Southwest Fisheries Science Center

NOAA FISHERIES - NATIONAL MARINE FISHERIES SERVICE - SOUTHWEST FISHERIES SCIENCE CENTER

JULY 2022

2022 HIGHLY MIGRATORY SPECIES ANNUAL REPORT

by

The Southwest Fisheries
Science Center

ADMINISTRATIVE REPORT LJ-22-02

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National Marine Fisheries Service
National Oceanic & Atmospheric Administration
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The United States is obligated to collect U.S. fisheries statistics and participate in advancing fishery science for species of interest. Fishery information feeds into domestic and international fishery management. Scientists at the National Oceanic and Atmospheric Administration Southwest Fisheries Science Center (NOAA SWFSC) have been tasked to fulfill this obligation. This report focuses on the work of SWFSC scientists on highly migratory fish species (HMS) and their fisheries. Contributions and activities of the past year, April 1, 2021 – March 31, 2022, are briefly described.

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

Fisheries Resources Division (FRD) scientists monitor seven U.S. HMS fisheries in the Pacific and routinely summarize the information into data products for HMS researchers, fisheries managers, and international management organizations in support of the conservation and management of HMS stocks in the Pacific. Yuhong Gu, Gabriel Arce, and Jacob Smith of the HMS Fisheries Monitoring Group (FMG) within FRD compile and manage 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 fisheries councils, commissions, state fisheries agencies, and others to collect and share information from HMS fisheries in the Pacific.

The Eastern Pacific Ocean (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 HMS fishery 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, 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 targets broadbill swordfish (*Xiphias gladius*), Pacific bluefin tuna (*Thunnus orientalis*, PBF), and common thresher (*Alopias vulpinus*) off the coast of central and southern California. The California harpoon fishery targets swordfish mostly in the California bight. Historically, the longline fishery that targets 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 2020 for the HMS fisheries monitored by the FMG.

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

FISHERY	2020 CATCH IN METRIC TONS	NUMBER OF VESSELS
North Pacific Albacore Troll and Pole-and-line	7516	404
South Pacific Albacore Troll	1908	18
Eastern Pacific Ocean Purse Seine	1882	12
California Large-mesh Drift Gillnet	100	12
California Harpoon	7	17
Hook and Line	96	129

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 Fisheries Management Council (PFMC) in 2005. Total annual catch of albacore from the North Pacific albacore troll and pole-and-line fishery decreased nearly 4% from 7,797 t in 2019 to 7,516 t in 2020. The number of vessels decreased from 554 vessels in 2019 to 404 vessels in 2020. The average weight of retained albacore in 2020 was 17 pounds, compared to 14 pounds in 2019.

[1] Numbers taken from RFMO submissions made in 2021.

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. Eighteen vessels participated in the fishery in 2020, down from the nine that participated in 2019. Total catch of albacore in the 2020 fishery was 1908 t, an increase of 119% from the 872 t landed in 2019. No 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 2020, 12 vessels participated in the fishery landing 116 t of Pacific bluefin tuna up from 11 vessels landing 226 t in 2019.

California Large-mesh Drift Gillnet

The California large-mesh drift gillnet fleet decreased from 16 vessels in 2019 to 12 vessels in 2020. In 2019, these vessels landed 52 t of swordfish and 10 t of Pacific bluefin tuna while in 2020, 35 t of swordfish and 28 t of Pacific bluefin 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 California state law and all remaining drift gillnet permits will be phased out by January 31, 2024.

California Harpoon

The California harpoon fishery increased from 16 vessels in 2019 to 17 vessels in 2020. Eleven metric tons of swordfish were caught in 2019 compared with six metric tons caught in 2020. No 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 2020, only three vessels were based in California but several Hawaii-based longline vessels operated out of West Coast ports. 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 260 t in 2020. The catch of Pacific bluefin tuna by U.S. recreational anglers was 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 88 t in 2020 from 37 t in 2019. The catch of Pacific bluefin tuna increased from 36 t in 2019 to 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 134 t of HMS in 2020 including 1 t of Pacific bluefin tuna and 125 t of Swordfish.

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 of North Pacific albacore (NPALB). FRD scientists Steve Teo and Kevin Piner are lead modelers and Steve Teo is also Vice Chair of the ALBWG. An additional FRD scientist, Desiree Tommasi, was the lead analyst for the NPALB management strategy evaluation conducted by the ALBWG. The primary focus of the ALBWG from 2021-2022 was completing the management strategy evaluation (MSE) in 2021 and beginning preparations for a stock assessment in 2023.

The ALBWG successfully organized a series of virtual MSE workshops for managers and stakeholders in March and April 2021. The primary objectives of the MSE workshops were to (1) help managers and stakeholders understand the preliminary results of the MSE; and (2) provide feedback to the ALBWG on improvements to the presentations of results. FRD ALBWG scientists also provided science support in a stakeholder workshop organized by NOAA managers at WCRO and PIFSC to solicit stakeholder input to develop a common harvest strategy for NPALB, with a focus on prioritizing the management objectives, reference points, and fleet controls evaluated in the MSE, as well as a timeline for the development of proposals to IATTC and the Western and Central Pacific Fisheries Commission Northern Committee (WCPFC NC).

The goal of the NPALB MSE was to examine the performance of candidate harvest strategies and associated reference points for NPALB under uncertainty. Performance was evaluated based on management objectives that were agreed upon by managers and stakeholders. MSE results showed that 1) under both total allowable catch (TAC) and mixed control, all harvest control rules (HCRs) were able to maintain the stock above the WCPFC's limit reference point (LRP) and the interim IATTC limit reference point used for tropical tunas with high probability (>0.8) when simulation outcomes across all reference scenarios where considered; 2) under mixed control, there was a tradeoff between the odds of biomass being above the WCPFC LRP and catch metrics; 3) under TAC control, median catch is higher for HCRs with an F40 target reference point (TRP), but that they are also more variable than F50 HCRs. This tradeoff between catch and catch variability leads to comparable probability of catch being above historical levels in both the F50 and F40 HCRs; 4) HCRs with the LRP reference points closer to the SSB associated with the TRP resulted in a higher frequency of management interventions; and 5) both mixed and TAC control are able to maintain the stock above the WCPFC LRP and the interim IATTC LRP for tropical tunas with high probability (>0.8), even with increasing catches from an unknown, unmanaged fleet. However, this comes at the expense of reduced catches for the managed fleets. The ALBWG successfully completed the MSE of NPALB in May 2021 and the ISC Plenary reviewed and approved the NPALB MSE in July 2021.

Detailed results and the full MSE report are available from the ISC website, *Report of the North Pacific Albacore Tuna Management Strategy Evaluation*.

North Pacific Blue Shark

North Pacific blue shark (*Prionace glauca*) 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. FRD scientist Steve Teo is a member of this working group. The primary focus of the SHARKWG from 2021 – 2022 was on completing the North Pacific blue shark stock assessment in 2022. In preparation for the assessment, the SHARKWG held a data preparation workshop in November 2021 and a pre-assessment workshop in March 2022. The SHARKWG has scheduled a stock assessment workshop in May 2022 to complete the assessment.

Pacific Bluefin Tuna

Pacific bluefin tuna has a single, Pacific-wide stock managed by both the WCPFC and the Inter-American Tropical Tuna Commission (IATTC). Huihua Lee and Kevin Piner act as members of the PBFWG on behalf of FRD. Although found throughout the North Pacific Ocean, spawning grounds are recognized only in the western North Pacific Ocean (WPO). A portion of each cohort makes trans-Pacific migrations from the WPO to the eastern North Pacific Ocean (EPO), spending up to several years of its juvenile life stage in the EPO before returning to the WPO. While a suite of fishing gears have historically been used in this fishery, the majority of the catch is currently made by purse seine fisheries (ISC, 2020b). Catches for 1952-2021 were predominately-juvenile PBF. The catch of age-0 PBF has increased substantially since the early 1990s but has decreased since the mid-2000s due to stricter control of the juvenile catch. In the EPO, PBF supported an important commercial fishery on the U.S. West Coast between the 1950s and 1990s. In the last decade, the primary U.S. fishery targeting this species has been the U.S. recreational fishery, including both private boaters and CPFVs operating in United States and Mexican waters. There remains an important commercial fishery for PBF in Mexican waters.

Population dynamics were estimated in the 2022 stock assessment using a fully integrated length-based and age-structured model (Stock Synthesis v3.30) fitted to catch (retained and discarded), size compositions, and catch-per-unit of effort (CPUE) based abundance indices from 1952 to 2021 (fishing years 1952-2020) provided by Members of the ISC Pacific Bluefin Working Group (PBFWG) and non-ISC countries (through the Secretariat of the Pacific Community). The 2022 assessment model structure generally remains the same as the 2020 assessment with additional data observations and model diagnostics. The key improvement was the inclusion of the additional model runs into the stock projections. A total of 25 fleets were defined in the stock assessment model based on country/gear/season/region/size stratification. Quarterly observations of catch, unseen kills, and size compositions, when available, were used to describe the removal processes. Annual estimates of standardized CPUE from the Japanese distant water, offshore, and coastal longline fisheries, the Taiwanese longline fishery, and the Japanese troll fishery were used as measures of the relative abundance of the population. The assessment model was fitted to these input data in a likelihood-based statistical framework.

Biological assumptions including growth, length-weight relationship, maturity, natural mortality, and the stock-recruitment relationship were from the 2020 assessment. An otolith-derived length-at-age relationship was used along with natural mortality estimates from a tag-recapture study and empirical-life history methods. Maximum likelihood estimates of model parameters, derived quantities, and associated variances were used to characterize stock status and develop simulation-based stock projections. The results of the stock assessment and stock projections will be reviewed by the ISC Plenary in July 2022, the Joint IATTC and WCPFC-NC working group on the management of PBF, the Northern Committee of the Western Center Pacific Fisheries Commission, and the IATTC.

III. SUPPORTING PACIFIC FISHERY MANAGEMENT COUNCIL ACTIVITIES

FRD economist Stephen Stohs continued his service as co-chair of the Highly Migratory Species Management Team (HMSMT), an advisory body of the Pacific Fishery Management Council (Council) over the past year. FRD staff member Matthew Craig also continued serving on the HMSMT. The HMSMT met several times in 2021 and early 2022, continuing the virtual meeting format the Council has utilized since June 2020. The main HMS fisheries concerns which the HMSMT and the Council addressed over the past year included: (1) completing the first 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) providing clarifications on permitting provisions for the deep-set buoy gear fishery for swordfish off the West Coast; (5) developing a range of alternatives to establish hard caps on protected species interactions for the large mesh drift gillnet fishery; (6) providing the drift gillnet fishery bycatch performance report; (7) developing recommendations for international management activities; and (8) preparing the 2021 Stock Assessment and Fishery Evaluation (SAFE) Report.

FRD scientist Desiree Tommasi supported development by the HMSMT of a web application to be used as a communication tool to help managers and stakeholders understand the North Pacific Albacore Tuna Management Strategy Evaluation (NPALB MSE) and evaluate the results of the MSE in relation to individual concerns about the fishery.

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, albacore, swordfish, and opah (*Lampris* sp.). 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 conservation and 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 contracts and works with state fishery personnel to collect size data from albacore fishing vessels when they unload their catches in coastal ports. In 2020, 13,070 fish averaging 71.3 cm fork length (FL) were measured at various West Coast ports.

Deep Set Buoy Gear

Over the last several years, a fishery has been under development to help replace the drift gillnet fishery that is terminal. This fishery, known as deep-set buoy gear, takes some components from the east coast where a similar gear has been authorized for years. DSBG employs a hook-and-buoy array configuration to target swordfish during the daytime in deep water, with hooks commonly set at depths below 250 meters. This method has been shown to reduce bycatch and increase the quality of the fish landed.

Natal Origin and Age-Specific Egress of Pacific Bluefin Tuna from Coastal Nurseries Revealed with Geochemical Markers

Rooker et al. (2021) constructed geochemical chronologies from otoliths of adult PBF to investigate the timing of age-specific egress of juveniles from coastal nurseries in the East China Sea or Sea of Japan to offshore waters of the Pacific Ocean. Researchers developed Element:Ca chronologies for otolith Li, Mg, Mn, Zn, Sr, and Ba, and this assessment focused on the section of the otolith corresponding to the age-0 to age-1 + interval. Next, researchers applied a common time-series approach to geochemical profiles to identify divergences presumably linked to inshore-offshore migrations (**Figure 1**). They detected conspicuous geochemical shifts during the juvenile interval for Mg:Ca, Mn:Ca, and Sr:Ca that were indicative of coastal-offshore transitions, or egress, generally occurring for individuals that were approximately 4–6 mo. old, with later departures (6 mo. or older) linked to more limited overwintering. Change points in otolith Ba:Ca profiles were most common in the early age-1 period (ca. 12–16 mo.) and appear associated with entry into upwelling areas such as the California Current Large Marine Ecosystem following trans-Pacific migrations. Researchers predicted natal origin of PBF using the early life portion of geochemical profile in relation to a baseline sample comprised of age-0 PBF from the two primary spawning areas in the East China Sea and Sea of Japan. Mixed-stock analysis indicated that the majority (66%) of adult PBF in the sample originated from the East China Sea, but individuals originating in the Sea of Japan were also detected in the Ryukyu Archipelago. These findings are consistent with other studies and confirm the value of using otolith microchemistry to examine migrations and population dynamics.

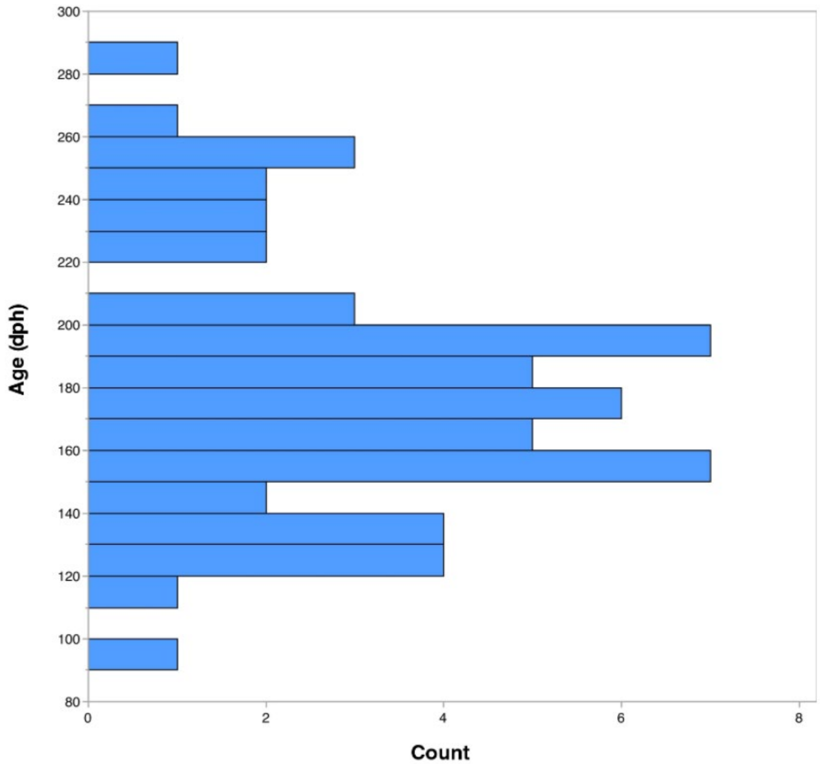

Figure 1. Age-frequency distribution of geochemical changepoints for PBF detected using otolith Mg:Ca, Mg:Ca, and Sr:Ba. Estimated changepoint age of each individual was based on average from all three markers.

Rooker, J.R., R.J. Wells, B.A. Block, H. Liu, H., Baumann, W.C. Chiang... , and J.C. Shiao. 2021. Natal origin and age-specific egress of Pacific Bluefin Tuna from coastal nurseries revealed with geochemical markers. Sci Rep, 11:1, pgs. 1-13.

Nursery Origin and Population Connectivity of Swordfish (*Xiphias gladius)* in the North Pacific Ocean

Wells et al. (2021) used Element:Ca ratios in the otolith cores of young-of-the-year (YOY) swordfish as natural tracers to predict the nursery origin of sub-adult and adult swordfish from three foraging grounds in the North Pacific Ocean (NPO; Figure 2). First, researchers used the chemistry of otolith cores (proxy for nursery origin) to develop nursery-specific elemental signatures in YOY swordfish. They used sagittal otoliths of YOY swordfish collected from four regional nurseries in the NPO between 2000-2005: 1) Central Equatorial North Pacific Ocean (CENPO), 2) Central North Pacific Ocean (CNPO), 3) Eastern Equatorial North Pacific Ocean (EENPO), and 4) Western North Pacific Ocean (WNPO). Researchers then quantified Calcium (^{43}Ca), magnesium (^{24}Mg), strontium (^{88}Sr), and barium (^{138}Ba) in the otolith cores using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Univariate tests indicated that three element:Ca ratios (Mg:Ca, Sr:Ca, and Ba:Ca) were significantly different among nurseries. Overall classification success of YOY swordfish to their nursery of collection was 72% based on quadratic discriminant analysis. Next, they examined element:Ca ratios in the otolith cores of sub-adults and adults collected from three foraging grounds where targeted fisheries exist (Hawaii, California, and Mexico) to calculate nursery-specific contribution estimates. Mixed-stock analysis indicated that the CENPO nursery contributed the majority of individuals to all three foraging grounds (Hawaii 45.6 ± 13.2%; California 84.6 ± 10.8%; Mexico 64.5 ± 15.9%). Results from this study highlight the importance of the CENPO nursery and provides researchers and fisheries managers new information on connectivity of the swordfish population in the NPO.

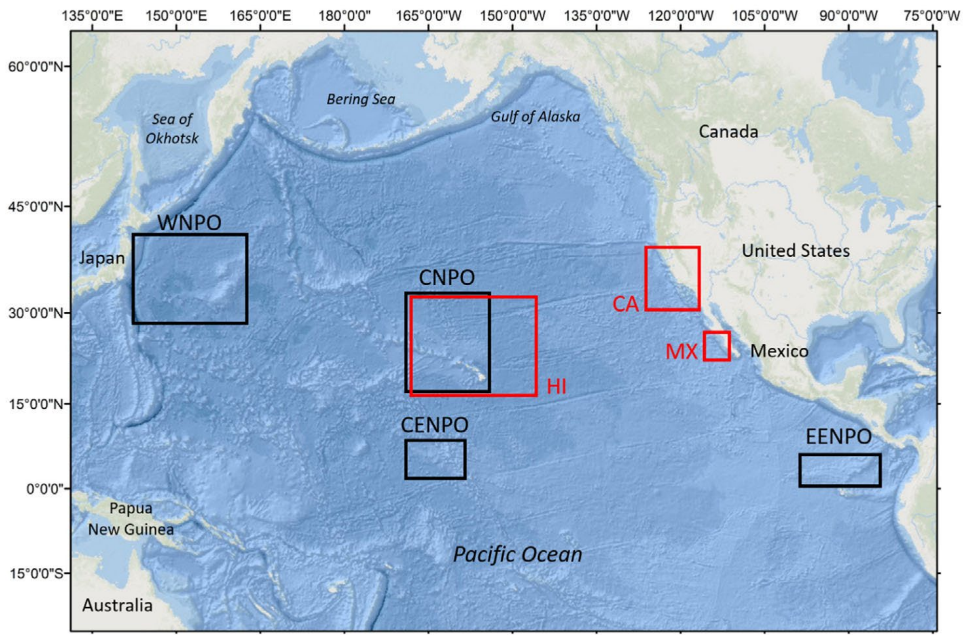

Figure 2. Map of the study regions located in the NPO where YOY and adult swordfish were collected. Regional nurseries are indicated by boxes outlined in black and adult fishing regions are indicated by boxes outlined in red.

Wells, R.D., V.A. Quesnell, R.L. Humphreys Jr., H. Dewar, J.R. Rooker, J. A. Bremer, and O.E. Snodgrass. 2021. Nursery origin and population connectivity of swordfish (Xiphias gladius) in the North Pacific Ocean. J Fish Biol, doi.org/10.1111/jfb.14723

Comparison of Length Sampling Programs for Recreational Fisheries of U.S. Pacific Bluefin Tuna from 2014 to 2020.

The U.S. recreational fishery for PBF is dominated by CPFVs, the landings of which are included in stock assessments. NOAA conducts a PBF Port Sampling Program (PSP) and supports the Sportfishing Association of California Fisheries Sampling Program (SAC) to collect length data to describe the length compositions of the CPFV fleet catch for use in the PBF stock assessment. The overall goal of James et al. (2021) was to determine whether the data generated by PSP and SAC were comparable and whether they reflected the CPFV fishery. To this end, researchers compared the number of PBF, number of trips, geographic extent, and length compositions between PSP and SAC. PSP length data was incorporated into the 2020 stock assessment; however, the SAC data was not investigated. This is the first comparison of the length data between PSP and SAC, and the results generated were intended to provide guidance on the utility of the SAC dataset to the PBF stock assessment.

NOAA's PSP collected straight fork length (FL) data starting in 2014 from PBF caught by the CPFV fleet. This program samples fish opportunistically from CPFV trips after they are unloaded at three public landings in San Diego, CA. For SAC, which started collecting lengths in 2015, CPFV vessel crew measure straight FL of landed PBF while onboard and prior to unloading. PSP measured 4.5% of the CPFV fleet between 2014 and 2019, while SAC measured 3.8% of the CPFV fleet between 2015 and 2020 (**Table 2**). PSP sampled PBF from more vessels than SAC in overlapping years (2015-2019), and it sampled more trips than SAC in most overlapping years. Both PSP and SAC sampled PBF from fishing blocks that were representative in space and effort to the entire CPFV fleet. Sampling overlap of the two programs was low; a maximum of 3.0% of PBF were measured by both sampling programs.

Table 2. Number of PBF landed by the CPFV fleet in California as reported by CDFW CPFV logbooks, and measured by PSP and SAC. SAC was not established until 2015, and PSP did not sample in 2020.

Year	California Recreational CPFV logbook PBF Catch	PBF measured by NOAA	% of PBF measured by NOAA	PBF measured by SAC	% of PBF measured by SAC
2014	26289	1732	6.6%	-	-
2015	22141	493	2.2%	146	0.7%
2016	10394	762	7.3%	382	3.7%
2017	15269	347	2.3%	966	6.3%
2018	12750	570	4.5%	479	3.8%
2019	15535	682	4.4%	550	3.5%
2020	28492	-	-	1454	5.1%
Total: 2014-2019	102378	4603	4.5%	2523	2.5%
Total: 2015-2020	104581	2871	2.7%	3977	3.8%
Total: 2015-2019	76089	2871	3.8%	2523	3.3%

PBF were measured throughout the year by PSP and SAC. The relatively quick growth rate of PBF made direct comparison across months untenable; therefore, researchers transformed lengths to a fixed date, August 15, using the von Bertalanffy growth model for this species. The length compositions of the programs had similar multimodal distributions (**Figure 3**) and only small differences in overall median fork lengths (PSP: 96.5 cm FL; SAC: 94.0 cm FL). However, PSP sampled larger PBF than SAC in several years, which may have been partially driven by the availability of smaller PBF to SAC that were often filleted at sea and unavailable to PSP. SAC sampled fewer vessels than PSP, but a subsampling simulation demonstrated that sampling fewer vessels had only a minor effect on the length compositions; the multimodal length peaks were all present in the simulation albeit some had a smaller magnitude. Finally, PSP and SAC data raised to the CPFV logbook catch reflected the raw data both seasonally and spatially.

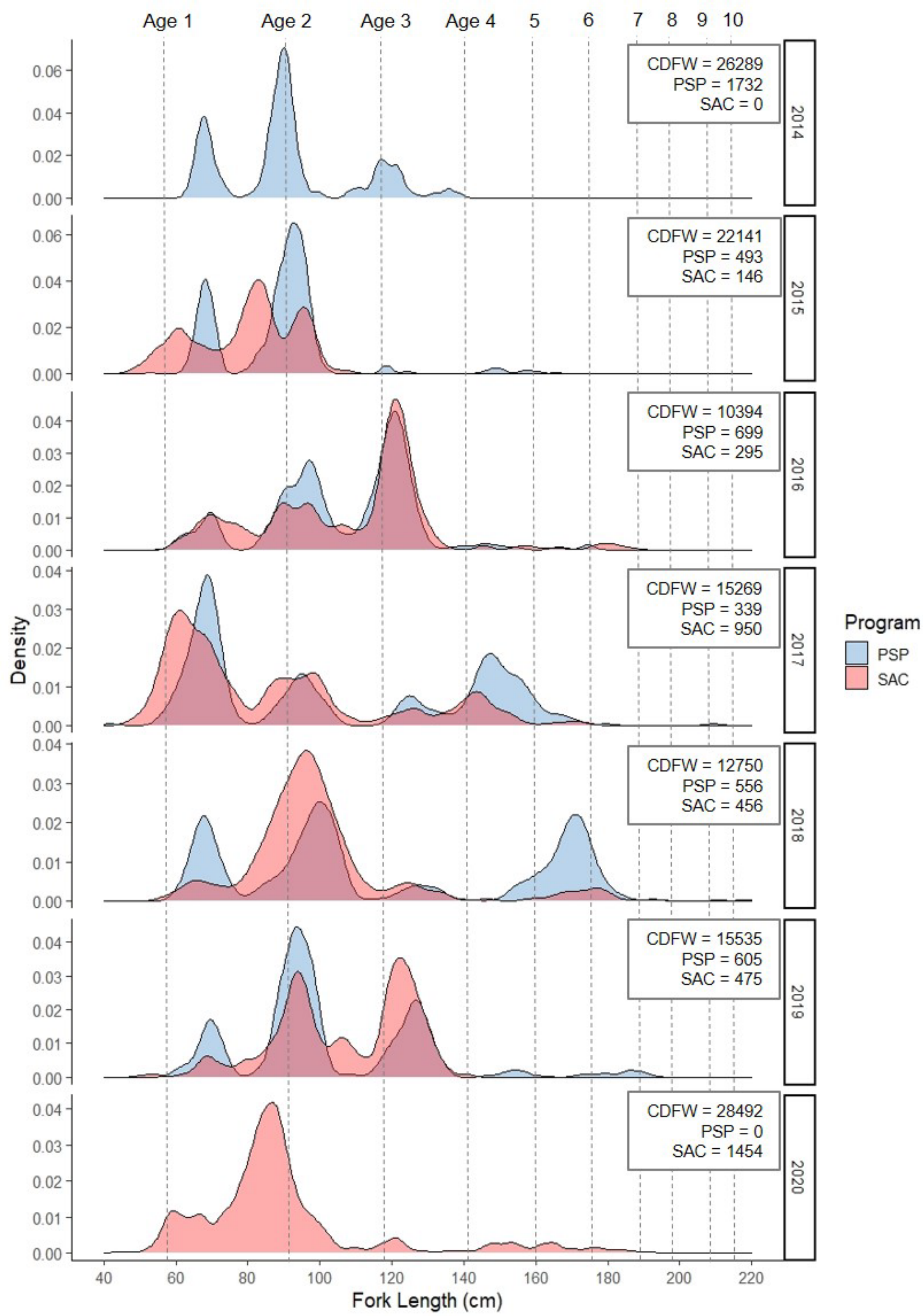

Figure 3. Transformed length frequency distributions of PSP and SAC samples from 2014-2020. The number of PBF measured by PSP and SAC are also listed. The vertical dotted gray lines represent the length-at-age for ages one through ten from ISC (2020). The scale of the y-axis varies among years. SAC was not established until 2015, and PSP did not sample in 2020.

The comparison of SAC and PSP identified similarities and differences in sampling design and catch-at-lengths. PSP sampled opportunistically by choosing sampling days each week conditional on non-zero PBF catch and sample multiple vessels (and therefore multiple trips) within each sampling day. However, PSP relied on catch reports from public landings and therefore may not have sampled if reports of PBF coming in were low. PSP also tended to sample in mostly high catch months and can be restricted by staff availability. In addition, this program only had access to fish unloaded at the dock, a potentially non-random subset of fish landed. In contrast, SAC assigned one set weekday to each vessel to sample throughout the entire year. This scheme allowed sampling over the entire PBF season, which was an advantage over PSP. However, the number of boats that participated was relatively low, 5-11 each year and may have a small effect of the resulting length compositions. In comparison to PSP, SAC had access to all fish landed. Additionally, SAC was able to sample during the 2020 COVID-19 pandemic but PSP was not. This data gap created in the PSP data set highlights the need for continuative size sampling of PBF in the Eastern Pacific Ocean through programs like PSP and SAC.

James, K.C., L.N. Heberer, H. Lee, H. Dewar, and A. Siddall. 2021. Comparison of Length Sampling Programs for Recreational Fisheries of U.S. Pacific Bluefin Tuna from 2014 to 2020. NOAA-TM-NMFS-SWFSC-652, 38 p. https://doi.org/10.25923/bmt9-6435.

Spatiotemporal Catch Patterns and Population Distributions of bigeye Pacific opah (*Lampris megalopsis*) and smalleye Pacific opah (*L. incognitus*) in the Eastern North Pacific

Opah (*Lampris spp.*) are commercially valuable, non-target fish that are regularly landed in pelagic longline fisheries in the central and eastern North Pacific. Genetic studies have confirmed two distinct regional species of opah: the bigeye Pacific opah (*L. megalopsis*), and the smalleye Pacific opah (*L. incognitus*). Spatial distributions of each species are not well defined and little is known about species-specific catch distributions, as the two species are difficult to distinguish visually and logbook data are not species-specific. The objectives of Cooper et al. (accepted) were to characterize spatiotemporal patterns of opah landings using CPUE from logbook and observer data (1995-2018), and genetics-based species identifications of landings. Generalized additive models indicated that bigeye Pacific opah dominate (≥70% proportion) waters west of 140°W and smalleye Pacific opah dominate waters east of 130°W, though bigeye Pacific opah are present in considerable numbers east of 130°W (**Figure 4**). Deep-set pelagic longline gear had notably higher opah CPUE than shallow-set gear across the entire fishery range. Opah CPUE increased from west-to-east on both longline gears, indicating higher overall opah CPUE in primarily smalleye opah dominated regions (**Figure 5**). Opah CPUE also increased over time as the Hawai'i-based longline fisheries expanded eastward (**Figure 5**). This study highlights the need for species-specific catch data and will help inform management.

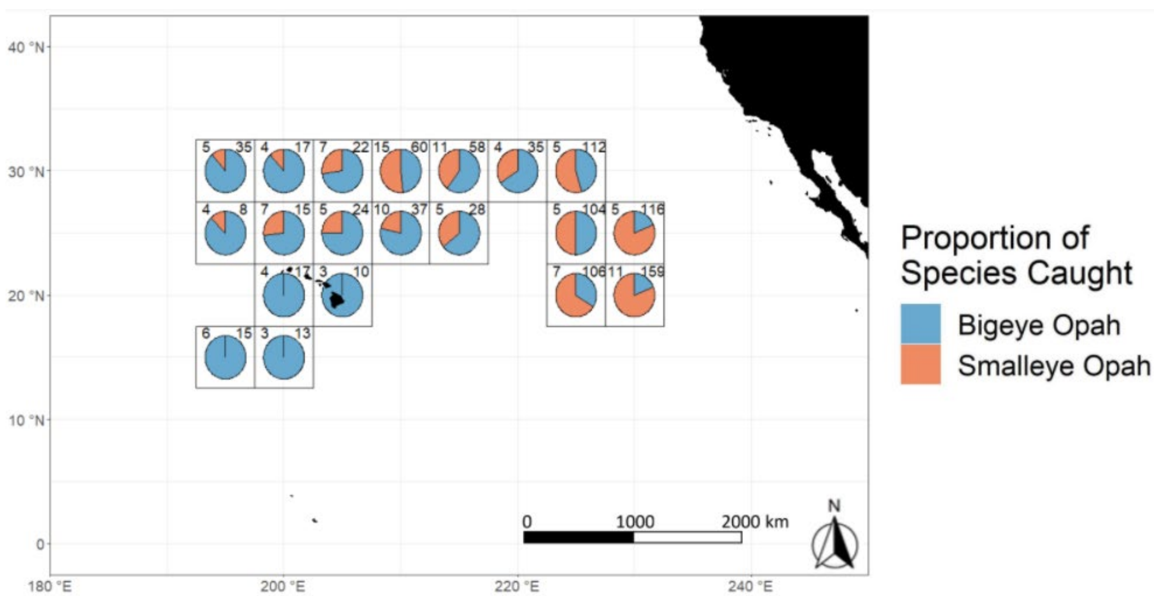

Figure 4: Proportion of genetically confirmed bigeye opah and smalleye opah caught by deep-set pelagic longline fisheries for 5° x 5° spatial blocks. For each block, the top-left number refers to total fishing vessel trips that caught opah used for genetic analysis, and the top-right number refers to total opah caught on those trips. Blocks with less than three vessels are not shown due to confidentiality.

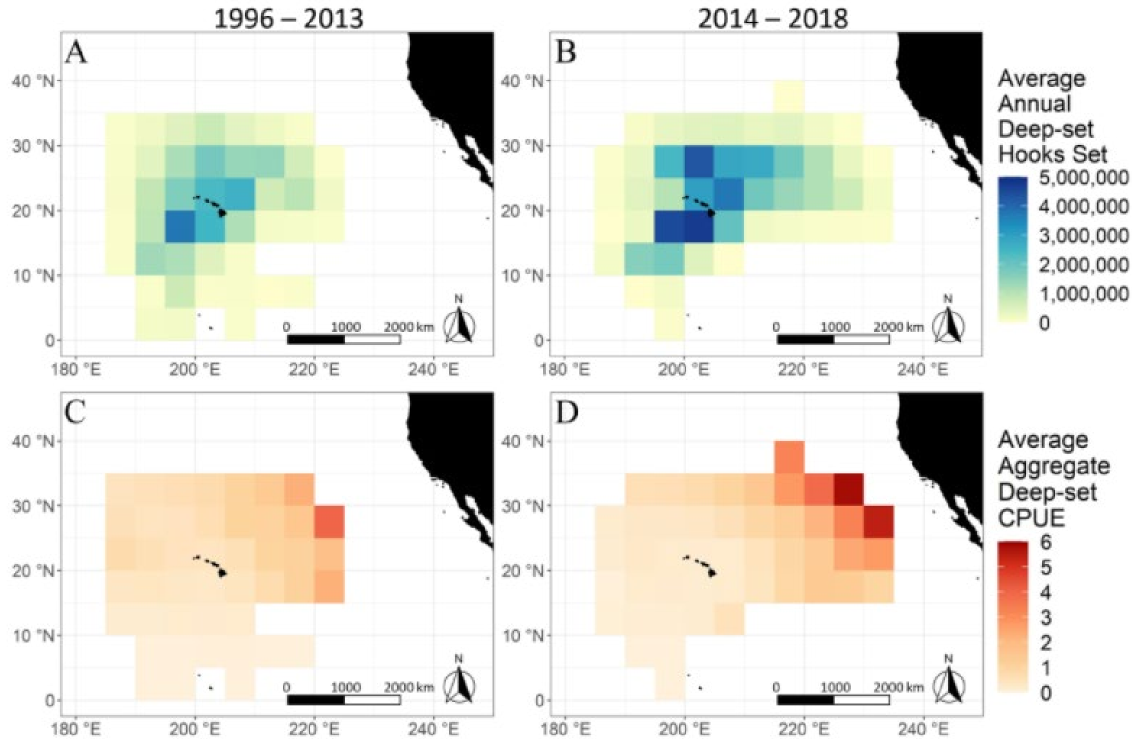

Figure 5. Average annual effort (number of hooks) and aggregate nominal opah catch-per-unit-effort (CPUE; Opah / 1000 hooks) of the U.S. deep-set longline fishery for 5° x 5° spatial blocks during 1996 to 2013 (A and C) and 2014 to 2018 (B and D). Blocks with less than three vessels are not shown due to confidentiality.

Cooper, R., S. Teo, B. Muhling, J. Hyde, and H. Dewar. 2022. Spatiotemporal catch patterns and population distributions of bigeye Pacific opah (Lampris megalopsis) and smalleye Pacific opah (L. incognitus) in the eastern North Pacific. Fish B-NOAA, (accepted).

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 (*Isurus oxyrinchus*), 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 feeds directly into these efforts.

Risk and Reward in Foraging Migrations of North Pacific Albacore Determined From Estimates of Energy Intake and Movement Costs.

North Pacific albacore are commercially important to U.S. West Coast fishing fleets, and are known to undertake extensive migratory movements between nearshore waters of the California Current and offshore environments in the central Pacific. However, these migration behaviors are highly variable, with some individuals traveling thousands of kilometers within a season, while others are largely resident in the southern California Current throughout the year. This impacts their availability to fisheries, especially the West Coast surface fishery.

In Muhling et al. (in press), researchers collaborated with the Tagging of Pacific Predators (TOPP) program to examine the movements, physiology, and ecology of albacore following different migratory pathways. They used data from 33 archival-tagged juvenile albacore released along the West Coast between 2003 and 2011 in collaboration with fishing industry partners. Researchers then used direct measurements of body temperature and ambient water temperature to estimate energy intake via the Heat Increment of Feeding (HIF) which is the increased internal heat production associated with digestion of food.

Results indicate that HIF is highly variable in space and time. However, the most successful foraging areas were in the offshore North Pacific Transition Zone and southern California Current, during spring and summer (example time series for 4 albacore shown in **Figure. 6**). Energy gain appeared to be lowest in the Transition Zone in fall, as fish migrated offshore from Oregon and Washington. Fish remaining resident in the southern California Current year-round incurred lower migration costs, and could access favorable foraging conditions off Baja California in the spring and summer. In contrast, fish which undertook longer migrations had much higher energetic costs during periods of faster transit times, but were able to reach highly productive foraging areas in the central and western Pacific. A biogeochemical model developed at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) determined that foraging success was partially predictable based on estimated mesozooplankton biomass. . However, some albacore had high foraging success in the offshore subtropical gyre where observed and modeled primary and secondary productivity is extremely low. This area is also an important foraging area for many other animals including white sharks, seabirds, whales, and cephalopods, and is a productive fishing ground for bigeye tuna (*Thunnus obesus*). Additional subsurface measurements of biogeochemistry and lower trophic levels in this region could thus improve understanding of migration dynamics and foraging ecology of multiple migratory species in the North Pacific.

Migratory movements in albacore are poorly understood and appear highly variable. Albacore have not been present in larger fishable aggregations off southern California for more than 10 years, and fishers report that fishing conditions offshore have been generally poor since the early 2000s. In the past 5 years, albacore landings have been historically low along the West Coast imposing economic hardships on the fishing industry. When combined with other ongoing studies of diet composition and growth at the SWFSC, this study can help improve understanding of distribution and migration drivers in albacore and their accessibility to the surface fleet.

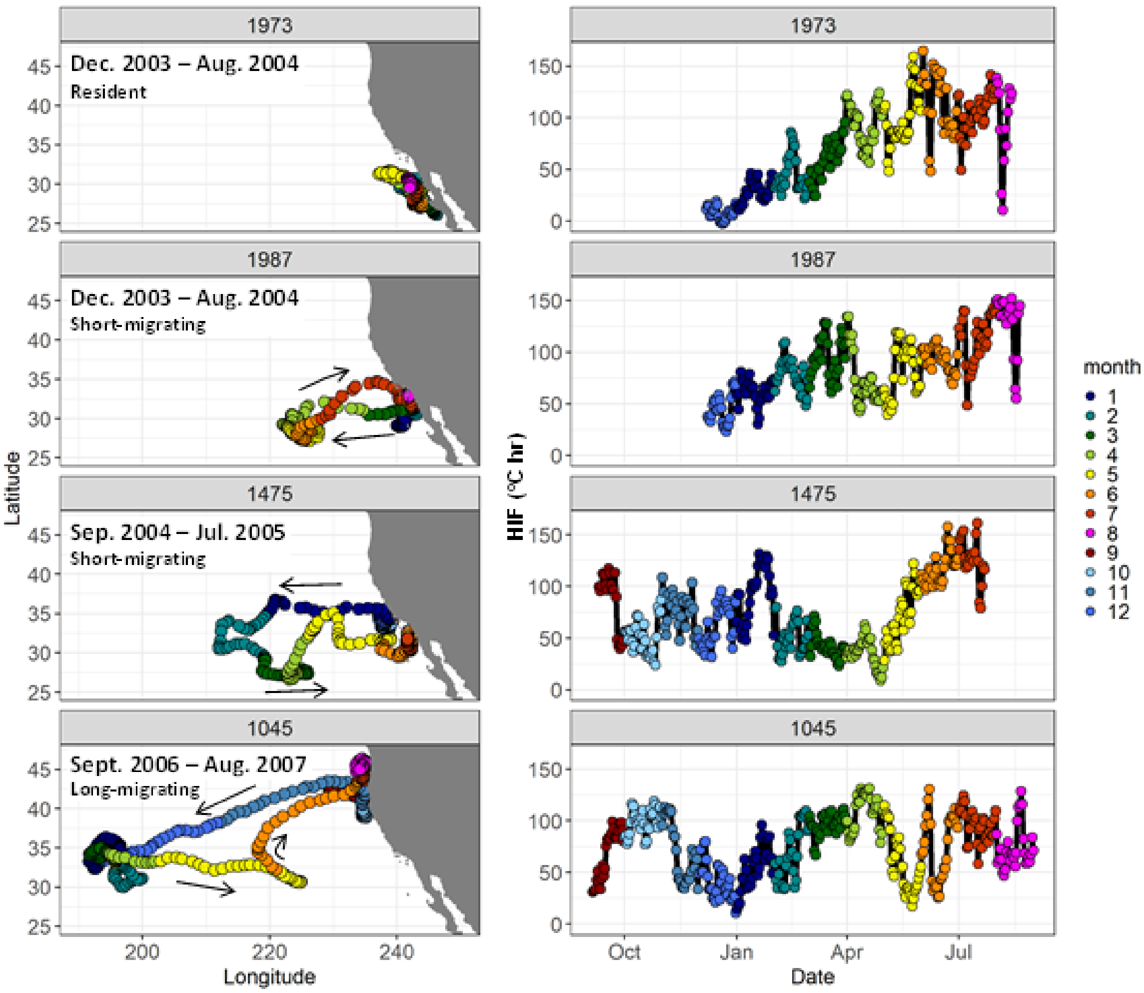

Figure 6. Daily locations (left), and daily mean energy intake (HIF: right) for four example fish showing different migration patterns. Colors denote month and arrows show migration directions.

Muhling, B.A., S. Snyder, E.L. Hazen, R.E. Whitlock, H. Dewar, J.Y. Park, C.A. Stock, and B.A. Block. 2022. Risk and reward in foraging migrations of North Pacific albacore determined from estimates of energy intake and movement costs. Front Mar Sci, (in press).

Albacore and Broadbill Swordfish Diets in the California Current

Quantifying the diets of highly migratory fishes in the CCE can complement existing trawl-based assessments of available forage species, lend insight into how forage varies over time and space, and provide a direct metric of forage utilization. North Pacific albacore and broadbill swordfish are both opportunistic predators that consume a wide variety of prey taxa across a range of depths and habitats. In Nickels et al. (2022), albacore and swordfish stomachs provided by commercial and recreational fishers were studied and prey were identified from whole or hard part remains and reported as a mean percent abundance. A subset of prey species are presented here focusing on prey that are either themselves under a management plan, or that are considered ecosystem component species, to highlight their links to highly migratory species.

Juvenile albacore were collected off Northern California, Oregon, and Washington during the summer and fall fishing season. Analysis of stomachs from 2021 is still ongoing, but preliminary data (N = 15)is included here for insight into the most recent trends. The processed samples for 2021 represent 93% of the expected diversity at the family level based on rarefaction and extrapolation curves, thus most of the expected diversity is already discovered (average among all years is 97%). The dominant prey from 2021 are northern anchovy (*Engraulis mordax*), euphausiids (Order: Euphausiacea), and Pacific saury (*Cololabis saira*). Northern anchovy consumption increased in 2020 and 2021 after a low in 2018-2019. While overall Pacific sardine (*Sardinops sagax*) is of limited importance, sardine consumption was also higher in 2020 and 2021, well above the long-term mean. Rockfish (*Sebastes* spp.) consumption demonstrated an opposite pattern with consumption declining in 2020 and 2021 after a peak in 2019 coinciding the with the northern anchovy low. The remaining Coastal Pelagic Species (CPS) observed were of minimal importance across years. The most important "other" contributors over the whole time series were the squid *Onychoteuthis borealijaponica*, Hyperiid amphipods (Suborder: *Hyperiidea*), and slender barracudina (*Lestidiops ringens*).

Swordfish were collected off Southern and Central California during the commercial drift gillnet season (August 15 through January 31). Stomachs are classified by the year the fishing season began (stomachs from January are assigned to the previous year's fishing season). Overall, swordfish fed mainly on fish and cephalopods. In 2019, the dominant prey was Northern Anchovy followed by market squid (*Doryteuthis opalescens*). In 2020, slender blacksmelt (*Bathylagus pacificus*) was the most important species followed by northern anchovy and market squid. Northern anchovy and market squid were consumed above the long term mean in 2019-2020. Pacific hake (*Merluccius productus*) fell near the mean in both years. Other CPS and rockfish were a minor part of swordfish diets across years. Over the whole time series the most important contributors to the "other" category were squids including humboldt (*Dosidicus gigas*) and armhook (*Gonatopsis borealis* and*Gonatus* spp). Humboldt squid was the most important prey throughout the early portion of the time series although its importance decreased in 2010 during a peak in market squid consumption, and then in both 2011 and 2014 during which time Pacific hake became more important. Fished species were less important in swordfish diets overall when compared with albacore.

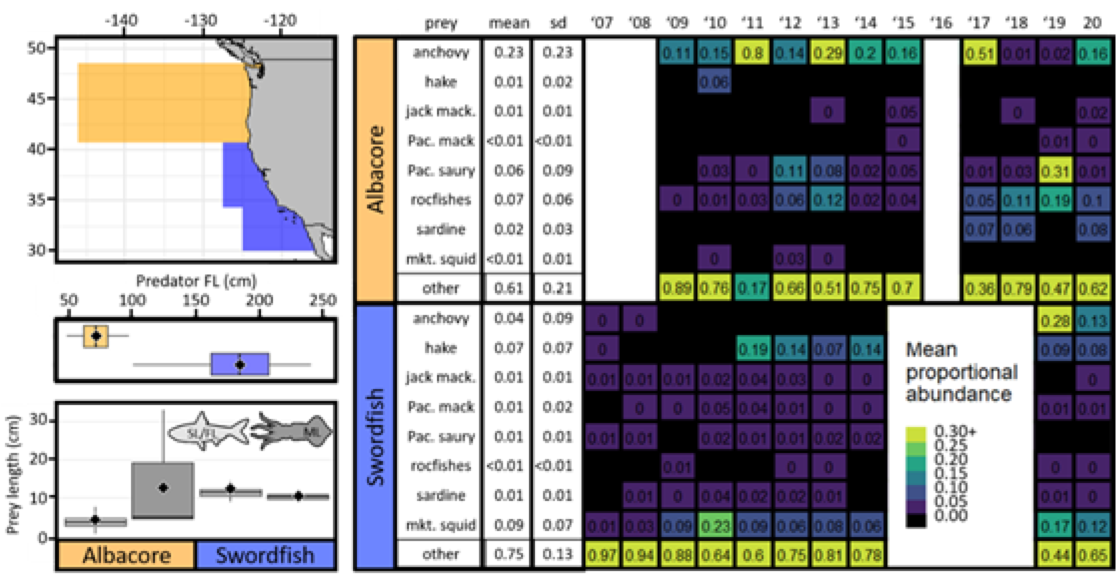

Figure 7. Diets were assessed via stomach content analysis for albacore (in orange) from the Pacific Northwest and broadbill swordfish (in blue) from Central and Southern California. Swordfish were larger on average, shown in the middle left plot. Mean lengths (black diamond) and boxplots of length distributions for forage fishes (light grey) and market squid (dark grey) are depicted on the lower left. Swordfish prey were generally larger with the exception of a large market squid consumed by an albacore. The right panel shows the annual mean proportional abundance of prey as a heat map, where the color saturates at 30%. Anchovy, Pacific saury, and rockfish were particularly important prey for albacore. Hake and market squid were important for swordfish throughout the time series, and reliance on anchovy increased in 2019 and 2020. Both species consume a broad range of prey with significant shifts in diet composition over relatively short time periods.

Nickels, C.F., A. Preti, and H. Dewar. 2022. HMS Diet Information. In J. Zwolinski (Ed.), State of the California Current 2020-2021. CalCOFI Conference, Virtual.

Nickels, C.F., A. Preti, and H. Dewar. 2022. HMS Diet Information. In C. Harvey, T. Garfield, G. Williams, N. and Tolimieri (Eds.), 2021-2022 California Current Ecosystem Status Report.

Feeding Ecology of Broadbill Swordfish in the California Current.

In addition to efforts to characterize the overlap between predators and specific coastal pelagic species, (Preti et al. accepted) involved a more detailed analyses of swordfish diets. Researchers studied swordfish stomachs provided by commercial fishers, identified prey to the lowest taxonomic level, and analyzed diet composition using univariate and multivariate methods. Of 299 swordfish sampled from 2007-2014 (74 to 245 cm eye-to-fork length), 292 non-empty stomachs contained remains from 60 prey taxa. Genetic analyses were used to identify prey that could not be identified visually. Diet consisted mainly of cephalopods but also included epipelagic and mesopelagic teleosts (**Figure 8**). Humboldt squid (*Dosidicus gigas*) and armhook squid (*Gonatopsis borealis*) were the most important prey based on the geometric index of importance, although swordfish diet varied with body size, location, and year. *Gonatus* spp. and Pacific hake were more important for larger swordfish, reflecting the ability of larger predators to catch larger prey. *Gonatus* spp. and market squid were more important for fish taken in inshore waters, while armhook squid and Pacific hake were more important in fish taken offshore. *Gonatus sp.* was more important in 2007-2010 than in 2011-2014, with Pacific hake being the most important prey item in the latter period. Diet variation by area and year likely reflects differences in swordfish prey preference, distribution, and abundance. For example, the range expansion of humboldt squid in the early 2000s was reflected in their increased occurrence in swordfish diets. While they tend to target cephalopods, swordfish feed on a range of species across habitats. A more generalist foraging strategy will add to resilience in a dynamic system like the California Current where there are relatively large-scale shifts in available prey.

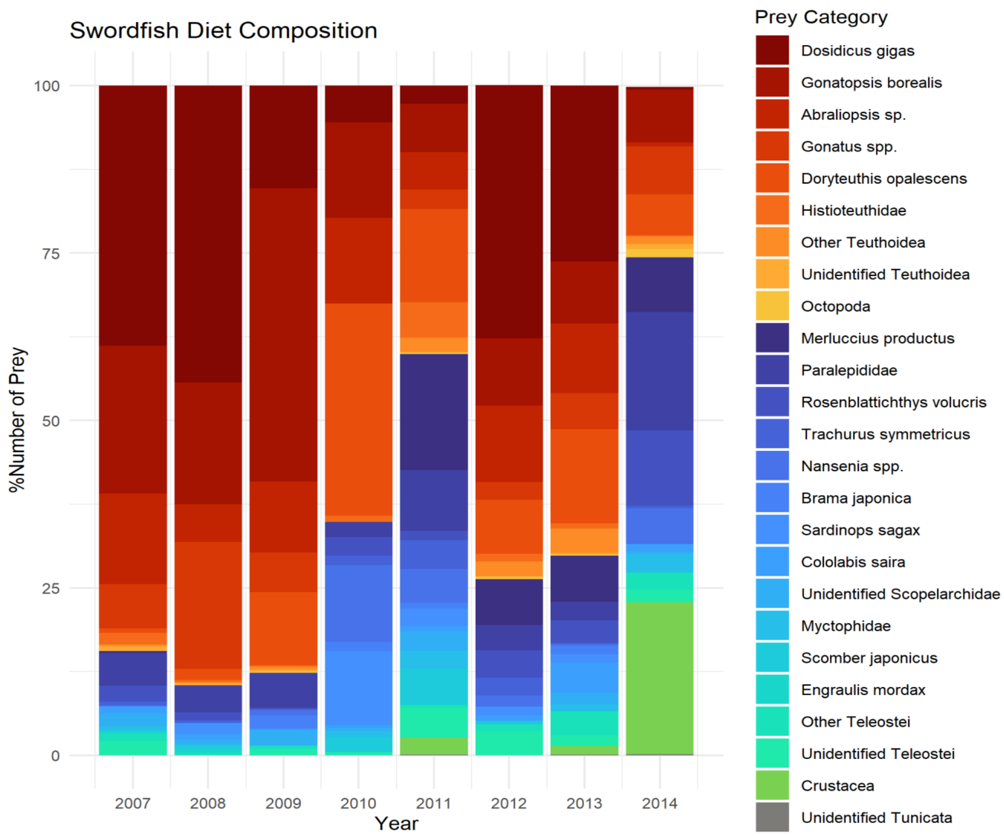

Figure 8. Annual %Number (%N=number of individual prey for a given prey category in a stomach divided by the total number of individual prey across prey categories) for different prey categories from 2007-2014. red = cephalopods; blue = fishes; green = crustaceans; grey = tunicates

Preti, A., S.M. Stohs, G.T. DiNardo, C. Saavedra, K. MacKenzie, L.R. Noble, C.S. Jones, and G.J. Pierce. 2022. Feeding ecology of Broadbill Swordfish (Xiphias gladius) in the California Current. Plos ONE, (accepted).

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 conservation and management bodies having stewardship for sharks.

Isotopic Tracers Suggest Limited Trans-Oceanic Movements and Regional Residency in North Pacific Blue Sharks

Blue sharks are globally distributed, large-bodied pelagic sharks that have been shown to migrate across entire ocean basins. In the North Pacific, mark-recapture studies have demonstrated trans-Pacific migrations, but knowledge gaps in migration frequency hinder understanding of regional connectivity and assessments of regional demography. Madigan et al. (2021) used gradients of stable isotope ratios (i.e., regional isoscapes) to determine exchange rates of blue sharks between the East and West North Pacific Ocean (**Figure 9**). Discriminant analysis suggested low trans-Pacific exchange (**Figure 10**), categorizing all western (100%) and most eastern (95.3%) blue sharks as resident to their sampling region, with isotopic niche overlap of Western Pacific Ocean (WPO) and Eastern Pacific Ocean (EPO) being highly distinct (0.01–5.6% overlap). Potential finer scale movement structure was observed within both eastern and western Pacific sub-regions, with mixing models suggesting potential region-specific residency and localized foraging. Considerations of species-specific isotopic dynamics and sample treatments and their effects on these results and future studies are discussed. These results suggest that blue shark population dynamics may be effectively assessed on a regional basis (i.e., WPO and EPO), though further studies are required to assess size- and sex-specific movement patterns based on empirical isotopic values from regional studies with large sample sizes. Strategically applied stable isotope approaches can continue to elucidate migration dynamics of migratory marine predators, complementing traditional approaches to fisheries biology and ecology.

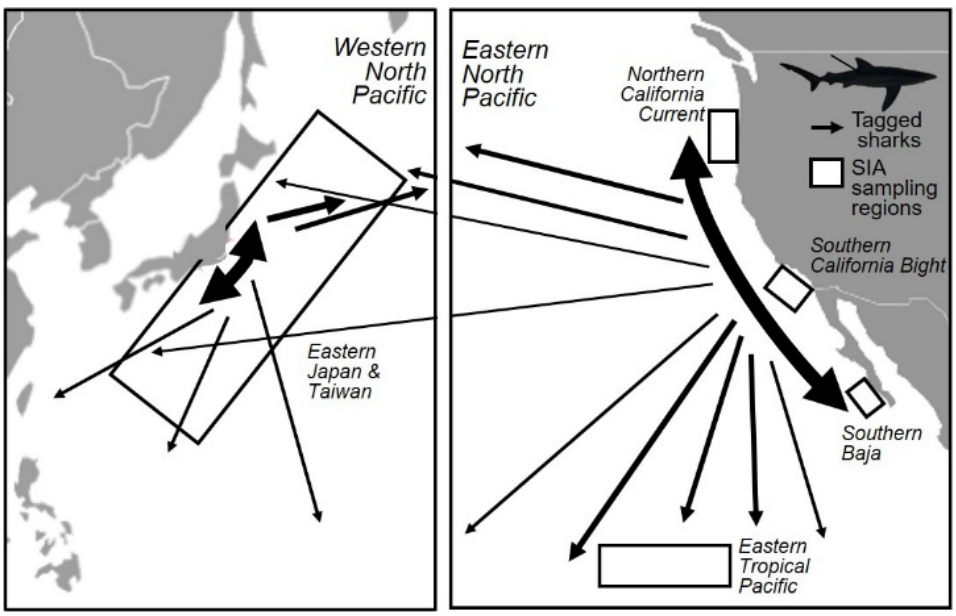

Figure 9. Map of summarized blue shark movements and sampling locations for isotopic studies in the North Pacific Ocean. Movements (black arrows) are based on conventional tagging data in the western and eastern Pacific Ocean (WPO and EPO), with arrow size scaled to relative proportion of observed movements. Boxes show regions of blue shark tissue sampling for stable isotope analysis (SIA; solid lines, EPO; dashed lines, WPO). Tagging data simplified from Sippel *et al.* 2011; SIA data from Miller *et al*. 2010, Madigan *et al*. 2012, Li *et al*. 2014, Hernández-Aguilar *et al*. 2015.

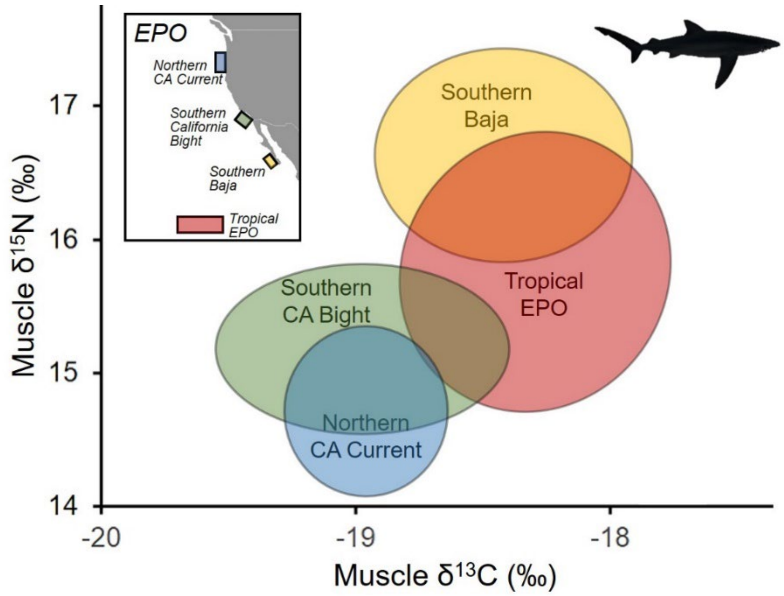

Figure 10. Differences in isotopic niches of blue shark across discrete regions within the eastern North Pacific Ocean. Map (upper left) shows regions where blue sharks were sampled and subsequently analyzed for $\delta^{13}C$ and $\delta^{15}N$ values. Ellipses represent 95% of blue shark $\delta^{13}C$ and $\delta^{15}N$ values following Swanson *et al*. (2015).

These results, drawing upon published $\delta^{13}C$ and $\delta^{15}N$ data for blue sharks and prey sampled at multiple locations in the EPO and WPO, provide a new and replicable means to assess blue shark residency and migration dynamics in the North Pacific. The analyzed data provide strong evidence for limited direct migrations between the WPO and EPO, and reiterated the utility of $\delta^{15}N$ isoscapes for the reconstruction of migratory predator movements in the North Pacific Ocean. Regional structure in $\delta^{13}C$ and $\delta^{15}N$ data have promise for further quantification of finer-scale blue shark movements, increasing the resolutions of movement patterns suggested, but consideration of isotopic parameters (*e.g.*, accurate DTDFs), appropriate sample preparation of shark tissues, and length/sex metadata of sampled sharks are necessary. With emerging research showing varying residency and trans-regional movements in migratory predators, isoscapes can employ high sample sizes across a breadth of animal life stages, regions, and timeframes to reconstruct habitat use of highly migratory animals. Through these isotopic approaches, population-level estimates of movement dynamics are feasible on scales that may not be readily available from conventional tagging or telemetry studies.

Madigan, D.J., O.N. Shipley, A.B. Carlisle, H. Dewar, O.E. Snodgrass, and N.E. Hussey. 2021. Isotopic tracers suggest limited trans-oceanic movements and regional residency in North Pacific Blue Sharks (Prionace glauca). Front Mar Sci, 8:489.

Spatial Distribution, Temporal Changes, and Knowledge Gaps in Basking Shark Sightings in the California Current Ecosystem

Among the largest fish species, the basking shark is found circumglobally in temperate and tropical waters. Though historical documents have recorded their presence in the California Current Ecosystem (CCE), basking sharks are now only rarely observed in this part of their range. McInturf et al. (2022) compiled recent and historical data from systematic surveys (1962–1997) and other sources (1973–2018; **Figure 11**) to (i) examine temporal patterns of basking shark sightings in the CCE, and (ii) determine the spatial, temporal, and environmental drivers that have affected basking shark presence and distribution in the CCE for the last 50 years. Researchers first calculated variation in basking shark sightings and school size over time and then generated species distribution models using the systematic survey data and evaluated the performance of these models against the more recent non-systematic sightings data. The sightings records indicated that the number of shark sightings was variable across years, but the number and probability of sightings declined in the mid-1980s. The systematic survey data showed that a maximum of 4,000 sharks were sighted per year until the 1990s, after which there were no sightings reported. In parallel, there was more than a 50% decline in school size from the 1960s to the 1980s (57.2 to 24.0 individuals per group). During the subsequent decades in the non-systematic data (>1990), less than 60 sharks were sighted per year. There were no schools larger than 10 reported, and the mean school size in the last decade (2010s) was 3.53 individuals per group. Low sea surface temperature and high chlorophyll *a* concentration increased sighting probability, and prevailing climatic oscillations (El Nino-Southern Oscillation index, North Pacific Gyre Oscillation, Pacific Decadal Oscillation) were also correlated with basking shark presence. Lastly, researchers observed a significant shift in the seasonality of sightings, from the fall and spring during the systematic survey period to the summer months after the 2000s. McInturf et al. concluded by offering suggestions for future research and conservation efforts, highlighting that coordinating the documentation of fisheries mortalities and sightings throughout the Pacific basin would facilitate more robust population estimates and identify sources of mortality. Additionally, monitoring shark fin markets and developing region-specific genetic markers would help ensure that Convention on International Trade in Endangered Species (CITES) regulations are being followed.

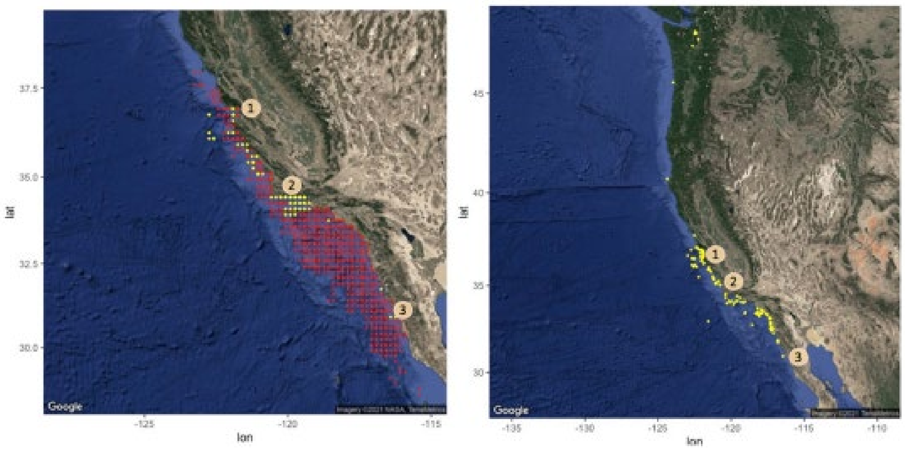

Figure 11. Maps of sightings data collected from 1962 to 2018, from systematic surveys (left; 1962–1997) and non-systematic data (right; 1973–2018) along the western coast of the United States and Mexico. Observations are in yellow. Those above 46° latitude were observed in the bay near Seattle, WA. Sightings from drift gillnet records have been excluded in this figure because of NOAA confidentiality policies. Centroids of blocks where sharks were not found, based on systematic surveys by pilots who had reported a basking shark at least once, are marked in red. Numbers indicate shark hotspots identified in both this and previous studies in (1) Monterey Bay, (2) Santa Barbara, and (3) Baja California.

McInturf, A.G., B. Muhling, J.J. Bizzarro, N.A. Fangue, D. Caillaud, and H. Dewar. 2022. Spatial distribution, temporal changes, and knowledge gaps in Basking Shark (Cetorhinus maximus) sightings in the California Current Ecosystem. Front Mar Sci, 77.

Validated Band Pair Periodicity of Juvenile Common Thresher Sharks in the Northeastern Pacific Ocean

Validation of the periodicity of band pair formation in elasmobranch vertebrae is essential for accurate age estimation. Spear et al. (Accepted) validated the vertebral band pair deposition rate for juvenile common thresher sharks in the northeastern Pacific Ocean (NEPO) using oxytetracycline (OTC) tagging and recapture (**Figure 12**). A total of 37 common thresher sharks marked with OTC from 1998 through 2013, were recaptured with times at liberty ranging from 0.53 to 3.81years with an average of 1.27 years (± 0.92 years standard deviation, SD). Shark size ranged from 63 to 128 cm fork length (FL) at the time of injection with OTC and from 83 to 168 cm FL at recapture. Vertebral band pair counts distal to the OTC marks indicate one band pair (1 translucent and 1 opaque) is deposited annually for the common thresher shark within the size range examined in the NEPO (**Figure 12**). This finding supports previous age and growth assumptions that have formed the basis of management decisions, and will support future studies and stock assessments of this species.

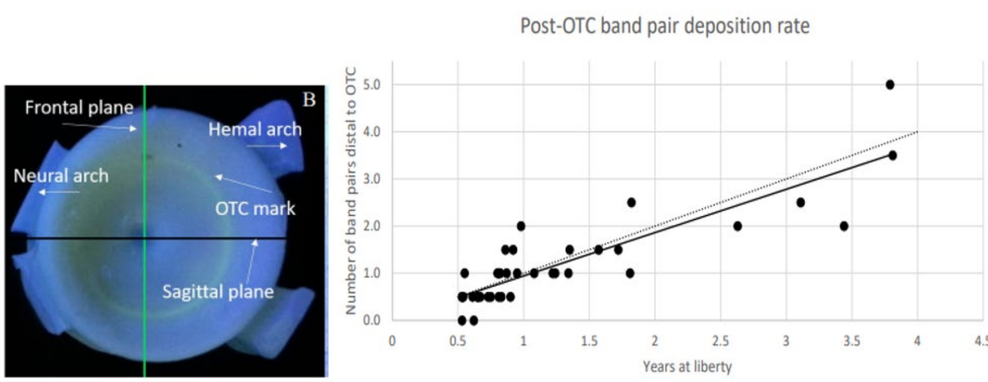

Figure 12. Left) Oxytetracycline mark fluorescing under UV light; section is cut along the green line. Right) Number of vertebral band pairs after the oxytetracycline mark compared to years at liberty for common threshers tagged and recaptured in the northeastern Pacific (1998-2013). The solid line represents the relationship of band pairs to years at liberty; the dotted line represents a deposition rate of 1 band pair per year.

Spear, N., S. Kohin, J. Mohan, and J.D. Wells. 2022. Validated band pair periodicity of juvenile Common Thresher Sharks (Alopias vulpinus) in the Northeastern Pacific Ocean. Fish. B-NOAA, (accepted).

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.

Seabird Abundance

Trevor Joyce of the Marine Mammal and Turtle Division (MMTD), along with scientists Robert Pitman and Lisa Balance, 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. Dr. Joyce presented revised estimates employing a zero-inflated negative binomial (ZINB) generalized additive model (GAM) framework at the most recent Pacific Seabird Group meeting (February 2019), and a revised manuscript is in the process of internal review and will be submitted to *Endangered Species Research* in summer 2021. 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

Trevor Joyce (MMTD), along with scientists Robert Pitman, and Lisa Balance, are collaborating to develop an atlas of seabird distribution patterns in the Central and Eastern Tropical Pacific based on NOAA research cruises from 1988 to 2017. This data has 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.

Drivers of Emergent Migratory Behavior

Understanding the drivers of movement, migration, and distribution of individuals is important for insight into how species will respond to changing environmental conditions. Both abiotic and biotic factors are thought to influence migratory behavior, but their relative roles are difficult to disentangle. For migratory marine predators, both temperature and prey availability have been shown to be significant predictors of space use, though often researchers rely on physical proxies due to the lack of data on dynamic prey fields. Dodson et al. (2020) generated spatially explicit, individual-based movement models to evaluate the relative roles of abiotic (sea surface temperature; SST) and biotic (prey availability) factors in driving blue whale (*Balaenoptera musculus*) movement decisions and migratory behavior in the eastern North Pacific. Using output from a lower trophic ecosystem model coupled with a regional ocean circulation model, researchers parameterized a blue whale movement model that explicitly incorporates prey fields in addition to physical proxies. A model using both SST and prey data reproduced blue whale foraging behavior including realistic timing of latitudinal migrations. SST and prey only population models demonstrated important independent effects of each variable. In particular, the SST only model revealed that warm temperatures limited krill foraging opportunities but failed to drive seasonal foraging patterns, whereas the prey only model revealed more realistic seasonal and interannual differences in foraging behavior. This individual-based movement model helps elucidate the mechanisms underlying migration and demonstrates how fine-scale individual decision making can lead to emergent migratory behavior at the population level. Moreover, determining the relative effects of the physical environment and prey availability on the movement decisions of threatened species is critical to understand how they may respond to changing ocean conditions.

Dodson, S., B. Abrahms, S.J. Bograd, J. Fiechter, and E.L. Hazen. 2020. Disentangling the biotic and abiotic drivers of emergent migratory behavior using individual-based models. Ecol Model, 432. doi.org/10.1016/j.ecolmodel.2020.109225.

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.

Connecting Fisheries Management Challenges with Models and Analysis to Support Ecosystem-Based Management in the California Current Ecosystem

One of the significant challenges to using information and ideas generated through ecosystem models and analyses for ecosystem-based fisheries management is the disconnect between modeling and management needs. Established by the Pacific Fisheries Management Council's Fisheries Ecosystem Plan, the stakeholder review of NOAA's annual ecosystem status report for the California Current Ecosystem (Tommasi et al. 2021) presented a case study from the U.S. West Coast, showcasing a process to identify management priorities that require information from ecosystem models and analyses. Researchers then assessed potential ecosystem models and analyses that could help address the identified policy concerns. They screened stakeholder comments and found 17 comments highlighting the need for ecosystem-level synthesis. Policy needs for ecosystem science included: (1) assessment of how the environment affects productivity of target species to improve forecasts of biomass and reference points required for setting harvest limits, (2) assessment of shifts in the spatial distribution of target stocks and protected species to anticipate changes in availability and the potential for interactions between target and protected species, (3) identification of trophic interactions to better assess tradeoffs in the management of forage species between the diet needs of dependent predators, the resilience of fishing communities, and maintenance of the forage species themselves, and (4) synthesis of how the environment affects efficiency and profitability in fishing communities, either directly via extreme events (e.g., storms) or indirectly via climate-driven changes in target species availability. Researchers concluded by exemplifying an existing management process established on the U.S. West Coast that could be used to enable the structured, iterative, and interactive communication between managers, stakeholders, and modelers that is key to refining existing ecosystem models and analyses for management use.

Tommasi, D., Y. deReynier, H. Townsend, et al. 2021. A Case Study in Connecting Fisheries Management Challenges with Models and Analysis to Support Ecosystem-Based Management in the California Current Ecosystem. Front Mar Sci, 8:624161.

Environmental Impacts on Bluefin Tuna Migration in the California Current

Animal migrations track predictable seasonal patterns of resource availability and suitable thermal habitat. As climate change alters this 'energy landscape', some migratory species may struggle to adapt. Carroll et al. (2021) examined how climate variability influences movements, thermal habitat selection and energy intake by juvenile PBF during seasonal foraging migrations in the California Current. Researchers tracked 242 PBF across 15 years (2002–2016) with high-resolution archival tags, estimating their daily energy intake via abdominal warming associated with digestion (the 'heat increment of feeding'). The poleward extent of foraging migrations was flexible in response to climate variability, allowing PBF to track poleward displacements of thermal habitat where their standard metabolic rates were minimized. During a marine heatwave that saw temperature anomalies of up to +2.5°C in the California Current, spatially explicit energy intake by PBF was approximately 15% lower than average. However, by shifting their mean seasonal migration approximately 900 km poleward, PBF remained in waters within their optimal temperature range and increased their energy intake. These findings illustrate how tradeoffs between physiology and prey availability structure migration in a highly mobile vertebrate, and suggest that flexible migration strategies can provide a buffer for energetic costs associated with climate variability and change.

Carroll, G., S. Brodie, R. Whitlock, S.J. Bograd, E.L. Hazen, and B.A. Block. 2021. Flexible foraging migrations buffer a marine predator against energetic costs of extreme climate variability. P Roy Soc B, 288: 20210671.

Exploring Timescales of Predictability in Species Distributions

Accurate forecasts of how animals respond to climate-driven environmental change are needed to prepare for future redistributions, however, it is unclear which temporal scales of environmental variability give rise to predictability of species distributions. Brodie et al. (2021) examined the temporal scales of environmental variability that best predicted spatial abundance of swordfish, a marine predator in the California Current. To understand which temporal scales of environmental variability provide biological predictability, researchers decomposed physical variables into three components: a monthly climatology (long-term average), a low frequency component representing interannual variability, and a high frequency (sub-annual) component that captures ephemeral features. Researchers then assessed each component's contribution to predictive skill for spatially-explicit swordfish catch. The monthly climatology was the primary source of predictability in swordfish spatial catch, reflecting the spatial distribution associated with seasonal movements in this region. Importantly, the low frequency component (capturing interannual variability) provided significant skill in predicting anomalous swordfish distribution and catch, which the monthly climatology cannot. The addition of the high frequency component added only minor improvement in predictability. By examining a models ability to predict species distribution anomalies, researchers assess the models in a way that is consistent with the goal of distribution forecasts – to predict deviations of species distributions from their average historical locations. The critical importance of low frequency climate variability in describing anomalous swordfish distributions and catch matches the target timescales of physical climate forecasts, suggesting potential for skillful ecological forecasts of swordfish distributions across short (seasonal) and long (climate) timescales. Understanding sources of prediction skill for species environmental responses gives confidence in the ability to accurately predict species distributions and abundance, and to know which responses are likely less predictable, under future climate change. This is important as climate change continues to cause an unprecedented redistribution of life on Earth.

Brodie, S., B. Abrahms, S.J. Bograd, G. Carroll, E.L. Hazen, B. Muhling, M. Pozo Buil, J. Smith, H. Welch, and M.G. Jacox. 2021. Exploring timescales of predictability in species distributions. Ecography, I44: 1–13.

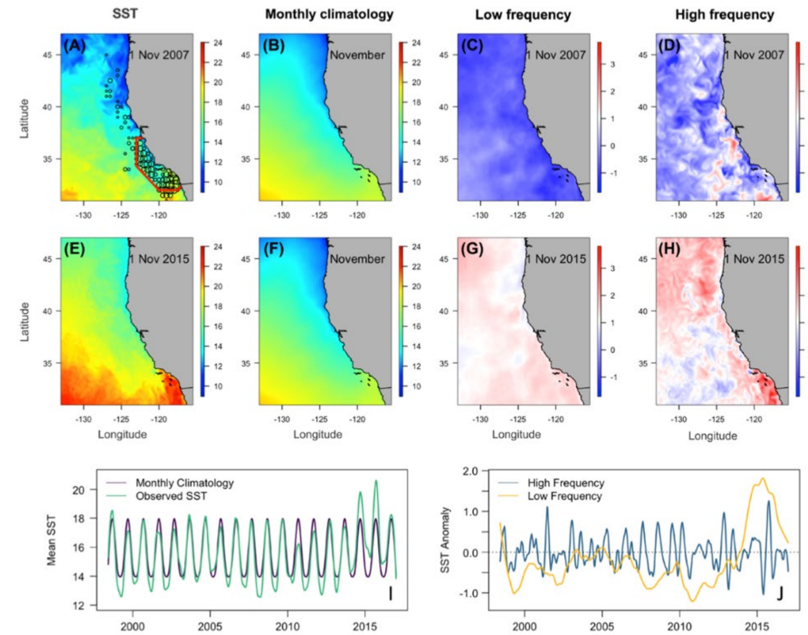

Figure 13. Map of the California Current System showing observed and decomposed sea surface temperature (SST) for two example days, 1 November 2007 (A-D), and 1 November 2015 (E-H). Swordfish catch locations aggregated to the nearest 0.5 degrees are shown, with the red polygon indicating 95% of the catch data (core fishing zone; top left). Time-series plots (I and J) show the spatially-averaged observed and decomposed sea surface temperature from 1998 to 2016, and were smoothed for illustrative purposes. Decomposition separated sea surface temperature into three component parts: a monthly climatology, a low frequency signal capturing interannual variability, and a high frequency signal capturing the remaining variability on sub-annual timescales.

Methodological Considerations of Species Distribution Modeling

Habitat suitability models give insight into the ecological drivers of species distributions and are increasingly common in management and conservation planning. Telemetry data can be used in habitat models to describe where animals were present,. However, this requires the use of presence-only modeling approaches or the generation of 'pseudo-absences' to simulate locations where animals did not go. To highlight considerations for generating pseudo-absences for telemetry-based habitat models, Hazen et al. (2021) explored how different methods of pseudo-absence generation affect model performance across species' movement strategies, model types, and environments.

This study built habitat models for marine and terrestrial case studies using Northeast Pacific blue whales (*Balaenoptera musculus*) and African elephants (*Loxodonta africana*). Researchers tested four pseudo-absence generation methods commonly used in telemetry-based habitat models: (1) background sampling, (2) sampling within a buffer zone around presence locations, (3) correlated random walks beginning at the tag release location, and (4) reverse correlated random walks beginning at the last tag location. Habitat models were built using generalized linear mixed models, generalized additive mixed models, and boosted regression trees.

Researchers found that the separation in environmental niche space between presences and pseudo-absences was the single most important driver of model explanatory power and predictive skill. This result was consistent across marine and terrestrial habitats, two species with vastly different movement syndromes, and three different model types. The best-performing pseudo-absence method depended on which created the greatest environmental separation: background sampling for blue whales and reverse correlated random walks for elephants. However, despite the fact that models with greater environmental separation performed better according to traditional predictive skill metrics, they did not always produce biologically realistic spatial predictions relative to known distributions.

Habitat model performance may be positively biased in cases where pseudo-absences are sampled from environments that are dissimilar to presences. This emphasizes the need to carefully consider spatial extent of the sampling domain and environmental heterogeneity of pseudo-absence samples when developing habitat models, and highlights the importance of scrutinizing spatial predictions to ensure that habitat models are biologically realistic and fit for modeling objectives.

Hazen, E.L., B. Abrahms, S. Brodie, G. Carroll, H. Welch, and S.J. Bograd. 2021. Where did they not go? Considerations for generating pseudo-absences for telemetry-based habitat models. Mov Ecol, 9:5, doi.org/10.1186/s40462-021-00240-2.

Global Analysis of Blue Marlin Distribution

Dale et al. (in review) described the global habitat suitability of blue marlin from satellite tracking tags and species distribution models. Researchers found that global blue marlin habitat has decreased since 2000.

Dale J.J., S. Brodie, A.B. Carlisle, M. Castleton, E.L. Hazen, S.J. Bograd, and B.A. Block. 2022. Global habitat loss of a highly migratory predator, the blue marlin (Makaira nigricans). Divers Distrib, (in review).

Climate Change Projections of HMS distributions

Lezama-Ochoa et al. (in prep) produced daily projections from 1980-2100 for seven highly migratory species (leatherback turtle, blue shark, common thresher shark, shortfin mako, humpback whale, swordfish, and California sea lion) 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 area occupied, center of gravity, 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.

Top Predator Responses to Northeast Pacific Marine Heat Waves

Welch et al. (in prep) built telemetry-based boosted regression tree models for albacore and bluefin tuna, and mako, blue, white, and salmon sharks. The models were used to quantify the impacts of the 2014, 2015, 2019, and 2020 marine heatwaves on the distributions of these species in the Northeast Pacific.

Examination of IUU Fishing in the Northeast Pacific

Marine fisheries around the globe are increasingly exposed to external drivers of social and ecological change. Though diversification and flexibility have historically helped marine resource users negotiate risk and adversity, much of modern fisheries management treats fishermen as specialists using specific gear types to target specific species. Frawley et al. (2021) describe the evolution of harvest portfolios among Pacific Northwest fishermen over 35+ years with explicit attention to changes in the structure and function of the north Pacific albacore (Scombridae) troll and pole-and-line fishery. This analysis indicates that recent socio–ecological changes have had heterogenous impacts upon the livelihood strategies favored by different segments of regional fishing fleets. As ecological change and regulatory reform have restricted access to a number of fisheries, many of the regional, small (<45 ft) and medium (45–60 ft) boat fishermen who continue to pursue diverse livelihood strategies have increasingly relied upon the ability to opportunistically target albacore in coastal waters while retaining more of the value generated by such catch. In contrast, large vessels (>60 ft) targeting albacore are more specialized now than previously observed, even as participation in multiple fisheries has become increasingly common for this size class. In describing divergent trajectories associated with the albacore fishery, one of the U.S. West Coast's last open-access fisheries, researchers highlighted the diverse strategies and mechanisms utilized to sustain fisheries livelihoods in the modern era while arguing that alternative approaches to management and licensing may be required to maintain the viability of small-scale fishing operations worldwide moving forward.

Frawley, T.H., B.A. Muhling, S, Brodie, M.C. Fisher, D. Tommasi, G. Le Fol, E.L. Hazen, S.S. Stohs, E.M. Finbeiner, and M.G. Jacox. 2021. Changes to the structure and function of an albacore fishery reveal shifting social-ecological realities for Pacific Northwest fishermen. Fish Fish, 22:2, 280-297.

VIII. INTERNATIONAL DOLPHIN CONSERVATION PROGRAM ACT RESEARCH

Marine Mammal and Turtle Division (MMTD) research at the SWFSC conducted under the International Dolphin Conservation Program Act (IDCPA) from 2021-22 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 understanding of ecosystem structure and function.

Phylogeographic and Population Genetic Analyses of Toothed Whales in the Context of Population and Phylogeographic Patterns in the North Pacific and Globally

Spinner dolphins in the eastern tropical Pacific (ETP) present a unique case for studying adaptation. Within this large geographic region, there are four spinner dolphin ecotypes with weak neutral genetic divergence and no obvious barriers to gene flow, but strong spatial variation in morphology, behavior, and habitat. These ecotypes have large population sizes, which could reduce the effects of drift and facilitate selection. To identify genomic regions putatively under divergent selective pressures between ecotypes, Andrews et al. (2021) used genome scans with 8,994 RADseq SNPs to identify population differentiation outliers and genotype-environment association outliers. Gene ontology enrichment analyses indicated that outlier SNPs from both types of analyses were associated with multiple genes involved in social behavior and hippocampus development, including fifteen genes associated with the human social disorder autism. Evidence for divergent selection on social behavior is supported by previous evidence that these spinner dolphin ecotypes differ in mating systems and associated social behaviors. In particular, three of the ETP ecotypes likely have a polygynous mating system characterized by strong pre-mating competition among males, whereas the fourth ecotype likely has a polygynandrous mating system characterized by strong post-mating competition such as sperm competition. These results provide evidence that selection for social behavior may be an evolutionary force driving diversification of spinner dolphins in the ETP, potentially as a result of divergent sexual selection associated with different mating systems.

Andrews, K.R., B. Epstein, M. Leslie, P. Fiedler, P.A. Morin, and A.R. Hoelzel. 2021. Genomic signatures of divergent selection are associated with social behavior for spinner dolphin ecotypes. Mol Eco, 30, 1993-2008.

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

Pooja Balaji (Scripps Institution of Oceanography student) and Eric Archer (MMTD) 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 attenuate* 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.

Taxonomy of Long- and Short-beaked Common Dolphins

Tom Jefferson and Eric Archer (MMTD) continue to collaborate on a morphometric and genetic re-analysis of long and short beaked common dolphins (*Delphinus* sp.) in the eastern Pacific. The project compares a suite of skull measurements and mitochondrial DNA sequences to establish a foundation to re-describe the long-beaked common dolphin, previously referred to as *D. capensis,* and now regarded as a subspecies within *D. delphis* as a separate species, *D. bairdii*. This re-description will better describe the biodiversity of cetaceans in the eastern Pacific, provide a more solid foundation for classifying stranded and bycaught individuals to taxa, and properly delineate taxa for management under the ESA as well as the MMPA.

Cranial Variation of Bottlenose dolphins

Eric Archer (MMTD) is collaborating with Ana Costa of the University of Glasgow on a morphometric study of bottlenose dolphin skulls from the western Pacific, eastern tropical Pacific, and California Current. This study will help inform a much-needed taxonomic revision of this wide-ranging species. It will also provide a context for the delineation of taxa and ESA and MMPA management units, especially offshore and coastal bottlenose dolphins in California and Mexico. This project is ongoing.

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