) used a simulation approach to evaluate the potential for fishery-dependent data to inform SDMs and abundance estimates, and to quantify the bias resulting from different fishery-dependent sampling scenarios in the California Current System.

Researchers based the simulated species on a highly migratory pelagic predator which responds to sea-surface temperature, prey fields and mixed layer depth, similar to albacore or swordfish. These species have high capacity to follow changing environmental conditions, potentially leading to greater future issues with cross-boundary management, viability of home-ports, bycatch interactions, and other consequences of climate-induced range shifts.

Results show that data generated from fishery-dependent sampling can still result in SDMs with high predictive skill several decades into the future, given specific forms of preferential sampling which result in low climate bias and novelty. Therefore, there is utility in using fishery-dependent data to project species distributions into the future.

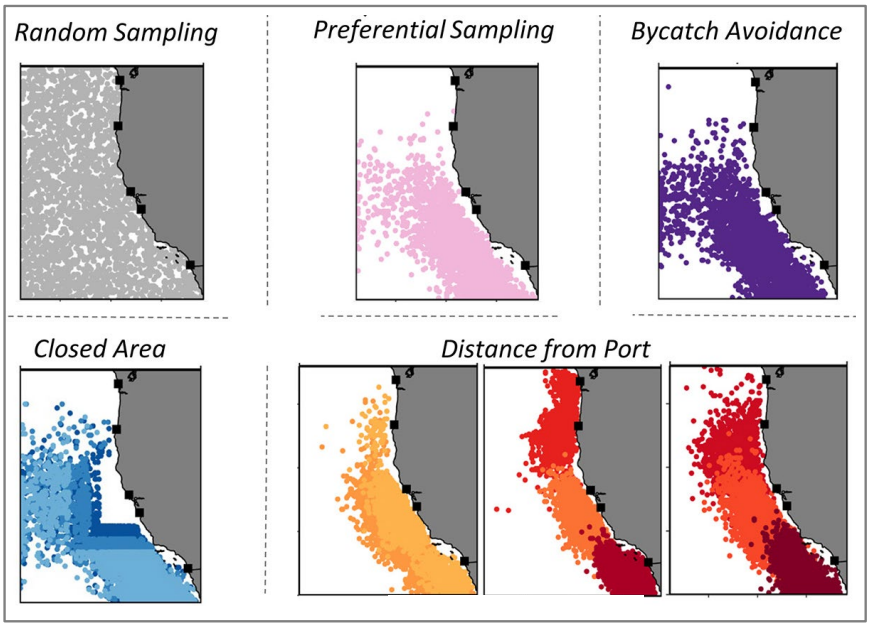

Figure 1. Examples of simulated sampling in space, designed to replicate some common sources of bias in fishery-dependent data.

Karp, M. A., Brodie, S., Smith, J. A., Richerson, K., Selden, R. L., Liu, O. R., Muhling, B. A., Samhouri, J. F., Barnett, L. A. K., Hazen, E. L., Ovando, D., Fiechter, J., Jacox, M. G. & Pozo Buil, M. (2023). Projecting species distributions using fishery-dependent data. Fish and Fisheries, 24(1), 71-92. https://doi.org/10.1111/faf.12711

Anticipating Fluctuations of Bigeye Tuna in the Pacific Ocean from Three-Dimensional Ocean Biogeochemistry

Subseasonal to decadal ocean forecasting can make significant contributions to achieving effective management of living marine resources in a changing ocean. Taboada et al. (2023) used three-dimensional forecasts of ocean biogeochemistry based on a global Earth system model to assess the capacity to anticipate fluctuations in the dynamics of bigeye tuna (*Thunnus obesus*) in the Pacific Ocean. Researchers reconstructed spatial patterns in catch per unit effort through a combination of physiological indices capturing habitat preferences and physiological tolerance limits in this species.

This analysis shows that habitat models accounting for fluctuations in the thermal structure and oxygen concentration of the water column captured interannual fluctuations in catch-per-unit-effort. These models also captured regime shifts in distribution that models based solely on surface information were unable to reproduce. Decade-long forecast experiments further suggested that forecasts of three-dimensional biogeochemical information might enable anticipation of fluctuations in bigeye tuna several years ahead. These results also lend support to incorporating subsurface biogeochemical information into ecological forecasts.

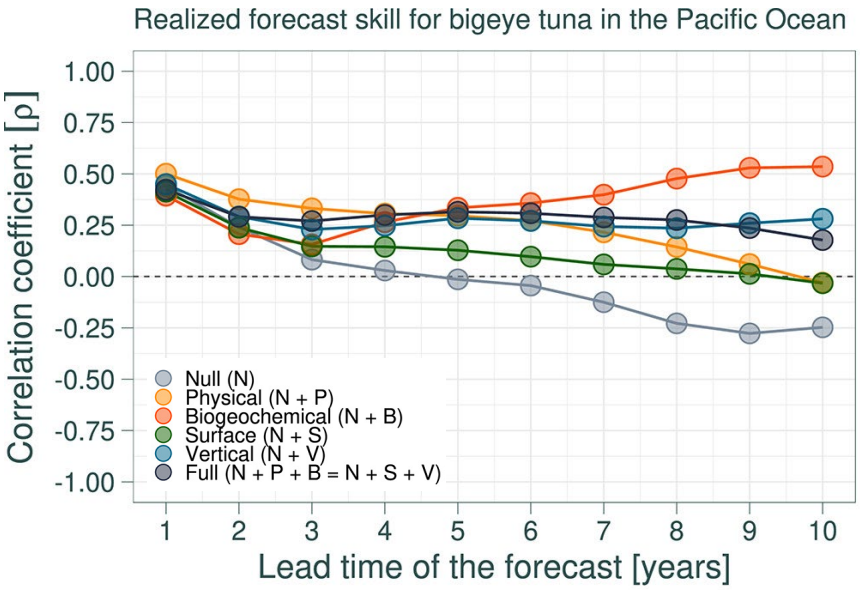

Figure 2: Skill of bigeye tuna catch-per-unit-effort forecasts at leads times between 1 and 10 years for the Pacific Ocean. Note the superior performance of the model incorporating biogeochemical predictors.

Taboada, F.G., Park, J.Y., Muhling, B.A., Tommasi, D., Tanaka, K.R., Rykaczewski, R.R., Stock, C.A., Sarmiento, J.L. 2023. Anticipating fluctuations of bigeye tuna in the Pacific Ocean from three-dimensional ocean biogeochemistry. J. Appl. Ecol. 60:3, 463-479. https://doi.org/10.1111/1365-2664.14346

Research Examining the Blood-Oxygen Binding Capacity of Smalleye Pacific Opah and Swordfish

Smalleye Pacific opah (*Lampris incognitus*) and swordfish are regionally-endothermic fishes that can conserve metabolic heat and maintain specific body regions warmer than ambient water temperature. Consequently, oxygen uptake at the gills occurs at ambient water temperature, but oxygen offloading will occur at different temperatures in different tissues. While several regionally heterothermic fishes (e.g., marlins, tunas, and sharks) have been shown to have a reduced temperature effect on hemoglobin (Hb)–O_2 affinity, the temperature dependence of Hb–O_2 affinity in opah and swordfish had not previously been studied. In Morrison et al., NOAA researchers worked with colleagues from the University of British Columbia, the Pfleger Institute of Environmental Research, and the University of Massachusetts, Dartmouth, to examine blood-oxygen binding capacity in these two large, commercially-important fish species. Results revealed that opah whole-blood–O_2 affinity exhibited a reverse temperature dependence above 50% Hb–O_2 saturation, while the temperature dependence of swordfish blood–O_2 affinity was saturation and pH dependent, becoming temperature independent below 50% Hb–O_2 saturation and pH 7.4. Experiments on stripped hemolysates showed that adding ATP decreased the temperature sensitivity of Hb–O_2 affinity, changing the overall oxygenation enthalpy (ΔH') values of opah and swordfish hemoglobin. Swordfish blood–O_2 affinity was high compared with that of other large, pelagic, marine teleosts, which likely enables swordfish to forage in the potentially low-oxygenated water of the upper reaches of the oxygen minimum layer. The existence of Hbs with reduced temperature sensitivity in regionally-endothermic fishes likely prevents marked changes in Hb–O_2 affinity between the cold and warm tissues, ensuring oxygen is properly distributed from the gills to the muscles, where it is used to power aerobic metabolism.

Morrison, P.R., Bernal, D., Sepulveda, C.A., Wegner, N.C. (NOAA/SWFSC/FRD), Brauner, C.J. (2022). Temperature independence of haemoglobin-oxygen affinity in smalleye Pacific opah (Lampris incognitus) and swordfish (Xiphias gladius). J. Exp. Biol. 225: jeb243820. https://doi.org/10.1242/jeb.243820

Recent and Historical Data Show no Evidence of Pacific Bluefin Tuna Reproduction in the Southern California Current System.

Despite their broad distribution across the North Pacific Ocean, the only known spawning grounds for Pacific bluefin tuna are around coastal Japan and the East China Sea. However, an increase in the prevalence of large Pacific bluefin tuna, up to 10 years old, in the California Current System during exceptionally warm ocean conditions has led to the question of whether they may be spawning in this region. To investigate this possibility, Dewar et al. (2022) collected samples from 36 females (estimated 3–8 years old) between 2015 and 2019. Histological analyses revealed that 2 of the 36 individuals had cortical aveoli and there was no sign of imminent, active, or recent spawning. Further examination of historical ichthyoplankton collections showed no records of larval Pacific bluefin tuna, but confirmed the presence of the larvae of other tuna species in waters > 24°C (**Figure 3**). Fishery-dependent records showed that Pacific bluefin tuna are rarely recorded in purse seine catches where surface temperatures exceed 23°C. Additionally, the conditions in the California Current differ from those in other Pacific bluefin tuna

spawning grounds. Typically, spawning grounds are located in warm oligotrophic waters with larvae being advected to cooler, more nutrient rich waters. This is the opposite of the conditions in the productive, south-flowing California Current. The study provided no evidence of Pacific bluefin tuna reproduction in the California Current.

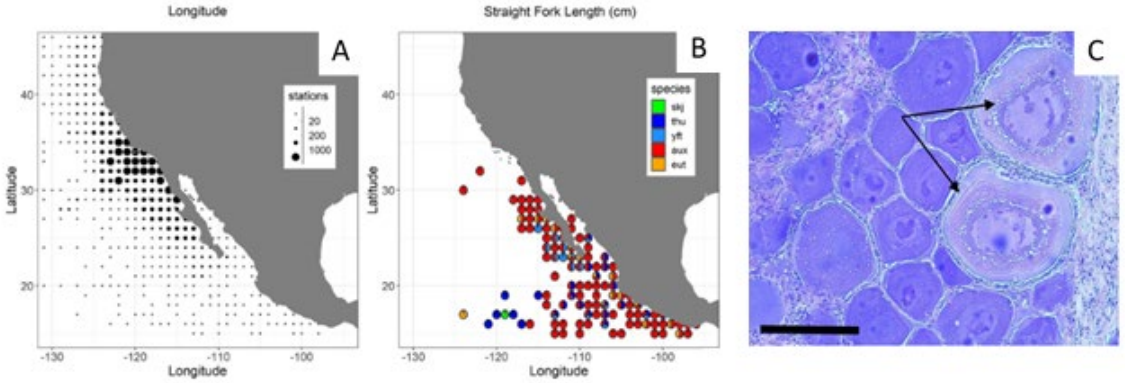

Figure 3. A) Ichthyoplankton sampling stations aggregated to 1 degree resolution from the CalCOFI and IMECOCAL sampling programs (1951-2020) and B) locations where tuna larvae were recorded. skj=*Katsuwonus pelamis*, thu=*Thunnus spp*, yft= *Thunnus albacares*, aux= *Auxis spp*., and eut = *euthynnus lineatus.* C) Ovarian section from 157 cm FL Pacific bluefin tuna female (estimated age 5 years), Note the two cortical alveolar oocytes indicated by the arrows. The black scale bar represents 100 µm.

Dewar, H., Snodgrass, O., Muhling, B., and Schaefer, K. 2022. Recent and historical data show no evidence of Pacific bluefin tuna reproduction in the southern California Current system. PLOS ONE.
https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0269069

Otolith Geochemistry Reflects Life Histories of Pacific Bluefin Tuna

Understanding biological and environmental factors that influence movement behaviors and population connectivity of highly migratory fishes is essential for cooperative international management. Pacific bluefin tuna spawn in the western Pacific Ocean and juveniles disperse to foraging grounds throughout the North Pacific before returning to the western Pacific. Several techniques have been used to characterize the distribution and movement of Pacific bluefin, but few methods can provide complete records across ontogeny from larvae to adult in individual fish. For example, tagging studies only provide data for the period between tagging and tag recovery. In Mohan et al. (2022), otolith biominerals of large Pacific bluefin collected from the western, eastern, and south Pacific Ocean (**Figure 4**), were analyzed for a suite of trace elements across calcified/proteinaceous growth zones to investigate patterns across ontogeny. Three element:Ca ratios (Li:Ca, Mg:Ca, and Mn:Ca) displayed enrichment in the otolith core (**Figure 4**), then decreased to low stable levels after age 1–2 years with little change after that point. Factors other than oceanography, including temperature, metabolism, and diet, likely influenced otolith crystallization, protein content, and elemental incorporation. Although similar patterns were also exhibited for other element;CA ratios (Sr:Ca, Ba:Ca and Zn:Ca) in the first year, variability in these elements differed significantly after age-2 and in the otolith edges by capture region (**Figure 4**), suggesting ocean-specific environmental factors or growth-related physiologies affected otolith mineralization across ontogeny. Results confirm differences in biomineralization across regions and that some elements are more useful than others for examining migratory pathways.

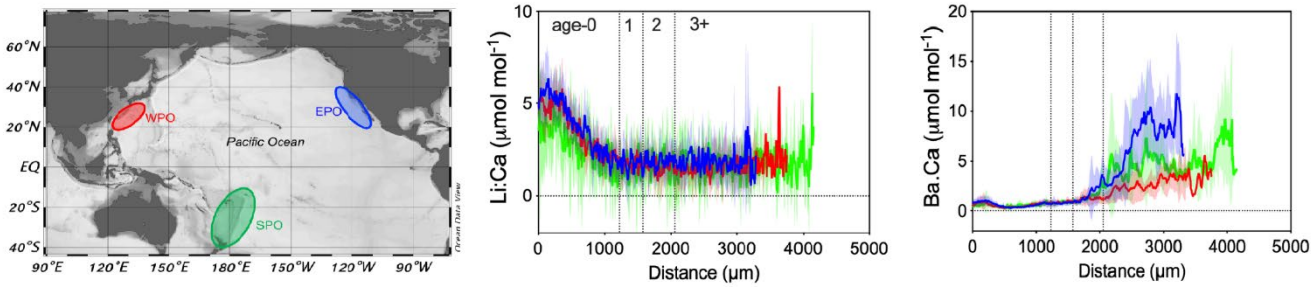

Figure 4. Left: distribution of sample collection around the Pacific. Middle and Right: Life history transect showing the Li:CA and Ba:C ratios (respectively) from the core to the edge.

Mohan, J. A., Dewar, H., Snodgrass, O. E., Miller, N. R., Tanaka, Y., Ohshimo, S., Rooker, J.R., Francis, M., and Wells, R. D. 2022. Otolith geochemistry reflects life histories of Pacific Bluefin Tuna. PLoS ONE, 17(10), e0275899.
https://doi.org/10.1371/journal.pone.0275899

Vulnerability to Climate Change of Managed Stocks in the California Current Large Marine Ecosystem

Understanding how abundance, productivity, and distribution of individual species may respond to climate change is a critical first step towards anticipating alterations in marine ecosystem structure and function, as well as developing strategies to adapt to the full range of potential changes. McClure et al. (2023) applied the NOAA Fisheries Climate Vulnerability Assessment Method to 64 species in the California Current Large Marine Ecosystem (CCLME) to assess their vulnerability to climate change. Vulnerability is a function of two factors (1) a species' exposure to environmental change and (2) its biological sensitivity to a set of environmental conditions. Sensitivity includes components of its resiliency, population status, reproductive rate, and adaptive capacity to respond to these new conditions. Species classified as highly or very highly vulnerable shared one or more characteristics including (1) having complex life histories that utilize a wide range of freshwater and marine habitats; (2) having habitat specialization, particularly for areas that are likely to experience increased hypoxia; (3) having long lifespans and low population growth rates; and/or (4) being of high commercial value combined with impacts from non-climate stressors such as anthropogenic habitat degradation. Species with Low or Moderate vulnerability were either habitat generalists, occupy deep-water habitats, or are highly mobile and likely to shift their ranges.

All HMS had a high level of exposure, given the level of expected change in the CCLME (**Figure 5**). The two factors which had the highest ranking for negative impacts were sea surface temperature and ocean acidification. Sensitivity to this exposure varied across species. Pacific bluefin tuna were rated to have high vulnerability primarily due to their population status as overfished with overfishing occurring at the time of this analyses. It should be noted that since the analyses was conducted, estimates of spawning stock biomass have increased significantly and the population is considered to be recovering. Three species had moderate vulnerability: common thresher sharks, striped marlin (*Kajikia audax*), and albacore. The increased sensitivity for common threshers sharks resulted from the fact that they have a more specialized diet than other HMS and have relatively low reproductive rates. Striped marlin's increased sensitivity was primarily due to their population status as being overfished with overfishing occurring. Albacore Tuna had two sensitivity factors, "early life history survival and settlement requirements" and "population growth rates" that scored higher. The remaining five HMS had Low sensitivity. The ability of HMS to undertake large-scale movements was a key factor reducing their overall vulnerability as a group.

This approach compiled a large amount of diverse biological and environmental information into a relatively simple metric. This metric can inform near-term advice for prioritizing species-level data collection and research on climate impacts and help fishers predict changes and shifts in available target and non-target species. In addition, the results can help managers in management decisions, determine when and where a precautionary approach might be warranted, and can help identify habitats or life history stages that might be especially effective to protect or restore.

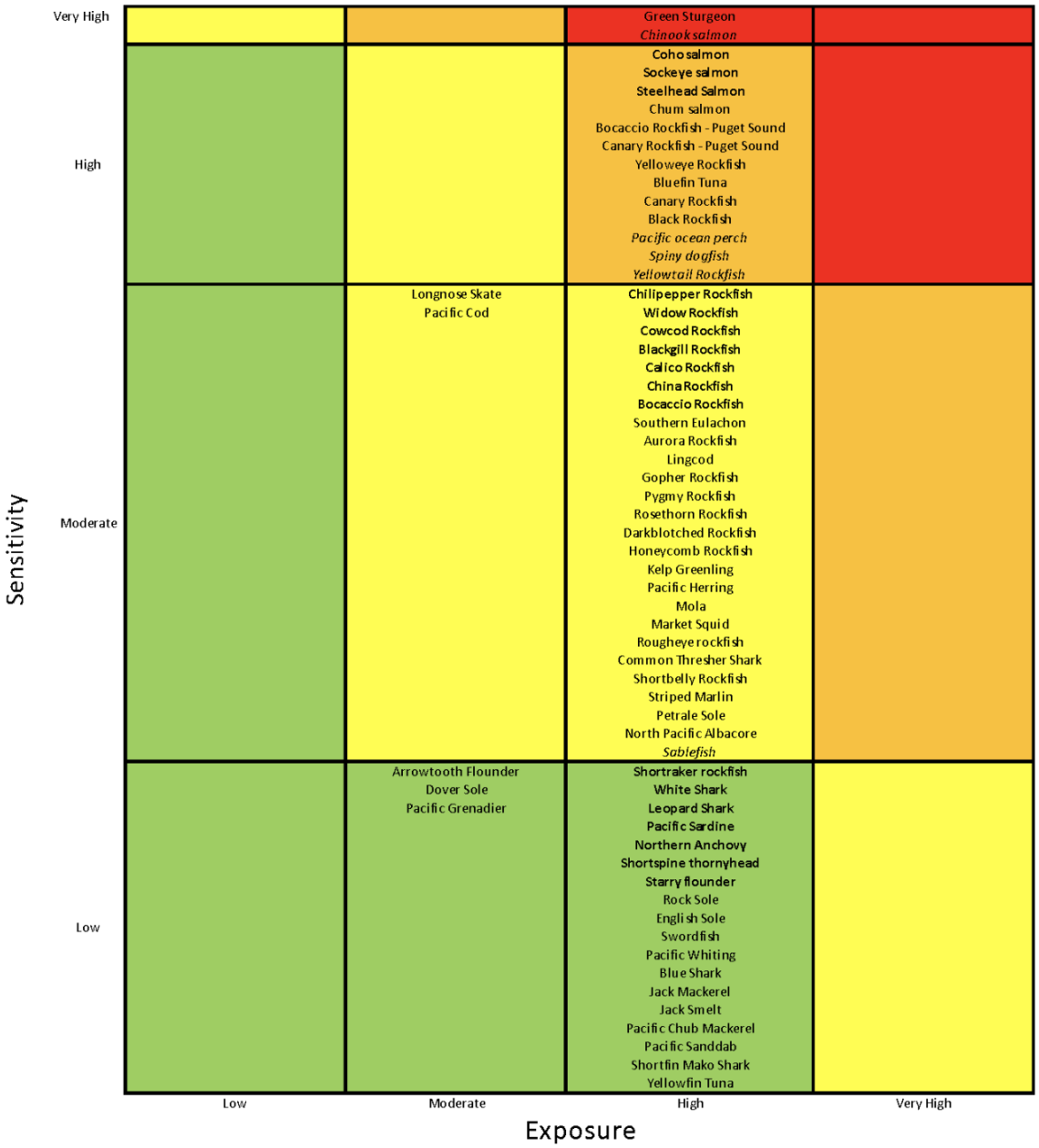

Figure 5. Overall vulnerability, a function of sensitivity and exposure, is indicated by color green = low, yellow = moderate, orange = High, and red = Very High. Note that all HMS shark species are indicated with an *.

McClure, M.M., Haltuch, M. A., Willis-Norton, E., Huff, D. D., Hazen, E. L., Crozier, L. G., Jacox, M.G., Nelson, M.W., Andrews, K.S., Barnett, L.A.K., Berger, A.M., Beyer, S., Bizzarro, J., Boughton, D., Cope, J.M., Carr, M, Dewar, H., Dick, E., Dorval, E., ... Bograd, S. J. 2023. Vulnerability to climate change of managed stocks in the California Current large marine ecosystem. Front. Mar. Sci. 10. https://doi.org/10.3389/fmars.2023.1103767

V. TROPHIC ECOLOGY IN THE CALIFORNIA CURRENT

The California Current is a productive eastern boundary current that provides important habitat for a number of highly migratory pelagic predators. The Life History program has been conducting long-term studies on the diets and foraging ecology of albacore, bluefin tuna, shortfin mako, common thresher shark, bigeye thresher (*Alopias superciliosus*), blue shark, opah, and swordfish. These species migrate to the California current to forage, taking advantage of the seasonally high productivity. Moving towards integrated ecosystem assessments and ecosystem management, researchers are focusing on the ecological interactions among species, both between and among trophic levels. The data collected feed directly into these efforts.

Pacific Bluefin Tuna Exhibits a Flexible Feeding Ecology in the Southern California Bight

Pacific Bluefin Tuna, a common visitor to the California Current, are thought to specialize on high energy, surface schooling prey. However, estimates of forage availability in the California Current System over the past two decades have varied, including dramatic fluctuations in surface schooling prey. To examine the foraging ecology of juvenile Pacific bluefin in the face of this variability, stomachs from 963 Pacific bluefin were collected in the Southern California Bight (SCB) from 2008 to 2016. Using classification and regression tree analysis, Portner et al. (2022) observed three periods characterized by distinct prey (**Figure 6**). In 2008, Pacific bluefin diet was dominated by midwater lanternfishes and enoploteuthid squids. From 2009–2014, Pacific bluefin tuna consumed diverse fishes, cephalopods, and crustaceans. Only in the period from 2015–2016 did Pacific bluefin tuna specialize on relatively high energy, surface schooling prey (e.g., anchovy, pelagic red crab). While from 2009-2014, Pacific bluefin tuna had the smallest sized prey in their stomachs, they consumed the highest number of prey (**Figure 7**). This work demonstrated that Pacific bluefin tuna is an opportunistic predator that can exhibit distinct foraging behaviors to exploit diverse forage. They can forage across the water column on diverse prey types, schooling and non-schooling. Expanding our understanding of Pacific bluefin foraging ecology is improving our ability to predict their responses to changes in resource availability as well as potential impacts to the fisheries it supports. This work is continuing to produce results for Pacific bluefin stomachs collected from 2017 to 2022. These data will be incorporated into annual reports on the status of the California Current produced by the SWFSC.

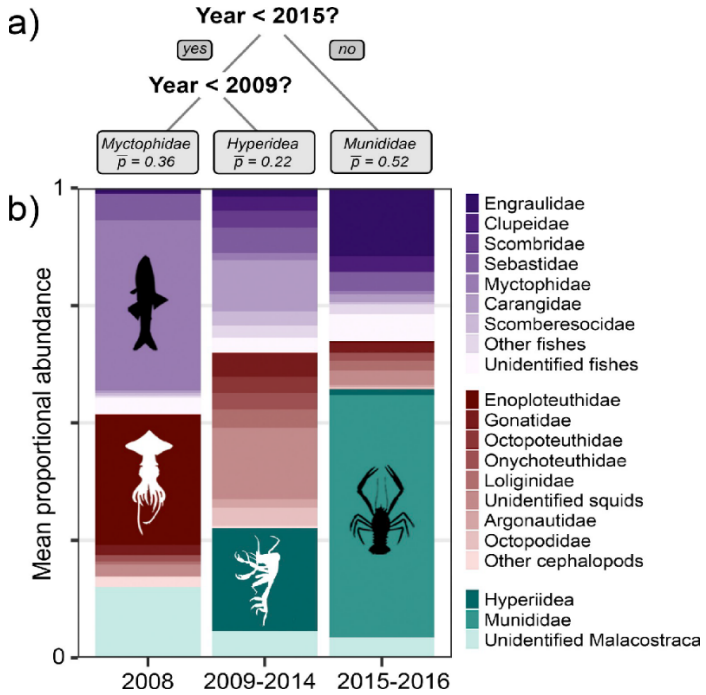

Figure 6. Classification and regression tree (CART) analysis describing groups of Pacific bluefin tuna with similar diets. (a) The selected tree, with splits based on responses to the condition listed at each branching point; left for positive, and right for negative. The mean cross validated proportion of the most abundant prey group is given below each terminal node. (b) Diet composition for prey contributing mean proportional abundance in each CART group (purples = fishes, browns = cephalopods, and greens = crustaceans).

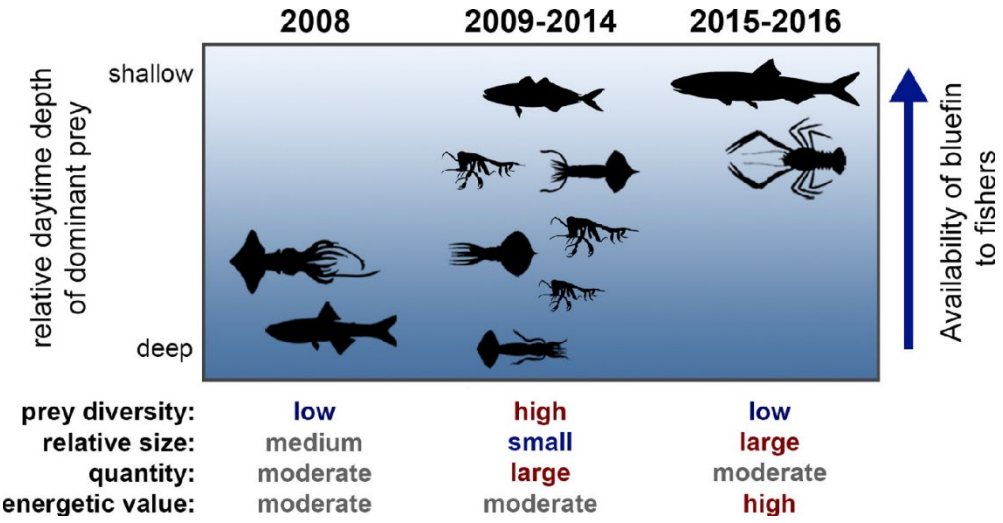

Figure 7. Relationship between stomach contents of Pacific bluefin and its availability to fishers in the SCB. Silhouettes describe the identity and relative daytime depth of dominant prey families. The relative diversity, size, quantity, and energetic value of prey are also given for each sampling period.

Portner, E.J., Snodgrass, O., and Dewar, H. 2022. Pacific Bluefin Tuna, Thunnus orientalis, exhibits a flexible feeding ecology in the Southern California Bight. PLOS ONE 17(8): e0272048. https://doi.org/10.1371/journal.pone.0272048

Juvenile Albacore Foraging Ecology Varies with Environmental Conditions in the California Current Large Marine Ecosystem

Juvenile North Pacific albacore support commercial and recreational fisheries in the CCLME where they forage during summer and fall. The distributions of the commercial and recreational fisheries and estimates of forage availability have varied substantially over the past century. Time-series data quantifying albacore diet can help link forage composition to variability in albacore abundance and distribution and, consequently, their availability to fishers. Previous diet studies in the CCLME are of relatively short duration, and long-term variability in albacore diet remains poorly understood. Nickels et al. (2023) described the diets of juvenile albacore from three regions in the CCLME from 2007 to 2019 and used classification and regression tree analysis to explore environmental drivers of variability (**Figure 8**). Important prey includes northern anchovy (*Engraulis mordax*), rockfishes (*Sebastes* spp.), boreal clubhook squid (*Onychoteuthis borealijaponica*), euphausiids (Order: Euphausiidae), and amphipods (Order: Amphipoda), each contributing >5% mean proportional abundance. Most prey items were short lived species or young-of-the-year smaller than 10 cm. Diet variability was related to environmental conditions over the first 6 months of the year (Pacific Decadal Oscillation, sea surface temperature, and North Pacific Gyre Oscillation) and conditions concurrent with albacore capture (region and surface nitrate flux). Nickels et al. described foraging flexibility over regional and annual scales associated with these environmental influences. Continuous, long-term studies offer the opportunity to identify flexibility in albacore foraging behavior and begin to make a predictive link between environmental conditions early in the year and albacore foraging during summer and fall.

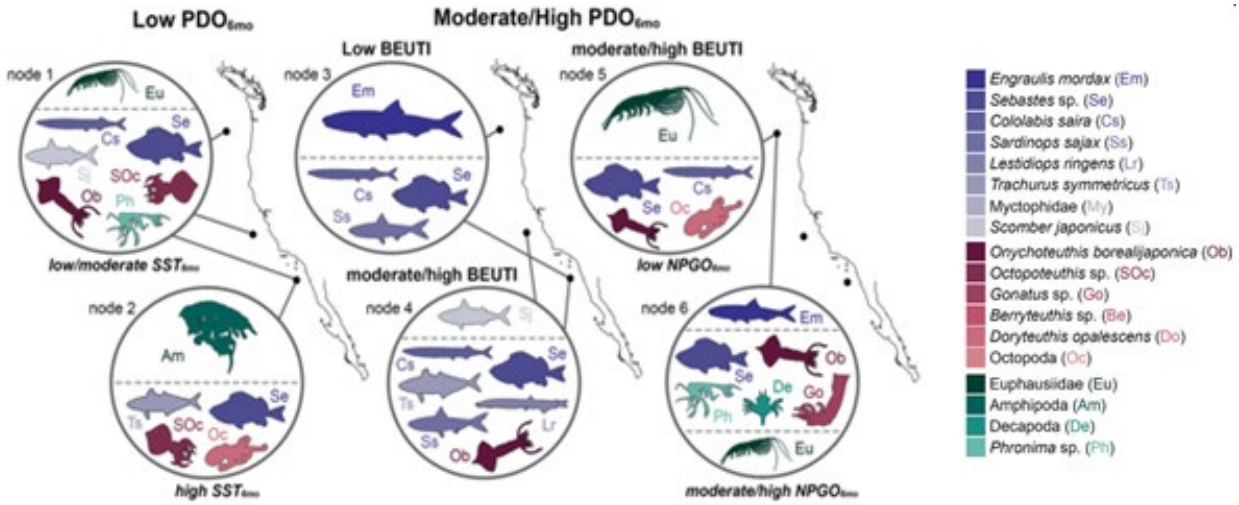

Figure 8. Conceptual diagram of juvenile albacore tuna diet under varying environmental conditions. Silhouettes and abbreviations describe the identity of prey. Fish prey are in purples, cephalopods are in reddish-browns, and crustaceans are in greens. Dashed lines separate potential species composition of individual stomachs.

Nickels, C. F., Portner, E. J., Snodgrass, O., Muhling, B., and Dewar, H. 2023. Juvenile Albacore Tuna (Thunnus alalunga) foraging ecology varies with environmental conditions in the California Current Large Marine Ecosystem. Fish. Oceanogr. https://doi.org/10.1111/fog.12638

Albacore and Broadbill Swordfish Diets in the State of the California Current Ecosystem Report

Quantifying the diets of highly migratory fishes in the California Current Ecosystem (CCE) can complement existing trawl-based assessments of the available forage, provide insight into how forage varies over time and space, as well as provide a direct metric of forage utilization. Albacore tuna and broadbill swordfish are both opportunistic predators that consume a wide variety of prey taxa across a range of depths and habitats. Albacore and swordfish stomachs were provided by commercial and recreational fishers, and prey were identified from whole or hard part remains and are reported as a mean percent abundance. A subset of prey species are presented here (**Figure 9**), focusing on prey that are either themselves under a management plan, or considered ecosystem component species to highlight their links to highly migratory species. The same data were included in the CalCOFI Conference State of the California Current Ecosystem presentation and the California Current Integrative Ecosystem Status Report, both of which were described in last year's Annual Report. Since that time, the paper that includes these data was published (Thompson et al. 2022).

Commercial and recreational fishers collected juvenile albacore tuna off Northern California, Oregon, and Washington during the summer and fall fishing season. Based on preliminary data from 2021, the dominant prey from 2021 were northern anchovy, euphausiids, and Pacific saury (*Cololabis saira*). Northern anchovy consumption increased in 2020 and 2021 after a low from 2018-2019. Sardine (*Sardinops sagax*) consumption was also high in 2020 and 2021, well above the long term mean. Rockfish consumption demonstrated an opposing pattern, with consumption declining in 2020 and 2021 after a peak in 2019, coinciding the with the northern anchovy low.

Swordfish were collected off Southern and Central California during the commercial drift gillnet season (August 15-January 31). Stomachs are classified by the year the fishing season began (stomachs from January were assigned to the previous year's fishing season). Swordfish fed mainly on fish and cephalopods. In 2019, the dominant prey was northern anchovy followed by market squid (*Doryteuthis opalescens*), and in 2020, slender blacksmelt (*Bathylagus pacificus*) was the most important followed by northern anchovy and market squid. Northern anchovy and market squid were consumed above the long-term mean in 2019-2020, northern anchovy well above the mean. Pacific hake (*Merluccius productus*) fell near the mean in both years. Other coastal pelagic species and rockfishes were a minor part of swordfish diets across the years. Fished species were less important in swordfish diets overall when compared with albacore.

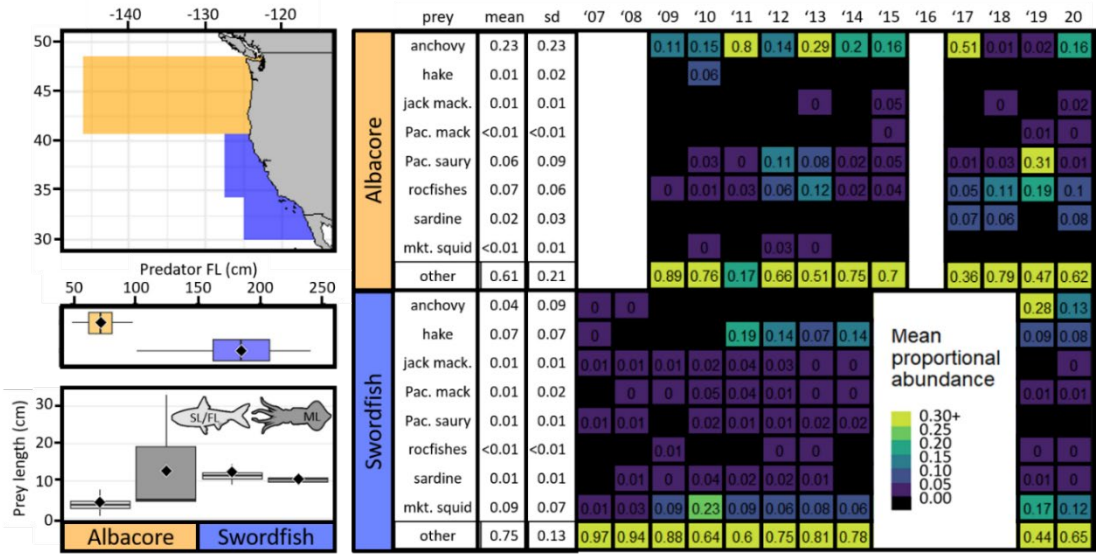

Figure 9. Diets were assessed via stomach content analysis for albacore (in orange) from the Pacific Northwest and broadbill swordfish (in blue) from Central and Southern California. Predator lengths are shown in the middle-left plot. Mean lengths (black diamond) and boxplots of length distributions for forage fishes (light grey) and market squid (dark grey) are depicted on the lower left. The right panel shows the annual mean proportional abundance of prey as a heat map, where the color saturates at 30%.

Thompson, A.R., Bjorkstedt, E.P., Bograd, Steven J., Fisher, J.L., Hazen, E.L., Leising, A., Santora, J.A., Satterthwaite, E.V., Sydeman, W.J., Alksne, M., Auth, T.D., Baumann-Pickering, S., Bowlin, N.M., Burke, Brian j., Daly, E.A., Dewar, H., Field, John c., Garfield, N.T., Giddings, A., Goericke, R., Hildebrand, J., Horton, C.A., Jacobson, K.C., Jacox, M.G., Jahncke, J., Johns, M., Jones, J., Kudela, R.M., Melin, Sharon r., Morgan, C.A., Nickels, C.F., Orben, R.A., Porquez, J.M., Portner, E.J., Preti, A., Robertson, R.R., Rudnick, D.L., Sakuma, K.M., Schroeder, I.D., Snodgrass, O.E., Thompson, S.A., Trickey, J.S., Warzybok, P., Watson, W., and Weber, E.D. 2022. State of the California Current Ecosystem in 2021: Winter is coming? Frontiers in Marine Science 9, 958727. https://doi.org/10.3389/fmars.2022.958727

VI. ADVANCING PELAGIC SHARK RESEARCH

The SWFSC's shark research program focuses on pelagic sharks that occur along the U.S. Pacific coast, including shortfin mako, blue sharks, basking sharks (*Cetorhinus maximus)*, and three species of thresher: common thresher shark, bigeye thresher, and pelagic thresher (*Alopias pelagicus)*. Center scientists have studied the sharks' life history, foraging ecology, distribution, movements, stock structure, and potential vulnerability to fishing pressure. This information is provided to international, national, and regional fisheries management bodies having stewardship for sharks.

Global-Scale Environmental Niche and Habitat of Blue Shark by Size and Sex: A Pivotal Step to Improving Stock Management.

Blue shark is among the most abundant shark species in international trade. Similar to other shark species, they are segregated by size and sex throughout their range. Given that the impact of fisheries removals differs depending on both size and sex, it is important to better understand distributions and their overlap with fisheries both geographically and vertically. Given the relatively high landings and recent electronic tagging programs, a large volume of data is available on the occurrence and movements of blue sharks globally that have yet to be combined. Druon et al. (2022) combined 265,595 blue shark observations (capture or satellite tag) with environmental data to present the first global-scale analysis of blue shark habitat preferences for five size and sex classes (small juveniles, large juvenile males and females, adult males and females). Researchers leveraged the understanding of blue shark biotic environmental associations to develop two indicators of foraging location, productivity fronts in mesotrophic areas and mesopelagic micronekton in oligotrophic environments.

To capture the horizontal and vertical extent of thermal habitat for the blue shark, researchers defined the temperature niche relative to both sea surface temperature (SST) and the temperature 100 m below the mixed layer depth ($T_{mld+100}$). This shows that the lifetime foraging niche incorporates highly diverse biotic and abiotic conditions: the blue shark tends to shift from mesotrophic and temperate surface waters during juvenile stages (**Figure 10**) to more oligotrophic and warm surface waters for adults. However, low productivity limits all classes of blue shark habitat in the tropical western North Atlantic, and both low productivity and warm temperatures limit habitat in most of the equatorial Indian Ocean (except for the adult males) and tropical eastern Pacific. Large females tend to have greater habitat overlap with small juveniles than large males that are defined more by temperature than productivity preferences. In particular, large juvenile females tend to extend their range

into higher latitudes than large males, likely due to greater tolerance of relatively cold waters. Large juvenile and adult females also seem to avoid areas with intermediate SST (~21.7-24.0°C), resulting in separation from large males mostly in the tropical and temperate latitudes in the cold and warm seasons, respectively. A greater understanding of sex- and size- specific habitat preferences of blue sharks will contribute to management and projections of shifts in distributions associated with climate variability over long- and short-time scales.

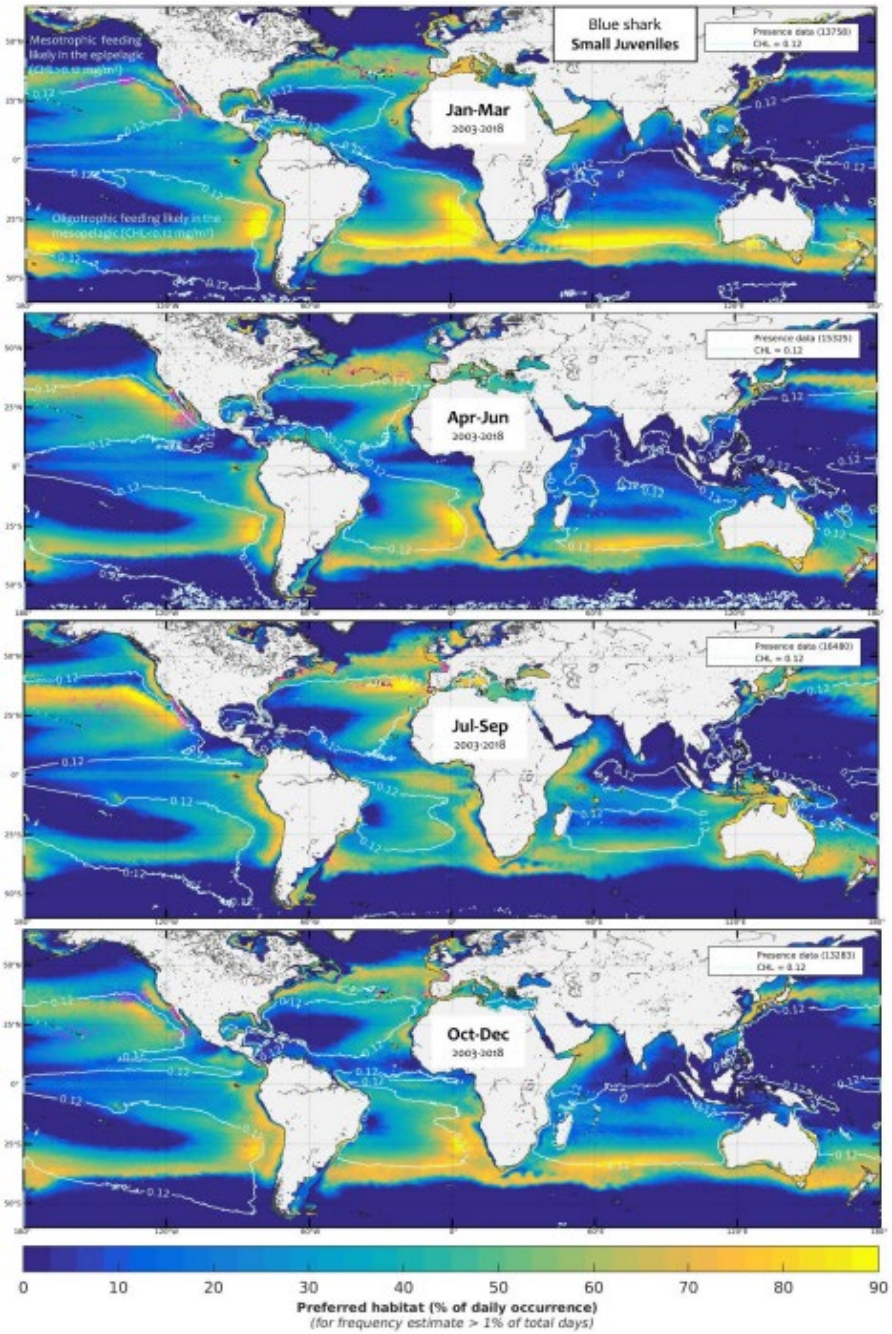

Figure 10. Mean seasonal distribution of blue shark foraging habitat for the small juveniles (2003-2018) in frequency of suitable habitat occurrence. The chlorophyll-a isocontour of 0.12 mg.m^{-3} (CHL_{min}) separates the mean area of oligotrophic foraging (below this value using mesopelagic micronekton as foraging proxy) and mesotrophic foraging (above this value using productivity fronts). Presence data (calibration and validation) are represented as pink dots for observer data and colored line transects for electronic tagging data (start and end of months are shown by a black star).

Druon, J. N., Campana, S., Vandeperre, F., Hazin, F.H.V., Bowlby, H., Coelho, R., Queiroz, N., Serena, F., Abascal, F., Damalas, D., Musyl, M., Lopez, J., Block, B., Afonso, P., Dewar, H., Sabarros, P.S., Finucci, B., Zanzi, A., Bach, P., … Travassos, P. 2022. Global-scale environmental niche and habitat of blue shark (Prionace glauca) by size and sex: a pivotal step to improving stock management. Front. Mar. Sci. 9:828412. https://doi.org/10.3389/fmars.2022.828412

Diving into the Vertical Dimension of Elasmobranch Movement Ecology.

Knowledge of the three-dimensional movement patterns of elasmobranchs is vital to understanding their ecological roles and exposure to anthropogenic pressures. To date, comparative studies among species at global scales have mostly focused on horizontal movements. Andrzejaczek et al (2022) addresses the knowledge gap of vertical movements by compiling the first global synthesis of vertical habitat use by elasmobranchs from data obtained by the deployment of 989 biotelemetry tags on 38 elasmobranch species (**Figure 11**). Elasmobranchs displayed a high intra- and inter-specific variability in vertical movement patterns (**Figure 12**). Substantial vertical overlap was observed for many epipelagic species indicating an increased likelihood to display spatial overlap, biologically interact and share similar risks to anthropogenic threats that vary on vertical gradients. Andrzejaczek et al. highlights the critical next steps towards incorporating vertical movement into global management and monitoring strategies for elasmobranchs, emphasizing the need to address geographic and taxonomic biases in deployment and to concurrently consider both horizontal and vertical movements.

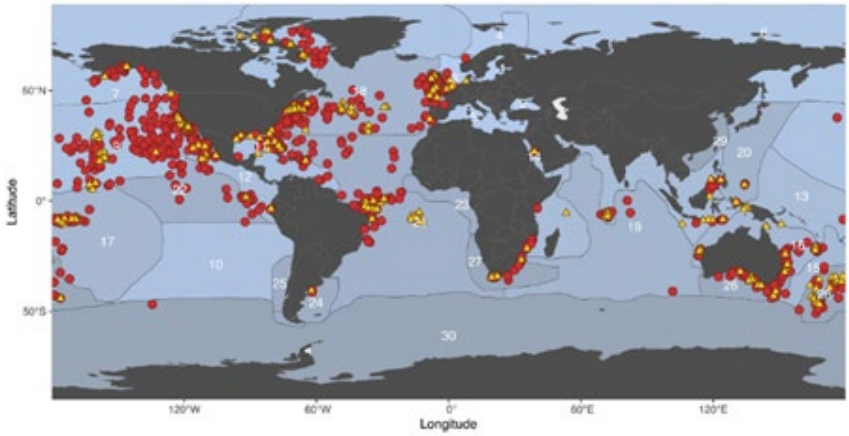

Figure 11. Yellow triangles indicate deployment and red circles indicate pop-up and/or recapture of the 989 elasmobranchs included within the analysis for this study. Numbers refer to the ocean biogeographic realms. Pop-up locations were not available for 144 tags.

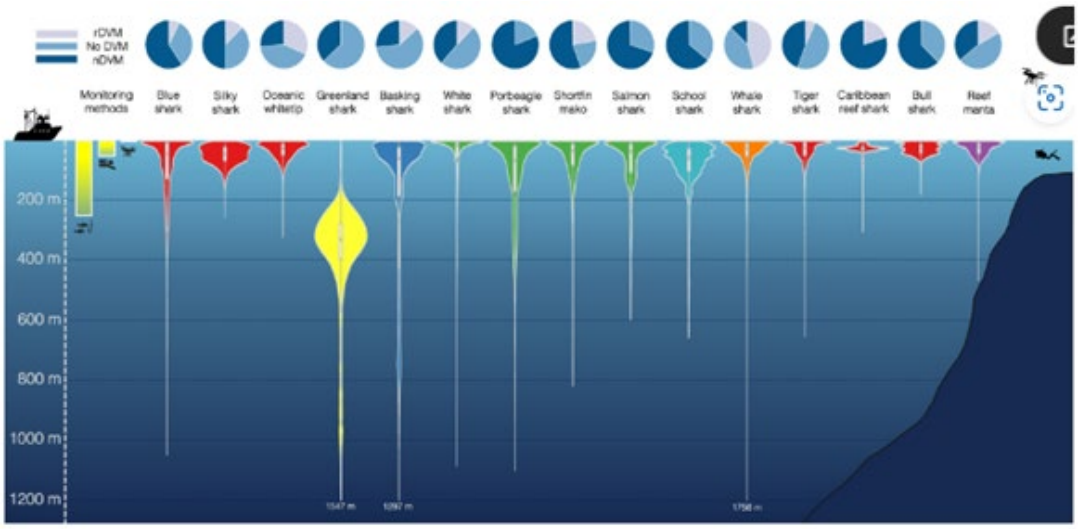

Figure 12. The hourly median depth distributions of 15 species determined from hourly median depths. Only species with >1000 days of depth time-series data were included. Violin plots represent the full distribution of the data, with colors relating to family. Boxplots depict the lower quartile, upper quartile, and median, with whiskers extending from the shallowest to the deepest depths. Whiskers are capped to 1200 m. Bars represent the estimated detection zones of aerial surveys (top 5 m), scuba-diving surveys (top 50 m), and longline fishing (top 250 m) used within this study. Pie charts represent the proportion of individuals within each species that primarily exhibited nDVM, rDVM, or no clear evidence of DVM (neutral). Species are ordered by habitat type, moving from oceanic to transient to coastal species from left to right.

Andrzejaczek, S., Lucas, T.C.D., Goodman, M.C., Hussey, N.E., Armstrong, A.J., Carlisle, A., Coffey, D.M., Gleiss, A.C., Huveneers, C., Jacoby, D.M., Meekan, M.G., Mourier, J., Peel, L.R., Abrantes, K., Afonso, A.S., Ajemian, M.J., Anderson, B.N., … Curnick, D.J. 2022. Diving into the vertical dimension of elasmobranch movement ecology. Sci. Adv. 8, eabo1754.
https://doi.org/10.1126/sciadv.abo1754

Vertebral Chemistry Distinguishes Nursery Habitats of Juvenile Shortfin Mako in the Eastern North Pacific Ocean
Shortfin mako are ecologically and economically important predators throughout the global oceans. The eastern North Pacific Ocean contains several coastal nurseries for this species where juveniles can forage and grow until venturing into offshore pelagic habitats. LaFreniere et al. (2023) opportunistically sampled vertebrae from both male and female juvenile shortfin mako (65.5–134.4 cm total length, neonate to age 2) sourced from two distinct nurseries in the eastern North Pacific: The Southern Shortfin mako are ecologically and economically important predators throughout the global oceans. The eastern North Pacific Ocean contains several coastal nurseries for this species where juveniles can forage and grow until venturing into offshore pelagic habitats. LaFreniere et al. (2023) opportunistically sampled vertebrae from both male and female juvenile shortfin mako (65.5–134.4 cm total length, neonate to age 2) sourced from two distinct nurseries in the eastern North Pacific: The Southern California Bight (n = 12), U.S.A., and Bahía Sebastián Vizcaíno (n = 11), Mexico. Researchers analyzed mineralized vertebral cartilage to determine concentrations of selected elements (Li, Mg, Mn, Zn, Sr, Ba, standardized to Ca) using laser ablation inductively coupled plasma mass spectrometry, targeting growth bands at specific life stages, including post parturition at the birth band and the recent life history of the individual at the vertebral edge (**Figure 13**). Comparing the vertebral core revealed significant differences between the two nursery grounds in Zn:Ca, Sr:Ca, and Ba:Ca. These differences are likely associated with factors such as temperature and water chemistry. Comparing the core with the recent history edge revealed variability across ontogeny in Li:Ca, Mg:Ca, and Zn:Ca which could relate to regional differences and/or developmental shifts in mineralization. Understanding what drives element variations in vertebrae is likely complicated but will further efforts to use elements as a tool in species management. The ability to determine the origin of highly migratory species allows fishery managers to better understand how nursery habitats contribute to adult populations.

LaFreniere, B. R., Sosa-Nishizaki, O., Herzka, S. Z., Snodgrass, O., Dewar, H., Miller, N., Wells, R.J.D., and Mohan, J. A. 2023. Vertebral Chemistry Distinguishes Nursery Habitats of Juvenile Shortfin Mako in the Eastern North Pacific Ocean. Mar. Coast. Fish. 15(2), e10234. https://doi.org/10.1002/mcf2.10234

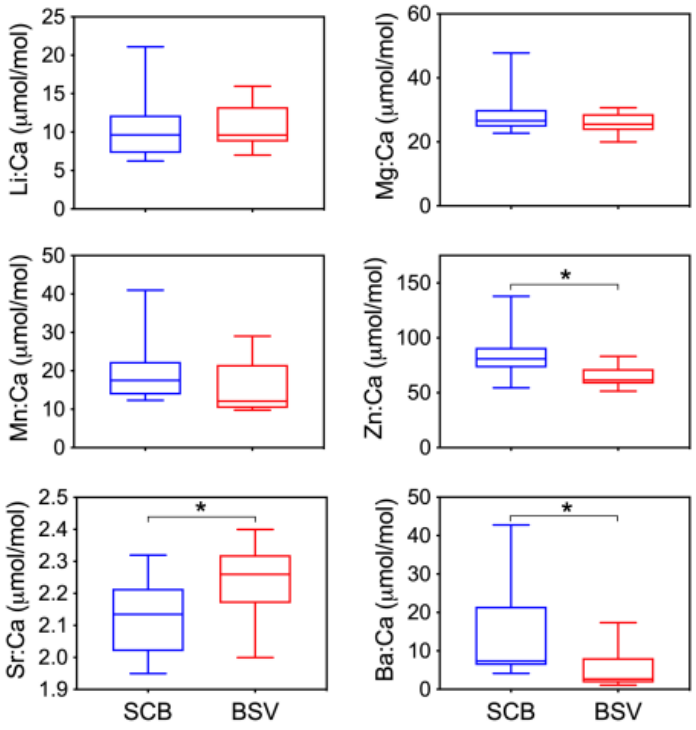

Figure 13. Box plots of vertebral element concentrations of the edge comparing shortfin mako sampled in the Southern California Bight (SCB: blue) and Bahia Sebastian Vizcaino (BSV: red); the line inside the box represents the median, box dimensions represent the 25th and 75th quartiles, whiskers represent minimum and maximum values, and asterisk brackets indicate significant differences between birth band and vertebral edge based on a Mann–Whitney rank-sum test.

VII. ADVANCING UNDERSTANDING OF ECOSYSTEM STRUCTURE AND FUNCTION

Healthy populations of species directly targeted for a fishery ultimately depend on healthy ecosystems. In this context, research on components of the ecosystem that are linked to these targeted species can facilitate their sustainable use.

Climate Change Projections of HMS Distributions

Lezama-Ochoa et al. (in prep) produced daily projections from 1980-2100 for ten highly migratory species (leatherback turtle, blue shark, common thresher shark, shortfin mako, humpback whale, fin whale, swordfish, California sea lion, northern right-whale dolphin, and Pacific white-sided dolphin) in the CCLME using an ensemble of three high-resolution (~10 km), downscaled ocean projections under high emissions scenario (RCP8.5). Researchers identified changes in the core habitat area and direction and intensity of distribution shifts for each species and found variable results among species and different Earth System Models used to force the projections. Outputs for this project are expected to be in multiple future projects and to feed ecosystem models to describe future dynamics of food webs in the CCS.

Blue Whale Projections in the California Current System

Lezama-Ochoa et al. (in prep) is producing daily projections from 1980-2100 for blue whale (*Balaenoptera musculus)* in the CCLME using an ensemble of three high-resolution (~10 km), downscaled ocean projections under high emissions scenario (RCP8.5). The historical model output is an ensemble of two GAMs models developed by season (winter/spring & summer/fall) by Abrahms et al. (2019). This model is part of the Future Sanctuaries project that aims to describe how species in the California Current will respond to future climate variability and change, and the subsequent impacts on the capacity of NMS to meet their mission to conserve, protect, and enhance biodiversity, ecological integrity and cultural legacy. This work is expected to be published separately as part of the project.

Projecting Changes to Habitat Suitability and Connectivity for Predators and Prey in California Sanctuaries

Climate change is expected to affect both the amount and location of habitat available to marine species. Researcher have projected humpback whale (*Megaptera novaeangliae*) distributions within the California Current Ecosystem (CCE) from 1980 to 2100 using a species distribution model coupled to climate projections from the Regional Ocean Modeling System (fig. below). We evaluate changes to the amount and location of humpback whale habitat 1) across the CCE, 2) within Greater Farallones National Marine Sanctuary (GF NMS), and 3) within Cordell Bank National Marine Sanctuary (CB NMS). This model is part of the Future Sanctuaries project that aims to describe how species in the California Current will respond to future climate variability and change, and the subsequent impacts on the capacity of NMS to meet their mission to conserve, protect, and enhance biodiversity, ecological integrity and cultural legacy. This report was produced to aid discussions during the Sanctuaries Advisory Council's scoping meeting, February 2023.

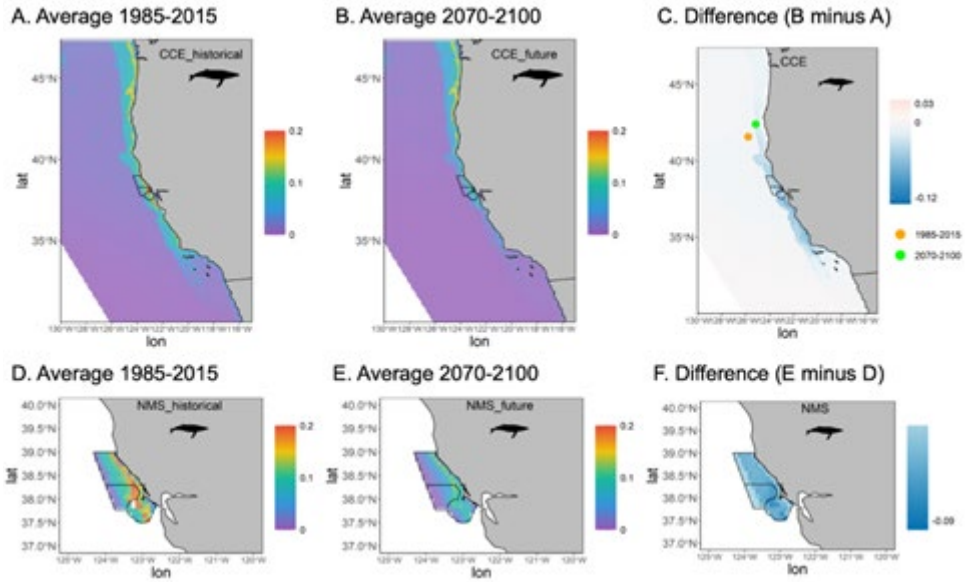

Figure 14. Historical and projected habitat suitability of humpback whales and their difference in the broader California Current and within the Greater Farallones National Marine Sanctuary and Cordell Bank National Marine Sanctuary.

Top Predator Responses to Northeast Pacific Marine Heatwaves

Marine heatwaves (MHWs) cause widespread environmental, biological, and socio-economic impacts, placing them at the forefront of 21st-century management challenges. However, MHWs vary in intensity and evolution, and a paucity of information on how this variability impacts marine species limits our ability to proactively manage for these extreme events. Welch et al. (in review) modeled the effects of four recent MHWs (2014, 2015, 2019, 2020) in the Northeastern Pacific on the distributions of 14 top predator species of ecological, cultural, and commercial importance. Predicted species responses were highly variable across species and MHWs, ranging from near total loss of habitat to a two-fold increase. MHWs rapidly altered political biogeographies, with an average of 10% of predicted habitat across all species shifting to U.S. waters during the 2015 MHW. The variability in predicted responses across species and heatwaves portends the need for novel management solutions that can rapidly respond to extreme climate events. As proof-of-concept, we developed an operational dynamic ocean management tool that predicts predator distributions in near real-time. https://oceanview.pfeg.noaa.gov/top-predator-watch/

Welch et al. In review. Idiosyncratic effects of marine heatwaves on top predator predicted habitat within the Northeast Pacific. Nature Communications.

Review of Future Seas Project, Phase I

The Future Seas project was initiated in 2017 with a focus on three fisheries off the U.S. West Coast, two of which targeted swordfish and albacore. Recently, the project team published a review paper in Progress in Oceanography (Smith et al., 2023) detailing project design and results from the first ~4 years. Included in this paper are descriptions of ecosystem models for albacore, multiple species of albacore prey, swordfish, and species that are of concern as bycatch in the California swordfish fishery. Ecological and economic effects of different management strategies and future climate change are highlighted, including simulated effects of static versus dynamic closures in the swordfish fishery and the projected impacts of climate change on albacore distribution and landings along the U.S. West Coast.

Smith, J.A., M. Pozo Buil, B. Muhling, D. Tommasi, S. Brodie, T.H. Frawley, J. Fiechter, S. Koenigstein, A. Himes-Cornell, M.A. Alexander, S.J. Bograd, N. Cordero-Quirós, L.G. Crowder, E. Curchitser, S.J. Green, N.A. Hardy, A.C. Haynie, E.L. Hazen, K. Holsman, G. Le Fol, N. Lezama-Ochoa, R.R. Rykaczewski, C.A. Stock, S. Stohs, J. Sweeney, H. Welch, M.G. Jacox. 2023. Projecting climate change impacts from physics to fisheries: a view from three California Current fisheries. Progress in Oceanography, 211, https://doi.org/10.1016/j.pocean.2023.102973.

Dynamic Management of Leatherback Turtles in the California Current

Researchers have evaluated the ability of a pre-existing leatherback model to capture patterns in newly collected telemetry data from 2011-2022, and updated the model to include the new data. Using the updated model, work is underway to 1) produce hindcasts of leatherback distributions, produce future projections to 2100 of leatherback distributions, and produce operational nowcasts of leatherback distributions to aid in the sustainability of the Dungeness crab fishery. This work is supported by multiple state and federal grants.

Designing Dynamic Management Strategies to Reduce Human-Wildlife Conflict

Conservation planning traditionally relies upon static reserves. However, there is increasing emphasis on dynamic management (DM) strategies that are flexible in space and time. Due to its novelty, the field of DM lacks best practices to guide its design and implementation. Welch et al. (in review) assesses the effect of planning unit (PU) size within the context of an applied DM tool designed to reduce entanglements of protected whales in a lucrative U.S. crab fishery. Researchers found that smaller PUs avoided up to $39M of revenue loss and reduced entanglement risk by up to 23% compared to the large PUs currently in use. However, larger PUs were more buffered against the effects of an unprecedented marine heatwave from 2014-16, and were less affected by delays in data availability. These findings suggest that novel and adaptive management solutions, rather than a one-size-fits-all approach, are needed to separate wildlife from their threats under a changing climate.

Welch et al. In review. Designing dynamic management strategies to reduce human-wildlife conflict. Conservation Biology.

Unseen Overlap between Fishing Vessels and Top Predators in the Northeast Pacific

Welch et al. (in prep) quantifies unseen overlap between 14 top predator species (tunas, sharks, mammals, seabirds, leatherback turtles) and fishing vessels in the Northeast Pacific. Previous studies have explored observed overlap between marine animals and fishing vessels using AIS data. This study seeks to build on these efforts using a new dataset of intentional AIS disabling. Hotspots of unseen overlap may be locations where fishing vessels are intentionally hiding their fishing activity for illegal reasons, or locations where bycatch of protected and vulnerable species may be occurring at higher rates than previously described.

Clustering of Disaggregated Fisheries Data Reveals Functional Longline Fleets across the Pacific

Ensuring the long-term sustainability of tuna, billfish, and other transboundary fisheries resources begins with data on the status of stocks, as well as information concerning who catches what fish, when, where, and how. Despite recent improvements in fisheries monitoring and surveillance, such dynamics remain poorly understood across the high seas. Frawley et al. (2022) delineates and describes pelagic longline activity in the Pacific Ocean using a framework that integrates descriptive vessel information and tracking data with species-specific catch reports. When parsed by distinct vessel behaviors and attributes, disaggregated fisheries data highlight the existence of multi-national, multi-specific (i.e., targeting multiple species) fishing fleets, many of which target waters that span more than one management area. These findings emphasize the need for increased coordination across regional and sub-regional governance bodies and suggest that effective and equitable management of the sector may require efforts to move beyond single-species, single-area controls and operational distinctions based primarily on vessel flag and/or gear type alone.

Frawley, T.H., Muhling, B., Welch, H., Seto, K.L., Chang, S.K., Blaha, F., Hanich, Q., Jung, M., Hazen, E.L., Jacox, M.G. and Brodie, S. 2022. Clustering of disaggregated fisheries data reveals functional longline fleets across the Pacific. One Earth, 5(9), pp.1002-1018.

Oceanography, Ontogeny, & Gear Usage Mediate Overlap Between High Seas Fishing Fleets and a Pacific Tuna

The management and conservation of tuna and other transboundary marine species have to-date been limited by an incomplete understanding of the oceanographic, ecological, and socioeconomic factors mediating fishery overlap and interactions, and how these factors vary across expansive, open ocean habitats. Despite advances in fisheries monitoring and biologging technology, few attempts have been made to conduct integrated ecological analyses at basin-scales relevant to pelagic fisheries and the highly migratory species they target. Frawley et al. (in review) uses vessel tracking data, archival tags, observer records, and machine learning to examine inter- and intra-annual variability in fisheries overlap of five pelagic longline fishing fleets with North Pacific albacore (2013-2020). Though progressive declines in catch and biomass have been observed over the past several decades, North Pacific albacore is one of the only stocks targeted by pelagic longlines not currently listed as overfished or experiencing overfishing. This study finds that fishery overlap varies significantly across time and space as mediated by: 1) differences in habitat preferences between juvenile and adult albacore, 2) variation of oceanographic features known to aggregate pelagic biomass, and 3) the different spatial niches targeted by shallow-set and deep-set longline fishing gear. These findings may have significant implications for stock assessment in this and other transboundary fishery systems, particularly the reliance on fishery-dependent data to index abundance. Indeed, the authors argue that additional consideration of how overlap, catchability, and size selectivity parameters vary over time and space may be required to ensure the development of robust, equitable, and climate-resilient harvest control rules.

Frawley, T.H., Brodie, S., Blondin, H., Welch, H., Tommasi, D., Smith, J., Fairchadi, N., Cimino, M., Braun, C., Arostegui, M., Hazen, E.L., Jacox, M.G. In review. Climate, ontogeny, and gear usage mediate spatial overlap between high seas fishing fleets and a Pacific tuna. Fish and Fisheries.

VIII. INTERNATIONAL DOLPHIN CONSERVATION PROGRAM ACT RESEARCH

The SWFSC research conducted under the International Dolphin Conservation Program Act (IDCPA) during 2022-23 was focused on mining existing Eastern Tropical Pacific Ocean (ETP) datasets to (1) clarify cetacean population structure, abundance estimation methods, behavior, and life history, and (2) advance our understanding of ecosystem structure and function.

Clarifying Cetacean Population Structure, Abundance Estimation Methods, Behavior, and Life History

Modelling Patchiness of Small Delphinid Group Sizes in the Eastern Tropical Pacific

Researchers are conducting a study of the STAR-LITE 2007 survey data to determine if there is a non-random distribution of schools and school sizes of ETP spotted and spinner dolphins (*Stenella attenuata* and *S. longirostris*) over both space and time. Dive patterns associated with time of day are known for *S. attenuata*, and there is a possibility that these behaviors, as well as others, associated with the formation and breaking up of schools affect the spatial and temporal distribution of these species. Results from these studies can improve estimates of indirect effects of purse seine fishing and the recovery of these depleted populations. This project is still ongoing.

Advancing Understanding of Ecosystem Structure and Function

Healthy populations of species directly targeted for a fishery ultimately depend on healthy ecosystems. In this context, research on components of the ecosystem that are linked to these directly targeted species can facilitate their sustainable use.

Seabird Abundance

Researchers are collaborating to develop updated model-based estimates of abundance for two endangered, endemic Hawaiian seabirds: the Newell's Shearwater (*Puffinus newelli*) and the Hawaiian Petrel (*Pterodroma sandwichensis*). These species are often involved in multi-species feeding flocks that also involve highly migratory species targeted by purse-seine fisheries. This research is based on seabird strip transect survey data that was collected aboard NOAA research cruises in the Central and Eastern Tropical Pacific from 1998 to 2017. A manuscript has been prepared on the revised estimates employing a zero-inflated negative binomial (ZINB) generalized additive model (GAM) framework which is planned for submission to *Endangered Species Research* in summer 2023. In addition to abundance estimates, the species density models derived in this effort also provide quantitative distribution information that could be useful in evaluating potential ecosystem impacts of purse-seine fisheries on Endangered Species Act listed species.

Seabird Distribution and Habitat Relationships

Researchers are also continuing their collaboration to develop an atlas of seabird distribution patterns in the Central and Eastern Tropical Pacific based on NOAA research cruises from 1988 to 2017. These data have been synthesized into standardized map outputs and will be developed as a NOAA Technical Memorandum or monograph manuscript in the coming year(s). Seabirds are important components of the multi-species feeding aggregations targeted by purse-seine fisheries and the distribution maps produced in this effort will provide important baseline information in working towards ecosystem-based fisheries management.

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