



# SOUTHWEST FISHERIES SCIENCE CENTER

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

JUNE 2017

2017 HIGHLY MIGRATORY SPECIES  
ANNUAL REPORT

by

The Southwest Fisheries  
Science Center

ADMINISTRATIVE REPORT LJ-17-04

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The Southwest Fisheries Science Center

Southwest Fisheries Science Center  
National Marine Fisheries Service  
National Oceanic & Atmospheric Administration  
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**ADMINISTRATIVE REPORT LJ-17-04**

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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 work of SWFSC scientists on highly migratory fish species (HMS) and their fisheries. Contributions and activities of the past year, April 1, 2016 – March 31, 2017, are briefly described.

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

### **Monitoring U.S. HMS Fisheries**

Southwest Fisheries Science Center (SWFSC) scientists monitor six U.S. HMS fisheries in the Pacific, providing information from these fisheries to HMS researchers, fisheries managers, and international management organizations in support of the conservation and management of HMS stocks in the Pacific. The fisheries monitoring group (FMG) under the Fisheries Resources Division (FRD) compiles and manages information on vessels, gears, effort, catch, bycatch, protected species interactions, landings, biological sampling, and observer data. This information is routinely summarized and data products are provided to researchers and fisheries management organizations, as well as other customers. 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 several commercial and recreational fisheries that target various HMS species. The 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 has expanded and contracted over the decades from southern California and Baja waters to the international dateline, to 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 of California targets swordfish (*Xiphias gladius*) and thresher sharks (*Alopias vulpinus*). The California harpoon fishery targets swordfish. The longline fishery that targets swordfish and tunas used to be 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, and albacore, bluefin (*Thunnus orientalis*), and yellowfin tunas (*Thunnus albacares*) in southern California and Mexican waters. The total landed catch in 2015 for the HMS fisheries monitored by FMG staff is shown in **Table 1**.



**Table 1.** Landed catch in the U.S. commercial HMS fisheries. Catches cannot be reported for fisheries for which fewer than three vessels participated.<sup>1</sup>

FISHERY	2016 CATCH IN METRIC TONS	NUMBER OF VESSELS
<b>North Pacific Albacore Troll and Pole-and-line</b>	11,571	587
<b>South Pacific Albacore Troll</b>	225	6
<b>Eastern Pacific Ocean Purse Seine</b>	758	11
<b>California Large-mesh Drift Gillnet</b>	107	19
<b>California Harpoon</b>	5	12

#### ***North Pacific Albacore Troll and Pole-and-line***

Total annual catch of albacore from the North Pacific albacore troll and pole-and-line fishery in 2015 totaled 11,571 t, a decrease of 13% from 13,369 t in 2014. The number of vessels decreased from 625 vessels in 2014 to 587 vessels in 2015. The average weight of retained albacore in 2015 was 15.1 pounds, compared to 17.5 pounds in 2014. Logbook data from this and other HMS fisheries are required to be submitted to SWFSC under the HMS Fishery Management Plan (FMP) enacted by the Pacific Fisheries Management Council (PFMC) in 2005.

#### ***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 annually. Six vessels participated in the 2015 fishery, compared to 13 vessels in 2014. Total catch of albacore in the 2015 fishery was 225 t, a decrease of 61% from the 582 t landed in 2014. 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 2014 to 19 vessels in 2015. These vessels landed 66 t of swordfish, 18 t of common thresher, and 23 t of other HMS species in 2015 compared to 124 t of swordfish, 25 t of common thresher, and 28 t of other HMS species caught in 2014. 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.

<sup>1</sup> Numbers taken from RFMO submissions made in 2016.

### ***California Harpoon***

The California harpoon fishery increased from 11 vessels in 2014 to 12 vessels in 2015. Five metric tons of swordfish were caught in 2014 and 2015. 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 2015, one vessel home-ported in California but several Hawaii based longline vessels began operating out of west coast ports but still fished under their Hawaii longline permit. Since 2015 logbook data from longline vessels are consolidated with the larger Hawaii-based deep-set tuna longline fishery that operates in overlapping areas and are managed by Pacific Islands Fisheries Science Center (PIFSC) and Pacific Islands Regional Office (PIRO).

### ***Recreational HMS Fisheries***

Several different fleets of recreational vessels target HMS along the U.S. West Coast. Albacore are targeted by both Commercial Passenger Fishing Vessels (CPFV) and private vessels off the coasts of Washington and Oregon. In recent years very few albacore have been caught by anglers in Southern California, however recreational catches of bluefin and yellowfin tunas in Southern California and Mexican waters have increased. The recreational catch of albacore by vessels that target albacore off the West Coast decreased from 1,04KbbzSfioP623!

5 t in 2014 to 924 t in 2015. The catch of bluefin tuna by U.S. recreational anglers decreased from 436 t in 2014 to 359 t in 2015. The recreational catches of yellowfin tuna decreased from 1,881 t in 2014 to 1,241 t in 2015

### ***Miscellaneous Fisheries***

HMS caught incidentally in other commercial fisheries are summarized from the Pacific Fisheries Information Network (PacFIN) database where state landings data from marine fisheries are maintained. These fisheries caught 76 t of HMS in 2015 compared to 40 t of HMS caught in 2014.

## **II. SUPPORTING U.S. OBLIGATIONS OF INTERNATIONAL AGREEMENTS**

The major customers that require detailed information on U.S. HMS fisheries in the Pacific Ocean include: the South Pacific Tuna Treaty (managed by the Forum Fisheries Agency), the U.S.-Canada Albacore Troll Treaty, the Western and Central Pacific Fisheries Commission (WCPFC), the Inter-American Tropical Tuna Commission (IATTC), and the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC). FMG staff compile and summarize a wide variety of fisheries statistics that are grouped by various time and space resolutions for submissions to the Regional Fishery Management Organizations (RFMO) and the Regional Fisheries Organizations (RFO) in order to fulfill the U.S. membership obligations. Statistics range from annual catch and bycatch estimates to size composition of the catches and estimations of fishing effort.

### **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. In preparation for the stock assessment in April 2017, SWFSC researchers attended a data preparation workshop of the ISC Albacore Working Group (ALBWG) in Nanaimo, Canada, from 8-15 November 2016. At the workshop, the ALBWG examined critical time-series for the stock assessment, like catch, abundance indices, size composition, and conditional age-at-length data. During the workshop, SWFSC scientists presented an analysis of the catch-per-unit-effort data of the U.S. and Canadian surface fleets, which led to improved abundance indices for these fisheries. After examining the data and preliminary model runs, the ALBWG agreed upon tentative fishery definitions, primary data sources, and important biological parameters.

A full stock assessment of North Pacific albacore tuna was completed by the ALBWG during a meeting at the SWFSC, La Jolla, in 11-19 April, 2017. Participants included scientists from SWFSC, IATTC, International Pacific Halibut Commission, National Research Institute of Far-Seas Fisheries, and National Kaoshiung Marine University. One of the key improvements to this stock assessment is the use of sex-specific growth models because recently published studies have shown strong evidence of sex-specific growth, with adult males growing to a larger size. Hence the stock assessment was conducted using fishery data through 2015 and a seasonal, length-based, age and sex-structured Stock Synthesis model (v3.24ab). The stock assessment will have to be reviewed and endorsed at the 17<sup>th</sup> meeting of the ISC Plenary in July 2017 before being released.

### **Pacific Bluefin Tuna**

Pacific bluefin tuna historically supported an important commercial fishery for HMS on the U.S. West Coast. In recent years, however, the primary U.S. fishery targeting this species has been the U.S. sport fishery operating out of San Diego, California. There remains an important commercial fishery for Pacific bluefin tuna in Mexican waters. In 2016, a benchmark stock assessment was completed using a fully integrated length-based and age-structured model (Stock Synthesis) fitted to catch size composition, and catch-per-unit of effort (CPUE) data from 1952 to 2015 (fishing years 1952-2014), provided by the Pacific Bluefin Tuna Working Group (PBFWG) members and non-member countries.

No new assessment was conducted this year. However, an additional 32 projections requested by the Northern Committee of WCPFC and Inter-American Tropical Tuna and Commission (IATTC) were conducted. Alternative harvesting scenarios (several combinations of fishing mortality and catch limit) and recruitment scenarios (randomly resampled from the whole stock assessment period or from the relatively low recruitment period) were evaluated based on the 2016 stock assessment. A suit of performance measures were examined: initial rebuilding target ( $SSB_{MED1952-2014}$ ) by 2024 (=41,000 mt), 150% $SSB_{MED1952-2014}$  by 2030 (=61,500 mt), 200% $SSB_{MED1952-2014}$  by 2030 (=82,000 mt), 20% $SSB_{current,F=0}$  by 2030 (=141,454 mt), and 20% $SSB_{F=0}$  by 2034 (=128,893 mt). Probability of achieving these performance measures for all scenarios and associated expected annual yield were calculated.

As for the most strict performance measure (20% $SSB_{current,F=0}$  by 2030), 10 out of 16 scenarios shows that the probability of spawning stock biomass (SSB) recovering to this performance measure is more than 60% when future recruitment is about the historical average. When future recruitment is low, 2 out of 16 scenarios shows that the probability of SSB recovering to this

performance measure is more than 40%.

As for the least strict performance measure ( $SSB_{MED1952-2014}$  by 2024), 16 out of 16 scenarios shows that the probability of SSB recovering to this performance measure is more than 60% when future recruitment is about the historical average. When future recruitment is low, 13 out of 16 scenarios shows that the probability of SSB recovering to this performance measure is more than 40%.

## **Sharks**

SWSFC staff provided 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. Suzanne Kohin, SWFSC) of the ISC (chaired by Dr. Gerard DiNardo, SWFSC). SWFSC scientists involved in the ISC SHARKWG worked on a new benchmark stock assessment for blue sharks (*Prionace glauca*) in the North Pacific during 2016 and it will be completed by mid-2017. Starting in the second half of 2017, the SHARKWG plans to update the shortfin mako shark stock indicator analysis with a full stock assessment.

### ***North Pacific Blue Shark***

In 2016, the ISC SHARKWG prepared data to conduct a new benchmark assessment of blue sharks in the North Pacific in 2017. The objective was to update the fishery data time-series from the 2014 assessment through 2015, review the latest biological research, and develop an age-structured model to provide conservation advice to managers at the WCPFC. Participants from Japan, Taiwan, Korea, Mexico, Canada, IATTC, and the U.S. contributed data and/or analytical work.

SWFSC and PIFSC scientists provided full catch time-series of blue sharks caught, landed, and released in U.S. commercial and recreational fisheries (Kohin *et al.* 2016) as well as information on the size and sex composition of blue sharks taken in several observed fisheries. North Pacific blue shark stock structure was investigated using spatially-explicit size and sex data contributed by the U.S., Mexico, Japan, Korea, and China (Sippel *et al.* 2016). Gear selectivity curves were modelled for major fleets using catch-at-length data to inform parameterization of selectivity in the assessment model (Carvalho and Sippel 2016). The SHARKWG developed two assessment models for consideration at the March 2017 working group meeting in La Jolla. The first was an age-based statistical catch-at length model developed with Stock Synthesis (SS) (Carvalho *et al.* 2017), and the second was a Bayesian state-space surplus production (BSP) model (Kai *et al.* 2017). The SS model made use of the latest biological and fishery data to develop a reference case which is considered the best representation of population dynamics given the data. This will form the basis for the construction of sensitivity analyses to depict the range of plausible alternatives given uncertainties about certain aspects of life history. The BSP model was developed primarily to provide a straight-forward link to the 2014 assessment which was used to provide conservation advice. The SHARKWG will provide the results of both approaches to the ISC Plenary in July 2017, and if accepted by the Plenary, the assessment will be presented to the WCPFC Science Committee as the basis for conservation and management advice.

### ***Common Thresher Shark***

The SWFSC is also involved in shark assessments outside of the ISC. Scientists from SWFSC and the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) collaborated to complete a stock assessment of common thresher sharks along the west coast of

North America (Teo *et al.* 2016). This is the first stock assessment of common thresher sharks along the west coast of North America that incorporates information from all fisheries exploiting the population. This assessment will be peer reviewed by a panel from NOAA's Center for Independent Experts (CIE) during June 26 – 28, 2017.

### **III. SUPPORTING PACIFIC FISHERY MANAGEMENT COUNCIL ACTIVITIES**

Center economist Dr. Stephen Stohs and biologist Dr. Tim Sippel continued serving on the Highly Migratory Species Management Team (HMSMT) of the PFMC over the past year. The team met several times in 2016 and early 2017 to review fishery information, complete assignments from the Council, and evaluate provisions of the FMP for U.S. West Coast Fisheries for HMS. The main HMS issues facing the team and the Council over the past year have been: (1) assisting the Council with drafting suitable language for HMS FMP Amendment 4; (2) aiding the Council with developing a fast-track process for approving exempted fishing permit operations to test alternative methods of targeting swordfish off the West Coast; (3) providing guidance on scoping requirements for authorizing deep-set buoy gear as a swordfishing method off the West Coast; (4) providing recommendations for international management activities; (5) helping the Council consider whether to amend the HMS FMP to create a federal drift gillnet permit; and (6) preparing the 2016 Stock Assessment and Fishery Evaluation (SAFE) Report, (7) Additionally, SWFSC scientists conducted a suite of research activities to advance the development of stock assessments.

### **IV. ADVANCING RESEARCH ON TUNAS, BILLFISH, AND OPAH**

SWFSC scientists have focused on improving the biological and ecological understanding of tunas and billfishes in the Pacific Ocean to better assess the effects of fishing and environment on the populations or stocks. Described here are studies that have been recently completed or are ongoing by Center staff. These studies are carried out largely in cooperation with stakeholders and in collaboration with colleagues both in the U.S. and abroad.

#### **Advanced Stock Assessment Methods**

##### ***Dealing with Data Conflicts in Statistical Inference of Population Assessment Models That Integrate Information from Multiple Diverse Data Sets***

Contemporary fisheries stock assessments often use multiple diverse data sets. However, models are simplifications of reality and, therefore, misspecified. These misspecified processes result in biased estimates of absolute abundance and abundance trends, which are often evident as “data conflicts.” The appropriate method to deal with data conflicts depends on whether it is caused by random sampling error, process variation, observation model misspecification, or misspecification of the system (dynamics) model.

Diagnostic approaches are urgently needed to evaluate goodness of fit and identify model misspecification. Carvalho *et al.* (in press) use simulation methods to evaluate the ability of commonly-used and recently-proposed diagnostic tests (residuals analysis, retrospective analysis, the  $R_0$  likelihood component profile, the age-structured production model (ASPM), and catch-curve analysis) to detect model misspecification in the observation model process (i.e., the incorrect form for survey selectivity), systems dynamics (i.e., incorrect assumed values for steepness of the stock-recruitment relationship and natural mortality), and incorrect data

weighting. Residual analyses were easily the best detector of misspecification of the observation model while the ASPM test was the only good diagnostic for detecting misspecification of system dynamics model.

Maunder and Piner (in press) recommend external estimation of the sampling error variance in likelihood functions, modelling process variation in integrated models, and internal estimation of the standard deviation of the process variation. Maunder and Piner (in press) provide a framework for model development that identifies and corrects model misspecification and illustrate the framework, using simulated data.

### ***Searching for M: Is There More Information About Natural Mortality in Stock Assessments Than We Realize?***

Sippel *et al.* (in press) use the recently proposed ASPM diagnostic to identify the conditions under which natural mortality (M) might be estimable. The ASPM diagnostic aims to determine if changes in the scale and trend of stock abundance can be explained by catch alone, which is a key indicator of the presence of a production function. They apply the ASPM diagnostic to the same suit of assessments used in the previous simulations to determine if a relationship between estimability of M and the presence of a production function can be identified. Our results indicate that the estimation of M will be more difficult when there is no evidence of an elucidated production function than when a production relationship is visually apparent. The lack of an elucidated production function does not mean that M cannot be estimated as part of the integrated assessment model, rather it means that it will likely be driven by age composition, which is reliant on the reliability of recruitment and selection pattern estimates.

### ***Effects of Age-Based Movement on the Estimation of Growth Assuming Random-At-Age or Random-At-Length Data***

Age determination and estimation of growth are fundamental components of fisheries biology. Growth is most often estimated by fitting a von Bertalanffy growth model (VBGM) to data consisting of age-length pairs collected from fisheries. The statistical methods used to estimate growth usually make one of two assumptions about the data. The most common assumption is random at age, referred to as the traditional method, where each paired observation is representative of the distribution of lengths for a given age. Less common is the assumption of random at length, referred to as the length-conditional method, where each paired sample is representative of the distributions of ages for a given length.

Paired samples that are taken from the population with an intervening length-based process, such as length-stratified sampling or random dockside sampling from length-selective gears, can invalidate this assumption. Simulations showed that using the approximate length-conditional method results in unbiased VBGM parameter estimates when the samples are length-stratified while the traditional method results in biased estimates (Piner *et al.* 2016).

However, if samples were collected with an intervening age-based process (e.g., movement), the assumption of random at length could be invalidated. Simulations showed that sampling from populations with spatial structure caused by the age-based process of movement can produce bias in the estimation of growth from the length-conditional method assuming random at length (Lee

*et al.* 2017). Estimates of the variability in the length-at-age relationship were better estimated with the length-conditional than the traditional method even when the assumptions of random at length were violated.

### **Cooperative Research with the U.S. Surface Albacore Fishery**

SWFSC scientists are working with the American Fishermen's Research Foundation (AFRF) and the American Albacore Fishing Association (AAFA) on monitoring programs and other research efforts to improve knowledge of the biology and migration of North Pacific albacore in the waters off the U.S. Pacific coast.

### ***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. FMG staff contract and work with state fishery personnel to collect size data from albacore fishing vessels when they unload their catches in coastal ports. During 2015, 35,626 fish averaging 69 cm fork length (FL) were measured at various west coast ports. In addition to the port sampling program, fishermen have been collecting size data during trips at the beginning and end of the season, and for catch that is landed at ports not covered under the port sampling program. The cooperative onboard size sampling data supplements the port sampling data to ensure that information from beyond the time/areas covered by the port sampling program are available for stock assessments. In 2016, fishermen measured 590 fish onboard. The mean size of the measured fish was 70 cm FL.

### ***North Pacific Albacore Electronic Logbook Project***

In 2005, a computer program was developed to allow albacore troll fishermen to enter their logbook data into a computer program rather than completing the traditional paper forms. The advantages of recording the data through a computer program include implementing validation rules at the point of entry thus limiting data entry errors, saving time and money on data entry costs, and making the data available in a timelier manner. Since 2006, the program has been used by 5-10 fishermen annually and has received positive feedback on its functionalities and ease of use. During the 2015 season, logs for 42 trips were submitted electronically. In 2013, FRD staff began developing a new, alternative electronic logbook in PDF format to upgrade the existing version and increase the use of electronic logbooks. Development is nearly complete and testing of the new electronic logbook will begin in 2017.

### ***North Pacific Albacore Archival Tagging Project***

Staff from SWFSC and AFRF initiated an archival tagging program in 2001 to study the migration patterns and stock structure of juvenile albacore in the North Pacific. Tags are deployed in cooperation with the albacore troll/pole-and-line fleet near the main fishing ground off Oregon and Washington, as well as in cooperation with the recreational charter fleet off southern California and northern Baja, Mexico, when the fish are present. The total number of tags deployed to date is 1043. In 2016 we were unable to conduct a tagging trip because of a problem with delivery of tags in time for a trip.

During 2016, two tags that were deployed off the coast of Oregon in 2015 were recovered. Efforts were focused on analyzing the data from all tags recovered since publication of our first paper on



the migrations of juvenile albacore in the North Pacific (Childers *et al.* 2011) and incorporating these data into new analyses. The recent recoveries include 11 tags, 6 of which were at liberty about 2 years and a seventh that was at liberty for nearly 3 years.

Stephanie Snyder, a recent PhD graduate from SIO, is working collaboratively with us on the albacore tagging data to understand influences of the environment on albacore thermoregulation, movements, and behavior. She examined the inherent properties of the temperature sensors on the tags and established an algorithm to accurately interpret time lags in water and peritoneal temperature changes (Snyder and Franks 2016). A draft paper looks at the thermoregulation of juvenile albacore. A third paper, nearly ready for review, examines the environmental conditions that govern the timing of departures and arrivals of juvenile albacore on the eastern Pacific foraging grounds. Finally, a fourth paper examines the behavior of four juvenile albacore as they simultaneously foraged across a front off the coast of Baja California (Snyder *et al.* In review).

### ***North Pacific Albacore Genetic Markers to Identify Sex Project***

In 2015, SWFSC scientists began a project entitled “Improving the stock assessment of north Pacific albacore tuna by developing cost-effective genetic markers to identify sex.” This project is an international collaboration between scientists from the Canada, Japan, Taiwan, and the U.S. This project will improve the stock assessment of north Pacific albacore tuna by developing cost-effective genetic markers to identify the sex of albacore and collecting sex composition data for future assessments, which are currently lacking and impractical to collect. During the first year of the project, genetic samples were collected from albacore tuna that have been sexed using traditional methods. As part of this project a draft genome has been assembled to help guide analysis of sex link regions and identify markers that can be used to identify sex. At present 20 loci are being examined to further evaluate their utility to genetically identify the sex of individuals.

### **Bluefin Tuna Modeling Research**

#### ***Simulation Testing to Evaluate Alternative Modeling Approaches to Account for Spatial Effects Due to Age-Based Movement***

Spatial patterns due to age-specific movement have been a source of un-modelled process error. Modeling movement in spatially-explicit stock assessments is feasible, but hampered by a paucity of data from appropriate tagging studies. Lee *et al.* (accepted) used simulation methods to evaluate alternative model structures that either explicitly or implicitly account for the process of age-based movement in a population dynamics model. They simulated synthetic population using a two-area stochastic population dynamics operating model. Two different states of nature governing the movement process were explored. Only the model that includes the correct spatial dynamic results in unbiased and precise estimates of derived and management quantities. In a single area assessment model, using the FAA approach and estimating both length-based and time-varying, age-based selectivity to implicitly account for the contact selection and annual availability may be the second best option. A FAA approach assuming each fleet represents a combination of gear and area and adds additional observation error performed nearly as well. Future research could evaluate which stock assessment method is robust to uncertainty in movement and is more appropriate for achieving intended management objectives.

### **Bluefin Close-Kin Mark Recapture Research**

The bluefin close-kin genetics study is a parentage based mark-recapture research program to develop an independent abundance estimate for Pacific bluefin tuna. During 2016, fin clips for genetics were collected from U.S. recreationally and commercially caught bluefin for the ISC-led project. The U.S. fisheries will be sampled indefinitely in support of the project, and other nations reported at the ISC Plenary in July 2016 that sampling was occurring North Pacific-wide. A proposed meeting of international genetic experts to decide upon standardized methodologies for generating genotypic data was not funded in 2016, thus processing of the U.S. samples has not yet begun.

### **Collection and Analysis of Biological Samples to Support Stock Assessments**

Given the uncertainty surrounding current growth models, stock structure, and ecosystem interactions of several tuna and tuna-like species in the North Pacific, scientists at the SWFSC have been working with a range of partners to collect biological samples of otoliths, muscle, DNA fin biopsies, gonads, and stomachs from a number of species along the U.S. West Coast. In 2007, the SWFSC and the Sportfishing Association of California initiated a sampling program to collect data on tuna and other HMS. Initially the program was focused on the Southern California Bight (SCB) but the program was expanded to include the northeast Pacific Ocean in 2009, working with commercial fishermen to collect samples from albacore off Oregon and Washington. In 2010, the program was again expanded to include central California (Monterey Bay and San Francisco) where albacore are sometimes encountered from August through November. Sample collection is ongoing and supports the ISC's proposed North Pacific-wide sampling program to address the uncertainties regarding biological information, notably growth models, maturity schedules, and stock structure of several tuna and tuna-like species.

Samples of albacore, Pacific bluefin, yellowfin, skipjack (*Katsuwonus pelamis*), yellowtail (*Seriola lalandi*), opah (*Lampris guttatus*), and dorado (*Coryphaena hippurus*) have been collected during NOAA research surveys and through cooperative programs with commercial passenger fishing vessels (CPFV), the commercial albacore troll and pole-and-line fleet, and recreational anglers (**Table 2**).

**Table 2.** Summary of all fish sampled in the SWFSC cooperative biological sampling program for tuna and related species.

Species	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
<b>Pacific Bluefin</b>	0	75	78	54	189	294	171	156	120	487	1624
<b>Albacore: Washington/Oregon</b>	0	0	42	191	49	60	60	39	50	1	492
<b>Albacore: Central California</b>	0	0	0	0	27	31	43	0	0	0	101
<b>Albacore: Southern California</b>	116	35	93	118	7	62	3	0	0	0	434
<b>Yellowfin</b>	15	45	95	71	128	132	112	134	50	112	894
<b>Skipjack</b>	0	5	9	8	15	16	25	0	0	0	78
<b>California Yellowtail</b>	0	0	7	30	190	186	90	36	30	0	569
<b>Opah</b>	0	0	1	11	16	64	30	30	15	0	167
<b>Dorado</b>	0	43	39	0	40	18	0	3	12	0	155

These biological samples are used to address an array of questions. Initial efforts centered on characterizing diets of tunas in the SCB using stomach contents to investigate inter-annual and interspecific differences. In the past few years, the research program expanded to include (1) stable isotope analysis of muscle tissue aimed at providing an integrated picture of foraging and migration patterns of tunas, opah, yellowtail, and swordfish in the California Current (CC), (2) using otoliths to better characterize age and growth of albacore, (3) radioanalysis of cesium-134 and 137 found in the muscle tissue of Pacific bluefin tuna exposed to radionuclides discharged from the failed Fukushima nuclear power plant in Japan, combined with stable isotope analysis to determine migration rates and stock structure of juvenile Pacific bluefin tuna in the CC, (4) using otolith microchemistry to determine the dynamics and stock structure of albacore, bluefin, and swordfish in the North Pacific, (5) characterizing the genetic diversity of California yellowtail in preparation for commercial aquaculture production off southern California, (6) comparing inshore-versus offshore-caught California yellowtail with respect to ontogeny and migration patterns using stable isotope analysis and lab derived trophic discrimination factors, (7) developing a sex-linked genetic marker for albacore, (8) characterizing the diet and physiology of opah, (9) exploring mercury dynamics in pelagic predators, (10) examining the reproductive maturity of bluefin in the SCB, (11) correlating larval abundances of prey species with tuna gut contents to model how changes in prey species affect predator abundancies and foraging success, and (12) developing methods to use tuna as biological samplers of prey species.

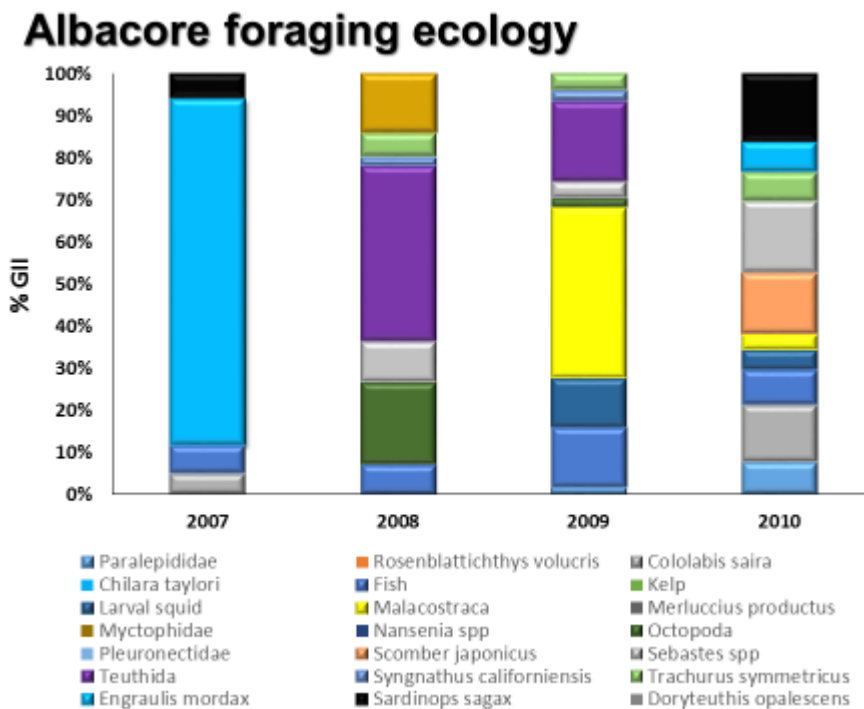
### ***Tuna Foraging Ecology***

There has been a move towards ecosystem-based management since the reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act in 2006. Understanding temporal and spatial patterns of predators and prey is critical to this approach. To determine the trophic relationships of highly migratory species in the CC, SWFSC scientists have been investigating the foraging ecology of a range of species since 1999.

Analyses of stomach contents of tunas conducted to date reveal a number of interesting patterns across species, regions, and years. Looking across years for albacore and yellowfin tuna, it is apparent that there was a shift in the available prey species in the SCB from 2007-2008. In 2007 juvenile anchovy and sardine dominated the diets of both albacore and yellowfin (**Figure 1** and **Figure 2**). In contrast few to no anchovy and sardine were present in 2008; diets became more diverse and were dominated by small squid, octopus, and other fish (juvenile rockfish [*Sebastes*], myctophids, and jack mackerel [*Trachurus symmetricus*]). Diets in 2009, 2010, and 2011 were similar to 2008, with high squid diversity, other fish, and increased numbers of crustaceans. Bluefin diet was similar to albacore and yellowfin during 2008-2014 (squid, fish, and crustaceans; **Figure 3**), although in 2015 and 2016 their diet was dominated by pelagic red crabs (*Pleuroncodes planipes*).

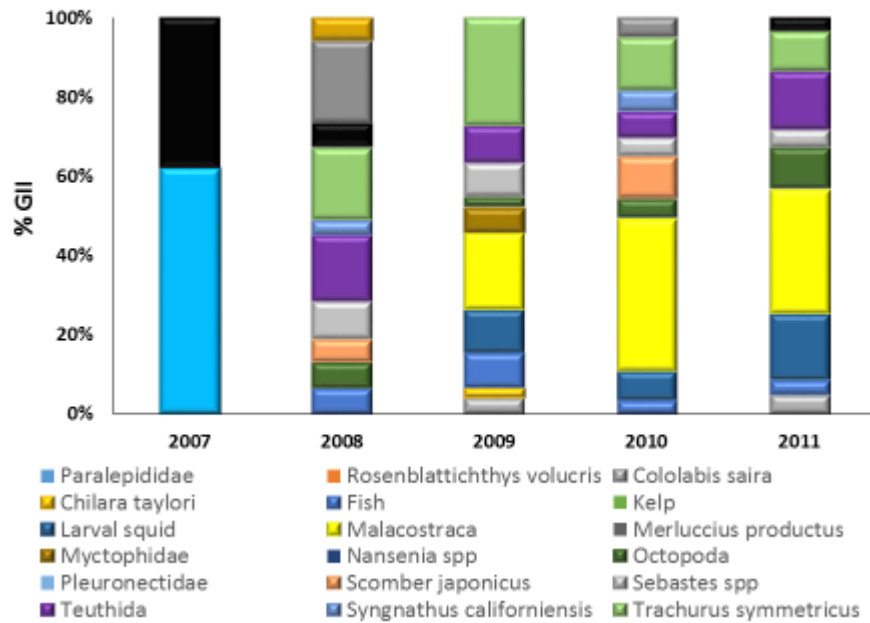
By comparing these results to other studies and across years, it is apparent that tuna in the SCB showed an increase in diet diversity, with a reduced reliance on anchovies and sardines and an increased reliance on squid, crustaceans, and other fish species. This likely relates to prey availability shifts associated with changes in oceanography, similarly documented in other biological indices, and the ability for tuna to exploit a diverse prey base. Stomach content analysis is helping to better understand both tuna behavior and how fluctuations in the availability of forage fish relate to changes in oceanography, such as the influx of pelagic red crab into the SCB during El Niño associated years (2015 and 2016).

Detailed data on tuna behavior and forage fish abundance are important for stock assessments and integral to making informed management decisions. Stomach content data may be reflective of the abundance of juvenile fish and other forage in the SCB and could provide an additional metric to be used in stock assessment models for forage fish. As tuna feed primarily on juvenile fish and squid, stomach content analysis can further our understanding of how egg and larval trawl data translates into the availability of forage for larger predators later in the year. Stomach content processing is currently ongoing with samples collected through 2016. Species availability complicates inter-annual comparisons. A manuscript is being drafted for publication containing the current results.



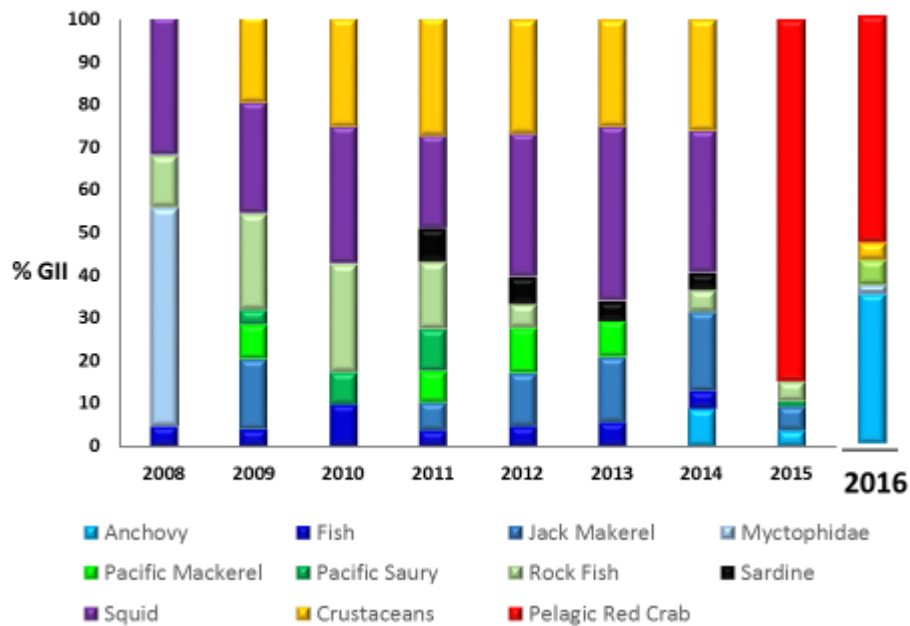
**Figure 1.** Relative importance of anchovy, sardine, other fish, squid, and crustaceans in the diets of albacore tuna by year based on a modified Geometric Index of Importance.

## Yellowfin foraging ecology



**Figure 2.** Relative importance of anchovy, sardine, other fish, squid, and crustaceans in the diets of yellowfin tuna by year based on a modified Geometric Index of Importance.

## Bluefin foraging ecology



**Figure 3.** Relative importance of anchovy, sardine, other fish, squid, pelagic red crabs, and other crustaceans in the diets of bluefin tuna by year based on a modified Geometric Index of Importance.

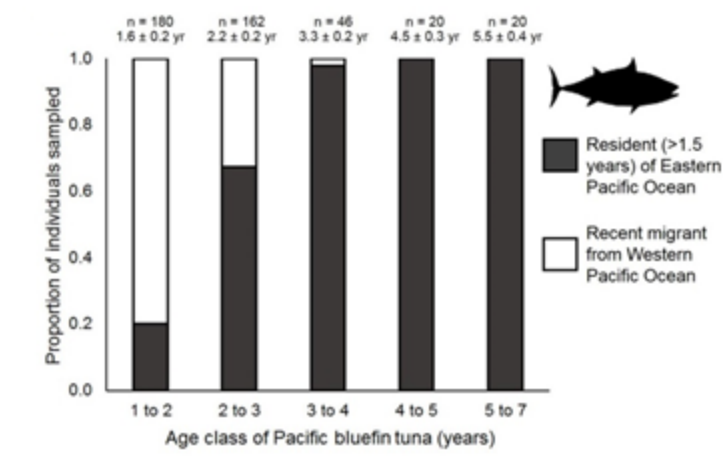
### ***Modeling Mercury Dynamics in the Pacific Bluefin tuna***

Mercury (Hg) is an environmental contaminant of global human health concern. The primary route of Hg transfer to humans worldwide is via consumption of marine fish. Studies of Hg dynamics in wild and farmed fish have been conducted but there are no quantitative models of Hg accumulation in the large pelagic marine fish that are the greatest contributors of Hg to human diets (e.g., tunas and billfish). A collaborative study with Harvard University, Monterey Bay Aquarium, and SWFSC scientists previously modeled Hg dynamics in Pacific bluefin tuna. Application of this same model to Hg data from nine large pelagic species showed that Hg dynamics were determined by the interaction of multiple parameters: biodilution via growth, prey Hg concentration, and Hg accumulation due to trophic increase. In some cases, relationships between Hg in the top predators and the Hg concentrations of their prey were counterintuitive, and could not be predicted or inferred from predator [Hg] patterns alone. This new model thus allows for quantitative comparison of factors driving Hg dynamics within and across pelagic species and/or ocean basins. In conjunction with measured data, the model can guide selective wild harvest or captive rearing conditions to minimize Hg in wild or farmed fish destined for human consumption and predict changes in wild fish [Hg] as a result of increasing inputs of Hg into the marine environment. A manuscript describing these results is currently being drafted.

### ***Using Chemical Tracers (Stable Isotopes and Cesium-134) to Characterize Migratory Patterns of Pacific Bluefin Tuna***

Understanding movement patterns of migratory marine animals is critical for effective management, but often challenging due to the cryptic habitat of pelagic migrators and the difficulty of assessing past movements. Chemical tracers can partially circumvent these challenges by reconstructing recent migration patterns. Typically, stable isotopes are used in studies of migrations, however the radionuclides released into the ocean off Japan after the 2011 tsunami provided a unique chemical tracer for animals occupying these waters, including Pacific bluefin tuna. Pacific bluefin tuna are hatched in the Western Pacific Ocean (WPO) before some portion migrates to the EPO. Understanding age-specific eastward trans-Pacific migration patterns can improve management practices, but these migratory dynamics have been challenging to quantify.

A collaborative study with the State University of New York (SUNY) and Harvard University combined a Fukushima-derived radiotracer ( $^{134}\text{Cs}$ ) with bulk tissue and amino acid stable isotope analyses of Pacific bluefin to distinguish recent migrants from residents of the EPO, and to time the migrations of juvenile bluefin as they cross the Pacific Ocean (Madigan *et al.* 2013). The presence of  $^{134}\text{Cs}$ , while detectable only until 2013, provided the opportunity to validate estimates using stable isotopes alone. Using additional samples, a more robust study was completed in 2016 (**Figure 4**, Madigan *et al.* In Review-a). The results from this work show that the proportion of recent migrants to residents decreased in older year classes. All fish smaller than 70 cm FL were recent migrants, confirming that fish caught locally are from the western Pacific. Looking across age classes, the number of recent migrants decreased from ~80% for 1-2 year olds to ~30% for 2-3 year olds and ~2% for 3-4 year olds. The peak arrival time from the western Pacific is April and May. This information provides important insight into the dynamics of movements across the Pacific. By linking relative arrivals to climate variability on both sides of the Pacific, we should gain insights into the forcing mechanisms behind the high degree of variability in trans-Pacific migrations (Madigan *et al.* In Review-a).



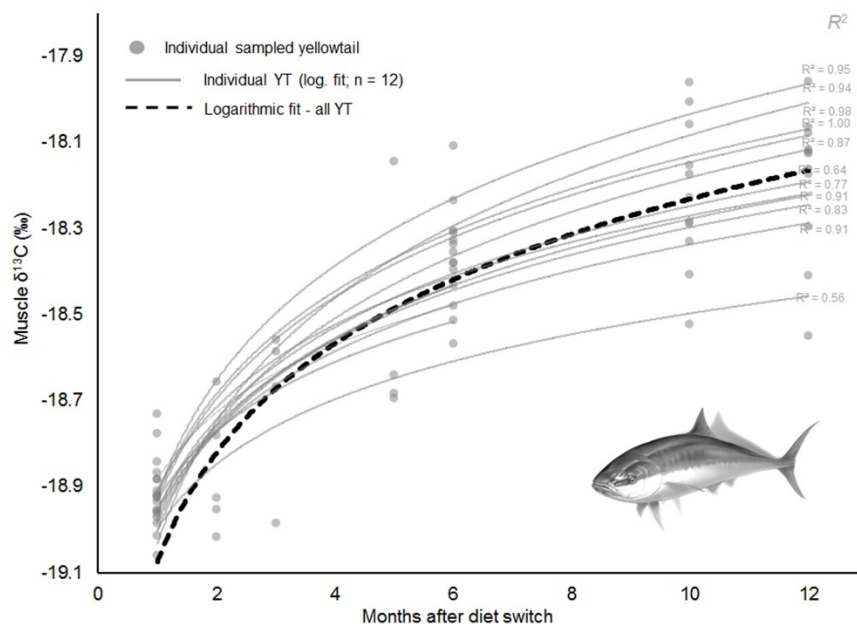
**Figure 4.** Migration dynamics of 428 age 1-7 Pacific bluefin tuna sampled from 2012 to 2015. Proportion of residents to migrants by year class. Residents and migrants were categorized by radiocesium and stable isotope analysis. Sample size and mean age ( $\pm$  SD) are shown above bar for each year class. All residents in year class 1-2 were 1.6 to 2.0 years old.

This novel toolbox of biogeochemical tracers has also been used to gain insights into the potential for continued influx of radionuclotides from the WPO. In an examination of stable isotopes and radionuclotides in 16 diverse species collected across the Pacific, only the olive ridley sea turtle had detectable levels of  $^{134}\text{Cs}$  by 2015. Species where stable isotopes indicated at WPO origin did not show elevated  $^{134}\text{Cs}$  or  $^{137}\text{Cs}$  levels. This includes bluefin (previous study) where  $^{134}\text{Cs}$  was detected in recent migrants in 2012 and 13, but not in 2014 or 15. These results confirm that the public need not be concerned about Fukushima derived radiation in marine organisms in the EPO. Stable isotope analyses also demonstrated limited movements across species between the WPO and that of the EPO or Central Pacific Ocean (CPO) (Madigan *et al. In Review -b*).

#### ***Tissue Turnover Rates and Isotopic Trophic Discrimination Factors in the California Yellowtail***

Work was conducted in the SWFSC aquarium to determine the muscle tissue turn-over rates and trophic discrimination factors for captive yellowtail. Yellowtail from the wild were placed into tanks at the SWFSC aquarium and fed a controlled diet for four years. The feed source was changed after year two and muscle tissue plugs were collected every month for the following year and a half. Results will help discern how long a change in food source or prey input takes before it is reflected in the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of a yellowtail's soft tissues, thereby allowing us to infer more about the life history of California yellowtail (**Figure 5**). Mercury turn-over and accumulation is also being looked at over time. A manuscript describing these results is currently being drafted.





**Figure 5.** Change in carbon in months after controlled diet switch. Carbon in individual fish muscle turns over rapidly at first, then appears to level off approaching an asymptote. Additional samples showed that carbon reaches a steady state at ~1.5 years post diet switch.

### Cooperative Research with Billfish Anglers

SWFSC researchers have been working alongside the billfish angling community for over 50 years to promote ethical angling and further our 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. Current ongoing efforts include two major components, the International Billfish Angler Survey and the Billfish Tagging Program. The Angler Survey was initiated in 1969 and the Tagging Program in 1963. The 2015 results of these programs were collected during 2016 and are summarized below.

#### *International Billfish Angler Survey*

More than 270 anglers submitted surveys this year to report over 2,000 fishing days and more than 1,500 billfish caught from destinations in the Pacific, Atlantic, and Indian Oceans. The 2015 season proved to be a successful one compared to 2014, as the number of billfish caught per day reported for the entire survey increased. The majority of fishing effort was reported off Hawaii, Southern California, and Baja California, Mexico. The regional nominal catch per unit of effort (nCPUE; number of billfish per day) off Southern California was up from the previous year, Hawaii remained nearly unchanged, while Baja was down.

Anglers from Hawaii have consistently reported the greatest number of fishing days for the past 5 years, and in 2015 they accounted for nearly 50% of the total reported fishing days. In their 1,035 combined fishing days, Hawaiian anglers also caught the most billfish in 2015, with Pacific blue

marlin remaining the most-caught species followed by shortbill spearfish (*Tetrapturus angustirostris*) and striped marlin.

The ocean conditions off Southern California were phenomenal for fishing in 2015, with warmer-than-average water temperatures during summer and extended distributions of subtropical species into temperate waters such as hammerhead sharks (*Sphyrnidae spp.*), wahoo (*Acanthocybium solandri*), and billfish (*Istiophoridae spp.*). While the number of angler days decreased by 191 from 2014 to 2015, the number of billfish increased by 84. As such, the nominal CPUE (nCPUE) for Southern California, 0.41, shattered last year's nCPUE of 0.21, which was the third-highest nCPUE on record for Southern California. The region's nCPUE was also exceptionally higher than the results for 2013 (0.03) and 2014 (0.07). Per usual, the major species caught in Southern California was the striped marlin.

Despite being one of the top three fishing areas season after season, the nCPUE for the Baja region has continuously declined over the past four years and we've also seen a decline in the number of reported fishing days from the area. For 2015, the nCPUE of 0.59 was relatively low compared to the nCPUE in 2014 (0.90) and 2013 (1.11). Regardless of this regional-specific decline, the nCPUE for Baja has almost always exceeded that of Southern California and Hawaii. The region is historically extremely productive for billfish fishing. Although striped marlin was the major species caught, blue marlin and sailfish were also caught and reported.

The nCPUE time-series were examined for Pacific blue marlin, striped marlin, Pacific sailfish, and black marlin in the main fishing areas (Hawaii, Baja California, Mexico, Southern California, Costa Rica, Panama, and Australia; **Figure 6**).

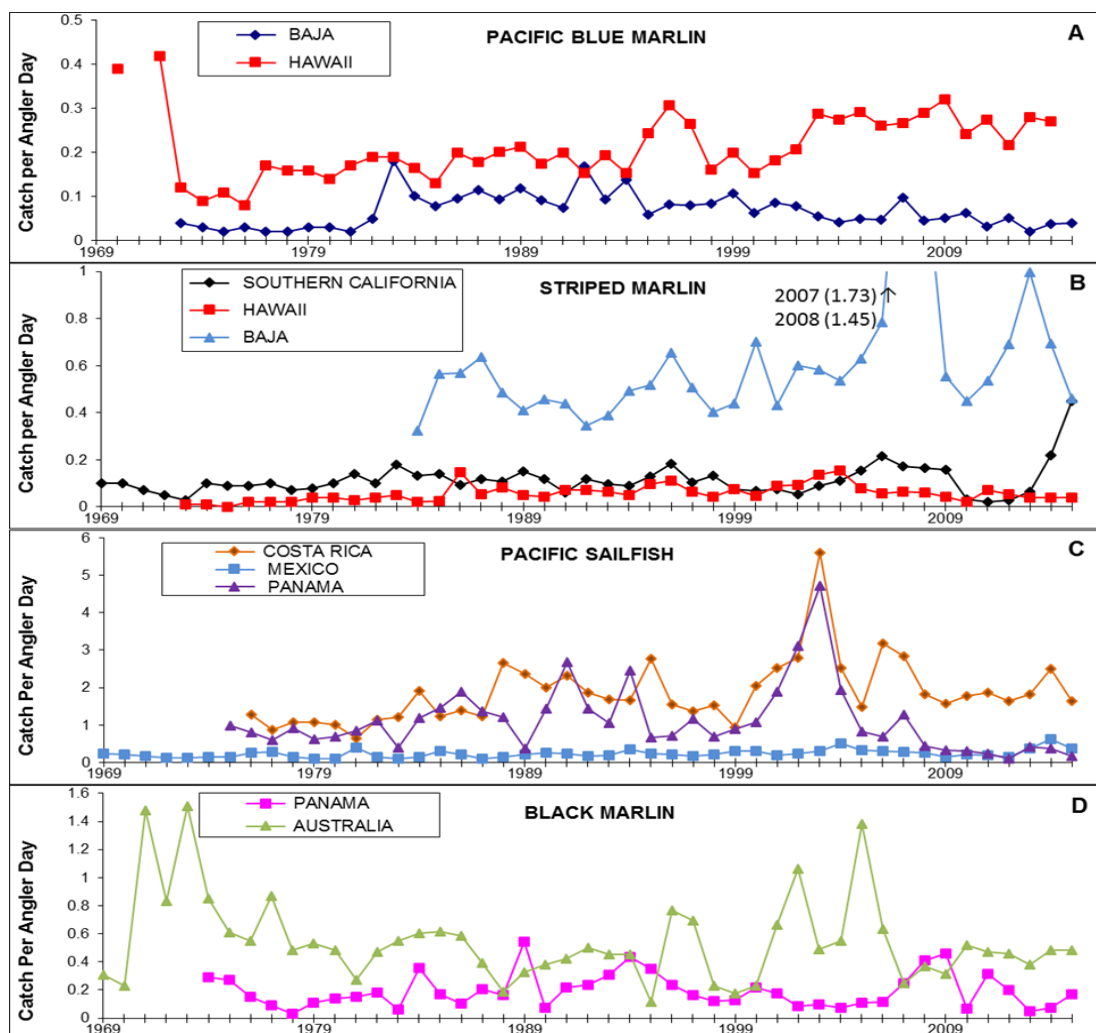
The 2015 Hawaii blue marlin nCPUE was 0.47, which is higher than the 2014 nCPUE of 0.27 and the recent 10-year average of 0.27. In contrast, Baja's blue marlin nCPUE remained unchanged at 0.04 and ranked lower than both the recent 10- and 20-year averages of 0.05 and 0.07, respectively. In fact, the recent results show a continued declining trend in the blue marlin nCPUE off Baja California since 1992. The blue marlin nCPUE has been at or below 0.10 since 2000, and at or below 0.06 since 2008.

Since 2011, the Southern California striped marlin nCPUE has been steadily increasing, but the 2015 value of 0.45 is the *highest ever* by more than double (0.22, occurring in 2014 and 2006)! The striped marlin fishing for the Baja California region appeared very similar to that of Southern California, with an nCPUE of 0.46. However, like the overall nCPUE for all species reported in the region of Baja, the striped marlin nCPUE has been declining for the past couple of years (2013: 1.00, 2014: 0.70) and this 2015 value is lower than both the 5- and 10-year average, 0.68 and 0.85, respectively. However, compared to the double-digit nCPUE values for Baja and Southern California, the striped marlin nCPUE for Hawaii remained steady in 2015 at 0.04, as it has been for the past three seasons.

The Costa Rica sailfish nCPUE has remained the highest for the three main locations since 2003, and anglers there reported a nCPUE of 1.63 for the 2015 season. Although neighbors, the 2015 sailfish nCPUE in Panama (0.17) was largely below that of Costa Rica and has been since 2003.

This 2015 season marked another drop in nCPUE for Panama the second year in a row, which is also below the overall average nCPUE of 1.11. The Mexico sailfish nCPUE value is based on fishing effort reported from locations across the entire country's west coast, including the mainland and the Baja Peninsula. The 2015 sailfish nCPUE of 0.38 dropped from the 2014 value (0.63) but still remains higher than the 5- and 10-year averages (0.31 and 0.29, respectively) and the region's overall nCPUE (0.23). Unlike Costa Rica and Panama, the sailfish nCPUEs of Mexico have not exceeded 1.0 in the history of the program. This may be in part due to the expansive and diverse coastline of the country which includes temperate waters as opposed to the strictly tropical waters off Costa Rica and Panama which sailfish tend to prefer.

The 2015 black marlin nCPUE for Australia was identical to last year's value, 0.48. This is higher than the 5-year average (0.46), but lower than the overall regional average nCPUE of 0.55. Black marlin fishing has stayed fairly consistent in the last 5 years and has remained between 0.38 and 0.48 since 2011. The runner-up for black marlin nCPUE is Panama, which reported an nCPUE of 0.17 for 2015. This is an increase from the previous two years (0.05 and 0.07) and above the 5-year average for the region (0.14). Papua New Guinea, Malaysia, Guatemala, and Thailand have all reported black marlin catches in the past, however, the consistent standouts for the species have been Panama and Australia since the early 1970s.



**Figure 6.** CPUE as catch-per-angler-day is shown from 1969 through 2015 for Pacific blue marlin, striped marlin, Pacific sailfish, and black marlin.

### ***Recreational Billfish Tagging Program***

The SWFSC's angler-based Billfish Tagging Program began in 1963 and has provided tagging supplies to billfish anglers for over 50 continuous years. Tag release and recapture data are used to examine movement and migration patterns, species distribution, and age and growth. This volunteer tagging program depends on the participation and cooperation of recreational captains and anglers, sportfishing organizations, and commercial fishers. In collaboration with the CDFW, over 80,000 fish have been tagged and released since the start of the program.

Anglers released 1,416 tags on billfish in 2015 (**Table 3**). Anglers in the Hawaiian Islands tagged the greatest number of billfish in 2015, followed by Acapulco/Ixtapa-Zihuatanejo, and then Southern California. This is the first time in 4 years that the tag releases in Southern California exceeded those of Baja. This switch in tagging effort, in conjunction with the drop of Baja's nCPUE (1.11 in 2013, 0.90 in 2014, and 0.59 in 2015), may be linked to changes in sea surface temperature (SST) and the occurrence of "the Blob" in the Northeast Pacific.

Tag recoveries (recaptures) provide data to assess growth and migration patterns. All known recaptures in 2015 were for blue marlin originally tagged in Hawaii. The most significant tag recovery was from a blue marlin tagged in Hawaii in 2011 which traveled a total of 3,122 nautical miles to Manzanillo, Colima, Mexico, and was at liberty for 1,270 days.

**Table 3.** Summary of billfish tagged during 2015 by region.

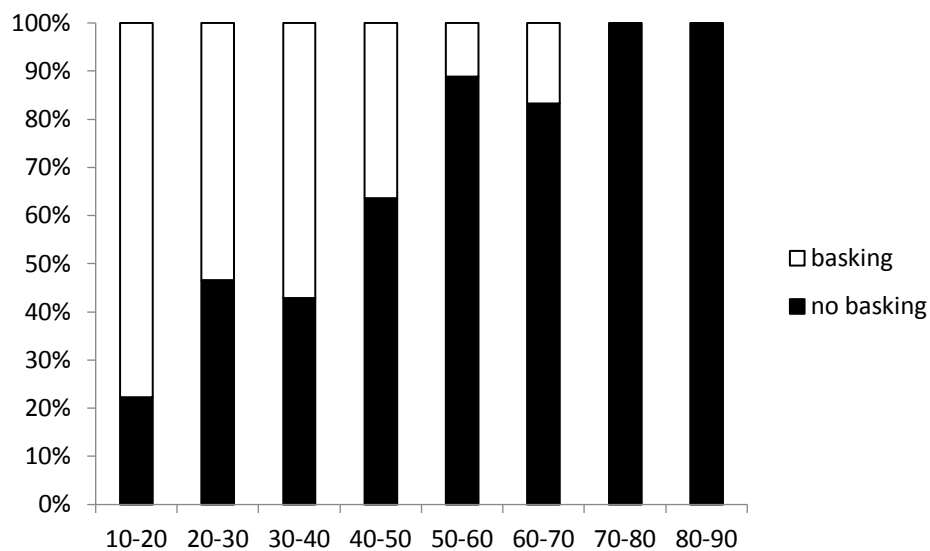
Location	Species	Tag totals
<b>Southern California</b>	Striped Marlin	94
<b>Baja California/Baja California Sur</b>	Striped Marlin	19
<b>Baja California/Baja California Sur</b>	Sailfish	4
<b>Baja California/Baja California Sur</b>	Pacific Blue Marlin	1
<b>Acapulco/Ixtapa/Zihuatanejo/Guerrero</b>	Sailfish	189
<b>Hawaii</b>	Pacific Blue Marlin	935
<b>Hawaii</b>	Shortbill Spearfish	117
<b>Hawaii</b>	Striped Marlin	33
<b>Hawaii</b>	Black Marlin	2
<b>Hawaii</b>	Broadbill Swordfish	1
<b>Guam</b>	Pacific Blue Marlin	1
<b>Samoa</b>	Pacific Blue Marlin	15
<b>Samoa</b>	Sailfish	2
<b>Tahiti</b>	Striped Marlin	1
<b>Tahiti</b>	Black Marlin	1
<b>Tahiti</b>	Pacific Blue Marlin	1

### **Swordfish Research and SLUH**

Since 2006, SWFSC researchers have been studying swordfish in the SCB to examine migratory patterns, foraging ecology, and local stock structure. In 2008, FRD teamed up with the Marine Mammal and Turtle Division (MMTD) and the NOAA WCR to launch a new initiative, Swordfish and Leatherback Use of Temperate Habitat (SLUTH). The overarching objective of SLUTH is to integrate studies of swordfish and leatherback sea turtles to inform management and conservation efforts. The endangered leatherback is taken incidentally in swordfish fisheries, and concerns about leatherback populations are currently shaping the management of swordfish fisheries along the U.S. West Coast. While a large organized initiative has yet to be established, FRD and MMTD have a number of ongoing research projects to characterize the habitat of swordfish and leatherback sea turtles to identify where habitat separation is maximized in time and space. Information on habitat separation can be used to increase the selectivity of fisheries and reduce bycatch. Additional research examines bycatch to better characterize difference among gear types and examine fin-fish bycatch. The research has been presented to the PFMC and should help managers make more informed decisions about potential gear alternatives.

### ***Swordfish Habitat Use in the Pacific Leatherback Closed Area (PLCA).***

Information on geographic and vertical habitat use in regions of overlap between swordfish and leatherbacks is critical to understanding habitat separation. While a relatively large number of satellite tags have been deployed on swordfish in the SCB, prior to these efforts, no tags had been deployed north of Point Conception where leatherbacks are known to aggregate and where the majority of bycatch occurred in the CA drift gillnet fishery. In collaboration with the Pflieger Institute of Environmental Research (PIER), 13 satellite tags were deployed in the Pacific Leatherback Conservation Area Closure (PLCA) to quantify habitat use. The 11 tags reported show more variable habitat use than in the SCB, with more time spent in the mixed layer during the day. Similar to tags deployed elsewhere, basking decreased as swordfish moved offshore and the mixed layer depth increased (**Figure 7**). Findings suggest that vertical habitat use may be less predictable in the PLCA, which could impact efforts to target swordfish at depth, but that offshore catchability may improve. A manuscript describing this work is in preparation.



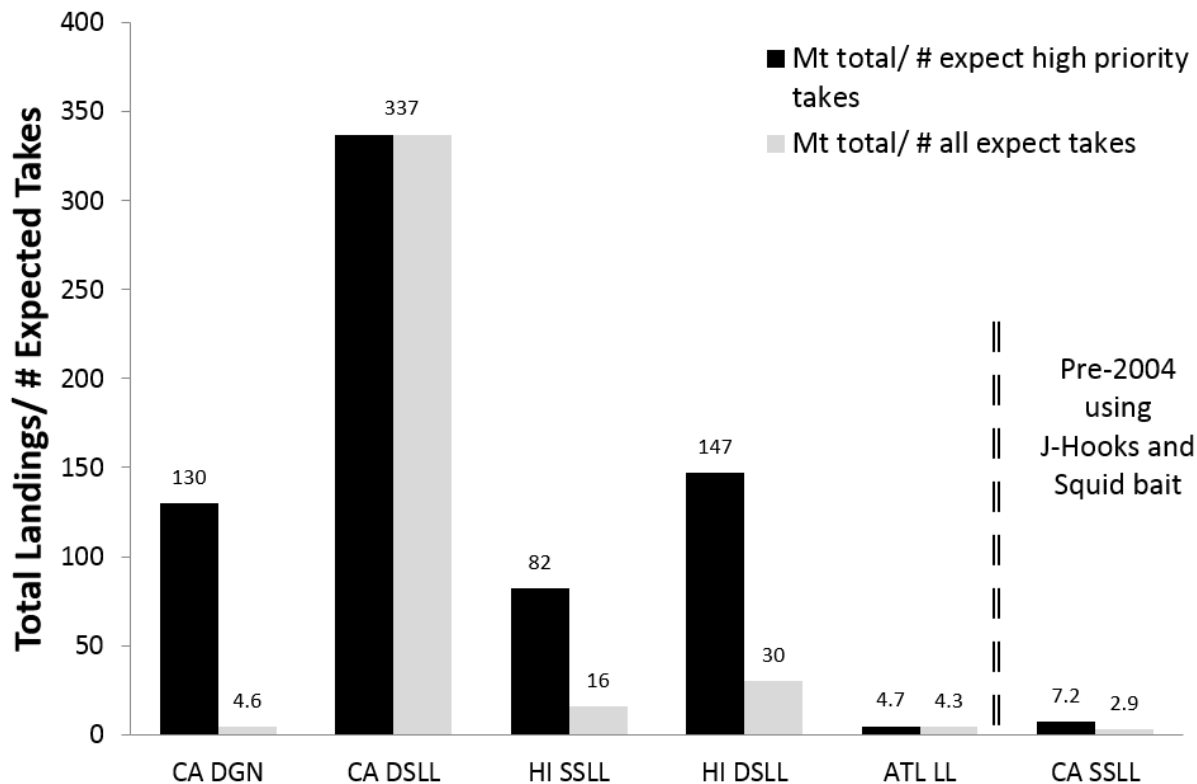
**Figure 7.** Percentage of days during which basking behavior was documented, along the y axis, in relation to the depth of the mixed layer in meters, along the x-axis.

### ***Comparative Bycatch Metrics of U.S. Commercial Swordfish Fisheries***

An additional component of gear alternative research is the examination of deep-set buoy gear in the broader context of all U.S. gears used to target swordfish (and in some cases tuna). Project objectives include: 1) providing a more comprehensive view of bycatch in current and historic U.S. fisheries targeting primarily swordfish, 2) creating standardized metrics across fisheries to allow for more effective comparisons, rather than looking at bycatch numbers for individual fisheries in isolation, 3) comparing measures of economic viability across fisheries, and 4) measuring the potential for commercial volume of harvest. Fisheries compared include the California drift gillnet (CA DGN), California deep-set longline (CA DSL) targeting tuna, California harpoon (CA HPN), Hawaii shallow-set longline (HI SSL), Hawaii deep-set longline (HI DSL) targeting tuna, Atlantic pelagic longline (ATL LL), and Atlantic buoy gear (ATL BG). Scientists also examined the California shallow-set longline for a historical comparison of shallow-

set longline swordfish fishery bycatch levels prior to the implementation of requirements to use circle hooks and finfish bait.

To compare bycatch across diverse taxonomic groups including marine mammals, turtles, and seabirds, species were separated into two categories. “High priority” protected species were ESA-listed or considered a strategic stock, and “other” if they were not. The total take for species in the “high priority” category and for “other” protected species was estimated based on observer coverage. The takes by category was then compared to metric tons of swordfish and total landings to get a relative measure of bycatch and productivity (**Figure 8**). Economic metrics were calculated as the ex-vessel profit per vessel. The commercial volume metric was then calculated as the metric tons of landings across the fleet. The CA DSLL, harpoon and buoy gear fisheries have little to no bycatch for either species category but have relatively low profits and production volume. Overall, the CA DGN had low catch of “high priority” protected species and compared favorably to the other fisheries in terms of overall bycatch, profitability and commercial volume. A publication on these results is currently in preparation.



**Figure 8.** Comparative bycatch metrics for fisheries with protected species interactions. Metric tons (mt) of all market species landings per high priority protected species takes by numbers (black bars) and all high priority and other protected species combined by number (gray bars). Note that there were no “other” protected species takes for the CA DSLL fishery; hence the two values are the same. Harpoon and ATL BG did not have any protected species interactions. Note that higher values translate into less relative bycatch.





While most of the focus on bycatch has been on marine mammals, turtles, and sea birds, there has been a growing concern about the bycatch of finfish species in pelagic fisheries including the CA DGN fishery. To address these concerns, a project to examine finfish bycatch in the CA DGN fishery was initiated with a graduate student at Scripps Institution of Oceanography (SIO). For the analyses, observer data collected between 1991 and 2013 were obtained. The total number and the estimated weight of catch of a given finfish species were compared to total landings as described above with protected species. Weight was considered a relevant measure given the broad range of weights of fish caught in the fishery, e.g., one bonito does not equal one swordfish. Results were compared across the entire time-series. Results reveal that 65 species of finfish have been observed caught in the CA DGN fleet including the target swordfish, and secondary target thresher shark. Of these, 18 constitute 98% of the total catch by number with 11 species having retention rates greater than 50%. Mola constitutes 28% of the catch, however more than 90% of these are release alive. There is a considerable difference in the bycatch rates, when comparing number versus weight with the percentage of total bycatch dropping from 59% to 24%, respectively. Additional analyses will examine patterns across time for insights into how regulatory measures designed to reduce protected species catch may have also influenced finfish bycatch

### ***Foraging Ecology of Swordfish in the SCB***

In support of ecosystem based studies, SWFSC researchers are investigating the foraging ecology of swordfish to examine predator-prey interactions and niche overlap with other pelagic predators. Stomach contents for this work have been predominantly provided through the CADGN observer program. Data are finalized for the period 2007-2014. During this period jumbo squid was the most important prey item by weight, number and combined indices. The boreopacific gonate squid (*Gonatopsis borealis*) was the second most important prey by GII and IRI, but the most important for frequency of occurrence. Other dominant cephalopod prey included *Abraliopsis* sp. squid, *Gonatus* spp. squid, and market squid (*Doryteuthis opalescens*). Pacific hake (*Merluccius productus*) ranked 6th and was the highest among teleost prey. Swordfish also preyed on barracudinas (*Paralepididae*), coastal pelagic fishes (jack mackerel, Pacific sardine, Pacific saury, northern anchovy), luvar (*Luvarus imperialis*), king-of-the-salmon (*Trachipterus altivelis*), halfmoon (*Medialuna californiensis*) and seven species of the Myctophidae family.

Some differences in prey composition with swordfish body size were apparent. GII results by size (classified as small fish up to 164cm eye fork length (EFL) and large fish  $\geq 165$ cm) revealed that for the smallest and also for the largest specimens, jumbo squid was the most important prey item followed by the boreopacific gonate squid, and *Abraliopsis* sp. Both size groups fed on similar prey. Northern anchovy was found only in the small size group and seven specimens in the large size group fed on luvar. Generalized Additive Models, Redundancy Analysis and ecological index calculations are in progress to determine how the prey of swordfish is affected by environmental and biological variables.

### **Opah Research in the Eastern Pacific Ocean**

The opah is a large, mid-water pelagic fish that occurs seasonally in the SCB. While they are not targeted, opah are taken incidentally in both local recreational fisheries for tuna and the CA DGN fishery targeting swordfish. In recent years, opah have become increasingly popular in seafood markets. Despite their value to commercial and recreational fishermen, little research on the basic biology and ecology of opah has been conducted, especially in the SCB. There is little data on

foraging ecology, size composition in fisheries, essential habitat, and stock structure, among other important information. In order to fill some of the data gaps, SWFSC scientists began collecting biological samples from caught opah in 2009 and initiated an electronic tagging program in 2011. In 2017, the SWFSC will work collaboratively to sample opah landed by California-based longliners. A cooperative research project with the California Pelagic Fisheries Association (CPFA) and Catalina Offshore Products aims to sample up to 50 opah per month to study life history including age and growth, reproductive biology, foraging ecology, and fishery catch composition by size, sex, and genetic lineage.

## **V. 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, bigeye thresher (*Alopias superciliosus*), and pelagic thresher (*Alopias pelagicus*). Center scientists are studying the sharks' biology, distribution, movements, stock structure, population status, and potential vulnerability to fishing pressure. This information is provided to international, national, and regional fisheries conservation and management bodies having stewardship for sharks.

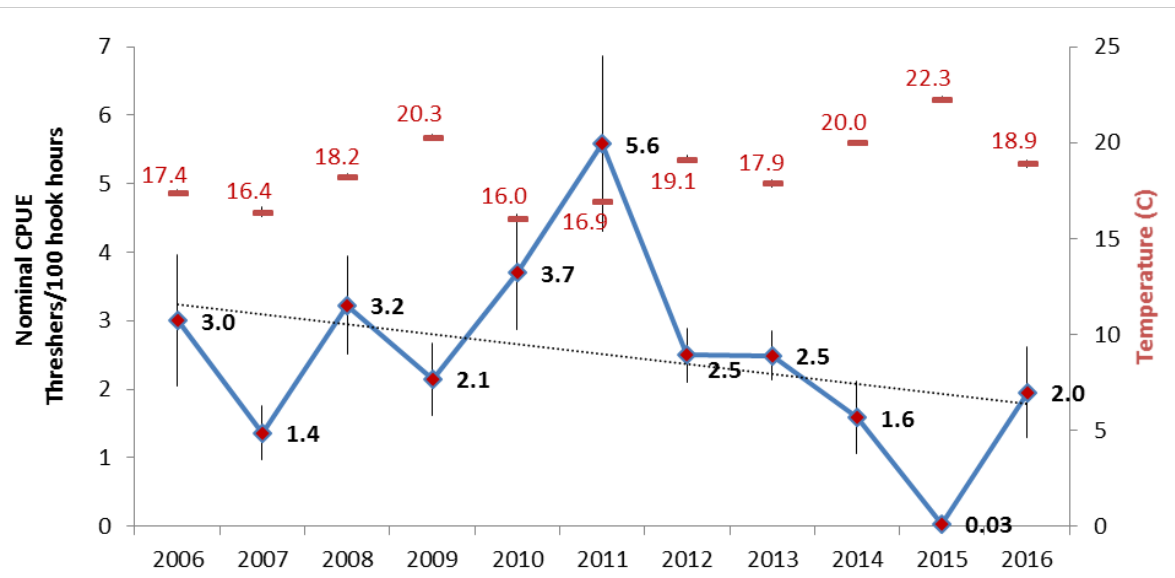
### **Abundance Surveys**

Blue, shortfin mako, and thresher sharks are all taken in regional commercial and recreational fisheries. Common thresher and mako sharks have the greatest commercial value and are also specifically targeted by sport fishers, especially off Southern California. While blue shark has little market importance in the U.S., it is a leading bycatch species in the CA DGN fishery and high-seas longline fisheries. Although catches of adult blue, thresher, and shortfin mako sharks do occur, the commercial and sport catch of these species off Southern California consists largely of juvenile sharks.

To track trends in the abundance of juvenile and sub-adult blue and shortfin makos, and neonate (0-1 year old) common thresher sharks, surveys are carried out in the SCB. Offshore longline surveys from large research vessels have proved most effective for sampling and estimating abundance trends of the more oceanic shortfin mako and blue sharks. Surveys for neonate thresher sharks are conducted using a small commercial longline vessel in near shore waters. During 2016, a survey for mako and blue sharks was not conducted but an expanded survey for thresher sharks was.

### ***Juvenile Thresher Abundance and Habitat Survey***

Twenty seven days of longline sampling were conducted aboard the chartered commercial vessel, F/V *Outer Banks* in August and September 2016. Unlike in 2015 when there was anomalously warm water due to El Niño and the "warm blob," conditions in the SCB were more typical. The catch rate (nCPUE) of thresher sharks in the SCB survey area was 1.98 threshers per hundred hook hours. Water temperature and nCPUE fell within the range of those recorded during prior surveys, with the exception of 2015 during which the warmest water and lowest catch of threshers were recorded (**Figure 9**). During the expanded effort beyond the SCB survey area, which was mostly in nearshore waters between Point Conception and San Francisco Bay, seven thresher sharks were caught. Total catch for the survey and exploratory sets is shown in **Table 4**.



**Figure 9.** Average ( $\pm$ SE) nominal catch rate per survey set (values in black) for common thresher sharks, 2006 - 2016. Average ( $\pm$ SE) sea surface temperature recorded during each survey is indicated by red bars with values in red. The 2016 values are only for the sets conducted for the SCB annual survey for continuity with prior years.

**Table 4.** Total longline fish catch, not including Pacific mackerel (*Scomber japonicus*), recorded during the 2016 Juvenile Thresher Abundance and Habitat Survey.

Species	Survey Sets	Exploratory Sets
Shark, Common Thresher ( <i>Alopias vulpinus</i> )	144	7
Stingray, Pelagic ( <i>Pteroplatytrygon violacea</i> )	14	-
Bass, Kelp ( <i>Paralabrax clathratus</i> )	14	-
Shark, Soupfin ( <i>Galeorhinus galeus</i> )	7	3
Shark, Leopard ( <i>Triakis semifasciata</i> )	4	2
Yellowtail ( <i>Seriola lalandei</i> )	4	-
Shark, Shortfin Mako ( <i>Isurus oxyrinchus</i> )	4	-
Bass, Giant Sea ( <i>Stereolepis gigas</i> )	4	-
Seabass, White ( <i>Atractoscion nobilis</i> )	3	4
Ray, Bat ( <i>Myliobatis californica</i> )	3	-
Bonito, Pacific ( <i>Sarda chiliensis</i> )	2	-
Bass, Barred Sand ( <i>Paralabrax nebulifer</i> )	2	-
Shark, White ( <i>Carcharodon carcharias</i> )	1	-
Shark, Swell ( <i>Cephaloscyllium ventriosum</i> )	1	-
Smelt, Unidentified ( <i>Osmeridae</i> )	-	7
Rockfish, Black ( <i>Sebastes melanops</i> )	-	7
Rockfish, Blue ( <i>Sebastes mystinus</i> )	-	5
Shark, Blue ( <i>Prionace glauca</i> )	-	2
Lingcod ( <i>Ophiodon elongatus</i> )	-	1

In addition to providing important information on abundance and distributions, the thresher shark survey enhances other ongoing research at the SWFSC including age and growth, foraging, and habitat-utilization studies. One hundred and sixty three (163) sharks were tagged with conventional tags for movement and stock structure studies. One hundred and forty five (145) of these sharks, including 141 threshers, 1 blue, and 3 mako sharks were marked with oxytetracycline (OTC) for age validation studies. A juvenile white shark (male, 145 cm FL) was caught near Rincon Point and released in good condition with a pop-off archival tag. The shark was tagged as part of a Monterey Bay Aquarium project to study the behavior and habitat use of juvenile white sharks. DNA samples were collected from 187 fish for genetic studies. Cloacal swabs to look for carnobacteria were collected from several thresher sharks to contribute to the Master's thesis project of a California State Long Beach researcher. In addition, SWFSC scientists collected detailed morphometric information and biological samples from animals that did not survive.

Habitat information was collected throughout the survey which, along with historical survey, tagging, and fishery data, will be used to develop a model of the potential habitat of juvenile thresher sharks.

### **Electronic Tagging Studies**

Starting in 1999, SWFSC scientists have been using satellite technology to study the movements and behaviors of large pelagic sharks; primarily blue, shortfin mako, and common thresher sharks, while other species are tagged opportunistically. Shark tag deployments have been carried out in collaboration with a number of partners in the U.S., Mexico, and Canada. The goals of these projects are to document and compare the movements and behaviors of these species in the California Current and to link these data to physical and biological oceanography. This approach will allow characterization of the essential habitats of sharks and a better understanding of how populations might shift in response to changes in environmental conditions over short or long time scales.

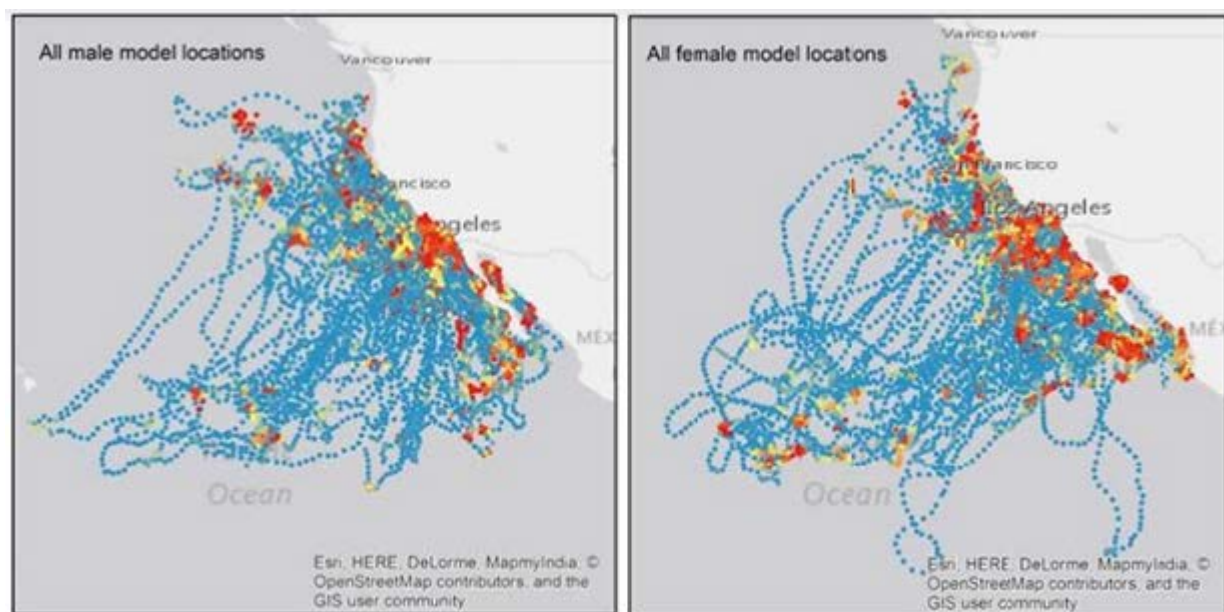
### ***Shortfin Mako Shark***

Since 2002, over one hundred shortfin mako sharks have been tagged with either SPOT or PSAT tags, or both, during the SWFSC's collaborative electronic tagging study. Partners include the Tagging of Pacific Pelagics (TOPP) Program, CICESE, the Guy Harvey Institute, and several recreational anglers.

Data from 55 PSAT tags and 85 SPOT tags are currently being analyzed. This is an enormously rich data set that includes tracks throughout a large part of the eastern North Pacific. Tracks range from near the U.S.-Canada border to the subtropics, into the Sea of Cortez and out near Hawaii. Tracks longer than six months showed that mako sharks tagged during the SWFSC HMS survey spent the summer and fall months near southern California after which they dispersed to the north, south, and offshore. Tags which recorded data for more than 12 months showed that the majority of tagged makos returned to the SCB the following summer. A comparison of habitat-use across regions show considerable diversity in vertical movements. In some areas, a distinct diel pattern is apparent whereas in others there is no obvious pattern. One consistent pattern, also observed in other species, is that as shark moved offshore they moved deeper into the water column. This is likely linked to the increased depth of the mixed layer and deep-scattering layer in more

oligotrophic waters. The high degree of variability in dive patterns suggests that they are likely foraging throughout the water column.

In addition to using these data to characterize the general movement patterns and habitat-use, additional analyses are now focused on state-space modeling which separates migratory from resident behaviors. The assumption is that resident behaviors occur in preferred habitats and are often linked to foraging. Foraging is one of the most important motivators for migrations and key to understanding movements over short-and longer time frames. The data for both males and females have been run through the state-space model (**Figure 10**). Results show that the majority of resident behavior occurs closer to the coast although there are some additional regions offshore that appear to be important. The next step will be to link the regions of high residency to environmental parameters in order to quantify the oceanographic characteristics that define preferred habitat in near and off-shore regions.

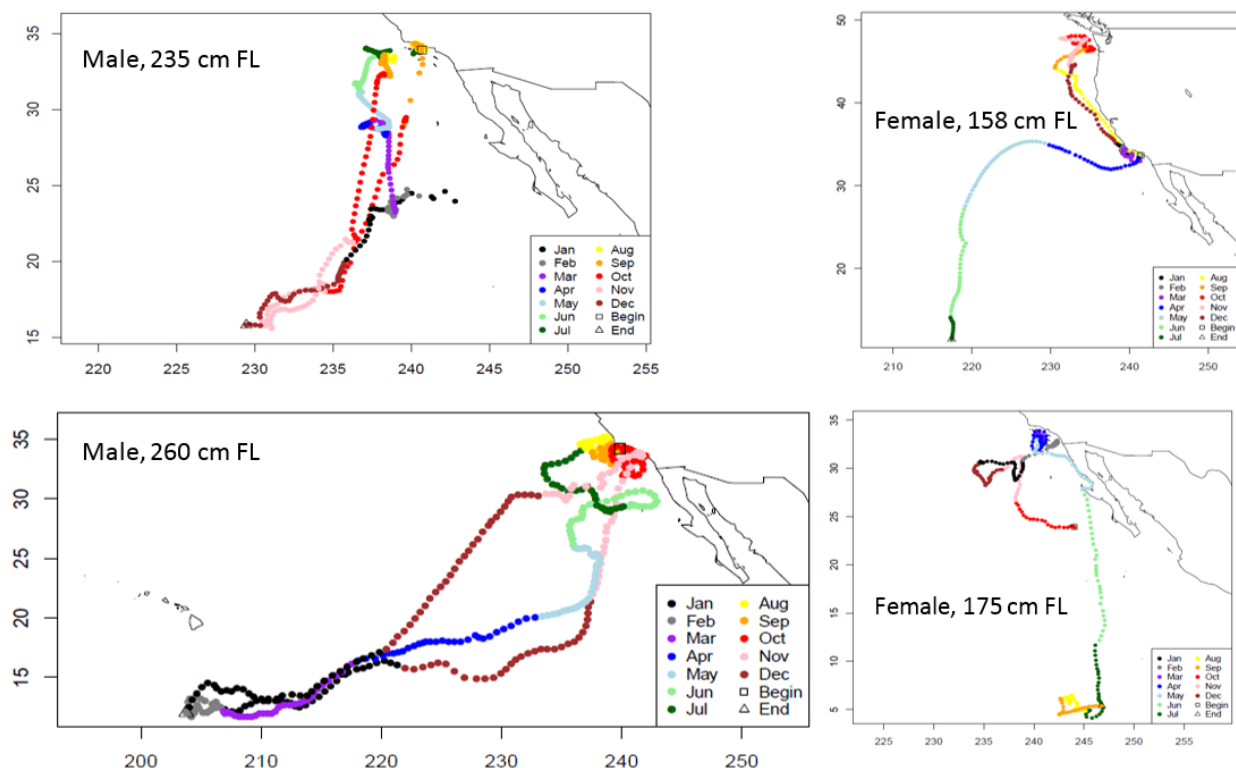


**Figure 10.** Results from state-space analyses showing the movements of shortfin mako sharks tagged with SPOT tags and the points where different migratory behaviors occurred. Red and orange show resident behaviors while blue shows time spent in transit.

### ***Blue Shark***

The SWFSC has been deploying satellite tags on blue sharks since 2002 to examine movements and habitat use in the eastern North Pacific. To date, a total of 100 sharks (51 males and 49 females) have been tagged with some combination of SPOT ( $n=95$ ) and/or PSAT tags ( $n=60$ ), with 55 sharks carrying both tag types. The majority of sharks were tagged in the SCB, although 14 sharks were tagged off Baja California Sur, Mexico, and another 12 off southwest Canada. Five sharks died shortly after tagging and seven PSAT tags were recovered providing archival data on temperature, depth, and light levels. Satellite tag deployment durations for both tag types are substantially shorter than for mako sharks. For the 37 PSAT tags that provided data, 8 of which remained attached until the programmed pop-up date, the average deployment duration was 115 days. The mean SPOT tag track duration was 88 days, however, six tags transmitted for 337 days

or more allowing for an examination of seasonal patterns. Interestingly, the four mature male sharks with long tracks all returned to the waters off southern California during the summer the year after they were tagged. Two of these tracks are shown in **Figure 11**. While the sample size is too small to draw conclusions about differences in migration patterns, the two females with longer tracks were far to the south the following summer (**Figure 11**). Additional tracks will be needed to determine if these patterns are consistent for females and large males for migrations greater than one year, and if so, if they are related to sex or maturity. The females were 4 and 5 years of age when tagged and maturity in females is reported to occur between 5-7 years of age.



**Figure 11.** Tracks from four blue sharks with tracks of 337 days or greater. Month is indicated by color.

Data transmitted and recovered from the PSAT tags provide information on vertical and thermal habitat use. Blue sharks occupied waters from 4.4 to 29.8°C, with sea surface temperature ranging from 10.8 to 29.8°C. A common pattern in archival records was repetitive dives to depths consistent with foraging in association with the deep-scattering layer during the day and the average maximum depth across all fish differed significantly comparing day (154 m) and night (65 m). However, archival records revealed a range of vertical movements with some periods of no diel activity. A comparison of size classes (either < or > 160 cm FL) reveals that smaller sharks have shallower average maximum depths (124 m) in comparison to larger sharks (175 m), which may be linked to behavioral thermoregulation and the increase in thermal inertia with size. A manuscript examining geographic and vertical movement patterns is in preparation.

### *Common Thresher Shark*

Since 2004, scientists at the SWFSC have been opportunistically tagging common thresher sharks

with electronic tags during the annual neonate thresher shark and HMS abundance surveys. To date 29 common thresher sharks have been released with either PSAT3, SPOT4, or both since 2004. Depth data indicate that threshers spend much more time near the surface in the mixed layer than they do at greater depths, and that vertical excursions below the mixed layer primarily occur during the day, potentially due to their unique hunting strategy which relies on visual prey detection. Work in 2015 and 2016 focused on developing a Bayesian movement model to provide a quantitative approach to inferring the effects of various environmental conditions on the horizontal movement of threshers.

Despite threshers being released with both SPOT and PSAT tags, to date SPOT tags have returned little to no data on the majority of tagged animals. PSAT data on the horizontal movements of these animals are harder to characterize than vertical movements because the light-based geolocation estimates determined from PSATs are less accurate than the locations from the satellite-linked SPOTs. Due to these difficulties, data from tags are being analyzed using a Bayesian approach which will allow us to generate posterior distributions with which to characterize the effects of tested environmental factors on thresher movement. This model was developed and tested during 2016 and a publication on its effectiveness at analyzing movement data for data-limited species was produced and is currently under review with PLOS One (Kinney *et al.* In Review). Using this Bayesian movement model, SWFSC researchers aim to understand what biological and environmental variables influence whether threshers remain within the SCB or move into the surrounding waters in a predictable manner. Analysis suggests that fork length and the spring season are the strongest predictors of thresher shark movement out of the SCB, with their posteriors shifted furthest from zero. El Niño index and sex are also influential drivers. The movement models will be used with fishery-dependent and -independent data to estimate the overlap of threshers with local fisheries and aid in the development of more adaptive surveys. A manuscript on the movement of thresher sharks based on this Bayesian model is currently being drafted.

### **Age Validation Studies**

Age and growth of mako, common thresher, and blue sharks are being estimated from band formation in vertebrae. In addition to being important for studying basic biology, accurate age and growth curves are needed in stock assessments. SWFSC scientists are validating ageing methods for these three species based on band deposition periodicity determined using OTC. Annual research surveys provide an opportunity to tag animals with OTC. When the shark is recaptured and the vertebrae recovered, the number of bands laid down since the known date of OTC injection can be used to determine band deposition periodicity. Since the beginning of the program in 1997, more than 4000 individuals have been injected with OTC. During the 2016 SWFSC surveys, 3 mako sharks, 1 blue shark, and 141 threshers were injected with OTC and released.

### **Blue Sharks**

Age validation work on blue sharks in the northeast Pacific Ocean culminated in a 2016 publication which demonstrated that blue sharks lay down one vertebral band pair per year. Vertebrae from 26 blue sharks were used to validate 1 growth band per year for blue sharks for sharks of ages 1 to 8 years. Length-frequency modal analysis from 26 years of research and commercial catch data also supported annual band pair deposition in blue sharks (Wells *et al.* 2016).

### ***Common Thresher Sharks***

During 2016, work continued on age validation of common thresher sharks and 141 threshers were injected with OTC. Since 1998, a total of 1,739 common thresher sharks ranging in size from 45 to 240 cm FL have been injected with OTC. Natalie Spear of Texas A&M University completed an age validation study of threshers as part of her master's thesis in March 2016. She examined vertebrae from 60 OTC marked sharks (size range at tagging: 63-145 cm FL) with an average time-at-liberty of 352 days. Annual vertebral band pair deposition was validated for 26 individuals at liberty for over 10 months, with a maximum time-at-liberty of 1,389 days (3.8 years). This work is currently being prepared for publication.

### **Foraging Ecology of Pelagic Sharks**

The California Current is a productive eastern boundary current that functions as an important nursery and foraging ground for a number of highly migratory predator species. To better understand niche separation and the ecological role of spatially overlapping species, SWFSC researchers have been analyzing the stomach contents of pelagic sharks since 1999. Stomachs are obtained primarily from the CA DGN observer program, but with decreasing effort in the fishery, fewer shark stomachs have been available for analysis in recent years.

### ***Stomach Content Analysis***

Stomach content analysis of blue, shortfin mako, thresher, and bigeye thresher sharks is ongoing. Data are finalized for the period 2002-2014.

For the mako shark, jumbo squid was the most important prey item by weight and combined indices. Pacific saury (*Cololabis saira*) was the second most important prey by GII and IRI but the most important for frequency of occurrence and the most abundant by number. Other dominant teleost prey included Pacific sardine, Pacific mackerel, striped mullet (*Mugil cephalus*) and jack mackerel. Makos also preyed on marine mammals and other elasmobranchs. One mako preyed on a short-beaked common dolphin (*Delphinus delphis*), blue sharks were found inside five mako stomachs, and one mako fed on four tope sharks (*Galeorhinus galeus*).

Squids of the genus *Gonatus* ranked first for GII and IRI and frequency of occurrence for the blue shark. Jumbo squid ranked second for GII and IRI but they were the most important in weight. Other dominant prey included octopuses of the genus *Argonauta*, and the flower vase jewell squid (*Histioteuthis dofleini*). One blue shark fed on an unidentified cetacean and another one fed on elephant seal (*Mirounga angustirostris*). Three blue sharks fed on elasmobranchs spiny dogfish (*Squalus acanthias*) and tope shark, and one ingested a common tern (*Sterna hirundo*). Forty-seven blue shark stomachs (23% of all stomach samples) contained prey that was bitten in chunks and were found in a fresh state of digestion (states 1 and 2) which were interpreted as prey caught in the net. One blue shark stomach contained a skipjack tuna head with a piece of net in his mouth. Other net-caught prey taxa included scombridae (F=31), ocean sunfish (*Mola mola*) (F=8), broadbill swordfish (F=3), opah (F=2), unidentified elasmobranchs (F=2), and Pacific pomfret (*Brama japonica*) (F=1). One stomach contained 21 pork steaks wrapped in paper and another stomach contained vegetables (onions, bell peppers, shredded carrots) and a tea bag, all these items were likely discarded at sea and scavenged by the blue sharks. Similar fresh chunks of prey were observed in one mako stomach and no thresher or bigeye thresher shark stomachs.



For the thresher shark, northern anchovy (*Engraulis mordax*) ranked first in both the GII and IRI and had the highest number and weight. Pacific sardine ranked second in both the GII and IRI. Other dominant identified prey included market squid, Pacific hake, and Pacific mackerel. Pacific saury, Jack mackerel (*Trachurus symmetricus*) and Duckbill barracudina (*Magnisudis atlantica*) were found in at least 16 stomachs. Pelagic red crab was the most frequent crustacean (F=12).

Jumbo squid was the most important prey (for GII and IRI) for the bigeye thresher shark, it was also the most frequent prey with the highest weight. Duckbill barracudina and other Paralepididae ranked second and third. Other important prey included Pacific hake, Pacific mackerel, Pacific saury and *Gonatus* spp. squids. Fourteen individuals of king-of-the-salmon were present in two bigeye thresher stomachs.

Generalized Additive Models, Redundancy Analysis, and ecological indices calculations are in progress to determine how the prey of these four sharks is affected by environmental and biological variables.

## **VI. IDCPA RESEARCH**

The SWFSC research conducted under the International Dolphin Conservation Program Act (IDCPA) during 2016-17 was focused on mining existing Eastern Tropical Pacific Ocean (ETP) datasets to (1) evaluate the use of tuna vessel observer data in assessments, (2) clarify cetacean population structure and life history, (3) identify critical habitat for large whales, and (4) advance our understanding of ecosystem structure and function.

### **Evaluating the Use of Tuna Vessel Observer Data in Assessments**

#### ***Tuna Vessel Observer Data Use in the Indexing of Relative Abundance ETP Dolphin Stocks***

Staff from the IATTC and MMTD scientist, Dr. Paul Fiedler, collaborated to explore whether tuna vessel observer data (TVOD) can be used to develop an index of relative abundance for ETP dolphin stocks (Lennert-Cody *et al.*, 2016). In the ETP, yellowfin tuna are often found in association with spotted (*Stenella attenuata*) and spinner (*Stenella longirostris*) dolphins. Purse-seine vessels use this co-occurrence to locate the tuna by searching for dolphins and associated seabirds. Data collected by onboard observers since the late 1970s were used to develop indices of relative abundance for dolphins, based on line-transect methodology, when the primary method of detection of dolphin herds was with binoculars. However, trend estimation was subsequently discontinued in 2000 due to concerns about changes in reporting rates of dolphin herd detections with increased use of helicopter and radar search. At present, as a result of a hiatus in fishery-independent surveys since 2006, fisheries observer data are the only source of information by which to monitor the status of ETP dolphin populations. In this paper, trend estimation with the onboard observer data is revisited using a sightings-per-unit-effort approach. Despite different assumptions and model structure, the results indicate a lack of independence between the distribution of search effort and the search methods used, and the abundance of dolphin herds associated with tunas, on several spatial and temporal scales. This lack of independence poses a considerable challenge to the development of a reliable index of relative abundance for dolphins with these data. Given these results, alternatives for dolphin abundance estimation are discussed.

One alternative is the use of purse-seine vessels for line-transect surveys during fishery closure periods. Another alternative is the use of purse-seine vessels during normal fishing operations as platforms for the collection of mark-recapture data (using, for example, passive integrated transponder tags or genetics sampling). Life-history data collection, as a supplement to the collection of other data types, is also discussed. Further research and development is needed to assess whether these alternative methods will be useful. An IATTC Workshop on Methods for Monitoring the Status of ETP Ocean Dolphin Populations was held at SWFSC, 18-20 October 2016, to investigate these alternatives.

### ***Variability of Dolphin Distribution Based on Tuna-Vessel Observer Data***

Dr. Paul Fiedler, in collaboration with the IATTC, is conducting an analysis of seasonal and inter-annual variability of dolphin distribution. This analysis is based on fisheries observer data from the yellowfin tuna purse-seine fishery that fishes tunas associated with dolphins (TVOD). Cetacean species distribution patterns in the ETP have been described and analyzed several times from a series of rigorous NOAA research vessel surveys conducted sporadically between 1986 and 2009. However, survey coverage is not adequate to describe seasonal and ENSO-related changes in distribution. We used TVOD to construct a binned spatiotemporal data set of the probability of presence of spotted, eastern spinner, and common dolphins by month from 1986 through 2015. Generalized additive models of predicted presence from surface temperature, surface salinity, mixed layer depth, thermocline depth and strength, and a stratification index showed seasonal and interannual changes in preferred habitat based on environmental variability in time and space. Spotted and spinner dolphins respond to seasonal changes in the position and size of the eastern Pacific warm pool and avoid the equatorial cold tongue in summer-fall. Common dolphins respond to seasonal and ENSO-related changes in the Costa Rica Dome, the cold tongue, and in coastal upwelling habitat along Baja California and Peru-Ecuador. The predictions based on tuna vessel observer data were validated with research vessel sightings. The paper presenting these results is being prepared for publication.

### **Clarifying Cetacean Population Structure and Life History**

#### ***Population Structure of Spotted and Spinner Dolphins***

Multiple subspecies of spinner and spotted dolphins have been described based on morphology but previous molecular studies have struggled to corroborate these intraspecific differences. Several demographic and evolutionary factors (high historical abundance, permeable barriers, and high mobility) combine to obscure patterns of population genetic structure in these long-lived pelagic animals. Questions of population structure in these species were the subject of the PhD dissertation of Dr. Matthew Leslie, a former SIO graduate student, working with Dr. Phil Morin (SWFSC). This work pioneered two novel approaches to collect DNA sequence data using existing skin samples from the SWFSC tissue archive:

#### ***Mitochondrial Genomes and Nuclear Single Nucleotide Polymorphisms (SNPs)***

To characterize genetic structure whole mitochondrial genomes and a suite of nuclear loci were collected from 104 spinner and 76 spotted dolphins using capture array library enrichment and highly paralleled DNA sequencing. Mitochondrial genome results showed weak but significant

differences between recognized subspecies of both spinner and spotted dolphins. Nuclear SNPs supported subspecies of spotted dolphins, but not spinner dolphins. However, there was strong differentiation between whitebelly and eastern spinner stocks using SNPs. There was very little support for the division of offshore stocks of spotted dolphins and no support for Tres Marias spinner dolphins. This work contributes to the identification of management units for the conservation of these highly depleted populations. A manuscript is in review with the scientific journal *Marine Mammal Science* (Leslie *et al.* Submitted).

### ***Restriction-Site Associated DNA Sequencing***

This project targeted DNA sequencing near restriction enzyme cut-sites to search for variation across many individuals. Over 3500 SNPs per species resulting from this method provided statistical power to test hypotheses of smaller alternative stocks. There was support for all existing stocks and evidence for differentiation of the Tres Marias Islands stock. In addition to ETP samples, this study has included samples from each ocean basin to provide context for the unique diversity of the ETP. We found highly structured populations throughout the range of spinner and spotted dolphins. Interestingly, ETP endemics are very genetically separated from western and central Pacific populations. Moreover, the northern Australia population of dwarf spinner dolphins may be a unique population different from Indonesia and the rest of the dwarf spinner dolphins. The first publication, focused on subspecies and populations within the ETP, was published in 2016 (Leslie and Morin, 2016). A second manuscript focused on global patterns of differentiation in spinner and spotted dolphins is in preparation for submission.

### ***Phylogeographic and Population Genetic Analyses of Short-finned Pilot Whales and Sperm Whales***

Two projects are underway to evaluate population structure of toothed whales in the ETP, in the context of population and phylogeographic patterns in the North Pacific and globally.

Short-finned pilot whales (*Globicephala macrorhynchus*) are a highly social species and a top predator in the ETP. They exhibit extremely low mitochondrial DNA diversity, but previous studies have determined that there may be two or three genetically distinct stocks in the North Pacific. Amy Van Cise, a current SIO PhD candidate and Phillip Morin (SWFSC), have evaluated mtDNA variation from samples in the SWFSC Marine Mammal and Sea Turtle Research (MMASTR) tissue and DNA collection, and shown that the two types of short-finned pilot whales previously described from Japan form distinct populations across the north Pacific, with the “Shiho” type found in North Japan and the eastern Pacific, and the “Naisa” type found in southern Japan and the western Pacific, including the Hawaiian islands (Van Cise *et al.* 2016). A project is currently underway to expand sampling globally and to use complete mitochondrial genomes and nuclear SNPs to further investigate taxonomic status and phylogeography of this species in the ETP and elsewhere.

Sperm whales (*Physeter macrocephalus*) also exhibit very low mtDNA diversity, with the majority of samples having one of three common haplotypes globally. This may have made it difficult to use the traditional sequencing approach based on short mtDNA sequences to understand sperm whale phylogeography and population structure. Past studies have shown very low levels of population structure in the Pacific, but have also been limited in statistical power to detect additional structures that may exist. Phil Morin (SWFSC) is leading an ongoing project based on 175 complete mitochondrial genome sequences that provides phylogeographic evidence for the isolation of female populations in the Pacific and Atlantic oceans, and inference of a late-Pleistocene expansion of sperm whales globally, likely from a small population in the Pacific. These data are important for assessing the global status of sperm whales post whaling, and provide new tools to assess population structure within ocean basins for better assessment of trends in abundance.

### ***Common Dolphin Reproduction and Population Structure***

Several research projects compared reproductive rates of long- (LB) and short-beaked (SB) common dolphins in the northern part of the eastern tropical Pacific off Baja, Mexico. The studies combined data collected during a 2009 common dolphin research cruise with data collected from fishery bycaught specimens. Kellar *et al.* (2013, 2014) measured blubber progesterone concentrations in biopsy samples to examine spatial variability in pregnancy rates, and Chivers *et al.* (2016) estimated calf production and characterized calving seasons. The proportion of females pregnant was 22.1% ( $n = 45$ ) for SB and 28.1% ( $n = 85$ ) for LB, and there were strong geographic patterns observed in both species suggesting that some areas are more conducive to pregnant females. Off Baja, the highest proportions of pregnant females were observed in the vicinity of Punta Eugenia. Calf production was significantly lower: 4.5% in SB and 6.9% in LB, than the pregnancy rates reported by Kellar *et al.* (2014), and they also varied regionally. Mean calving seasons occurred during winter and were offset by about three months, with SB calving occurring earlier in the winter season than that of LB. Chivers *et al.* (2016) also reported regional variability in adult female size of LBs suggesting that there may be additional structure within the population, which is not currently recognized. The morphological and biological differences presented in these studies as well as those previously documented in the literature between long- and short-beaked common dolphins support recognition of these two forms as separate species in the eastern North Pacific, and the recent genetic study by Segura-Garcia *et al.* (2016) provides additional support for recognition of the long-beaked common dolphin as a species.

### ***Coastal Spinner Dolphin Life History and Population Structure***

Analyses of morphological data collected from photogrammetric images of coastal spinner dolphins during the 2006 *Stenella* Abundance Research (STAR) cruise identified them as Central American spinner dolphins. These data were collected by Mr. Wayne Perryman and colleagues in the nearshore waters off Guerrero, Mexico, where the presence of spinner dolphins had not been previously documented. These are the northernmost records for this subspecies whose range was previously described as being from Panama to the Gulf of Tehuantepec to off Guerrero, Mexico. North of Guerrero off Nayarit, Mexico, the Tres Marias spinner dolphins is found. In addition to the range extension for Central American spinner dolphins, Dr. Susan Chivers and colleagues combined the photogrammetric data from 2006 with those collected during earlier research cruises and those collected by observers from fishery by-caught specimens to characterize the calving season for all forms of spinner dolphins recognized in the eastern tropical Pacific. This research

provides the first biological data for coastal spinner dolphin populations, which provides additional support for the recognition of the Tres Marias spinner dolphin as a distinct coastal form with a relatively restricted range off the coast of Nayarit, Mexico.

### ***Short-finned Pilot Whale Population Structure and Distribution***

Adult size data for short-finned pilot whales (SFPWs) sampled from fishery by-catch, stranding events and vertical aerial photographs were combined to investigate the range of northern and southern form whales in the eastern North Pacific Ocean (ENP). Dr. Susan Chivers and colleagues assembled data from Hawaii, California, and the ETP for this study. Results revealed that the northern, larger, form ranges from the pelagic waters off California south through the ETP, and that the southern, smaller, form inhabits the waters around the main Hawaiian Islands. These findings are consistent with the presence of northern form genotypes in the ETP (VanCise *et al.* 2016). The addition of these morphological data for the ENP will ultimately facilitate resolving the taxonomic status of SFPWs by providing additional context for interpretation of the genetic data given that geographic variability in body size is likely genetically rather than ecologically driven.

### **Identifying Critical Habitat for Large Whales**

#### ***Review of Spatial Habitat Modeling for Large Whales***

A study comparing two commonly-used methods for spatial habitat modeling of large whales has been completed and is in preparation for submission. The paper shows that systematic survey data can be modeled either with presence-absence GAM or with MaxEnt presence-only methodologies, giving similar predictions in both geographical and ecological (niche) space. The paper also shows that opportunistic presence-only data that can be modeled with MaxEnt will compromise model results if sampling bias is not corrected. (Fiedler *et al.*, in prep.).

#### ***Prediction of Species Distributions***

MMTD scientist, Dr. Jessica Redfern, continued to collaborate with scientists from Fundación Omacha (a Colombian non-governmental organization) to develop species-habitat models that can be used to predict species distributions throughout Colombian waters. Scientists from Fundación Omacha are revising and updating their marine mammal sightings database, which will provide the foundation for the modeling efforts. Once MMTD has the most complete and up-to-date data, we will finalize the models. Ultimately, these models can be used to assess risks to marine mammals and develop conservation plans by identifying areas where human activities overlap with marine mammal habitat.

#### ***Assessment of the Transferability of Blue Whale Distribution Models***

Human activities are creating conservation challenges for cetaceans. Spatially explicit risk assessments can be used to address these challenges, but require species distribution data, which are limited for many cetacean species. This study explores methods to overcome this limitation. Blue whales (*Balaenoptera musculus*) are used as a case study because they are an example of a species that have well-defined habitat and are subject to anthropogenic threats. Dr. Redfern and colleagues used 12 years of survey data (377 blue whale sightings and approximately 225,400km of effort) collected in the CC and ETP to assess the transferability of blue whale habitat models.

They used the models built with CC and ETP data to create predictions of blue whale distributions in the data-poor NIO because key aspects of blue whale ecology are expected to be similar in these ecosystems. They found that the ecosystem-specific blue whale models performed well in their respective ecosystems, but were not transferable. For example, models built with CC data could accurately predict distributions in the CC, but could not accurately predict distributions in the ETP. However, the accuracy of models built with combined CC and ETP data was similar to the accuracy of the ecosystem-specific models in both ecosystems. MMTD predictions of blue whale habitat in the NIO from the models built with combined CC and ETP data compare favorably to hypotheses about NIO blue whale distributions, provide new insights into blue whale habitat, and can be used to prioritize research and monitoring efforts. Predicting cetacean distributions in data-poor ecosystems using habitat models built with data from multiple ecosystems is potentially a powerful marine conservation tool and should be examined for other species and regions. This research was published in April 2017 (Redfern, J.V., Moore, T.J., Fiedler, P.C., de Vos, A., Brownell, R.L., Forney, K.A., Becker, E.A. & Ballance, L.T. 2017 Predicting cetacean distributions in data-poor marine ecosystems. *Diversity and Distributions*, 23, 394-408).

## **Advancing Understanding of Ecosystem Structure and Function**

### ***Ecosystem Indicators***

A critical component of ecosystem-based management (EBM) is the development and use of indicators. Data characterizing the physical environment are commonly used as indicators but in this research fishery data they are used to predict additional biological characteristics of the ecosystem. Focusing on the ETP, Dr. Summer Martin (PIFSC) and Lisa T. Ballance (SWFSC) use two sources of spatially explicit data (2° x 2° grid) for 1986-2006: (1) yellowfin tuna catch and effort data from the IATTC, and (2) cetacean sightings and effort data from SWFSC's Cetacean and Ecosystem Assessment Surveys. Metrics for 3 types of purse-seine sets ("dolphin," "log," and "school"), including number of sets ("Sets"), tons of yellowfin tuna ("Catch"), and tons of yellowfin tuna per day ("CPUE") were computed and related to sightings per hour ("SPUE") for 19 taxa of cetaceans. Canonical correspondence analysis indicated associations between: (1) dolphin fishing metrics (Sets, Catch) and SPUE of offshore spotted and eastern spinner dolphins, rough-toothed dolphins (*Steno bredanensis*), and dwarf sperm whales (*Kogia sima*); (2) log fishing metrics (Sets, Catch) and SPUE of sperm whales, Bryde's whales (*Balaenoptera edeni*), and short-finned pilot whales; (3) school fishing metrics (Sets, Catch, CPUE) and SPUE of blue whales, bottlenose dolphins (*Tursiops truncatus*), Risso's dolphins (*Grampus griseus*), and offshore common dolphins. Predictive maps of cetacean densities, constructed from generalized additive models with fishery metrics as predictors, were qualitatively similar to those developed using environmental variables. They captured historically observed ranges and sightings rates remarkably well for 11 taxa. These regularly-collected fishery data may prove valuable in understanding general characteristics of cetacean distribution and density when expensive at-sea surveys are not an option, and provide a proof of concept for applying EBM principles to oceanic ecosystems. This research is in manuscript form and will soon be submitted to a peer-reviewed journal.

### ***Ecosystem Services***

Dr. Summer Martin (PIFSC) and Lisa T. Ballance (SWFSC) conducted research currently in press in *Frontiers in Marine Science* (Martin *et al.* 2016). Traditional single-issue management largely failed to protect the full suite of ecosystem services (ES). Ecosystem-based management (EBM) promotes resilient social-ecological systems that provide ES. To implement EBM, an ES approach is useful: 1) characterize major ES provided (magnitude, geographic extent, monetary value, trends, and stakeholders), 2) identify trade-offs, 3) determine desired outcomes, and 4) manage anthropogenic activities accordingly. This research applies the ES approach (steps 1-2) to the ETP, and uses fisheries and economic data from 1975-2010, and ship-based survey data from 1986-2006. PIFSC and SWFSC researchers examined commercial fisheries, carbon storage, biodiversity, and recreational fishing as the major provisioning, regulating, supporting, and cultural ES, respectively. Average catch value (using U.S. import prices for fish) for the 10 most commercially fished species was \$2.7 billion yr<sup>-1</sup>. The value of carbon export to the deep ocean was \$12.9 billion yr.<sup>-1</sup> (using average European carbon market prices). For two fisheries-depleted dolphin populations, the potential value of rebuilding carbon stores was \$1.6 million (cumulative); for exploited fish stocks it was also \$1.6 million (an estimated reduction of 544,000 mt). Sport fishing expenditures totaled \$1.2 billion yr.<sup>-1</sup>, from studies of three popular destinations. These initial, conservative estimates do not represent a complete summary of ETP ES values. Researchers produced species richness maps for cetaceans, seabirds, and ichthyoplankton, and a sightings density map for marine turtles. Over 1/3 of cetacean, seabird, and marine turtle species occur in the ETP, and diversity (or density) hotspots are widespread. This study fills several gaps in the assessment of marine and coastal ES by focusing on an oceanic habitat, utilizing long-term datasets, mapping the spatial distribution of ecological components, and concentrating on an area beyond Europe and the USA. Our results improve our understanding of ETP ES, highlight their variety, and offer a new perspective for a fisheries-dominated system. This study sets the stage for further analyses of trade-offs, which can inform decisions about resource management and biodiversity conservation.

### ***Influence of Tropical Pacific Processes on California Current Variability***

Dr. Paul Fiedler, in collaboration with Nathan Mantua of SWFSC/FED, has completed a study of relationships between warm and cool events in the tropical Pacific and the California Current System. The record of warm and cool events in the California Current System (CCS) for 1950-2016 was updated. Composite sea level pressure (SLP) and surface wind anomalies were used to explore the different atmospheric forcing mechanisms associated with tropical and CCS warm and cold events. CCS warm events are associated with negative SLP anomalies in the NE Pacific – a strong and southeastward displacement of the wintertime Aleutian Low, a weak North Pacific High and a regional pattern of cyclonic wind anomalies that are poleward over the CCS. We use a 1st order auto-regressive model to show that regional North Pacific forcing is predominant in SST variations throughout most of the CCS, while remote tropical forcing is best correlated in the far southern portion of the CCS. Cool events in the CCS tend to be more closely associated with tropical La Niñas than warm events in the CCS are with tropical El Niño; the forcing of co-occurring cool events is analogous, but nearly opposite, to that of warm events. This paper will be submitted for publication in *Geophysical Research Letters*.

## VII. PUBLICATIONS CITED

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