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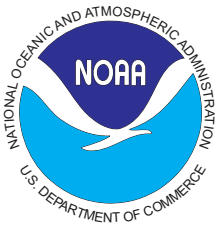
AUGUST 2016

THE 2016 ANNUAL REPORT ON RESEARCH REGARDING HIGHLY MIGRATORY SPECIES (HMS) AND THEIR FISHERIES IN THE NORTH PACIFIC OCEAN

by

The Southwest Fisheries
Science Center

ADMINISTRATIVE REPORT LJ-16-02



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The United States is obligated to collect fishery statistics from U.S. fisheries and participate in advancing fishery science for species of interest. Fishery information feeds into domestic and international fisheries management. Scientists at the National Oceanic and Atmospheric Association 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, 2015 – March 31, 2016, are briefly described.

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

Monitoring U.S. HMS Fisheries – Southwest Fisheries Science Center (SWFSC) scientists monitor eight 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 purse-seine fishery in the Eastern Pacific Ocean (EPO), 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 (*T. orientalis*), and yellowfin tunas (*T. 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** below.

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

FISHERY	2015 CATCH IN METRIC TONS	NUMBER OF VESSELS
North Pacific Albacore Troll and Pole-and-line	11,571	586
South Pacific Albacore Troll	224	6
Eastern Pacific Ocean Purse Seine	758	11
California Large-mesh Drift Gillnet	107	19
California Harpoon	5	12
Longline (California-based)	--	1

North Pacific Albacore Troll and Pole-and-line **-** Total annual catch of albacore from the North Pacific albacore troll and pole-and-line fishery (a.k.a. albacore surface 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 586 vessels in 2015. The average weight of retained albacore in 2015 was 15.8 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 Fisheries Management Plan 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 224 t, a decrease of 62% from the 583 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.

Purse-seine Fisheries (WCPO and EPO) **–** The U.S. has purse-seine vessels fishing in the Eastern Pacific Ocean (EPO) and Western and Central Pacific Ocean (WCPO). In the EPO, the purse-seine fishery has two components. Smaller coastal purse-seine vessels based out of southern California ports normally target mackerel, sardine, anchovy, and other coastal pelagic species and opportunistically target tuna when schools are available during summer months. Eleven purse-seine vessels landed 758 t of skipjack, yellowfin, and bluefin tunas in 2015 compared to 1,413 t of skipjack, yellowfin, and bluefin landed by eight vessels in 2014. Larger purse-seine vessels based out of American Samoa target tropical tunas in the WCPO, but occasionally fish in the EPO. In recent years very few of these vessels fished in the EPO.

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 (*Alopias vulpinus*), 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 done by staff from both offices. The NOAA West Coast Regional Office (WCR) observer program monitors approximately 20% of the fishery effort and conducts on-board size sampling.

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 in 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) **-** Most longline vessels targeting tunas and swordfish are currently permitted out of Hawaii. Logbook data from longline vessels are submitted to the Pacific Islands Fisheries Science Center (PIFSC). During 2015, there was one California-based longline vessel targeting tunas.

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 1045 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 PacFIN (Pacific Fisheries Information Network) database where state landings data from marine fisheries are maintained. These fisheries caught a total of 62 t of HMS in 2015 compared to 35 t of HMS caught in 2014.

The major customers that require detailed information on U.S. HMS fisheries in the Pacific Ocean include the South Pacific Tuna Treaty, the U.S.-Canada Albacore Troll Treaty, two Regional Fisheries Management Organizations (RFMOs): the Western and Central Pacific Fisheries Commission (WCPFC) and 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 and groups summaries by various time and space resolutions for submission to the RFMOs and the ISC 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.

II. SUPPORTING U.S. OBLIGATIONS OF INTERNATIONAL AGREEMENTS

North Pacific Albacore Stock Assessment and Research – 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. A full stock assessment of North Pacific albacore tuna was completed by

the Albacore Working Group (ALBWG) during a meeting at the SWFSC, La Jolla, from 14-28 April, 2014. Participants included scientists from SWFSC, Inter-American Tropical Tuna Commission (IATTC), International Pacific Halibut Commission, National Research Institute of Far-Seas Fisheries, and National Kaoshiung Marine University. The next stock assessment is scheduled to be completed by the ALBWG during the first half of 2017. In addition, the ALBWG is also beginning the process to conduct a management strategy evaluation (MSE) of north Pacific albacore tuna and will be conducting a MSE workshop with international managers and stakeholders in Yokohama, Japan during May 23 – 24, 2016.

In 2015, SWFSC scientists were submitted a successfully funded proposal to the Stock Assessment and Analytical Methods (SAAM) RFP under NOAA/NMFS/OST entitled "Developing an user-friendly ADMB and R package to estimate growth model parameters using a length-conditional approach". This project is a 6 month project to develop a ADMB package to estimate growth model parameters using the length-conditional approach described in Piner et al (in press) and Xu et al (in press), with an user-friendly R package as a front end.

In 2014, SWFSC scientists submitted a successfully funded proposal to the Improve a Stock Assessment (ISA) RFP under NOAA/NMFS/OST entitled "Improving the stock assessment of north Pacific albacore tuna by developing cost-effective genetic markers to identify sex". This project is a two-year international collaboration between scientists from the Canada, Japan, Taiwan, and the US. 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 and these samples are currently being analyzed to determine the markers that can be used to identify sex. In addition, sampling kits were recently sent out to the various collaborators to collect genetic samples from albacore caught by U.S. and international longline fleets.

Bluefin Tuna Stock Assessment– 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 February-March 2016, SWFSC hosted a meeting of the ISC Pacific Bluefin Tuna Working Group (PBFWG) to conduct a benchmark stock assessment (base-case run) of Pacific bluefin tuna. Participants included scientists from SWFSC, IATTC, Chinese-Taipei, Japan, Korea, and Mexico.

Population dynamics were estimated using a fully integrated length-based and age-structured model (Stock Synthesis v3.23f) fitted to catch size composition, and catch-per-unit of effort (CPUE) data from 1952 to 2015 (fishing year 1952-2014), provided by ISC PBFWG members and non-ISC countries. Life history parameters included a length-at-age relationship from otolith-derived ages, and natural mortality estimates from a tag-recapture study and empirical-life history methods. A total of 19 fleets were defined for use in the stock assessment model based on country/gear/season/region stratification. Quarterly observations of catch and size compositions, when available, were used as inputs to the model to describe the removal processes. Annual

estimates of standardized CPUE from the Japanese distant water, off-shore and coastal longline fleets, the Taiwanese longline fleet, and the Japanese troll fleet were used as measures of the relative abundance of the population. The assessment model was fitted to the input data in a likelihood-based statistical framework. Maximum likelihood estimates of model parameters, derived outputs, and their variances, were used to characterize stock status and to develop stock projections.

In the 2014 assessments, conflicts existed among data in the model. However, stock biomass trends were consistent among tested model runs and the PBFWG provided the conservation advice based on those results. The 2016 assessment model was developed and refined in the intervening three years based on the efforts and improvements made by the PBFWG. The improvements include; more accurate historical catch data, a better estimate of size composition by fleet, improved standardization of abundance indices, a revised growth curve based on additional otolith information and standardization of aging techniques, and improved model settings to represent best input data.

The base-case model fits the data well and is internally consistent among most of the sources of data. The model is substantially improved from the 2014 assessment. The base-case model indicates: (1) spawning stock biomass (SSB) fluctuated throughout the assessment period and (2) the SSB decline from 1996 seems to have ceased in the most recent period (2010-2014) although the stock remains near the historic low. The model diagnostics suggest that the estimated biomass trend for the last 30 years is considered robust although SSB prior to the 1980s is uncertain due to data limitations. The 2014 SSB was estimated to be around 17,000 t, which is about 9,000 t below the terminal year estimated in the 2014 assessment (26,000 t in 2012). This is because the assessment model was refined and SSB shifted down over all; not because the SSB has declined since 2012. Recruitment estimates fluctuate widely without an apparent trend. The 2014 recruitment was relatively low and the average recruitment for the last five years may have been below the historical average level. Note that recruitments in terminal years in an assessment are highly uncertain due to limited information on the cohorts. However, two of the last three data points from the Japanese troll CPUE-based index of recruitment, which was consistent with other data in the model, are at their lowest since the start of the index (1980). Estimated age-specific fishing mortalities during 2011-2013 for intermediate age (2-10) are substantially above the 2002-2004 level (the base period for WCPFC Conservation and Management Measure 2015-04) while those for age 0 as well as ages 11 and above are lower.

The ratio of SSB in 2014 relative to unfished SSB ($SSB_{2014}/SSB_{F=0}$ or the depletion ratio) is 2.6% and $SSB_{2012}/SSB_{F=0}$ is 2.1% possibly indicating a slight increase from 2012 to 2014. Although the $SSB_{2014}/SSB_{F=0}$ for this assessment is lower than $SSB_{2012}/SSB_{F=0}$ from the 2014 assessment (4.2%), this is due to the changes in the model assumptions and new data because SSB gradually increased in the last 4 years and does not represent a decline in SSB from 2012 to 2014.

Although no limit reference points have been established for the Pacific bluefin stock under the auspices of the WCPFC and IATTC, the 2011-2013 F exceeds the calculated biological reference points (BRPs) except for F_{MED} and F_{loss}. Note that possible effects on Fs by the measures of both the WCPFC and IATTC starting in 2015 or by other voluntary measures were not incorporated.

In summary, overfishing is occurring based on reference point ratios or just at the threshold based on F_{MED} and the stock is overfished.

Historically, the Western Pacific Ocean (WPO) coastal fisheries group has had the greatest impact on the Pacific bluefin stock, but since about the early 1990s the WPO purse seine fleets, in particular those targeting small fish (age 0-1), have had a greater impact and the effect of these fleets in 2014 was greater than any of the other fishery groups. The impact of the EPO fisheries group was large before the mid-1980s, decreasing significantly thereafter. The WPO longline fleet has had a limited effect on the stock throughout the analysis period. This is because the impact of a fishery on a stock depends on both the number and size of the fish caught by each fleet; i.e., catching a high number of smaller juvenile fish can have a greater impact on future spawning stock biomass than catching the same weight of larger mature fish.

The projection results indicate that the probability of SSB recovering to the initial WCPFC target (SSB_{MED} by 2024) is 69% or above the level prescribed in the WCPFC Conservation and Management Measures (CMMs) if recruitment is low and WCPFC CMM (2015-04) and IATTC resolution (C-14-06) continue in force and are fully implemented (Scenario 2 with low recruitment).

There were technical inconsistencies in how SSB_{MED} was calculated in this assessment compared to the projection and the calculation of SSB_{MED} in this projection uses the most recent estimates of SSB. Unless a fixed period of years is specified to calculate SSB_{MED}, the calculation of SSB_{MED} could be influenced by future trends in spawning biomass. The Commissions may wish to refine the definition of the target taking this into consideration.

Scenario 2 with low recruitment has the lowest prospect of recovery among the examined harvest scenarios. The probability of achieving the WCPFC's initial target (SSB_{MED} by 2024) would increase if more conservative management measures were implemented, such as increasing the size in the definition of "small fish" or further reducing the catch limit. The projection results indicate that a 10% reduction in catch limit for small fish would have a larger effect on recovery than a 10% reduction in the catch limit for large fish under the definition of small/large fish in WCPFC CMM 2015-04. The projection results assuming a stronger stock-recruitment relationship (where h=0.9) than in the assessment model are not necessarily more pessimistic than the low recruitment scenario.

The projection results assume that the CMMs are perfectly implemented and are based on certain biological or other assumptions. If conditions change, the projection results would be more uncertain. Given the low SSB, the uncertainty in future recruitment, and the influence of recruitment has on stock biomass, monitoring recruitment and SSB should be strengthened so that the recruitment trends can to be understood in a timely manner.

Bluefin tuna catch time series and associated composition data by U.S. fleets - The time series of seasonal catches from U.S. commercial and recreational fleets were provided by Lee *et al.* (2015a). Catch from commercial fleets are given in tons and recreational fleets in 1000's of fish. The recreational fleet is dominated by the Commercial CPFV fleet. In recent years, the recorded catch from private boats for recreational fleets has increased due to the warmer than average waters

in the EPO as well as improvement of sampling. Catch estimates for private boats were retrieved from the Recreational Fisheries Information Network. A new NOAA biological sampling program conducted for recreational fleets was also used to provide raised observations of length compositions for the most recent years. The new estimate of length composition of the recreational catch is appropriate for use in the stock assessment; however, some consideration of parsimony (prevention of fleet proliferation) should be given.

Bluefin tuna modeling research –

Simulation testing on how to deal with age-based movement in Pacific bluefin stock assessment- Spatial patterns in the distribution of age-classes are often the result of movement. The data needed to include movement in stock assessment models typically do not exist, and modelers use areas-as-fleets approach. In an attempt to better understand the effect of the age-based movement, Lee *et al.* (2015b) used simulation methods and a factorial design with modeling movement, ignoring movement, modeling with substitute process, increasing observation error to reduce effect of un-modeled movement, and aggregated fleet structure. Two different states of nature governing the movement process were explored. Only the inclusion of the correct spatial structure along with estimation of movement rates produced unbiased and precise estimates of derived quantities, although some management quantities were less biased in non-spatially explicit models. This goal may not be attainable in the near future due to data limitation. Lacking a correctly specified model, special emphasis will need to be placed on how the inevitable size composition misfit is affecting model performance. The influence of composition misfit should be reduced wherever possible.

Pacific Bluefin Stock Assessment Model Guideline- Lee *et al.* (2016) presents objective criteria by which a stock assessment model was developed for Pacific bluefin tuna based on the previous simulation study (Lee *et al.* 2015b). The goal of the work was to create an internally consistent model that follows objective criteria using recommendations from a series of CAPAM (Center for the Advancement of Population Assessment Methodology) workshops on population modeling as a guideline. Modelers assert that agreed upon data should be considered true. Unacceptable diagnostics for model fits to data or conflict between data series is indicative of model misspecification. Misspecification was addressed using either additional model process in the form of flexible and time-varying selectivity patterns or by adding the un-modeled process to the observation error. To keep the model parsimonious, prioritization criteria were developed to determine which data sources would be addressed by time-varying selectivity and which would be addressed by data weightings.

Advanced stock assessment methods –

Evaluation of Using Random-At-Length Observations in Fitting the Growth Function Using Simulation Testing- Modeling the growth of fish is a key component of most fish stock assessments and can strongly influence the estimated spawning biomass and exploitation levels. Growth is most often estimated by fitting a von Bertalanffy growth model (VBGM) to data consisting of age-length pairs collected from fisheries, with the assumption that each length observation is a random sample for a given age. This assumption can be approximated by randomly sampling the population, but most growth studies do not randomly sample the population and instead sample by size class due to logistical and cost reasons, which violates the assumption. A

recent study proposed an alternative method (approximate length-conditional), which instead assumes each age observation is a random sample at length (Piner *et al.* in press). The length-conditional method is typically used within an assessment model because the age structure of the sampled population is required for the method. However, Piner *et al.* (in press) instead approximates the length conditional method by assuming an equilibrium population age structure with a constant total mortality rate and estimating the VBGM parameters outside an assessment model. 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. In addition, the estimates were robust to small errors in the assumed mortality rate. The approximate length-conditional approach was subsequently applied to North Pacific albacore tuna, albeit with some modifications in the code to allow for more flexible binning structure and robust parameterization, which resulted in less biased estimates of length-at-age, especially for the youngest and oldest ages (Xu *et al.* in press).

Diagnostic methods to evaluate the absolute abundance information contained in the data- Interpretation of data used in fisheries assessment and management requires knowledge of population (e.g. growth, natural mortality, and recruitment), fisheries (e.g. selectivity), and sampling processes. Without this knowledge, assumptions need to be made, either implicitly or explicitly based on the methods used. Incorrect assumptions can have a substantial impact on stock assessment results and management advice. Unfortunately, there is a lack of understanding of these processes for most, if not all, stocks and even for processes that have traditionally been assumed to be well understood (e.g. growth and selectivity). Maunder and Piner (2015) use information content of typical fisheries data that is informative about absolute abundance to illustrate some of the main issues in fisheries stock assessment. They concentrate on information about absolute abundance from indices of relative abundance combined with catch, and age and length-composition data and how the information depends on knowledge of population, fishing, and sampling processes. They also illustrate two recently developed diagnostic methods (R0 likelihood component profile and age-structured production model) that can be used to evaluate the absolute abundance information content of the data. Both diagnostic methods were used in the 2016 Pacific bluefin tuna stock assessment.

Use of likelihood profiling over a global scaling parameter as a diagnostic to structure the population dynamics model- The R0 profile has been used to diagnose model misspecification (Kell *et al.* 2014, Lee *et al.* 2014a, Wang *et al.* 2014). The R0 likelihood component profile diagnostic estimates all model parameters while fixing the population scaling parameter (often the virgin recruitment) at different values and plotting the resultant likelihood value for each data component against this parameter. The likelihood profiles of each data component usually follow a smooth parabolic curve, indicating the value with most support and the amount of uncertainty in that support. Different maxima (minima if the negative log-likelihood is used) among data components indicate possible conflict in the data sources about absolute abundance. The higher the gradient in the likelihood profile the more influential that data source on the model's estimate of scale. This R0 profile will illustrate the information content of the data expected if the model is correctly specified and any differences from the actual R0 profile indicates conflict in the data or model misspecification.

Bluefin Close-Kin Mark Recapture Research - During 2015, the SWFSC convened a meeting of international stakeholders and experts to discuss the potential of developing a Close-Kin genetic parentage based mark-recapture research program to develop an independent abundance estimate for Pacific bluefin tuna. The Close-Kin approach has previously been applied by Commonwealth Scientific and Industrial Research Organisation (CSIRO) researchers to develop an abundance estimate for Southern bluefin tuna (*Thunnus. maccoyii*) with fairly tight confidence intervals. Analysis of life history and fishery data for Pacific bluefin were used to assess viability of this method. Though a number of unknown variables exist (e.g. connectivity between two known spawning grounds, potential bias in migration/life history parameters between animals from different spawning areas, etc.) it was decided that there were no fatal flaws in the methodology. Given the listed uncertainties, current estimates of abundance, and regional fisheries, a sampling plan was developed that is conservative enough to account for known uncertainties. The method overview and sampling plan were presented at the ISC meeting, whereupon ISC members decided to go forward with developing this program. Sampling by international partners began in 2015 and is planned to continue indefinitely. In 2016, the plan is to convene an international set of genetic experts to decide upon standardized methodologies for generating genotypic data and once these protocols are in place the samples will be routinely processed to generate genotype data.

Shark Stock Assessments - 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 indicator analyses of shortfin mako shark (*Isurus oxyrinchus*) in 2015 and are currently working on a benchmark blue shark (*Prionace glauca*) assessment to be completed in 2017. In addition, through bilateral efforts with Mexico, SWFSC scientists completed the first collaborative northeast Pacific thresher shark (*Alopias vulpinus*) assessment.

North Pacific shortfin mako shark - In 2015, the ISC SHARKWG conducted an indicator analysis of the stock status of shortfin mako sharks in the North Pacific. The analysis included the most complete data on north Pacific shortfin mako shark catch, fishery effort, and size data compiled to date. Participants from Chinese-Taipei, Japan, Mexico, SPC (Secretariat of the Pacific Community), IATTC, and the U.S. contributed data and/or to the analytical work.

SWFSC and PIFSC scientists provided full catch time series of mako sharks caught, landed, and released in U.S. commercial and recreational fisheries (Sippel *et al.* 2014) as well as information on the size and sex composition of makos taken in several observed fisheries. Abundance indices were developed for the California/Oregon drift gillnet fishery (Lee *et al.* 2014b), the SWFSC's annual juvenile shark survey (Runcie *et al.* 2014) and the Hawaii-based longline fisheries (Carvalho and DiNardo 2014). In addition, SWFSC led a comprehensive analysis of the spatial patterns of mako sharks in the north Pacific based on sharks measured and sexed at known locations throughout the North Pacific (Sippel *et al.* 2015). U.S., Mexico, and Japan observer and research data were used to show hotspots for newborn and young-of-the-year sharks near the continental margins in the eastern and western Pacific, while larger adult sharks are found in higher numbers in the central Pacific (Sippel *et al.* 2015). Finally, simulations showed that indices that

have the greatest value in informing about stock status are the more precise abundance indices that have longer time series and derived from areas where adults dominate (Lee *et al.* 2015c).

The results of the indicator analysis showed that many of the indices had relatively flat or increasing trends, while others showed declining trends. The SHARKWG considered three indices: the Japan kinaki shallow-set longline CPUE, Hawaii deep-set longline CPUE, and Hawaii shallow-set longline CPUE - to have the greatest value in informing stock status based on their length, precision, fishery area of operation, and the results of the indicator analyses. Of these three indices, two of the series appear to be stable or increasing, while the abundance trend in the third series appears to be declining. Shortfin mako is considered a data poor species. Recognizing that some information on important fisheries is missing, the untested validity of indicators for determining stock status, and conflicts in the available data, stock status (overfishing and overfished) could not be determined. The SHARKWG plans to continue to improve the catch estimates and abundance indices, reduce uncertainty in biological parameters through ongoing life history studies, and complete a benchmark assessment of North Pacific shortfin mako in 2018.

Common thresher shark assessment - 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. The Stock Synthesis modeling platform (v3.24U) was used to conduct the analysis and estimate management quantities. The base case model began in 1969, assuming that the stock was at equilibrium prior to 1969 in a near unfished state, and ended in 2014, which was the last year that data were available.

The model included eight fishing fleets that operated in USA and Mexico waters. Five abundance indices from fishery-dependent fisheries and one abundance index from a fishery-independent survey were available (USA juvenile thresher sharks survey). However, the survey abundance index was not fit in the base case model. Length composition data were available for the majority of the fleets and were fit in the base case model, with the exception of the Mexico drift gillnet and longline fleet. Conditional age-at-length data from two USA fleets were also fit in the base case model.

A large number of alternative model configurations were investigated to develop the base case model, which provided a realistic but parsimonious description of common thresher shark population dynamics based on the best available scientific information. The base case model reflected the best aspects of these exploratory models. Overall, the base case model appeared to have converged to a global minimum; while fitting the observed data well, with plausible model processes and parameters that were within reasonable bounds.

In this assessment, the reproductive capacity of the population was calculated as the number of mature female sharks (i.e., spawning abundance) rather than spawning biomass, because the size of mature female sharks did not appear to affect the number of pups produced (i.e., larger female sharks did not produce more pups). The reproductive output of the stock (i.e., the number of pups

produced by the stock) was calculated using four pups produced per year per mature female shark.

The stock experienced a relatively large and quick decline in the late 1970s and early 1980s, soon after the onset of the U.S. swordfish/shark drift gillnet fishery, with spawning depletion dropping to 0.4 in 1985. The population appeared to have stabilized in the mid-1980s after substantial regulations were imposed. Over the past 15 years, the stock began recovering relatively quickly and is currently close to an unexploited level.

The estimated fishing intensity (1-SPR) on common thresher sharks off the west coast of North America is currently relatively low at 0.08 (average of 2012 – 2014) and substantially below the estimated overfishing threshold (MFMT), with $(1\text{-}SPR_{1214})/(1\text{-}SPR_{MSY})$ at 0.21. Similarly, the estimated number of mature female sharks in 2014 (S_{2014}) for this stock is at 94% of its unexploited level and is substantially larger than the estimated minimum stock size threshold (MSST), with S_{2014}/MSST at 2.33. Thus, this stock of common thresher sharks is unlikely to be in an overfished condition nor experiencing overfishing.

Besides the base case model, the status of the stock was also examined under three alternative states of nature, based on alternative reproductive biology and two alternative stock-recruitment relationships. These alternative states of nature addressed the most important sources of uncertainty identified in the sensitivity analysis. The estimated management quantities from models assuming these alternative states of nature all indicated that this stock of common thresher sharks is unlikely to be in an overfished condition nor experiencing overfishing.

III. SUPPORTING PACIFIC FISHERY MANAGEMENT COUNCIL ACTIVITIES

Center economists Stephen Stohs and Tim Sippel continued serving on the Highly Migratory Species Management Team (HMSMT) of the Pacific Fishery Management Council (PFMC) over the past year. The team met several times in 2015 and early 2016 to review fishery information, complete assignments from the Council, and evaluate provisions of the Fishery Management Plan for U.S. West Coast Fisheries for Highly Migratory Species. The main HMS issues facing the team and the Council over the past year have been: (1) assisting the Council with final action on hard cap management of protected species interactions in the drift gillnet fishery; (2) supporting the Council 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 swordfish method off the West Coast; (4) providing recommendations for international management activities; and (5) preparing the 2015 Stock Assessment and Fishery Evaluation (SAFE) Report.

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.

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. SWFSC 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, 11,988 fish averaging 69 cm fork length (FL) were measured at various west coast ports.

North Pacific Albacore Electronic Logbook Project – In 2005, a computer program was developed to allow albacore troll fishermen to enter their logbook data directly into a digital worksheet 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 will be ongoing in 2016.

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. In September 2015, we conducted a tagging trip off the Columbia River on the F/V *Royal Dawn*. One hundred and twenty three tags were deployed between 45N and 47N latitude in the 125W longitude block. This was our most successful tagging trip ever, in terms of the number of tags deployed, bringing the total number of archival tags deployed during the project since 2002 to 1043. Additional trips are planned to deploy 80 tags during 2016.

During 2015, efforts were focused on analyzing the data from all tags recovered since publication of FRD scientists' 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 nine tags, six of which were at liberty about two years and a seventh that was at liberty for nearly three years.

Stephanie Snyder, a PhD student at 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 in the eastern Pacific foraging grounds. Finally, a fourth draft paper examines the behavior of four juvenile albacore as they

simultaneously foraged across a front off the coast of Baja California. Snyder defended her thesis in March 2016. Three of the draft papers are hoped to be submitted for publication by the end of the summer.

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), however 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	Total
Pacific Bluefin	0	75	78	54	189	294	171	156	120	1137
Albacore: WA/OR	0	0	42	191	49	60	60	39	50	491
Albacore: Central CA	0	0	0	0	27	31	43	0	0	101
Albacore: So. CA	116	35	93	118	7	62	3	0	20	454
Yellowfin	15	45	95	71	128	132	112	134	50	782
Skipjack	0	5	9	8	15	16	25	0	0	78
California Yellowtail	0	0	7	30	190	186	90	36	30	569
Opah	0	0	1	11	16	64	30	30	15	167
Dorado	0	43	39	0	40	18	0	3	12	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 waters containing 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 of opah, (9) exploring mercury dynamics in pelagic predators and (10) examining the reproductive maturity of bluefin in the SCB.

Tuna Foraging Ecology **–** With the reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act in 2006, there is a move towards ecosystem-based management. Understanding temporal and spatial patterns of who is eating whom 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*] and jack mackerel [*Trachurus symetricus*]). 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 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, a reduced reliance on anchovies and sardines, and an increased reliance on squid, crustaceans, and other fish species. This likely relates to shifts in prey availability associated with changes in oceanography that have also been documented in other biological indices. 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.

Detailed data on tuna behavior and forage fish abundance are important for stock assessments and are 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 2015; a manuscript is being drafted for publication containing the current results.

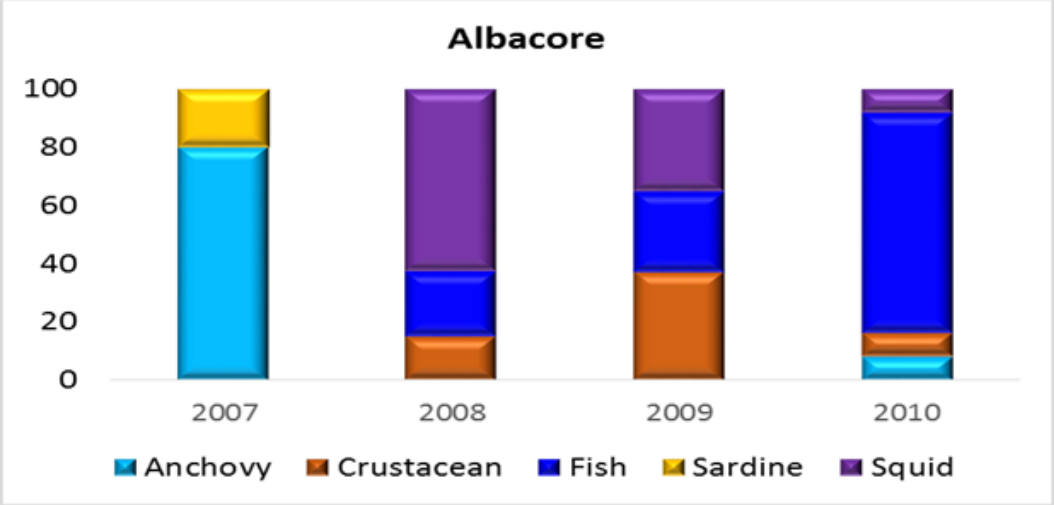

Figure 1. Relative importance of anchovy, sardine, other fish, squid, and crustaceans in the diets of albacore tuna by year based on a modified Geometric Index of Importance.

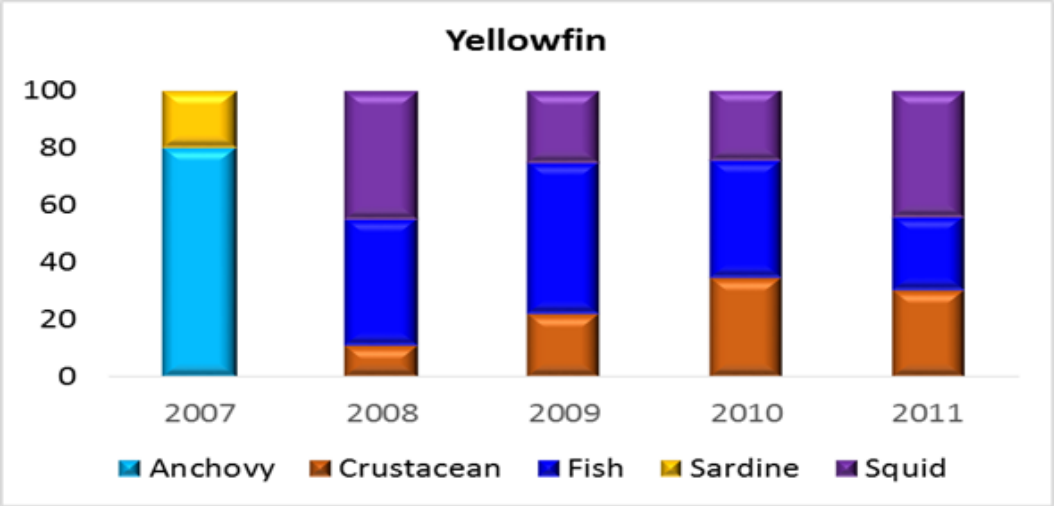

Figure 2. Relative importance of anchovy, sardine, other fish, squid, and crustaceans in the diets of yellowfin tuna by year based on a modified Geometric Index of Importance.

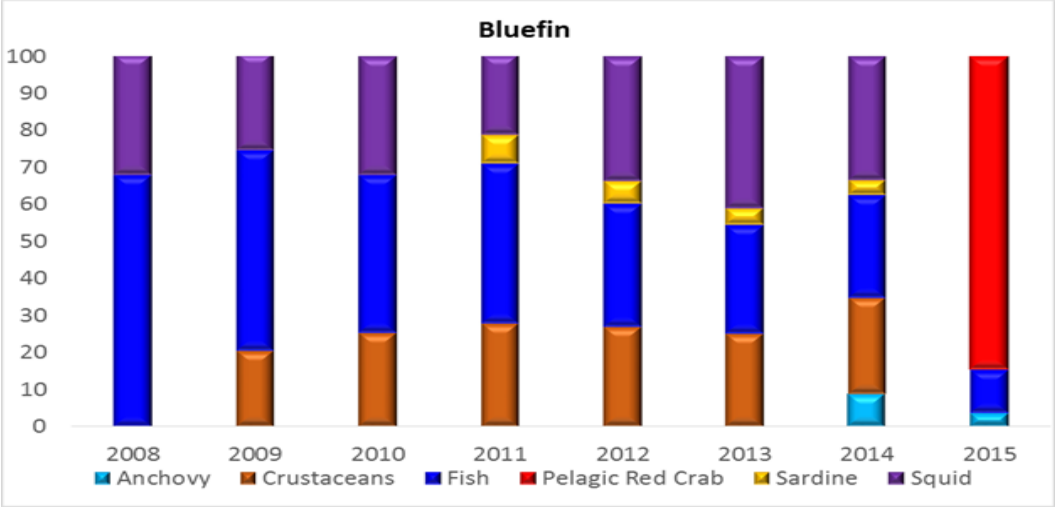

Figure 3. Relative importance of anchovy, sardine, other fish, squid, and pelagic red crabs, and other crustaceans in the diets of bluefin tuna by year based on a modified Geometric Index of Importance.

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 has modeled Hg dynamics in Pacific bluefin tuna. Application of the 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.

Radioanalysis of Cesium-134 Found in the Muscle Tissue 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. Radionucleotides released into the ocean off Japan provide a unique chemical tracer for animals occupying these waters including Pacific bluefin tuna. Pacific bluefin tuna inhabit the WPO and EPO, and current stock assessments indicate that they are overfished. 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) combined a Fukushima-

derived radiotracer (^{134}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 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 novel toolbox of biogeochemical tracers can provide new insights into the dynamics of migration and can be applied to any species that crosses the North Pacific Ocean. See list of publications for several manuscripts on these results. This work is ongoing and an additional publication is in preparation.

Stable Isotope Analysis of Muscle Tissue in Albacore and California Yellowtail – Work continues on defining the feeding ecology of the northern and southern albacore groups using Stable Isotope Analysis (SIA). Combining this work with stomach content analysis will allow for an investigation of foraging ecology and trophic level over longer time periods than is possible using stomach contents alone. Our current investigation looks to use prey SIA data collected from several unique environments across the eastern Pacific to inform a mixing model aimed at understanding the dietary differences between the northern and southern groups of albacore. Additionally, CalCOFI larval fish abundance data are being compared to our SIA and stomach content findings in order to determine if albacore are simply feeding on the most abundant prey at any given time or if they selectively choose certain prey.

The California yellowtail is found in both coastal and pelagic regions of the southern California Current Large Marine Ecosystem. Although little is known about their life history, historical tagging data suggests that yellowtail utilize both coastal and pelagic waters to migrate seasonally. These yellowtail travel north from Baja California, Mexico into southern California during spring and summer months, spawn in pelagic waters, and return south during fall and winter. To better understand yellowtail movements, and their utilization of both coastal and pelagic regions, SWFSC scientists collected soft tissues (muscle and liver) from 94 yellowtail (52-107 cm fork length). Fish were collected between 2011-2014 from both coastal and pelagic waters off southern CA. Soft tissues were analyzed for stable isotopes to determine the extent to which pelagic- and coastal-caught yellowtail resemble their environment of capture, and to ascertain the size(s) over which the potential shift from pelagic to coastal waters takes place. δ^{13}C and δ^{15}N values were used to group yellowtail into 'coastal' or 'pelagic' using discriminant analysis, with δ^{13}C and δ^{15}N values of a pelagic predator, yellowfin tuna (*Thunnus albacares*), and a coastal predator, white sea bass (*Atractoscion nobilis*), serving as training data. Two separate Bayesian mixing model approaches were also used to determine the extent to which coastal- and pelagic-yellowtail reflect; (1) pelagic or offshore prey inputs, and (2) their similarity to the predators above. Results suggest an ontogenetic shift in habitat use, based on changes in δ^{13}C and δ^{15}N, between 81 and 96 cm fork length. Mixing models confirmed that smaller, offshore yellowtail predominately reflected pelagic prey resources and SIA values were similar to yellowfin tuna. In contrast, larger, coastal yellowtail reflected higher input from coastal resources and were similar to white sea bass, though there was significant contribution (25-45%) of offshore prey to the diet of inshore yellowtail. Smaller individuals appear to rely heavily on pelagic offshore waters before potentially gaining a large

enough size to settle into coastal nearshore waters. Additional work is being done 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 two years. The feed source was changed after year one and muscle tissue plugs were collected every month for the following year. Results will help discern how long a change in food source or prey input takes before it is reflected in the $\delta^{13}C$ and $\delta^{15}N$ values of a yellowtail's soft tissues, thereby allowing us to infer more about the life history of California yellowtail. A manuscript describing these results is currently being drafted.

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 2014 results of these programs were collected during 2015 and are summarized below.

International Billfish Angler Survey – Over 400 anglers submitted their 2014 billfish fishing results from destinations in the Pacific, Atlantic, and Indian Oceans. The majority of fishing effort was reported off Hawaii, Southern California, and Baja California, Mexico. The 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.

The greatest number of fishing days was reported off Hawaii, which was consistent with recent years. In comparison to the results from 2013, both the reported catch and effort off Hawaii increased in 2014. As a result of proportionally similar increases in both these values, the overall nCPUE (0.42) had minimal change.

An anomalously warm water blob in the northeastern Pacific brought typically warmer water species farther north (see http://www.nwfsc.noaa.gov/news/features/food_chain/ for information on the blob). Conditions off the coast of California were favorable for billfish fishing and 2014 was the third highest nCPUE on record for this location (0.21). The 2014 result was greater than both the overall annual average (0.12) and the most recent five-year (2009-2013) average (0.06).

Three billfish species made up the catch composition reported off Baja during 2014. Striped marlin (*Kajikia audax*) made up 78%, Pacific sailfish (*Istiophorus platypterus)* 18%, and blue marlin (*Makaira indica*) 4%. Respondents did not report any black marlin (*Istiompax indica*), which was unusual as this species has been a component of the Baja catch in all but two years. The 2014 nCPUE reported off Baja California was 0.90. This was the fourth highest value from the area. The average annual nCPUE off Baja for the lifetime of the Survey is 0.80. The 2014 result was greater than the average from the most recent five years (0.77), but less than the average from the most recent 10 years (2004 – 2013; 0.97 nCPUE). The recent 10-year average included the three best years on record - 2007, 2008, and 2013, when the nCPUE was 1.90, 1.57 and 1.11, respectively.

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 4**). In 2014, the blue marlin nCPUE off Hawaii was 0.27 (Plot A). This result was similar to that reported in 2013 (0.28). In contrast, blue marlin nCPUE reported off Baja California (0.04) was down from the previous year, continuing a downward trend. The average blue marlin nCPUE off Baja over the most recent 20 years was 0.07, compared to 0.05 over the most recent 10 years, and 0.04 over the most recent five years. The low nCPUEs reported in the most recent 5 years were more typical of results during the 1970s.

Anglers reported relatively high striped marlin nCPUEs in the northeastern Pacific during 2014. A notable difference from the previous year was an increase in striped marlin nCPUE off the coast of Southern California (Plot B). The warm water blob that occurred off Southern California during the summer and fall of 2014 presented favorable conditions and anglers reported an nCPUE of 0.21, which was the second highest on record. The highest striped marlin nCPUE off Southern California was 0.22 in 2006.

The sailfish nCPUE for Mexico was examined. Mexico nCPUE was based on fishing efforts reported from locations across the country. The 2014 Mexico sailfish nCPUE (0.63) was the highest value on record (Plot C). The result was nearly three times greater than both the recent five-year average (0.21) and the overall average (0.23).

Black marlin were caught by survey respondents at several locations during 2014, including Australia, New Zealand, Hawaii, Tahiti, Mexico, Guatemala, Panama, and Costa Rica. Australia had the highest black marlin nCPUE across all locations. Australia was also the only location where this species was caught in greater numbers than other billfish. The 2014 nCPUE was 0.48, which was similar to results reported in recent years but slightly less than the annual average (0.55) (Plot D).

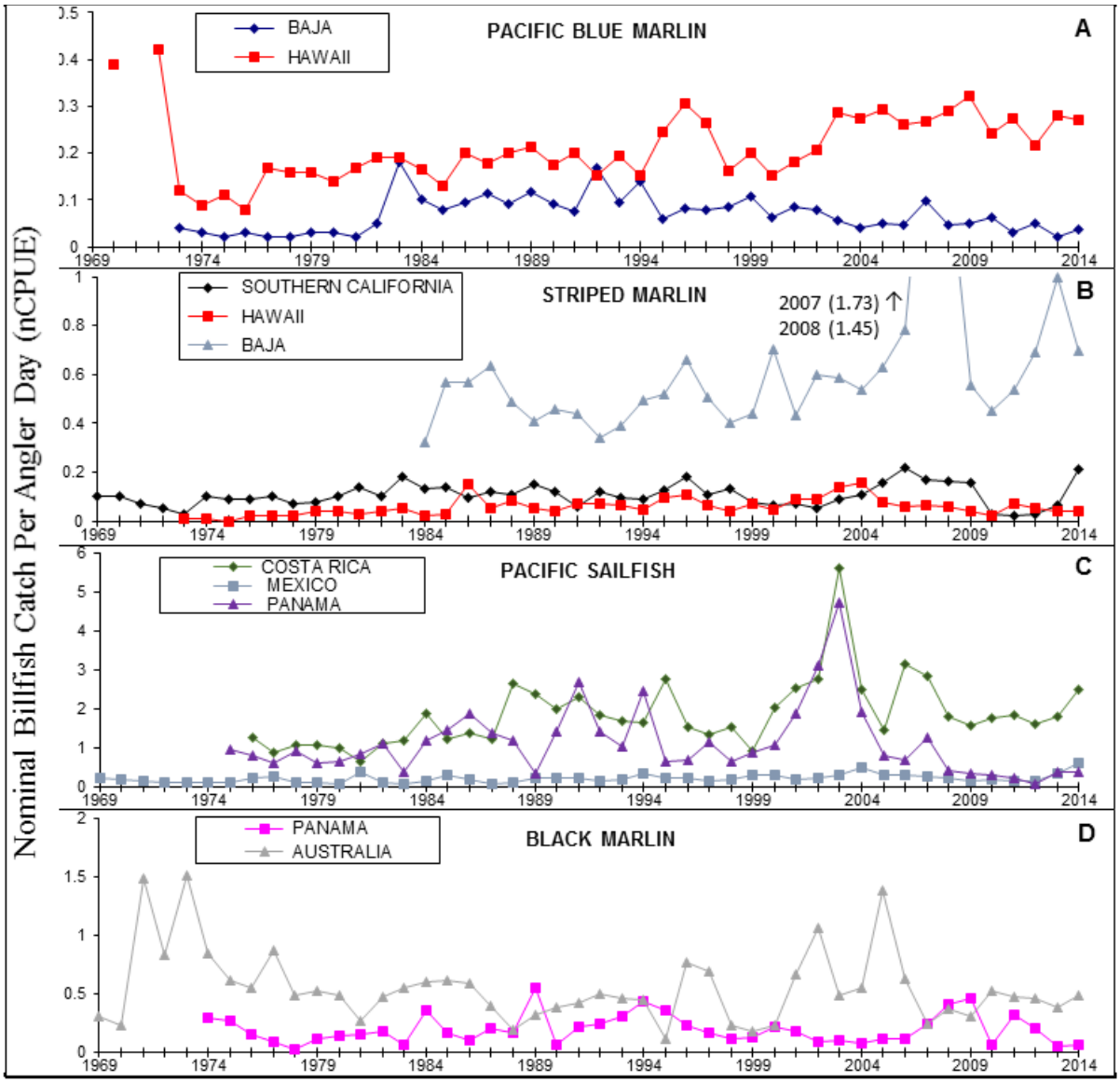

Figure 4. CPUE as catch-per-angler-day is shown from 1969 through 2014 for Pacific blue marlin, striped marlin, Pacific sailfish, and black marlin.

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 California Department of Fish and Wildlife over 80,000 fish have been tagged and released

A total of 1,054 tags were released on billfish during 2014 (**Table 3**). This was the first time in nearly a decade that the billfish tagging program eclipsed 1,000 tag releases during a calendar year. It was a great achievement as tags were spread across several species from numerous locations across the Pacific Ocean. The majority of tag releases were on Pacific blue marlin and over 90% of those

occurred off the coast of Hawaii. Anglers and captains in Hawaii are stalwarts of the tagging program, in large part due to the cooperation of operations out of Kona.

Table 3. Summary of billfish tagged during 2014 by region.

Pacific Ocean		
Southern California	Striped Marlin	33
	Marlin, unidentified	1
	Pacific Blue Marlin	1
Baja California	Striped Marlin	41
	Sailfish	7
	Pacific Blue Marlin	3
Puerto Vallarta, Jalisco	Sailfish	1
Manzanillo, Colima	Sailfish	4
Acapulco/Ixtapa/Zihuatanejo, Guerrero	Sailfish	304
	Striped Marlin	1
Panama	Pacific Blue Marlin	1
Hawaii	Pacific Blue Marlin	463
	Striped Marlin	81
	Shortbill Spearfish	72
	Sailfish	2
	Broadbill Swordfish	1
Tahiti	Pacific Blue Marlin	3
Fiji	Shortbill Spearfish	1
Samoa	Pacific Blue Marlin	18
	Sailfish	6
New Zealand	Pacific Blue Marlin	3
	Striped Marlin	1
Unknown Locations	Pacific Blue Marlin	2
	Sailfish	1
	Striped Marlin	1
	Shortbill Spearfish	2
TOTAL		**1,054**

Swordfish Research and SLUTH –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 to reduce bycatch.

Additional research focuses on two research projects related to new gear types. The first addresses whether it is possible to exploit the habitat differences between swordfish and leatherback sea turtles by targeting swordfish in deeper waters during the day. While collaborators at the Pfleger Institute of Environmental Research (PIER) are working on deep-set buoy gear, scientists at the SWFSC tested the use of deep-set longline gear. Both gears have proved effective at catching swordfish, although catch rates during deep daytime longline sets were apparently not as high as during typical shallow nighttime sets. The second research element compares the bycatch rates, economics, and production volume across nearly all fisheries that commercially land swordfish in the U.S. The research has been presented to the Pacific Fishery Management Council (PFMC) and should help managers make more informed decisions about potential gear alternatives.

Swordfish Habitat Use in the Pacific Leatherback Closed Area (PLCA).
Critical to understanding habitat separation is having information on geographic and vertical habitat use in regions of overlap between swordfish and leatherbacks. While a relatively large number of satellite tags have been deployed on swordfish in the southern California Bight (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 PIER, 13 satellite tags were deployed in the PLCA to quantify habitat use. The eleven tags reported show more variable habitat use, with more time spent in the mixed layer during the day than that in the SCB. Similar to tags deployed elsewhere, basking decreased as swordfish moved offshore and depths occupied during the day increased (**Figure 9**). Findings suggest that vertical habitat use may be less predictable in the PLCA, which could impact efforts to target swordfish at depth. Results of this work are currently being prepared for publication.

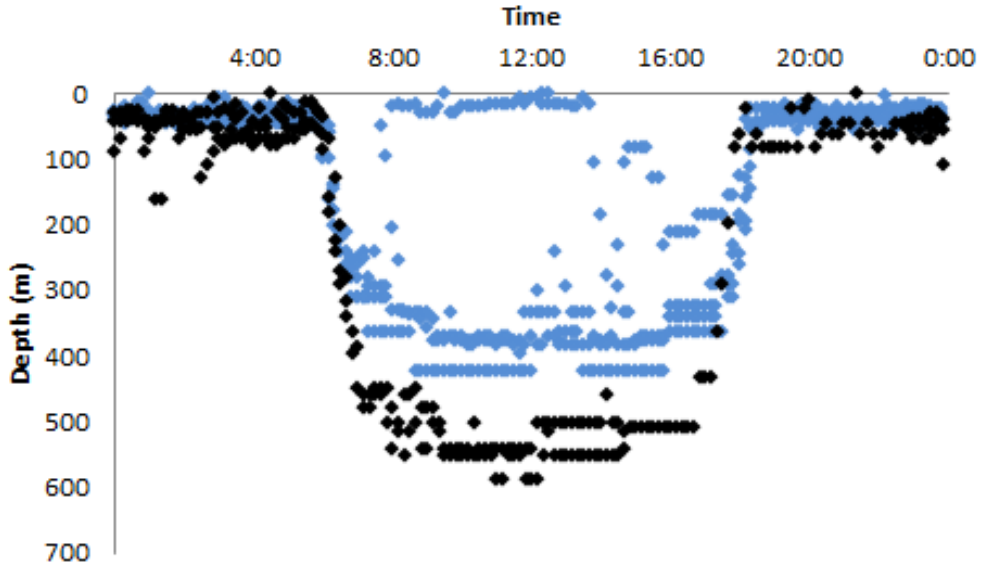

Figure 9. Twenty-four hour track of a "typical" swordfish in nearshore (light blue) and offshore (black) waters.

Swordfish Deep-Set Buoy Gear (DSBG) Research – PIER's application to the Pacific Fishery Management Council (PFMC) for an exempted fishing permit (EFP) in 2015 was approved after several of promising outcomes with DSBG targeting swordfish and other marketable species while avoiding bycatch of protected species and other unmarketable catch. The EFP was awarded to allow expansion of usage through the training of several additional vessels in the use of the gear. The EFP will hopefully aid in the process of introducing the gear into the West Coast Fishery Management Plan. Experiments with making the gear more efficient by linking DSBG sets into a connected series may be undertaken in 2016 as part of this research as well. The SWFSC has collaborated on and supported this research since it began.

Comparative Bycatch Metrics of U.S. Commercial Swordfish Fisheries – An additional component of gear alternative research is the examination of DSBG 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 (CADGN), California deep-set longline (DSLL) targeting tuna, California harpoon, Hawaii shallow-set longline, Hawaii DSLL targeting tuna, Atlantic pelagic longline, and Atlantic buoy gear. 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 all species was estimated based on observer coverage and then divided into retained catch and discards to calculate the proportion retained per individual caught for the two species categories. 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 had little to no bycatch for either species category but have relatively low profits and production volume. Overall, the California 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.

A new element of this research is a comparison of the finfish bycatch not included in previous analyses. Preliminary steps will include an examination of the CADGN fleet focusing on the effectiveness of management measures enacted to reduce the bycatch of protected species, and a a result finfish. While data analyses are in the early stages, preliminary results reveal that 65 species of finfish have been observed caught in the CADGN fleet including the target swordfish, and secondary target thresher shark. Of these, 18 constitute 99% of the total catch by number with 10 species having high retention rates ranging from 64-99%. Further analyses will explore temporal patterns in bycatch and characterize bycatch in terms of relative biomass.

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. Since 2014, 34 stomachs have been analyzed. Current levels of analysis have allowed SWFSC researchers to identify some of the most frequently encountered prey species (F=Frequency of prey occurrence, GII = Geometric index of importance.) The top three prey in broadbill swordfish stomachs during the 2014 season included Pacific hake (*Merluccius productus*) (F=10; GII=48.84), *Gonatopsis borealis* squid (F=18; GII=37.77), and Duckbill barracudina (*Magnisudis atlantica*) (F=15; GII=32.63). These preliminary results show a possible shift in feeding trends. In 2012, the presence of 13 jumbo squid had shown a resurgence of their dietary importance for swordfish, whereas Pacific hake has become the most important prey item in 2014.

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 CADGN 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.

Incidental Catch of Opah during Juvenile Mako and Blue Shark Abundance Surveys Conducted by the SWFSC – From 2009 to 2015 a total of 109 opah were caught during the cruises associated with the SWFSC's annual Juvenile Mako and Blue Shark Abundance Survey. In contrast, during the first 19 years of the survey, only one opah was caught prior to 2009. The increase in opah catch starting in 2009 is likely influenced by many factors including fishing methods and environmental variability. The research vessel historically used to conduct the survey, the 171 foot R/V *David Starr Jordan* (DSJ), was no longer available after 2007. To continue the shark survey in the absence of the DSJ, the SWFSC began chartering smaller commercial longline fishing vessels in 2008. Although the survey methodologies were configured to match that used on the DSJ, switching the fishing platform to commercial longline vessels could have impacted the fishing methods and explain the increased opah catch thereafter. SWFSC researchers are further analyzing the variability in survey catch, including opah catch, through logbooks from the CADGN fishery and recreational sportfishing. Initial analysis of the CADGN fishery shows an increase in opah catch per set from 0.89 in 2006 to 2.23 in 2009. Additional efforts will focus on the impacts of environmental variability, and how opah catch rates are influenced by El Niño Southern Oscillation (ENSO) events. The increased occurrence of opah in survey catch has enabled SWFSC scientists to conduct a number of biological studies on this species about which little is known.

Opah Foraging Ecology– To gain further insight into this little known species and characterize the foraging ecology of opah in the California Current, SWFSC researchers have collected stomach and tissue samples from 138 opah. Opah were collected from 2009-2015 during the cruises associated with the SWFSC's annual Juvenile Mako and Blue Shark Abundance Surveys. Sampled fish ranged from 72 cm to 126 cm FL with a mean of 98 cm FL. Stomach contents included species of squid and fish typically associated with mesopelagic waters. Thirteen species of cephalopods were identified with three making up the most important prey items (*Loligo opalescens*, *Gonatus* spp., and *Dosidicus gigas*) based on the IRI (Index of Relative Importance). Squid ranged dramatically in size from 30 mm (*Gonatus* spp.) to 266 mm mantle length (*D. gigas*). Although the majority of stomachs contained species typically associated with mesopelagic waters, a few stomachs were dominated by epipelagic fish including Pacific saury (*Cololabis saira*). Interestingly, 30% of stomachs contained either small pieces of kelp, tar, or plastic. Based on the data collected to date, opah appear to feed primarily on species associated with the deep scattering layer (DSL). This is consistent with their diel migrations and similar to those of swordfish that also feed on the DSL. Comparison of the diets of opah, tunas, and swordfish from the SCB suggest greater niche overlap between opah and swordfish than between opah and tunas. Considering opah are often caught in association with tunas, differences in their diets could reflect habitat partitioning related to differences in behavior and physiology. Regional diet differences comparing opah caught off central to those caught off southern California are also being examined. A manuscript describing these results is currently being drafted.

Opah Physiology– SWFSC staff published an article in *Science* in May 2015 describing the unique ability of the opah to warm nearly its entire body (a whole body form of endothermy). Additional muscle, blood, fat, and gill tissue samples were collected from opah on an opportunistic basis during the 2015 Juvenile Mako and Blue Shark Abundance Survey, with special emphasis on its specialization for heat retention and elevated levels of aerobic performance. In addition, an Ernest

F. Hollings Scholar conducted a 10-week internship at the SWFSC examining opah gill structure (the site of oxygen uptake and heat conservation) as well as assessing short-term movement and temperature data from opah tagged with custom-made pop-up satellite tags with an external thermocouple implanted into the pectoral muscle. Because opah live in a relatively deep habitat where both low temperatures and low dissolved oxygen concentrations can limit physiological processes, understanding opah adaptations to withstand these conditions can provide insight into their thermal and dissolved oxygen tolerances and behavior.

IV. ADVANCING PELAGIC SHARK RESEARCH

The SWFSC's shark research program focuses on pelagic sharks that occur along the U.S. Pacific coast, including shortfin mako, blue sharks, basking sharks (*Cetorhinus maximus)*, and three species of thresher sharks: common thresher (*Alopias vulpinus)*, bigeye thresher (*A. superciliosus)*, and pelagic thresher (*A. 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 CADGN 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 each summer. 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.

HMS Abundance Survey– The 2015 annual abundance survey was completed between June 22 and July 11 aboard F/V *Ventura II*. Twenty-eight (28) survey sets were completed and a total of 5,835 hooks were deployed during the survey. Average surface water temperature recorded at the beginning of each survey set was 68.7 F (21.03 C), which was warm in comparison to previous years. Survey catch included 9 different species and totaled 143 fish (**Table 4**). The preliminary data indicate that the nominal survey catch rate was 0.06 per 100 hook-hours for blue sharks and 0.407 per 100 hook-hours for shortfin mako (**Figure 10**). The annual nominal CPUE for both species has a negative trend over the duration of the Survey. The blue shark nominal CPUEs have been at record lows in recent years.

Ancillary longline sets were also conducted. A total of thirty three (33) longline sets, including survey sets, were completed resulting in the deployment of 6,786 hooks. The total number of fish captured

was 163; ancillary work resulted in 20 of captures. Most animals were brought onboard, measured, tagged, and a DNA sample was collected. A total of 107 animals were tagged and released with a combination of conventional and electronic tags to examine movement habitat use.

Table 4. Catch summary by species for the 2015 HMS Abundance Survey.

Species	Survey Catch	Ancillary LL Catch	Total Tagged
Isurus oxyrinchus	94		91
Prionace glauca	13	2	13
Pteroplatytrygon violacea	26		
Lampris guttatus	5	11	
Mola Mola	1		1
Coryphaena hippurus	1		
Sphyrna zygaena	1		1
Thunnus albacares	1	5	
Alopias vulpinus	1		1
Thunnus thynnus		2	
Total	**143**	**20**	**107**

Three electronic tags were deployed on two sharks to examine the habitat-use patterns of these species in the California Current. A 190 cm FL female blue shark was tagged and released with a combination of a radio position transmitting (SPOT) tag and a pop-off satellite archival (PSAT) tag. A 226 cm FL female smooth hammerhead (*Sphyrna zygaena*) was tagged and released with a Wildlife Computers radio position transmitting tag.

Detailed morphometric information and biological samples were collected from animals that did not survive capture for numerous studies. Stomachs and reproductive tracts were collected from sharks and tunas for ongoing studies at the SWFSC. Numerous samples were collected for Christine Bedore (Duke University) including tuna and dorado (*Coryphaena hippurus*) heads to quantify the extent of the visual field; opah (*Lampris guttatus*) and pelagic stingray (*Pteroplatytrygon violacea*) eyes as part of a survey of color vision in fishes; pelagic stingrays to examine brain morphology and vascularization of cranial tissues and the possibility of cranial endothermy, and also to examine electroreception used for prey detection; and blood was collected from makos and pelagic stingrays and analyzed for phosphate content to examine a potentially more active remodelling function in elasmobranch cartilage compared to teleosts. Additionally, a blue shark was sampled for Shelby Creager (Florida Atlantic University) in support of a project on the mechanical properties of shark skin. Muscle and liver samples were collected to contribute to a collaborative study with Dan Madigan (Harvard University) to examine stable isotopes.

There is no plan to continue the HMS Abundance Survey in 2016.

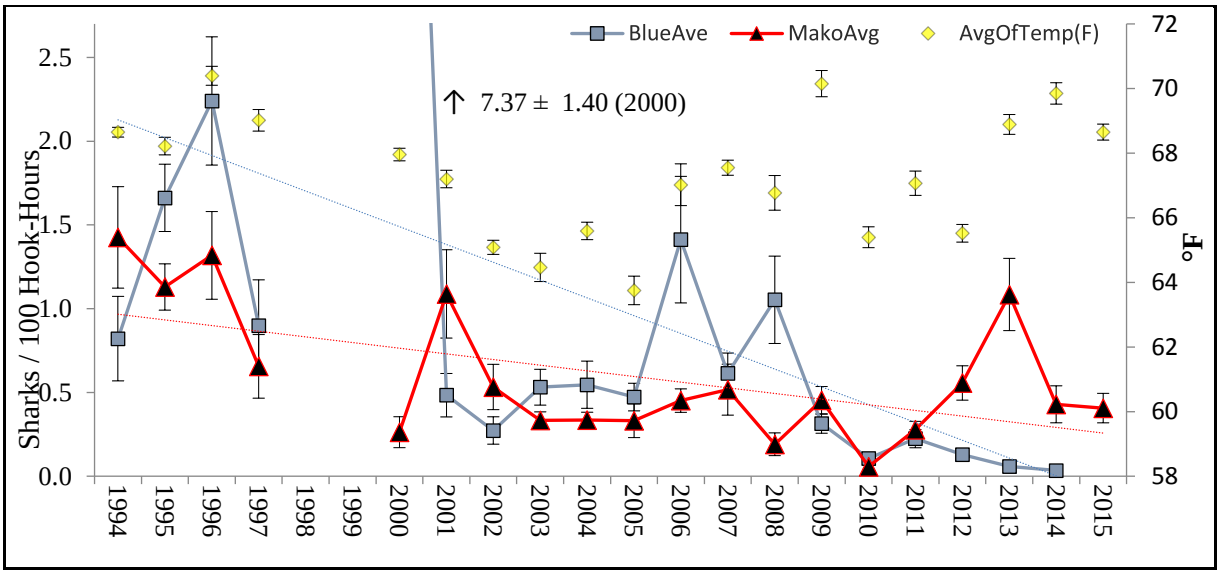

Figure 10. Average (± se) temperature and nominal CPUE during HMS surveys from 1994-2015. Survey was not completed from 1998-1999. Blue shark nominal CPUE was 7.37 in 2000.

Neonate Thresher Shark Survey– A total of 4700 hooks were fished during 47 daytime sets. Average soak time was 2 hour 14 minutes. Bottom depth of set locations ranged from 2 to 24 fathoms; average bottom depth was of 9.7 fathom. Average water temperature measured at the beginning of each set was 22.3 Celsius. This was the warmest average temperature in Survey history.

Excluding baitfish, a total of 188 fish were captured. This total was down in comparison to recent years. Nearly two thirds of the total catch was pelagic stingray, which was very unusual. The number of thresher sharks captured (3) was extremely low. As a result, the thresher nominal CPUE indicated by catch per hundred hook hours was nearly zero and well below previous years. However, the distribution of common threshers is very patchy and areas of high abundance are not consistent across years. In 2016, SWFSC scientists plan to sample further up the California coast to examine the northern extent of the juvenile thresher habitat.

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. Sixteen sharks were tagged with conventional tags for movement and stock structure. Four of these sharks, including three thresher and one mako, were marked with oxytetracycline (OTC) for age and growth research. DNA samples were collected from 34 fish for genetic studies. A researcher from California State Long Beach (CSULB) utilized the research platform to collect swab samples of carnobacteria from thresher sharks. In addition, SWFSC scientists collected detailed morphometric information and biological samples from animals that did not survive capture.

Electronic Tagging Studies – Since 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. SWFSC scientists have been collecting data on shortfin mako, common thresher, and blue sharks for over a decade and continue to look at horizontal and vertical movement patterns on many different time scales. In 2015, a blue shark and smooth hammerhead shark were released with electronic tags for habitat and movement studies.

Smooth Hammerhead Shark – SWFSC scientists tagged a hammerhead shark with a SPOT tag for the first time off Southern California in collaboration with the TOPP program. Hammerhead sharks were seen more frequently than usual during the summer of 2015, likely due to the anomalous warm water conditions associated with the warm blob. The shark traveled more than 1,000 miles from near San Clemente Island to off central Baja California, Mexico, and back again during its first two months at liberty. The shark provided new insight into the great distance hammerheads may cover in search of food, their main prey being fish and squid.

The shark, a female of more than 220 cm TL, was tagged during the annual HMS survey on June 30, 2015, with a SPOT tag on its distinctive dorsal fin. The tag relayed high resolution location data for about two months and then transmitted sporadically for another month before transmissions ceased (Figure 12).

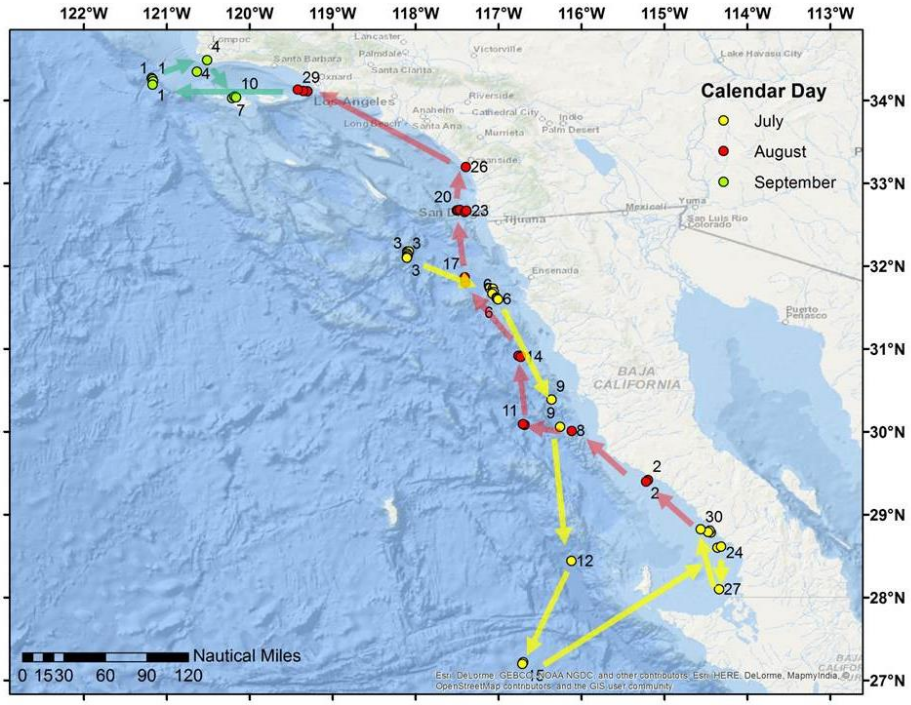

Figure 12. Track of a smooth hammerhead shark tagged during the annual SWFSC HMS survey.

Shortfin Mako Shark – Since 2002, one hundred and nine 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, and into the Sea of Cortez and out 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 from July to October followed and 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 Southern California Bight the following summer. This rich data set is being used to validate a Bayesian movement model currently being developed for more data poor species such as thresher shark (see below).

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. One blue shark was tagged in 2015. Unfortunately, the tag and presumably the shark were eaten within a month of the deployment. To date, a total of 100 sharks (51 males and 49 females) have been tagged with some combination of SPOT (n=95) and PSAT tags (n=60), with 55 sharks carrying both tag types. The majority of sharks were tagged in the Southern California Bight, 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. For the 37 PSAT tags that provided data, 8 of which remained attached until the programmed pop-up date, and the average deployment duration was 115 days. The mean SPOT tag track duration was 88 days, with 7 tags reporting for more than 300 days. Satellite tag deployment durations for both tag types are substantially shorter than for mako sharks.

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^{o}C, with sea surface temperature ranging from 10.8 to 29.8 ^{o}C. A common pattern in archival records was repetitive dives to depths consistent with foraging in association with the deep-scattering layer. There were significant differences in the average maximum depth across all fish comparing day (154 m) and night (65 m), indicating a diel pattern. Archival records however, 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.

SPOT tag transmissions provide insight into geographic movement patterns. While seasonal patterns are difficult to discern given the limited number of long-term tracks, a number of patterns were apparent. The majority of fish moved south following release regardless of their initial tagging location. Females moved farther south than males. Of the 21 individuals that occurred south of 13^{o}N, 18 were females. These blue sharks were in waters associated with the north equatorial current and counter current. Interestingly, they were found at these low latitudes across

seasons and sizes. The occurrence of small females in the south differs from previous models of size and sexual segregation for blue sharks, although data for the eastern North Pacific were limited.

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. Preliminary analysis of horizontal and vertical data is ongoing. 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 focused on developing a Bayesian movement model to use to test hypotheses regarding thresher habitat use.

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. Despite this difficulty, data from tags are being analyzed using a Bayesian approach. Using a Bayesian movement model, 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. Preliminary 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 to 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 oxytetracycline (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 2015 SWFSC surveys, 92 shortfin mako, 12 blue sharks, and 4 thresher were injected with OTC and released.

Shortfin Makos– In July of 2014, a large adult male mako which had been injected with OTC in 2008 was recaptured after more than 6 years at liberty (2,196 days). This represented the first recapture of a large adult male mako injected with OTC and subsequently recaptured in the northeastern Pacific after an extended period at liberty. The band pair count from this adult animal clearly indicated that, post OTC injection, the shark displayed annual band pair deposition (5+ bands in six years). Combined with previous age validation of juvenile makos in the northeastern Pacific, these results point toward an ontogenetic shift in band pair deposition, with a transition

from two band pairs per year to one at or near the size at maturity in male mako sharks in the northeast Pacific Ocean. Proper age determination and accurate growth models are important components of a stock assessment. More research will be needed to corroborate the timing of this shift in band pair deposition in males, and determine if the same shift occurs in females. The results from this study are being published in the Journal of Fish Biology (Kinney *et al. in press*).

Blue Sharks – Work continued on age validation studies of blue sharks. During 2015, 12 blue sharks were injected with OTC, tagged and released during SWFSC research cruises. SWFSC and Texas A&M scientists completed a study on the age validation of blue sharks based on the return of 26 vertebrae samples from OTC tagged blue sharks. A manuscript of the results is in review. The results show annual vertebral band pair deposition in juvenile blue sharks in the northeast Pacific Ocean.

Common Thresher Sharks – During 2015, work continued on age validation of common thresher sharks and four common threshers were injected with OTC. Since 1998, a total of 1,598 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).

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 CADGN 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 and thresher sharks is ongoing. Interannual variation provides insight into the relative abundance of mid trophic level prey. The stomachs of several species of pelagic sharks caught during the 2014 fishing season have been analyzed. For the 2014 season, shortfin mako stomachs (n=3) contained yellowfin tuna (*Thunnus albacares*) (F=1; GII=79.37), unidentified eucarida (F=1; GII=44.39), and *Octopus bimaculatus* (F=1; GII=39.35). One blue shark stomach contained *Gonatus spp*. and the giant octopus (*Haliphron atlanticus*). Common prey in thresher shark stomachs (n=2) was market squid (*Loligo opalescens*), duckbill barracudina (*Magnisudis atlantica*), unidentified Teleostei and unidentified Tunicata (all items with F=1).

Blue and Thresher Shark Spiral Valve Parasite Analysis – The basic principle underlying the use of parasites as tags in shark population studies is that sharks may become infected with a parasite only when they come within the endemic area of that parasite. The endemic area is the geographical region in which conditions are suitable for the transmission of the parasite (MacKenzie and Abaunza 1998). In addition, different parasites can be associated with different prey.

A preliminary study on the spiral valve parasite content of blue and thresher sharks was started in 2011 and terminated in 2015. These species co-occur along the U.S. and Mexico West Coasts during certain times of the year. While they are both caught in the CADGN fishery, a prior study showed that their diet and ecology differ (Preti *et al.* 2012). The contents of 20 blue and 20 thresher shark spiral valves were analyzed for parasite loads in order to determine if there are differences in parasite loads between these two shark species, and how parasites are associated with different prey and the areas where these predators forage. Results show that blue and thresher sharks have different parasites in their spiral valves suggesting that the two predator species spend time in different areas and/or eat different prey. A spirurid nematode (*Piscicapillaria* sp.) found inside a few specimens of thresher sharks is now under review with two world parasite experts. It could be a species not previously recorded or known to thresher sharks.

V. IDCPA RESEARCH

The SWFSC research conducted under the International Dolphin Conservation Program Act (IDCPA) during 2015 was focused on mining existing Eastern Tropical Pacific Ocean (ETP) datasets to (1) identify critical habitat for large whales, (2) evaluate the use of tuna vessel observer data in assessments, (3) identify ecosystem indicators, (4) conduct genetic analysis of dolphin stock structure, and (5) quantify ecosystem services.

Identifying Critical Habitat for Large Whales –

Review of Spatial Habitat Modeling for Large Whales – A completed study comparing two commonly-used methods for spatial habitat modeling of large whales is in review at Methods in Ecology and Evolution. 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.,* Submitted).

Predication of Species Distributions – Martine Mammal and Turtle Division (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. 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 – Dr. Redfern and colleagues used 12 years of line-transect survey data (377 blue whale sightings and approximately 225,400km of effort) collected in the California Current (CC) and ETP to assess the transferability of blue whale (*Balaenoptera musculus*) distribution models. Blue whales are an example of marine predators with well-defined habitats and subject to anthropogenic threats in data-poor areas. This analysis indicated that the ecosystem-specific blue whale models were not transferable. Specifically, models built with CC data could not accurately predict distributions in the ETP and

vice versa. However, models built using both CC and ETP data were as accurate as the ecosystem-specific models. Models built with CC and ETP data were used to create ensemble predictions of blue whale distributions in the data-poor northern Indian Ocean (NIO) because blue whale ecology is expected to be similar in the eastern Pacific Ocean and NIO. These ensemble predictions compare favorably to hypotheses about NIO blue whale distributions, provide new insights into blue whale habitat, and can be used to explore risk in some of the busiest shipping routes in the world. Using a suite of models developed from data collected in multiple ecosystems to create ensemble predictions of species distributions in novel, data-poor marine ecosystems represents a powerful tool for addressing marine conservation needs.

Data Collection and Estimation of Marine Mammal Abundance Practices – Dr. Jessica Redfern (SWFSC) partnered with the Permanent Commission for the South Pacific (CPPS) to host a training workshop on best practices to collect data to estimate marine mammal abundance. The workshop was held in Salinas, Ecuador, August 18-20, 2015. The annual oceanographic surveys coordinated by CPPS in four countries (Chile, Colombia, Ecuador, and Peru) have been identified as potential platforms for collecting data that can be used to estimate marine mammal abundance. The goal of the workshop was to develop best data collection practices that can be used on these surveys. The workshop was attended by 23 people from 5 countries and included representatives from governmental research institutions, universities, and NGO´s.

The current data collection practices in the four countries were reviewed. Regional expertise was shared with respect to using line-transect methodology to estimate the abundance of river dolphins and baleen whales in coastal areas. Personnel from the SWFCS shared their expertise about data collection protocols used during their marine mammal and ecosystem assessment surveys in the ETP and California Current. These procedures have been extensively used and tested. Numerous publications are available about these protocols. Participants also received information about the basics of line-transect sampling theory. On the second day, participants had the opportunity to apply data collection protocols and use new equipment during five hours of field training on board a yacht rented for this purpose. Trainees filled out sightings and effort logs and estimated group sizes, distance to sightings, and angle to sightings. On the final day of the workshop, participants discussed the field training and agreed on the best data collection procedures. Specifically, they reached agreement on equipment, data recording, observers and effort, protocols for sightings, estimating group size, passing and closing protocols, and topics for future workshops.

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 Fielder, 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.*, In Press). In the ETP, yellowfin tuna (*Thunnus albacares*) 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.

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 based on TVOD. These data, collected by observers aboard tuna purse seiners that fish tunas associated with dolphins, were edited and processed to yield sightings and effort data. While of lower quality than data collected on research vessel surveys, the data are continuous from 1980 to the present and thus much more effectively resolve seasonal and inter-annual changes in distribution of dolphins associated with tuna. These changes will be related to environmental variability such as seasonal and ENSO-related changes in temperature, winds, and upwelling. The results of this study should be submitted for publication by the end of 2016.

Spatial Extent and Duration of Dolphin Sets in the Eastern Tropical Pacific – The spatial extent and duration of dolphin sets in the Eastern Tropical Pacific (ETP) have never been examined in detail. Better knowledge about the movements of seiner, speedboats, and dolphins during these sets would provide valuable information regarding effects of dolphin sets on dolphin behavior and physiology. Scientific observers stationed on tuna purse-seiners during routine fishing trips in the ETP have been collecting dolphin set data since the early 1970s. During 2015, a collaborative study was initiated between MTTD scientist, Dr. Elizabeth Edwards, and IATTC which examined TVOD collected during two fishing eras: current (2010-2014) and historical (1985-1989; prior to Dolphin Mortality Limit legislation). TVOD provide direct measurements of three locations (location of seiner when dolphin cue was sighted, location of dolphins when dolphin cue was sighted, and location of net set), and three times (time of cue sighting, time of speedboat launch, and time of net set). These locations and times provide general boundaries for dolphin set spatial and temporal extent, as well as a basis for estimating minimum distance traveled by dolphins before and after speedboat launch, distance between seiner and dolphins at speedboat launch, and minimum average speed of dolphins during each set. Ongoing analyses are examining differences between these various measures as a function of cue sighting method and fishing era.

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 are used to predict additional biological characteristics of the ecosystem. Focusing on the ETP, Dr. Summer Martin (Pacific Islands Fisheries Science Center) and Lisa T. Ballance (SWFSC) use two sources of spatially explicit data (2° x 2° grid) for 1986-2006: (1) yellowfin tuna (*Thunnus albacares*) catch and effort data from the Inter-American Tropical Tuna Commission (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 (*Stenella attenuata* and *S. longirostris orientalis*), rough-toothed dolphins (*Steno bredanensis*), and dwarf sperm whales (*Kogia sima*); (2) log fishing metrics (Sets, Catch) and SPUE of sperm whales (*Physeter macrocephalus*), Bryde's whales (*Balaenoptera edeni*), and short-finned pilot whales (*Globicephala macrorhynchus*); (3) school fishing metrics (Sets, Catch, CPUE) and SPUE of blue whales (*Balaenoptera musculus*), bottlenose dolphins (*Tursiops truncatus*), Risso's dolphins (*Grampus griseus*), and offshore common dolphins (*Delphinus delphis*). 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.

Conduct Genetic Analysis of Dolphin Stock Structureb – Spinner (*Stenella longirostris*) and spotted dolphins (*S. attenuatta*) in the eastern tropical Pacific Ocean (ETP) currently show little-to-no signs of recovery after the stoppage of massive bycatch in the tuna purse-seine fishery nearly four decades ago. Multiple subspecies have been described within both of these species 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. To test questions of population structure in these species, Matthew Leslie, a graduate student at Scripps Institution of Oceanography, working with Dr. Phil Morin (SWFSC), has 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*.

Restriction-Site Associated DNA Sequencing – Laboratory work and analyses are complete for this project, which targets DNA sequencing near restriction enzyme cut-sites to search for variation across many individuals. Over 6,000 SNPs 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. These results will be published in two separate manuscripts, anticipated to be complete in summer or fall of 2016.

Analysis of Ecosystem Services – Dr. Summer Martin (Pacific Islands Fisheries Science Center, 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 eastern tropical Pacific (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^{-1}. The value of carbon export to the deep ocean was \$12.9 billion yr^{-} (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^{-}, 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.

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