Southwest Fisheries Science Center

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

SEPTEMBER 2021

2021 HIGHLY MIGRATORY SPECIES ANNUAL REPORT

edited by

Stephanie Flores

ADMINISTRATIVE REPORT LJ-21-04

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2021 HIGHLY MIGRATORY SPECIES ANNUAL REPORT

Southwest Fisheries Science Center
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, 2020 – March 31, 2021, are briefly described.

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

Southwest Fisheries Science Center (SWFSC) 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. The HMS Fisheries Monitoring Group (FMG) under the Fisheries Resources Division (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 fisheries councils, commissions, state fisheries agencies, and others to collect and share information from HMS fisheries in the Pacific.

The Eastern Pacific Ocean (EPO) is home to 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 over decades 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 swordfish (*Xiphias gladius*), Pacific bluefin (*Thunnus orientalis*, PBF), and common thresher sharks (*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 that target albacore off of Washington, Oregon, and central California, as well as albacore, Pacific bluefin, and yellowfin (*Thunnus albacares*) tuna 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 2019 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	2019 CATCH IN METRIC TONS	NUMBER OF VESSELS
North Pacific Albacore Troll and Pole-and-line	7,797	554
South Pacific Albacore Troll	789	9
Eastern Pacific Ocean Purse Seine	598	11
California Large-mesh Drift Gillnet	103	16
California Harpoon	12	16
Hook and Line	46	101

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 increased 1% from 7,728 t in 2018 to 7,797 t in 2019. The number of vessels increased from 452 vessels in 2018 to 554 vessels in 2019. The increase of vessels and landings for 2019 is mostly attributed to an increase in small vessels participating in the fishery due to albacore being caught closer to the coast than in years past. In 2018, there were 249 vessels that had landings greater than 5 t, while in 2019, 253 vessels had landings greater than 5 t, but over 300 vessels had landings of less than 5 t. The average weight of retained albacore in 2019 was 14 pounds, compared to 15 pounds in 2018.

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. Nine vessels participated in the fishery in 2019, down from the 13 that participated in 2018. Total catch of albacore in the 2019 fishery was 789 t, an increase of 84% from the 429 t landed in 2018. 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.

California Large-mesh Drift Gillnet
The California large-mesh drift gillnet fleet decreased from 21 vessels in 2018 to 16 vessels in 2019. These vessels landed 52 t of swordfish and 10 t of Pacific bluefin in 2019 compared to 148 t of swordfish and 18 t of Pacific bluefin caught in 2018. 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.

[1] Numbers taken from RFMO submissions made in 2019.

California Harpoon
The California harpoon fishery increased from 14 vessels in 2018 to 16 vessels in 2019. Twelve metric tons of swordfish were caught in 2019 compared with 14 metric tons caught in 2018. 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 2019, four longline vessels (up from less than three vessels in 2018) were based in California but several Hawaii-based longline vessels operated out of west coast ports. These Hawaii 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 Commercial Passenger Fishing Vessels 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 increased from 381 t in 2018 to 1,364 t in 2019. The catch of Pacific bluefin by U.S. recreational anglers decreased from 505 t in 2018 to 428 t in 2019.

Hook and Line Fisheries
The hook and line fisheries target primarily tunas in Southern California waters with an emphasis on Pacific bluefin in recent years. The fishery has also begun targeting swordfish using rod and reel style gear in deep waters in the past several years. The hook and line catch increased from 40 t and 100 participating vessels in 2018 to 46 t and 101 vessels in 2019. The catch of Pacific bluefin increased from 31 t in 2018 to 36 t in 2019.

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 264 t of HMS in 2019 compared to 103 t of HMS caught in 2018, an increase of 61%.

II. SUPPORTING U.S. OBLIGATIONS OF INTERNATIONAL AGREEMENTS

North Pacific Albacore
North Pacific albacore tuna supports the most important HMS commercial fishery on the U.S. West Coast and is an essential stock for recreational fisheries. The ISC Albacore Working Group (ALBWG) performs the stock assessments of North Pacific albacore tuna (NPALB). Scientists from SWFSC/FRD are the lead modelers and include the vice-Chair of the ALBWG. The primary focus of the ALBWG from 2020 – 2021 was completing an assessment of the stock in 2020, followed by the completion of the management strategy evaluation (MSE) in 2021. Given the COVID-19 situation during this period, the ALBWG met in virtual meetings.

The ALBWG successfully conducted the stock assessment of NPALB in April 2020 and the ISC Plenary subsequently reviewed and approved the stock assessment in July 2021. The stock assessment provided the following information on the status of the NPALB stock:

1. The stock is likely not overfished relative to the limit reference point adopted by the Western and Central Pacific Fisheries Commission ($20\%SSB_{current,\ F=0}$), and

2. No F-based reference points have been adopted to evaluate overfishing. Stock status was evaluated against seven potential reference points. Current fishing intensity (F 2015-2017) is likely at or below all seven potential reference points.

After completing the stock assessment, the ALBWG turned its attention towards the MSE for this stock. The ALBWG reviewed the preliminary MSE results in December 2020 and planned for a series of MSE workshops for managers and stakeholders in March and April 2021. Several virtual workshops were held to accommodate time zone and language differences. The primary objectives of the MSE workshop will be 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. The meeting for the managers and stakeholders from the U.S. and Canada was held March 22-25, 2021.

Pacific Bluefin Tuna

Pacific bluefin tuna (PBF) has a single Pacific-wide stock managed by both the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC). 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 catch is currently made by purse seine fisheries (ISC, 2020b). Catches from 1952-2018 were predominately juvenile PBF. The catch of age-0 PBF has increased significantly since the early 1990s with a decreasing trend since the mid-2000s. In the EPO, PBF supported an important commercial fishery on the U.S. West Coast between the 1950s and 1990s. In the past decade, however, the primary U.S. fishery targeting this species has been the U.S. recreational fishery, including both private boaters and publicly chartered CPFV operating in U.S. and Mexican waters. There remains an important commercial fishery for PBF in Mexican waters.

Population dynamics were estimated in the 2020 benchmark 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 2019 (fishing years 1952-2018), provided by Members of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC20-Annex11, 2020), Pacific Bluefin Tuna Working Group (PBFWG), and non-ISC countries (through the Secretariat of the Pacific Community). The 2020 assessment model structure generally remains the same as the 2018 assessment. The key improvement was the inclusion of fleets with estimated unaccounted mortality from released PBF. 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 reviewed. When there was better biological information, outside studies were used to inform some of the life history parameters. For example, a length-at-age relationship was from otolith-derived ages and natural mortality estimates were 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 were endorsed/reviewed by the ISC Plenary in July 2020 (ISC20, 2020), the Joint IATTC and WCPFC-NC working group on the management of Pacific Bluefin tuna (IATTC-WCPFC-NC-05, 2020), the Northern Committee of the Western Center Pacific Fisheries Commission (WCPFC-NC16, 2020) in October 2020, and the Inter-American Tropical Tuna Commission (IATTC-SAC) in October 2020.

The base-case assessment model showed that: (1) spawning stock biomass (SSB) fluctuated throughout the assessment period (fishing years 1952-2018); (2) the SSB steadily declined from 1996 to 2010; (3) stock biomass has slowly increased since 2011; (4) total biomass in 2018 exceeded the historical median with an increase in immature fish; and (5) fishing mortality (F%SPR) declined from a level producing about 1% of SPR1 in 2004-2009 to a level producing 14% of SPR in 2016- 2018 (ISC20-Annex11, 2020). Based on the model diagnostics, the estimated biomass trend for the last 30 years is considered robust although SSB prior to the 1980s is uncertain due to data limitations. The SSB in 2018 was estimated to be around 28,000 t (ISC20-Annex11, 2020), which is a 3,000 t increase from 2016 according to the base-case model. An increase of young fish (0-2 years old) was observed from 2016-2018 (ISC20-Annex11, 2020), likely resulting from low fishing mortality on those fish (ISC20-Annex11, 2020) and is expected to accelerate the recovery of SSB in the future. Historical recruitment estimates have fluctuated since 1952 without an apparent trend. The 2015 recruitment estimate is lower than the historical average while the 2016 recruitment estimate (about 17 million fish) is higher than the historical average (ISC20-Annex11, 2020). The recruitment estimates for 2017 and 2018, which are based on fewer observations and are more uncertain, are below the historical average. Estimated age-specific fishing mortalities (F) on the stock during the periods of 2011-2013 and 2016-2018 compared with 2002-2004 estimates (the reference period for the WCPFC Conservation and Management Measure) showed a substantial decrease in estimated F in ages 0-2 in 2016-2018 relative to the previous years. Note that stricter management measures in the WCPFC and IATTC have been in place since 2015.

The historical impacts of the fleets on the PBF stock analyzed the estimated biomass when fishing mortality from the respective fleets is zero. The WPO coastal fisheries group has had the greatest impact on the PBF stock, but since around the early 1990s, the WPO purse seine fishery group targeting small fish (ages 0-1) has had a greater impact and the effect of this group in 2018 was greater than any other fishery group. The impact of the EPO fisheries group was large before the mid-1980s, decreasing significantly thereafter. The WPO longline fisheries group has had a limited effect on the stock throughout the analysis period because the impact of a fishery on a stock depends on both the number and size of the fish caught by each fleet (i.e., catching a high number of smaller juvenile fish can have a greater impact on future spawning stock biomass than catching the same weight of larger mature fish). There is greater uncertainty regarding discards than other fishery impacts because the impact of discarding is not based on observed data.

The WCPFC and IATTC adopted an initial rebuilding biomass target (the median SSB estimated for the period from 1952 through 2014) and a second rebuilding biomass target (20%SSBF=0 under average recruitment) without specifying a fishing mortality reference level. The 2020 assessment estimated the initial rebuilding biomass target (SSBMED1952-2014) to be 6.4%SSBF=0 and the corresponding fishing mortality expressed as SPR of F6.4%SPR (ISC20-Annex11, 2020). The Kobe plot shows that the point estimate of the SSB2018 was 4.5%SSBF=0 and the recent (2016-2018) fishing mortality corresponds to F14%SPR (ISC20-Annex11, 2020). Although no reference points have been adopted to evaluate the status of PBF, an evaluation of stock status against some common reference points (ISC20-Annex11, 2020) shows that the stock is overfished relative to biomass-based limit reference points adopted for other species in WCPFC (20%SSBF=0) and fishing mortality has declined but not reached the level corresponding to that reference point (20%SPR).

After the steady decline in SSB from 1995 to the historically low level in 2010, the PBF stock has started recovering slowly, consistent with the management measures implemented in 2014-2015. The SSB in 2018 was below the two-biomass rebuilding targets adopted by the WCPFC, while the 2016-18 fishing mortality (F%SPR) has reduced to a level producing 14%SPR. The simulation-based projection results based on the base-case model under several harvest and recruitment scenarios and time schedules requested by the RFMOs showed that under all examined scenarios, the initial goal of WCPFC and IATTC, rebuilding to SSBMED by 2024 with at least 60% probability, is reached and the risk of SSB falling below SSBloss at least once in 10 years is negligible. PBF SSB recovers to the biomass-based rebuilding targets due to reduced fishing mortality by applying catch limits as the stock increases. In most of the scenarios, the SSB biomass is projected to recover to the initial rebuilding target (SSBMED) in the fishing year 2020 (April of 2021) with a probability above the 60% level prescribed in the WCPFC CMM (ISC20-Annex11, 2020).

Sharks

SWSFC staff provides scientific advice on stock status of pelagic sharks to international and domestic fishery management organizations. SWFSC participation in international collaborations on pelagic shark stock assessments is organized primarily through the Shark Working Group (SHARKWG, chaired by Dr. Mikihiko Kai, National Research Institute of Far Seas Fisheries) of the ISC. There were no assessments, working group reports, or working papers in 2020.

III. SUPPORTING PACIFIC FISHERY MANAGEMENT COUNCIL ACTIVITIES

Fisheries Resources Division economist Dr. Stephen Stohs continued serving as co-chair of the Highly Migratory Species Management Team (HMSMT) of the Pacific Fishery Management Council (Council) over the past year, and was joined by Dr. Matthew Craig as a new member of the HMSMT. The HMSMT met several times in 2020 and early 2021, in a virtual meeting format beginning in June 2020. The main HMS fisheries concerns which the HMSMT and the Council addressed over the past year included: (1) conducting the first phase of a review of essential fish habitat for HMS and scoping the second phase of the review, which involved collaboration between the HMSMT and SWFSC FRD Life History Program staff; (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) reconsidering the Council's action to establish hard caps for the large mesh drift gillnet fishery; (6) developing recommendations for international management activities; and (7) preparing the 2020 Stock Assessment and Fishery Evaluation (SAFE) Report.

IV. ADVANCING RESEARCH ON TUNAS, BILLFISH, AND OPAH

SWFSC 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 (*Lampris sp.)*. Studies use a range of methods and quantitative approaches to 1) examine movements and behaviors and 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 U.S. 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. During 2019, 31,609 fish averaging 65.9 cm fork length (FL) were measured at various west coast ports.

HMS Logbook Form Redesign

In 2019, the HMS Fishery Monitoring program put new HMS logbook paper forms for all the West Coast HMS fisheries (Pacific Albacore Troll fishery, Surface Hook and Line Fishery, Harpoon fishery, Gillnet fishery and Deep-set buoy fishery) into effect. Currently, these newly designed logbook forms have been distributed to the fishery permit holders through NOAA WCRO.

Newly Developed HMS Data Entry Web Application Project.

The HMS Fisheries Monitoring program developed a modernized oracle apex HMS logbook data entry and data report web application in 2018. The application has not only been used by the SWFSC HMS program, but also used by PacFIN and WCRO staff for logbook data entry, in the Albacore port sampling program, and referenced by the logbook non-compliance PacFIN report. The application is also being used in an effort to create several automatically generated reports for both reporting and compliance purposes.

Changes to the Structure and Function of an Albacore Fishery Reveal Shifting Social-Ecological Realities for Pacific Northwest Fishermen.

SWFSC staff, in collaboration with other researchers, studied the evolution of harvest portfolios amongst Pacific Northwest fishermen over 35+ years with explicit attention to changes in the structure and function of the albacore (Thunnus alalunga, Scombridae) troll and pole-and-line fishery. Their analysis indicated that as ecological change and regulatory reform 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 became more specialized, even as participation in multiple fisheries became 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. This work is part of the Future Seas project.

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

Status of Albacore Age and Growth and Possible Future Sampling Programs

Accurate age and growth parameters are essential for managing fish stocks. The past several North Pacific albacore stock assessments have identified age and growth as a key uncertainty. Researchers reviewed the available age and growth data to determine if the sex-specific von Bertalanffy growth model currently used in the albacore stock assessment is still the best available science. Researchers also examined patterns in mean fork length (FL) between sex and region to assess any potential gaps in the current data. To fill these potential gaps and address the uncertainty in age and growth, collection of additional biological samples is required. Any new sampling program needs to be scientifically rigorous and consider potential biases, resource requirements, logistics, and the ultimate goal of the sampling. Researchers outlined some potential sampling programs that would fill data-gaps and improve age and growth data for future North Pacific albacore stock assessments.

Data used are from previously published age and growth studies of North Pacific albacore. Lengths-at-adjusted age were fit to a von Bertalanffy growth model. The adjusted age is a decimal incorporating date of birth and date of collection. Mean length-at-age were calculated for each discrete age class for males and females separately and sex-specific differences were examined. To better understand patterns in albacore size across the Pacific Ocean, regional analyses were performed. For potential future sampling, three sampling program design options were explored: age-stratified, proportional, and random. The structure of both the age-stratified and proportional sampling programs was informed using the previously published age data. The calculated mean lengths-at-age were used to define appropriate length bins for the sampling programs. The three potential sampling programs were compared in light of potential biases, resource requirements, and logistics.

The previously published albacore ages (n = 759) were collected from 1990 to 2012 across three regions (Western, Central, and Eastern Pacific Ocean). A reanalysis of length-at-adjusted age data resulted in the exact same parameter estimates for a sex-specific model as previously used in the stock assessment (**Fig. 1**). All eastern Pacific fish (n = 295) and some central Pacific fish (n = 65) were of unknown sex and therefore not included in the sex-specific model. Sex-specific mean lengths-at-age (excludes fish of unknown sex) were significantly different between sexes only for ages 6 and 7 ($p > 0.001$). There was a significant difference between mean FL among regions ($p < 0.001$). The Western region had a large number of samples and covered the widest range of sizes (n = 294; mean = 86.6 cm FL; range 45 – 118 cm FL). The Eastern region also had a large number of samples, but no albacore over 100 cm FL (n = 295; mean = 77.6 cm FL; range 52.4 – 96 cm FL). The Central region represented mostly large individuals (n = 170; mean = 104.9 cm FL; range 67 – 128 cm). For both the age-stratified and proportional sampling programs, the length bins were

0-60 cm, 60-70 cm, 70-80 cm, 80-90 cm, 90-100 cm, 100-110 cm, and 110+ cm. There are several pros and cons for each of the three proposed sampling programs (**Table 2**).

Table 2. Pros and cons of each of three proposed sampling programs.

Sampling Program	Introduce age bias into assessment	Sampling of albacore is representative of…	Total resources required
Age-stratified	Likely No	Age	Least
Proportional	Likely Yes	Fishery	Variable
Random	Likely No	Fishery	Most

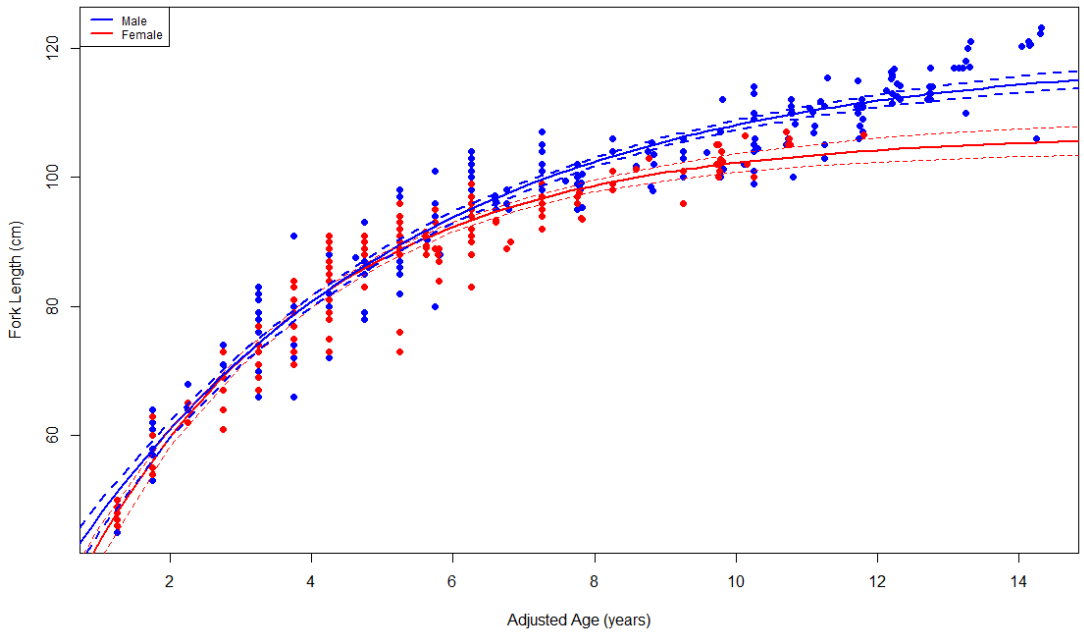

Figure 1. Sex-specific von Bertalanffy growth curves for male and female albacore. Dotted lines indicate 95% confidence intervals around the model.

The sex-specific growth curves previously used in the stock assessment are still the best available science for use in the North Pacific albacore stock assessment. However, certain regions, fish lengths, and fish ages are not well represented. These growth models exclude all data from the eastern Pacific and some large fish from the central Pacific due to the difficulties of sex determination. At this point, the most recent length-at-age data being used for the stock assessment is from 2012 while the rest of the samples were collected in 2007 and earlier. This highlights a need for new sampling to be statistically rigorous and consider potential sampling biases, resource requirements, sampling logistics, and define the ultimate goal of the sampling plan. One key consideration in deciding on a sampling plan is resource availability. Since resources are likely limiting, the sampling plan that requires the fewest samples collected from the fewest fishery components is the age-stratified program. This plan also introduces less bias than the proportional sampling program. This can be executed on an ocean-wide basis, or by fishery component. To improve sex-specific growth curves, additional information is needed on sex- and region-specific

length-at-age. The available information and past sampling regimes were not systematically coordinated across the Pacific Ocean or between fleets and consequently do not provide the information to address these questions. Moving forward, any sampling program would benefit from a coordinated effort among different countries and fisheries.

James, K., H. Dewar, & Teo, S. (2020). Review of current status of North Pacific albacore (*Thunnus alalunga*) age and growth. ISC/20/ALBWG-01/07.

James, K., H. Dewar, & Teo, S. (2020). Ideas for future sampling programs of North Pacific albacore (*Thunnus alalunga*). ISC/20/ALBWG-01/09.

Natal Origin of Pacific Bluefin Tuna from the California Current Large Marine Ecosystem

Pacific bluefin are widely distributed throughout the North Pacific Ocean and, to a lesser degree, in the western South Pacific Ocean, although this distribution is not well understood and uncertainties about stock structure continue to complicate fisheries management. PBF is managed under the assumption of a single stock in the Pacific Ocean with two discrete spawning areas in the western Pacific Ocean (WPO): one located around the Philippines north to the Ryukyu Islands (hereafter: East China Sea, ECS) and the second in the Sea of Japan (SoJ). Age-0 PBF remain in waters around Japan, but at age 0.5-2 years, an unknown portion of the fish migrate east across the Pacific Ocean and enter the California Current Large Marine Ecosystem (CCLME), where they remain for several years before returning to the WPO. While the general pattern of these trans-Pacific migrations has been documented, questions remain about the distribution of PBF in the CCLME and the contribution rates of recruits from the two spawning areas.

For this study, researchers used natural chemical tags in PBF otoliths to identify natal origin of individuals after their trans-Pacific migration to the CCLME. First, researchers examined chemical signatures of multiple cohorts of age-0 PBF from both spawning areas (ECS and SoJ) to obtain yearly baseline chemical signatures. Next, core material of the otolith from subadult PBF in the CCLME was analyzed to estimate the relative contribution of each spawning area.

Otoliths from 119 age-0 PBF (ca. 30 per year) collected from 2014-2017 were analyzed to establish baseline signatures for each spawning area. Element:Ca ratios in otolith cores of age-0 PBF significantly differed both between ECS and SoJ spawning areas and among years ($p<0.01$). Significant interactions between spawning area and year highlights the necessity of obtaining element:Ca baselines for age-0 PBF each year from both the ECS and SoJ.

The natal core of age-1 fish (40 per year) collected from CCLME were analyzed for assignment to spawning region matched to age-class. Mixed-stock analysis of age-1 PBF collected in the CCLME indicate that migrants from both the ECS and SoJ recruited into the Eastern Pacific Ocean (**Fig. 2**). Contribution rates varied from year to year, with both spawning areas contributing significant numbers of recruits to the CCLME with a minimum value of 20% contribution.

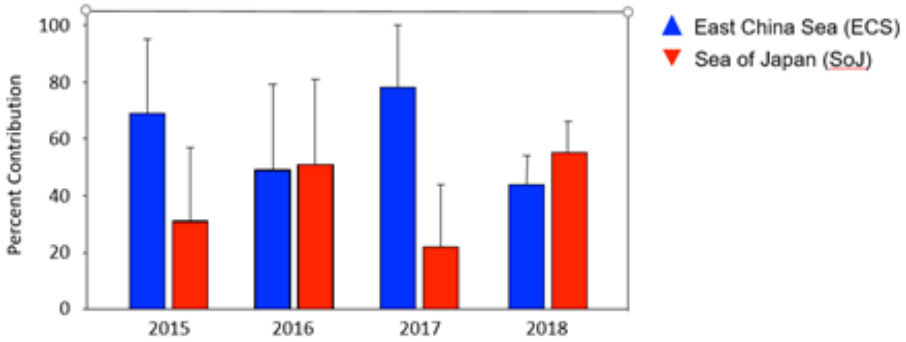

Figure 2. Natal origin contribution estimates (mean ± SD percent contribution) of sub-adult (age-1) Pacific bluefin tuna collected in the CCLME.

Results highlight the importance of both the ECS and SoJ spawning areas to the PBF fishery in the CCLME. In the western Pacific, there have been multiple efforts to identify natal origin, all capitalizing on the difference in spawning time between the two spawning areas. These studies have each had their own limitations and have not provided insight into the relative contribution of the spawning ground to the CCLME. This study provides a four-year assessment sourcing the natal origin of recruits in the Eastern Pacific Ocean using laser ablation with high spatial resolution sampling. Inter-annual variability observed in element:Ca ratios emphasizes the need to have annual baseline samples of age-0 PBF collected from both spawning areas to enable age-class matching. Interestingly, both spawning grounds make a significant contribution to the population of fish in the CCLME, with variability in the relative contribution across years. This insight will improve the ability to examine the environmental forcing mechanisms associated with the westward migrations and recruitment. Results also support the utility of the approach to examine sourcing of PBF and movement dynamics throughout the Pacific Ocean.

Wells, R.D., Mohan, J, Dewar, H., Rooker, J., Tanaka, Y., Snodgrass, O., Kohin, S., Miller, N., and Ohshimo, S. (2020) Natal origin of Pacific bluefin tuna from the California Current Large Marine Ecosystem. Biology Letters https://doi.org/10.1098/rsbl.2019.0878

Predictability of species distributions deteriorates under novel environmental conditions in the California Current System

Spatial distributions of marine fauna are determined by complex interactions between environmental conditions and animal behaviors. As climate change leads to warmer, more acidic, and less oxygenated oceans, species are shifting away from their historical distribution ranges, and these trends are expected to continue into the future. Correlative Species Distribution Models (SDMs) can be used to project future habitat extent for marine species, with many different statistical methods available. However, it is vital to assess how different statistical methods behave under novel environmental conditions before using these models for management advice, and to consider whether future projections based on these techniques are biologically reasonable. This approach is relevant to studies of HMS both because anchovies and sardines are key prey for HMS in the California Current and because SDMs are used to project shifts in the distribution of tuna, billfish and sharks.

In this study, researchers built SDMs for adults and larvae of two keystone pelagic fishes in the California Current System: Pacific sardine (*Sardinops sagax*), and northern anchovy (*Engraulis mordax*), using NOAA Fisheries survey data. Researchers used five different SDM methods,

ranging from simple (thermal niche model) to complex (artificial neural networks).

Our results show that some SDMs trained on data collected between 2003 and 2013 lost substantial predictive skill when applied to observations from more recent years (2014 – 2018), when ocean temperatures associated with a marine heatwave were outside the range of historical measurements (**Fig. 3**). This decrease in skill was particularly apparent for adult sardine, which showed non-stationary relationships between catch locations and sea surface temperature through time. While sardine adults and larvae shifted their distributions markedly during the marine heatwave, anchovy largely maintained their historical spatiotemporal distributions. This was particularly evident for larval anchovy, resulting in the persistence of SDM skill between the two time periods.

Our results suggest that correlative relationships between species and their environment can become unreliable during anomalous conditions. Understanding the underlying physiology of marine species is therefore essential for the construction of SDMs that are robust to rapidly changing environments. Developing distribution models that offer skillful predictions into the future for species such as sardine and anchovy, which are migratory and include separate sub-stocks, may be particularly challenging. Future work will investigate several methods to improve SDMs, such as the inclusion of non-local or lagged predictors, or the incorporation of information from physiological laboratory studies.

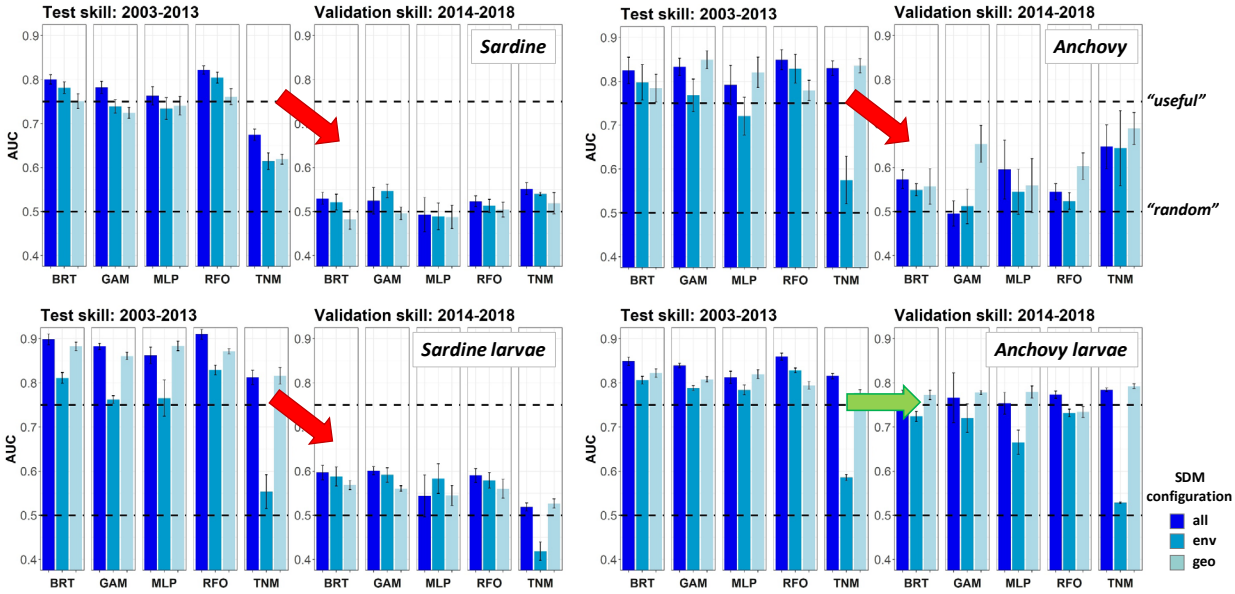

Figure 3. Area under the Receiver Operating Curve (AUC) skill metrics for SDMs trained on near-average years (2003 – 2013), and externally validated on data from 2014 -2018. Means and standard deviations across all SDM ensembles are shown for each life stage of each species. Colors of bars denote the SDM configuration ("all", "env", or "geo"). The SDM type is shown on the x-axis: "GAM" denotes Generalized Additive Models, "BRT" Boosted Regression Trees, "MLP" Multilayer Perceptrons, "RFO" Random Forests, and "TNM" Thermal Niche Models. The horizontal black dashed lines show AUC values of 0.5 (no better than a random model), and 0.75 (a rough approximation of a "useful" model), for reference.

Muhling BA, Brodie S, Smith JA, Tommasi D, Gaitan CF, Hazen EL, Jacox MG, Auth TD, Brodeur RD. 2020. Predictability of species distributions deteriorates under novel environmental conditions in the California Current System. Frontiers in Marine Science Jul

29;7:589.

Albacore Tuna Diet in the State of the California Current Report

For the first time, the 2020 State of the California Current Report included content on the foraging ecology of a highly migratory fish species (HMS), the albacore tuna. Currently, the time series data for albacore is the most complete with data as recent as 2019. Consequently, the albacore data were the most appropriate to include. The addition of HMS to the report provides direct insight into the forage base available to and consumed by predators as well as shifts in forage over time. Including albacore in the report was one of the first steps to integrating higher trophic levels into ecosystem assessments and management.

Albacore stomachs were collected through collaborations with commercial and recreational fishers from about 40-50°N (**Fig. 4a**) and 10-800 km off the U.S. West Coast. Under a dissecting microscope, whole prey and partial remains were identified to the lowest possible taxonomic level, counted, and measured. Genetics were occasionally used to confirm prey identity. Prey size was primarily estimated from hard parts using standard equations. Mean proportional abundances were calculated for each prey type, which is the average over all stomachs of the number of each prey type in a stomach divided by the total number of prey in that stomach. Commercially important prey were highlighted, including anchovy, hake (*Merluccius productus*), jack mackerel (*Trachurus symmetricus*), Pacific mackerel (*Scomber japonicus)*, rockfishes (*Sebastes spp.)*, sardine, and market squid (*Doryteuthis opalescens*). All remaining prey were grouped into a single category called "other." Annual variability from the time series mean for each species was assessed by calculating z-scores. The z-scores were calculated as the mean proportional abundance of a given species in a given year minus the mean proportional abundance of that species across all years, divided by the standard deviation.

From 2009 to 2019, 383 albacore stomachs were examined, with samples available from all years except 2016. Albacore ranged in size from 50-94 cm (mean 66 cm). A total of 57 different species were identified from stomachs. Anchovy was the single most important species overall, contributing 28% mean proportional abundance across all stomachs. Albacore diets changed significantly from 2009-2019. In 2019, albacore consumed greater proportions of Pacific saury (*Cololabis saira)*, rockfishes, and Pacific mackerel than in any year in the past decade (**Fig. 4d**), although Pacific mackerel comprised only a small portion of their total diet. In 2018, sampled albacore consumed a smaller proportion of anchovy than any previous year since 2009 followed by relatively low anchovy consumption again in 2019. Sardine consumption peaked in 2017, with relatively high consumption in 2018, but returned to a lower value in 2019. Most prey items consumed by albacore were in the range of 5-9 cm total length (**Fig. 4c**). The small size of prey indicates that albacore are feeding primarily on YOY fish and squid.

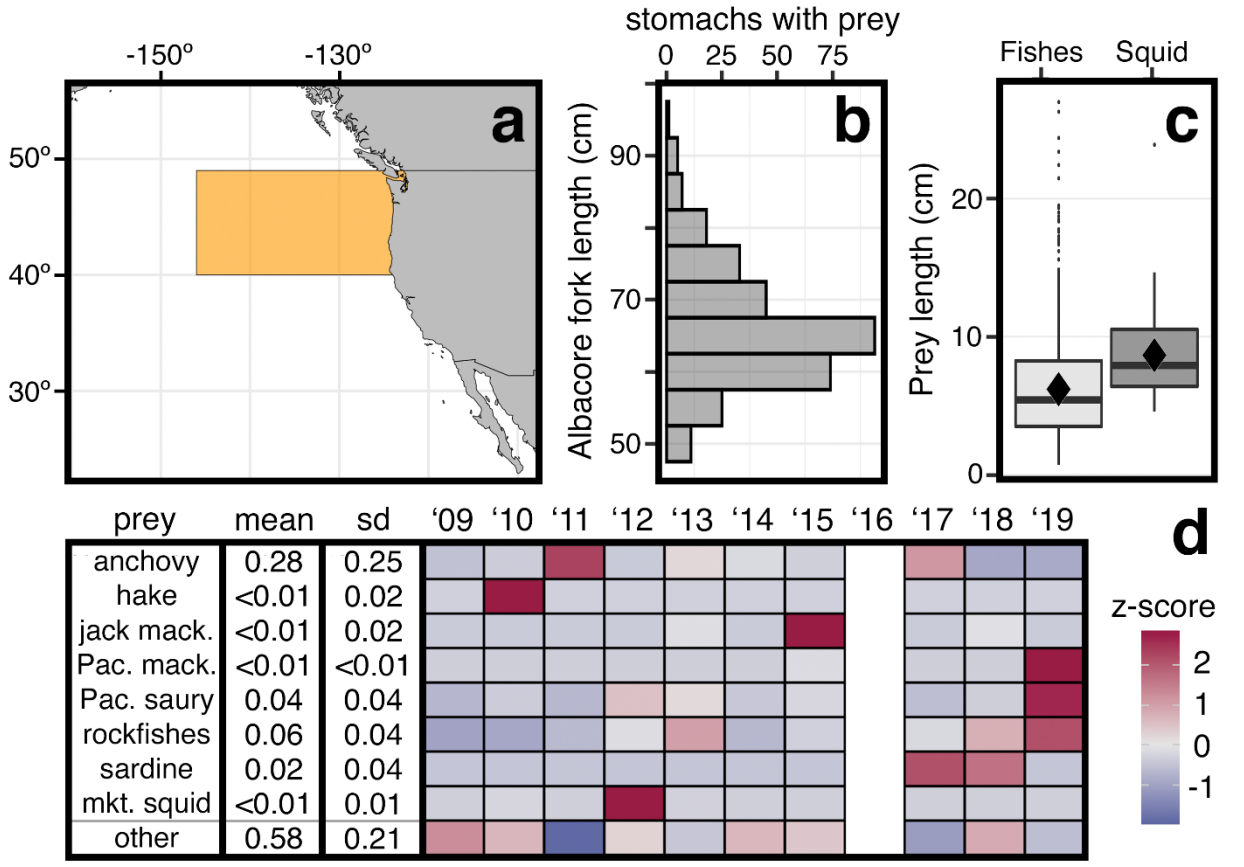

Figure 4. Sampling area in orange (a) and size range (b) for albacore tuna. Mean lengths (black diamond) and boxplots of length distributions for market squid (dark grey) and forage fishes (light grey) are given in panel (c). Fish prey size were quantified as standard lengths (SL), while market squid size was quantified as mantle length (ML). Annual variability from the time series mean proportional abundance of prey ("mean", and "sd") are given as a heat map of z-scores in units of standard deviations ("sd") in panel (d). Non CPS, groundfish, or market squid prey were included in an "other" group.

Weber, E.D., Auth, T.D., Baumann-Pickering, S., Baumgartner, T.R., Bjorkstedt, E.P., Bograd, S.J., Burke, B.J., Cadena-Ramírez, J.L, Daly, E.A., de la Cruz, M., Dewar, H., Field, J.C., Fisher, J.L., Giddings, A., Goericke, R., Gomez-Ocampo, E., Gomez-Valdes, J., Hazen, E.L, Hildebrand, J., Horton, C., Jacobson, K.C., Jacox, M.G., Jahncke, J., Kahru, M., Kudela, R.M., Lavaniegos, B.E., Leising, A., Melin, S.R., Miranda-Bojorquez, L.E., Morgan, C.A., Nickels, C.F., Orben, R.A., Porquez, J.M., Portner, E.J., Robertson, R.R., Rudnick, D.L., Sakuma, K.M., Santora, J.A., Schroeder, I.D., Snodgrass, O.E., Thompson, A.R., Villegas-Mendoza, J., Warzybok, P., Watson, W., Zeman. S.M., (in review) State of the California Current 2019-2020: Back to the Future with Marine Heatwaves? *Frontiers in Marine Science.*

Documenting the SWFSC Cooperative Billfish Tagging Program Operations and Database
The SWFSC Cooperative Billfish Tagging Program (CBTP) is a conventional mark-recapture research venture between NOAA scientists and the global recreational and commercial fishing community, with efforts focused in the Pacific Ocean. The CBTP has provided conventional analog tags to anglers around the world to tag billfish and other large pelagic species to collect distribution, abundance, movement, and morphometric data valuable in quantifying life history parameters used in management. The CBTP comprises the Billfish Tagging Program, the International Billfish Angler Survey, outreach, and reporting. All three components require year-round operations to distribute tagging equipment, deliver and receive surveys, and process, store, and manage data.

SWFSC staff, in collaboration with other researchers, reviewed the technical aspects of the CBTP as it operates in 2021, including equipment acquisition, database structure, and operational design and execution. Given the CBTP protocols could serve as a template for current or future conventional mark-recapture programs, researchers provided recommendations to improve upon current protocols. *The NOAA Southwest Fisheries Science Center Cooperative Billfish Tagging Program Operations and Database* Tech Memo serves as the official reference for the program and provides detailed metadata for the historical dataset available to the public.

Heberer, L.N., Wraith, J., Kohin, S., Gu, Y., Nasby-Lucas, N.D., and Dewar, H. 2021. The NOAA Southwest Fisheries Science Center Cooperative Billfish Tagging Program Operations and Database. NOAA Tech. Memo. NMFS-SWFSC-640.

Cooperative Research with Billfish Anglers
The annual *Billfish Newsletter* has communicated the results of the Cooperative Billfish Tagging Program for 57 years. Southwest Fisheries Science Center researchers have been working alongside the billfish angling community for nearly six decades to promote ethical angling and further understanding of various aspects of billfish biology and ecology. Billfish research conducted over the years as a result of this collaboration has included recreational fishery monitoring, biological research into the life history and ecology of specific billfish species and determining the economic importance of billfish resources. Recent ongoing efforts included two major components, the International Billfish Angler Survey, initiated in 1969, and the Cooperative Billfish Tagging Program (CBTP), initiated in 1963.

The 2020 Billfish Newsletter, a public outreach material sent to participating anglers and captains, documented the 2018, 2019, and 2020 results of these programs. SWFSC sponsorship of the CBPT will be ending as of 2021 and with it the Billfish Newsletter. However, the SWFSC will be making the historical archives of tagging and survey data available in 2021.

Heberer, L.N. and Nasby-Lucas, N.D. 2021. The SWFSC 2020 Billfish Newsletter. NOAA Administrative Report. NMFS-SWFSC- 640.

Comparing Dynamic and Static Time-Area Closures for Bycatch Mitigation
Time-area closures are a valuable tool for mitigating fisheries bycatch. There is increasing recognition that dynamic closures, which have boundaries that vary across space and time, can be more effective than static closures at protecting mobile species in dynamic environments. Researchers created a management strategy evaluation to compare static and dynamic closures in a simulated fishery based on the California drift gillnet swordfish fishery, with closures aimed at reducing bycatch of leatherback turtles. Researchers tested eight operating models that varied

swordfish and leatherback distributions, and within each evaluated the performance of three static and five dynamic closure strategies. Researchers repeated this under 20 and 50% simulated observer coverage to alter the data available for closure creation. Researchers found that static closures can be effective for reducing bycatch of species with more geographically associated distributions, but to avoid redistributing bycatch the static areas closed should be based on potential (not just observed) bycatch. Only dynamic closures were effective at reducing bycatch for more dynamic leatherback distributions, and they generally reduced bycatch risk more than they reduced target catch. Dynamic closures were less likely to redistribute fishing into rarely fished areas, by leaving open pockets of lower risk habitat, but these closures were often fragmented which would create practical challenges for fishers and managers and require a mobile fleet. Given the simulation's catch rates, 20% observer coverage was sufficient to create useful closures and increasing coverage to 50% added only minor improvement in closure performance. Even strict static or dynamic closures reduced leatherback bycatch by only 30–50% per season, because the simulated leatherback distributions were broad and open areas contained considerable bycatch risk. Perfect knowledge of the leatherback distribution provided an additional 5–15% bycatch reduction over a dynamic closure with realistic predictive accuracy. This moderate level of bycatch reduction highlights the limitations of redistributing fishing effort to reduce bycatch of broadly distributed and rarely encountered species, and indicates that, for these species, spatial management may work best when used with other bycatch mitigation approaches. Researchers recommend future research explores methods for considering model uncertainty in the spatial and temporal resolution of dynamic closures. This work is part of the Future Seas project.

Smith James A. et al. 2021. Comparing Dynamic and Static Time-Area Closures for Bycatch Mitigation: A Management Strategy Evaluation of a Swordfish Fishery. Frontiers in Marine Science 8:272. DOI:10.3389/fmars.2021.630607

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. In addition to the work described above on albacore, the Life History program has been conducting long-term studies on the diet of shortfin mako (*Isurus oxyrinchus*), common thresher (*Alopias vulpinus*), bigeye thresher (*Alopias superciliosus*), blue sharks (*Prionace glauca*), and swordfish. Similar to albacore, these species migrate to the California current to forage, taking advantage of the seasonally high productivity. For the blue, mako, and common thresher sharks, the region, especially the southern California Bight, is also an important nursery area. Moving towards integrated ecosystem assessments and ecosystem management, researchers are focusing on the ecological interactions among species, both between and among trophic levels. To that end, this section focuses on a comparison of the diets across teleosts, sharks and cetaceans. The cetacean stomachs were analyzed in collaboration with MMTD.

Stomach Content Analysis

FRD Scientist, Antonella Preti, provided the first comprehensive analysis of the diets of nine top predators that co-occur in the CCLME (shortfin mako [*Isurus oxyrinchus*], blue [*Prionace glauca]*, thresher [*Alopias vulpinus*], bigeye thresher [*Alopias superciliosus*] sharks, broadbill swordfish [*Xiphias gladius*], short-beaked common dolphin [*Delphinus delphis delphis]*, Eastern North Pacific long-beaked common dolphin [*Delphinus delphis bairdii*], northern right whale dolphin [*Lissodelphis borealis*], and Pacific white-sided dolphin [*Lagenorhynchus obliquidens*]).

Comparisons among predators provides insights into potential competition, niche overlap, and degrees of diet specialization. Also, given the shifts towards integrated ecosystem assessments and ecosystem management, there is movement away from looking at species in isolation. Consequently, all nine predators are included although the sharks are the main focus.

The primary goals of this research were to better understand their foraging ecology in the CCLME, and how and why diets changed in space, time, by size and with sex. This study also examined dietary diversity, richness, and niche overlap to provide insight into the level of specialization and potential competition among species. Detailed data on diets from diverse species provides insights into the links among trophic levels, the reliance of predators on commercially important species, as well as the potential impacts of predator removal. This type of information is key to understanding ecosystem and trophic dynamics.

Stomachs for the nine predator species were collected by federal fishery observers aboard large-mesh drift gillnet vessels from 1990-2014. While historically the fishery spanned the U.S. West Coast, since 2001, the majority of the fishery has operated in the Southern California Bight (SCB) between Point Conception, California, and the U.S.-Mexico border. Stomachs from long-beaked dolphin and Pacific white-sided dolphin were also obtained from stranded animals. Prey were weighed, counted, and identified to the lowest possible taxonomic group. Data analyses included prey accumulation curves and relative indices of importance including the standard metrics Index of relative (IRI) and Geometric index of importance (GII). The % GII is the arithmetic mean between percent numeric occurrence (%N), percent weight (%W), and percent frequency of occurrence (%F) of food items and it is based on a multivariate approach to vector geometry. Because of its basis in vector geometry, it provides a more precise method for interpreting stomach contents, although numerical comparisons among species are complicated. To examine patterns in prey importance, including the impacts of size, region, season, and sea surface temperature, a number of additional analyses were conducted including redundancy analysis (RDA) and generalized additive modelling (GAM).

The stomachs of 2,044 predators were analyzed and 1,676 contained prey. For each of the fish species, other than bigeye thresher, more than 150 individuals were examined. **Table 3** provides a summary of the diet composition by number of individual prey (as a percentage, %N) for all predators. **Table 4** illustrates the top three prey categories for each predator ranked by %GII.

Table 3. Percent composition by number (%N) of prey for the nine predators. Predator sample size includes only stomachs with food. Prey sample size is count of prey individuals of any taxa.

	Teleosts	Cephalopods	Other taxa	Predator Sample size	Prey Sample size
Mako	64.8	30.83	4.37	366	1790
Blue	3.83	67.71	28.46	150	1307
Thresher	82.79	16.58	0.63	434	6520
Bigeye thresher	81.2	18.3	0.5	45	399
Swordfish	31.16	65.71	3.13	292	5244
D. d. delphis	72.38	26.33	1.29	259	55009
D. d. bairdii	52.8	33.95	13.25	49	3072
L. borealis	69.9	29.74	0.36	56	18570
L. obliquidens	50.23	49.77	0	25	3008

Across predators, fish and squid were the most important prey items overall. Mako, thresher, bigeye thresher, short-beaked common dolphin and northern right whale dolphin, all had more than 60% teleosts in their diet, with fish being the most important for the two thresher species. Blue shark and swordfish both consumed less fish, with cephalopods making up over 65% of the diet. Blue shark was the only species in which other taxa (in this case 28.5%) were of major importance in the diet. Shortfin mako fed on teleosts, cephalopods, elasmobranchs, and marine mammals in broad agreement with previous research. Blue sharks specialized on cephalopods but fed across a broad range of species. These results are in contrast with those from previous studies in this geographic area that reported teleosts and crustaceans to be more important in blue shark diets. Bigeye thresher shark fed on teleosts, cephalopods and crustaceans from a range of habitats. Broadbill swordfish fed primarily on cephalopods, mesopelagic, and epipelagic teleosts similar to results from some studies in other geographic areas although the relative importance of squid and fish varied across studies. Thresher sharks had a predominance of coastal pelagic species in their diet, similar to previous studies from the same area. Fish dominated the diets of all cetaceans, although cephalopods were also important. Note that for all cetaceans, other than stranded animals, the most dominant fish species were myctophids and other mesopelagic fish.

There were two notable differences in the findings compared to other studies in the same region. First, in this study, jumbo squid were more important in the diets of mako, blue, bigeye thresher, and swordfish than reported previously. The increased importance of jumbo squid as prey is likely tied to its range expansion in the CCLME during the 2000s. Another interesting difference was the lack of northern anchovy in blue shark diets. While they were an important prey item in previous studies, northern anchovy were not detected in this study.

Table 4. Top three prey items ranked by % GII for the nine predators in the study.

	Top 3 prey items	%GII							%GII 2way					
									DGN				strandings	
		Mako	Blue	Thresher shark	Bigeye thresher	Swordfish	*D. d. delphis*	*L. borealis*	*D. d. delphis*	*D. d. bairdii*	*L. borealis*	*L. obliquidens*	*D. d. bairdii*	*L. obliquidens*
Pelagic teleosts	Mexican lampfish, *T. mexicanus*							40.2						
	Dogtooth lampfish, *C. townsendi*						30.5		58.0					
	Bigfin lampfish, *S. californiensis*						32.2							
	California headlightfish, *D. theta*										67.9			
	Barracudinas, Paralepididae				15.9									
	Duckbill barracudina, *Magnisudis atlantica*				16.7									
	Pacific saury, *Cololabis saira*	23.3												
	Northern anchovy, *Engraulis mordax*			31.9									53.6	40.0
	Pacific sardine, *Sardinops sagax*	7.3		18.4										
	Unidentified Teleostei			16.6										
Demersal	Plainfin midshipman, *P. notatus*													33.3
	California lizardfish, *S. lucioceps*												33.6	
	Pacific hake, *M. productus*									43.8				
Cephalopods	*Argonauta* sp.		12.7											
	Abraliopsis sp.					16.3	36.7	40.9	66.0		75.9	40.6		
	Gonatus spp.		23.4						59.8	35.8	70.1			
	Boreopacific gonate squid, *Gonatopsis borealis*					29.1						41.4		
	Jumbo squid, *Dosidicus gigas*	24.9	18.7		26.8	44.2								
	Market squid, *D. opalescens*							50.1		69.4		50.0	63.9	68.3

Multiple metrics were used to compare diet composition across species. Considering all four shark species, thresher, and blue sharks had the lowest similarity and the lowest niche overlap (**Fig. 5**). When comparing across all species, threshers and swordfish had the lowest similarity and the lowest niche overlap (**Fig. 6**). This is likely related to the thresher's reliance on small, schooling, coastal pelagic species and their associated foraging mode (using their tail to stun prey), as well as differences in preferred habitat. Interestingly, swordfish and bigeye threshers had the highest degree of niche overlap. These two species have adaptations that enhance foraging in deep, cool waters, including large eyes and cranial endothermy, allowing them to effectively exploit prey associated with the deep scattering layer. Bigeye thresher are less specialized in diet than common thresher sharks (**Fig. 7**).

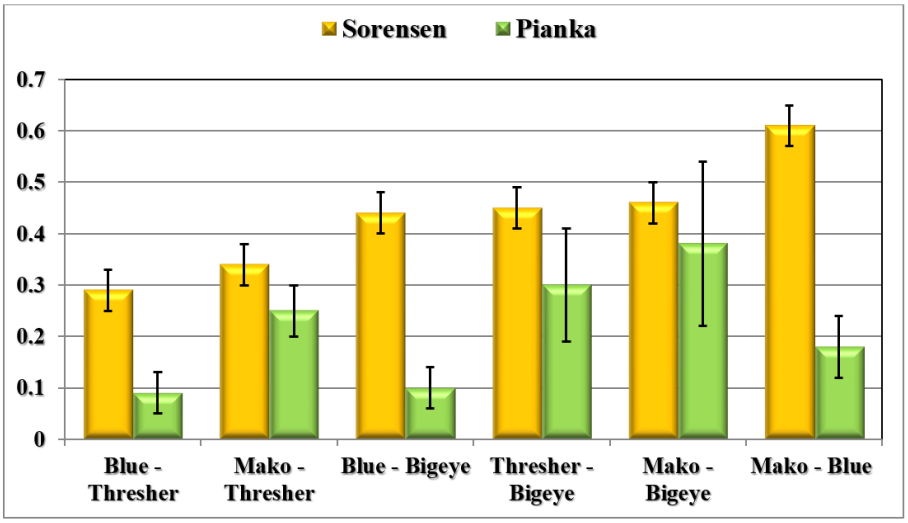

Figure 5. Shark comparisons. Sorensen Index of Similarity of diets based on presence/absence of prey only (yellow) and Pianka's index of Niche Overlap (green) based on prey counts. Zero indicates no similarity/ no overlap and one indicates identical diets/complete overlap. Mean value of the index based on 10,000 bootstraps estimates; SE=std error.

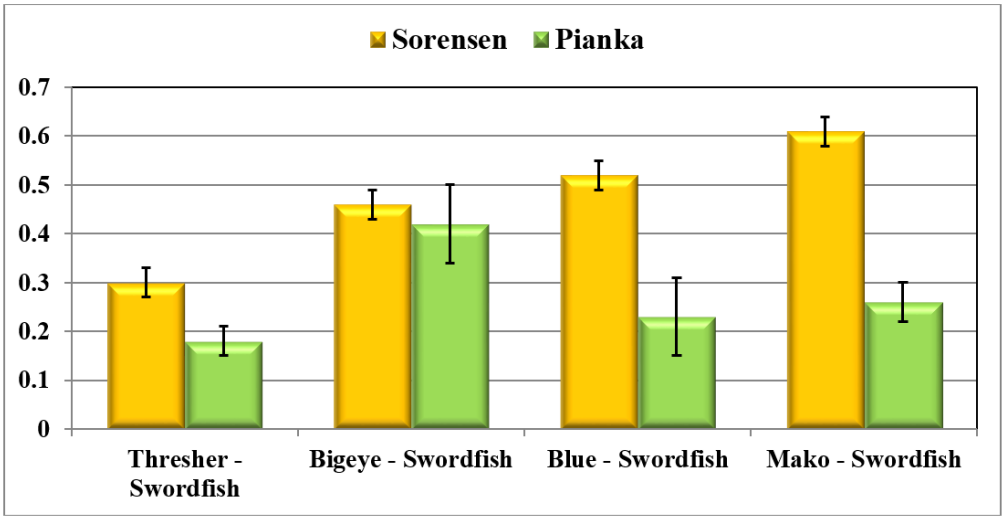

Figure 6. Sharks and swordfish comparisons. Sorensen index of similarity of diets and Pianka's index of Niche Overlap. See description in Fig. 5 caption.

Examining the richness and evenness provides insights into diet diversity and specialization. Simply speaking, high richness indicates a diverse diet and high evenness indicates less specialization. Rarefied diet richness was the highest in mako and the lowest in short-beaked common dolphin Species evenness was the highest for *L. borealis* and the lowest for thresher sharks. When only compared to other sharks and swordfish, threshers had both the lowest richness and evenness indicating they have a higher degree of specialization (**Fig. 7**). Again, this is likely associated with their reliance on small schooling coastal pelagic prey.

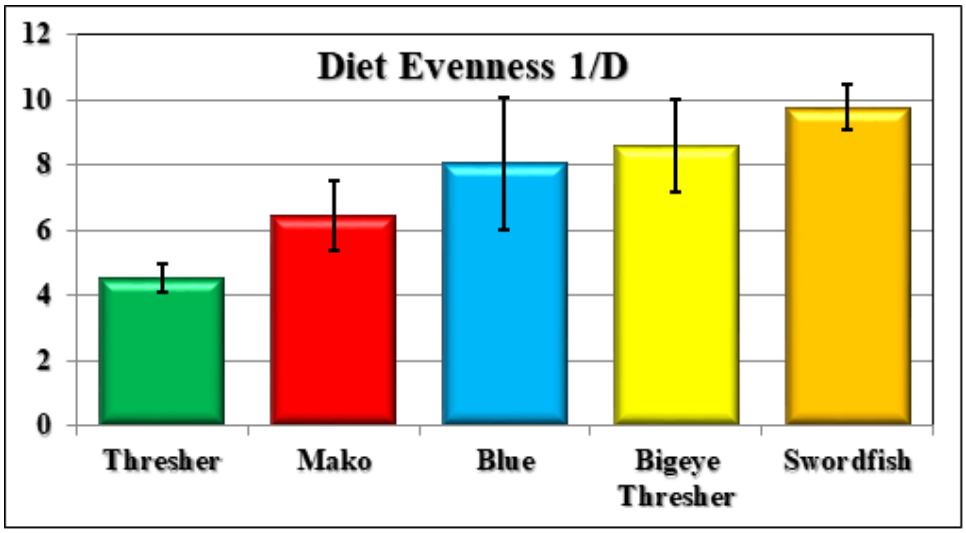

Figure 7. Comparisons of Diet Evenness among sharks and swordfish. D=Simpson's index of diversity. Mean value of the index based on 10,000 bootstraps estimates; SE=std error.

Significant inter-annual shifts were observed for a number of species. After 2010, the overall importance of jumbo squid in the diets of swordfish, mako, and blue sharks declined. These results reflect a decline in the abundance of jumbo squid off California after their range expansion into U.S. waters 2002-2010. After 2010, makos relied more on Pacific saury and blue sharks relied more on squid of the genus *Gonatus* . These changes demonstrate the ability of these predators to shift between available forage species. The dietary importance of sardines and anchovies also varied across years. The relative importance of Pacific sardine was greatest for mako and blue sharks around 2005-2007. The abundance of sardines in the CCLME was high during the mid-2000s, but followed by a period of dramatic decline in biomass (Hill et al. 2017). A similar pattern is apparent for northern anchovy, which declined in thresher shark stomachs after 2007. Analysis of northern anchovy stock size from 1951–2011 suggested that the population was near an all-time low from 2009–2011 (MacCall et al. 2016). Again, the shift in diet reflects the ability of these predators to target different prey, even the more specialized thresher, Shifts in prey species are linked to large- and small-scale climatic and oceanographic shifts and are highly complex. These results indicate the potential of using stomach contents as an indicator of shifts in the forage base over time.

Preti, A. 2020. Trophic ecology of nine top predators in the California Current. Ph.D. Dissertation. The School of Biological Sciences, University of Aberdeen, Scotland, UK

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 sharks: common thresher (*Alopias vulpinus*), bigeye thresher (*Alopias superciliosus*), and pelagic thresher (*Alopias pelagicus)*. Center scientists are studying 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.

Spiral Valve Parasites as Indicators of Shark Feeding Behavior and Ecology

Elasmobranchs are hosts to many metazoan parasites. The spiral valve or intestine is a suitable habitat for parasites and home to digeneans, nematodes, cestodes and, infrequently, monogeneans (Caira et al. 2012). The spiral valve is the most heavily parasitized internal organ of elasmobranchs and is the primary site occupied by cestodes, the most diverse group of elasmobranch parasites. It is rare to find a wild-caught elasmobranch that does not host at least one species of cestode in its spiral valve (Caira et al. 2012). Despite the ubiquity of shark cestodes, including tapeworms, relatively little is known about the parasite fauna of pelagic sharks, in particular common thresher sharks.

This study is a preliminary attempt to analyze the gut parasite faunas of blue and thresher sharks caught in the CCLME north of the Mexican border, with the ultimate objective of investigating possible links between parasites, shark diet, and the environment.

The spiral valves of 18 blue and 19 thresher sharks caught in the CCLME from 2009 to 2013 were examined for parasites. Blue shark intestines were predominately infected with cestodes and a small number of nematodes, while thresher sharks presented a more diverse parasite fauna. Blue and thresher sharks shared one nematode species (*Hysterothylacium* sp.) and two cestode genera (*Paraorygmatobothrium* and *Molicola*). The difference in parasite species composition is an indication of the different feeding and migratory behaviors of these two predators. The occurrence of two parasites (*Rhadinorhynchus cololabis* and *Pennella* sp.) of Pacific saury in threshers indicates recent feeding on saury, while the high prevalence of *Anisakis* sp. in the same host may be a result of intensive feeding on Pacific sardine (Baldwin et al. 2011); both saury and sardine are important components of the diet of threshers in the study area (Preti et al 2020). The *Piscicapillaria* sp. (**Fig. 8**). found in threshers and the *Hysterothylacium* sp. found in both shark species are new host records and may represent new species.

This study paves the way for a more comprehensive examination, including more samples and a wider variety of shark species, to provide a greater understanding of shark feeding behavior and possibly provide information on shark population biology.

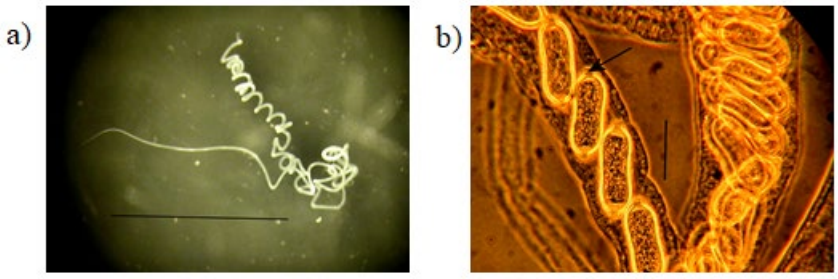

Figure 8. (a) Piscicapillaria sp.: a whole nematode; (b) Eggs with the protruding polar pugs arrowed. Scale bars: a = 1 mm, b = 50µm.

Preti, A., MacKenzie, K., Spivey, K.A., Noble, L.R., Jones, C.S., Appy, R.G. and Pierce, G.J., 2020. Spiral valve parasites of blue and common thresher sharks as indicators of shark feeding behaviour and ecology. *Journal of Fish Biology*, *97*(2), pp.354-361.

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 directly targeted species can facilitate their sustainable use.

Seabird Abundance

Trevor Joyce (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. Researchers 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, E.L. Hazen, 2020. Disentangling the biotic and abiotic drivers of emergent migratory behavior using individual-based models. *Ecological Modeling*, *432*, doi.org/10.1016/j.ecolmodel.2020.109225.

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. Researchers examined the temporal scales of environmental variability that best predicted spatial abundance of a marine predator, swordfish, 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, researchers found that 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 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. This work is part of the Future Seas project.

Brodie, S., B. Abrahms, S.J. Bograd, G. Carroll, E.L. Hazen, B. Muhling, M. Pozo Buil, J. Smith, H. Welch, M.G. Jacox, 2021. Exploring timescales of predictability in species distributions. *Ecography*, i 44: 1–13, 2021. doi: 10.1111/ecog.05504.

VIII. INTERNATIONAL DOLPHIN CONSERVATION PROGRAM ACT RESEARCH

The SWFSC research conducted under the International Dolphin Conservation Program Act (IDCPA) during 2020-21 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 system for studying adaptation. Within this large geographic region 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, researchers 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 (Andrews et al., 2021) 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.

Taxonomy of Long- and Short-beaked Common Dolphins

Tom Jefferson and Eric Archer 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 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 still ongoing.

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