# Nursery Functions of West Coast Estuaries: Data Assessment for Juveniles of 15 Focal Fish and Crustacean Species

FINAL REPORT, NOVEMBER 2015

Pacific Marine & Estuarine Fish Habitat Partnership

NATIONAL FISH HABITAT PARTNERSHIP

Jason D. Toft[1], Stuart H. Munsch[1], Jeffery R. Cordell[1], Kiira Siitari[2], Van C. Hare[2], Brett Holycross[2], Lisa A. DeBruyckere[3], and Correigh M. Greene[4]

1 University of Washington, School of Aquatic and Fishery Sciences; 2 Pacific States Marine Fisheries Commission; 3 Pacific Marine and Estuarine Fish Habitat Partnership; 4 Northwest Fisheries Science Center, National Marine Fisheries Service

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# EXECUTIVE SUMMARY

Estuarine systems provide nursery functions to many species of fish and crustaceans, and are often targeted by conservation and restoration efforts. However, there are un-answered questions about which habitats within estuarine environments provide optimal benefits for various species, and which habitats might be most sensitive to disturbance so that strategic investments in conservation and restoration can be targeted.

In collaboration with the Pacific Marine and Estuarine Fish Habitat Partnership (PMEP), we addressed the status of estuarine use along the West Coast for 15 "focal" fish and crustacean species. These species were chosen based on input from scientists at the PMEP 2014 Summit to Advance Juvenile Fish Habitat in West Coast Estuaries, and subsequent input. These species are intended to represent major guilds, species of commercial, recreational, and cultural importance, and species whose life histories span all or a significant portion of West Coast estuaries. The 15 species are: Dungeness crab (*Cancer magister*), bay shrimp (*Crangon franciscorum*), leopard shark (*Triakis semifasciata*), bat ray (*Myliobatis californica*), green sturgeon (*Acipenser medirostris*), steelhead trout (*Oncorhynchus mykiss*), coho salmon (*Oncorhynchus kisutch*), Chinook salmon (*Oncorhynchus tshawytscha*), California halibut (*Paralichthys californicus*), English sole (*Parophrys vetulus*), starry flounder (*Platichthys stellatus*), brown rockfish (*Sebastes auriculatus*), Pacific staghorn sculpin (*Leptocottus armatus*), shiner perch (*Cymatogaster aggregata*), and Pacific herring (*Clupea pallasii*).

The overall objectives of our work were to synthesize the available data into a common format allowing for (1) creation of maps displaying species location, average frequency of occurrence, and average catch per unit effort (CPUE), and (2) comparison of the data, using the best quality portions of the dataset, to presumed habitat impacts measured by estuarine stressor scores. Our hypothesis was that there would be lower probability of presence or CPUE with higher stressor scores for species that were most estuarine dependent and negatively affected by human impacts.

To accomplish the first objective, we conducted a data call for previously collected datasets in estuaries of California, Oregon, and Washington. For our meta-analysis, we combined data from the 15 focal species representing 34 sampling programs across 47 estuaries, with over 468,000 individual records. Analysis focused on juvenile life-stages of the focal species, using sampling data starting in the 1990s and ending in 2014.

To accomplish our second objective, we used the estuarine stressor scores that were calculated by the National Oceanic and Atmospheric Administration (NOAA) for their 2010 National Assessment (Greene et al. 2015b). These scores are a composite of 43 indicators that represent four main categories (land use, river flow alteration, pollution sources, and eutrophication). The composite stressor score provides a uniform method to indicate level of human impact to estuarine habitats (scaled 0 to 1, higher is more impaired).

We discuss the opportunities and constraints associated with previously collected data that we encountered while conducting the meta-analysis. Organizing such disparate data into a consistent and comparable format took considerable effort. One of the main constraints for our study was that comparability of data was compromised because gear types, metrics of abundance, and temporal and spatial experimental designs often differed among sampling programs. For this reason, we focused analysis on beach seine data, the most common and data-rich sampling method.

Adequate data was available to quantify relationships between abundance metrics and estuarine stressor scores for eight species using generalized additive mixed models (GAMM): Chinook salmon, coho salmon, Dungeness crab, English sole, Pacific herring, shiner perch, staghorn sculpin, and starry flounder. In these models, the response variables were presence/absence or CPUE, the fixed effects were estuarine stressor and salinity category, the random effect was estuary, a smoother was applied to day of the year, and length of the net was used as an offset for sampling intensity.

There was evidence for a negative relationship between presence or CPUE and estuarine stressor score for four of the modeled species—Chinook salmon, coho salmon, English sole, and Pacific herring—although this relationship was statistically significant at an alpha of 0.05 only for CPUE of Chinook salmon. Juvenile Chinook salmon may depend more on estuarine nursery functions and be more prone to stressors in the estuary. Lack of response among the other modeled species could be related to limitations in data across all species and habitats, as well as the data that was used to develop the stressor score.

There was comparatively less evidence for a negative effect of stressor on staghorn sculpin, shiner perch, starry flounder, and Dungeness crab. Species such as English sole, Pacific herring, and Dungeness crab occur more in colder deeper waters further south in their range in California, and we were unable to assess their use in these deeper waters because of the limited amount of submitted otter trawl data.

Addressing nursery function of different habitat types was an original goal of our study, and one that could not be addressed due to limitations in the amount of habitat-specific data and overlap of habitat classifications among studies. Historic habitat loss should also be taken into account, and combined with long-term datasets of fish abundance when available. Improved spatial data of site locations and GIS layers of habitat types, along with density estimates of species of interest, would allow future data synthesis efforts to accomplish more precise analyses. This may require new sampling specifically designed to provide more information about species-habitat linkages.

Acquiring these specific measures of nursery function—especially those targeting changes that accompany anthropogenic modifications, restoration actions, and sea level rise—will guide future management actions along the West Coast, and help us to predict the potential for improving and maintaining nursery functions of estuaries given climate change scenarios.

The following recommendations result from our work and analyses:

- Of the 8 species that had suitable data for a modeling analysis, Chinook salmon, coho salmon, Pacific herring, and English sole may be the most impacted by estuarine stressors and therefore may receive the largest benefit from restoration efforts in shallow water areas that were the focus of beach seine efforts in our analysis.
- One recommendation for planning of West Coast restoration actions is to target estuaries that have higher stressor scores (over 0.4), with the goal of decreasing the score toward a more natural state.
- Future analysis should seek to isolate effects of individual versus cumulative estuarine stressors, and conduct concurrent fish sampling with measurement and updating of stressors to illustrate dynamic trends.
- Standard habitat classification categories should be used so that labeling and documentation of sampled habitats are consistent (e.g., the Coastal and Marine Ecological Classification Standard—CMECS), facilitating future overlap for meta-analyses.

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- When possible, standard gear types should be used to facilitate accurate calculations of density of fishes that would give more precise measurements and comparability across studies (e.g., 37—m length for beach seines, 10-minute tow for otter trawls).
- Major habitat types, such as emergent tidal marshes, tidal flats, and seagrass beds, would be best suited for analyzing broad-scale habitat patterns in shallow waters. Especially focusing on species with rich datasets, such as the four in our analysis that showed a negative response to estuarine stressors (Chinook salmon, coho salmon, Pacific herring, and English sole).
- Improved spatial data of sampling locations along with current and historic habitat types and habitat losses would allow future data synthesis efforts to accomplish more precise analyses and habitat linkages.
- Acquiring specific measures of nursery function that target changes due to anthropogenic modifications, restoration actions, and sea level rise, will help us to predict the potential for improving and maintaining nursery functions given climate change scenarios.

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# INTRODUCTION

Providing nursery habitat for juvenile fish and invertebrates is a major function of estuaries, and one that is commonly referred to in conservation and restoration efforts (Beck et al. 2001). To help assess the status of nursery habitats in West Coast estuaries for the Pacific Marine and Estuarine Fish Habitat Partnership (PMEP), we conducted a data call for meta-analysis on 15 focal fish and crustacean species. The boundaries of our assessment were estuarine systems in the geographic range spanning California, Oregon, and Washington.

PMEP and its assessment partners (National Oceanic and Atmospheric Administration, National Fish Habitat Partnership, The Nature Conservancy) are conducting three Pacific Coast fish habitat assessments to inform future estuary resource protection and restoration efforts and improve understanding of the role estuaries play in the health and production of commercial fish stocks. These assessments have several tasks in common, including application of a unifying estuary classification scheme, creation of a spatial framework, gathering and compiling habitat and fish data, and developing shared tools and products:

1. PMEP's Nursery Habitat Assessment (this report) focuses on nursery functions for juvenile fish in West Coast estuaries (15 species).
2. The National Fish Habitat Plan (NFHP) National Estuary Assessment focuses on conditions and key threats to habitats of recreationally and commercially important fish and shellfish stocks (50 species).
3. A Nearshore Forage Fish Assessment focuses on habitat-related changes over time in distribution and abundance of forage fish inhabiting estuary and nearshore habitats (nine species), similar to that as completed recently for Puget Sound (Greene et al. 2015a).

Early notions (in the 1940s–1950s) of estuaries as nurseries revolved around the concept of estuarine dependence—juveniles of marine organisms requiring low salinity areas for nursery grounds (e.g., Günter 1945, 1950). In fact, referring largely to data from Texas estuaries, Günter (1967) stated that "the fauna of low-salinity estuarine waters is marine", meaning that the preponderance of both fish and invertebrates were juveniles of marine species. One outcome of these kinds of observations was that the terms "estuarine dependence" and "nurseries" were used interchangeably because early researchers considered the entire estuary to be a nursery (Able 2005). Beck et al. (2001) refined the estuarine nursery concept by proposing that a nursery is a habitat that contributes higher biomass of juveniles per unit area to the adult population compared to other habitats, due to lower mortality, higher densities and growth rates. Noting that this per-unit-area based approach under-values juvenile habitats that have low densities but large areas (and thus might make larger overall contributions to adult populations), Dahlgren et al. (2006) suggested that the definition of nurseries (which they termed effective juvenile habitat) should be based on their total contribution to the adult population.

Both of these approaches were criticized by Sheaves et al. (2006) because: (1) they fail to consider it is the contribution to the production of succeeding generations—not just recruitment to adult populations—that determines real nursery-ground value; (2) habitat, boundaries, and spatial scales are undefined and/or unaccounted for; (3) they concentrate on single habitats as the unit of nursery ground value when in fact many habitat types or areas may cumulatively contribute to juvenile fitness; (4) many nursery ground values are process-based and not necessarily features of a habitat unit, i.e., events that occur outside the identified nursery ground may give the impression of a nursery ground being important; (5) reducing inherently complex functions to simple categories is risky because it may lead ecosystem managers to fail to adequately recognize and understand critical links and processes that support marine nurseries; and (6) assigning value to habitats may cause the ranking of well-studied habitats to be higher than those that are poorly understood, with the value of unstudied nursery grounds thus being overlooked.

Although Sheaves et al. (2006) offered no solutions to these problems (Layman et al. 2006), Nagelkerken et al. (2013) addressed some of them, conceptualizing a nursery as a spatially explicit seascape consisting of multiple mosaics of habitat patches that are functionally connected, and offering practical steps to analyzing a seascape nursery. These nursery concepts are important to consider in our report, as we apply juvenile presence and use to signify nursery value.

For this report we focused our efforts on 15 fish and crustacean species that are intended to represent major guilds, species of commercial, recreational, and cultural importance, and species whose life histories span all or a portion of West Coast estuaries (see Hughes et al. 2014 for the process of choosing these and maps of geographical range):

- Dungeness crab (*Cancer magister*)
- Bay shrimp (*Crangon franciscorum*)
- Leopard shark (*Triakis semifasciata*)
- Bat ray (*Myliobatis californica*)
- Green sturgeon (*Acipenser medirostris*)
- Steelhead trout (*Oncorhynchus mykiss*)
- Coho salmon (*Oncorhynchus kisutch*)
- Chinook salmon (*Oncorhynchus tshawytscha*)
- California halibut (*Paralichthys californicus*)
- English sole (*Parophrys vetulus*)
- Starry flounder (*Platichthys stellatus*)
- Brown rockfish (*Sebastes auriculatus*)
- Pacific staghorn sculpin (*Leptocottus armatus*)
- Shiner perch (*Cymatogaster aggregata*)
- Pacific herring (*Clupea pallasii*)

*Nursery Functions of U.S. West Coast Estuaries: The State of Knowledge for Juveniles of Focal Invertebrate and Fish Species* (Hughes et al. 2014) synthesized information on juvenile nursery requirements of the 15 focal species, including life history and ecology, habitat associations, documentation of presence in 303 specific West Coast estuaries, and threats. Heady et al. (2014) provided an inventory of 303 West Coast estuaries (with a total open water and wetland area larger than 0.4 hectares) likely to provide juvenile fish habitat, using a common classification scheme (the Coastal and Marine Ecological Classification Standard [CMECS]; FGDC 2012). These recent reports continue a string of West coast syntheses, with concurrent increases in amount and precision of data sources available (e.g., Monaco et al. 1990, Emmett et al. 1991, Monaco et al. 1992, Gleason et al. 2011). Our data assessment seeks to build from these previous efforts by incorporating location-specific sample data on the 15 focal species collected across a range of West Coast estuaries, and where appropriate, incorporating an analysis using values of estuarine stressor scores that indicate level of human impact to estuarine habitats (Greene et al. 2015b).

Our basic approach was to compile available survey data that have already been collected, and target those that represent estuarine use of the 15 focal species. Similar data summaries have been conducted elsewhere on the West Coast (e.g., Monaco et al. 1990, Helmbrecht and Boughton 2005), and complement but do not supersede targeted field studies. Large-scale meta-analysis efforts, in general, illustrate the strengths of a broad-scale approach, recognizing the limitations of what can be accomplished due to sources of variability, such as differences in experimental sampling, model parameters, and functional differences in underlying biological processes (Thorson et al. 2013). Our overall objectives are to synthesize the available data into a common format that allows for (1) creation of maps that display species location, frequency of occurrence (FREQ), and catch per unit effort (CPUE), and (2) analysis of FREQ and CPUE using characteristics of estuaries and specific locations, and using the best quality aspects of the dataset.

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# METHODS

### Data collection

No new field studies were conducted specifically for this project. Data collection relied on professional networking to identify and obtain relevant data from across the West Coast. Attendees of a PMEP-sponsored West Coast Summit (January 14–15, 2014, in Seattle, WA) generated a pool of potential data holders with nearshore and estuarine fish, habitat, and water quality information. From this pool, 120 managers and researchers responded to a PMEP online survey with descriptions of the scope and availability of their data ("Tier 1", Appendix A). The PMEP Science and Data Committee used this list of data sources to prioritize individual requests for data. To address data needs for the assessment, online survey respondents with fish and shellfish data from Washington, Oregon, and California estuaries were contacted first. This contact list expanded with additional professional referrals and estuary-specific queries of federal and state data portals to fill geographic gaps.

We targeted fishery independent, spatially referenced presence/absence and abundance information for the 15 nursery assessment focal species that had been sampled within estuaries ("Tier 2", Appendix B). Data on additional species and non-juvenile fish and shellfish were accepted in support of other planned assessments in the West Coast region. Paired habitat data (e.g., salinity, temperature, vegetation type) were accepted when available, but not required. Given the timeline of the assessment and comparability of results among sampling methods, the following data types were not targeted in our request for data: fish movement (tagging/passage) studies, habitat or water quality data not paired to fish samples, modeled species distributions, or remotely operated underwater vehicle surveys. Ultimately, over 200 individuals from 73 different agencies were contacted regarding the PMEP data request, leading to data from 34 sampling programs representing 47 estuaries being combined and synthesized for this report.

### Data processing

Submitted datasets were compiled and uploaded to a Microsoft Access database based on an Observations Data Model to provide a consistent format for the storage and retrieval of point observations in a relational database, which is designed to facilitate an integrated analysis of large data sets collected by multiple investigators (Horsburgh et al. 2008). Priority was placed on processing datasets that sampled multiple species and specified life-stage or length parameters. When geographic coordinates were unavailable, fish observations were resolved to an estuary polygon if metadata allowed. Prior to analysis, data were queried by species, life-stage (when available), and location to include only samples collected within West Coast estuary boundaries using current NOAA designations.

### Data presentation and analysis

For our original data call, we planned to summarize information into three nested spatial scales:

**Ecoregion**—four zones, north to south:

1. Puget Trough/Georgia Basin
2. Oregon, Washington, Vancouver Coast and Shelf (including California north of Cape Mendocino)
3. Northern California (Cape Mendocino south to Point Conception)
4. Southern California Bight

**Estuary type**—four CMECS classifications (described in Hughes et al. 2014):

1. Riverine Estuary
2. Lagoonal Estuary
3. Embayment/Bay
4. Sound

**Habitat**—such as eelgrass, emergent wetland, tidal flat, etc.

Ecoregion and estuary type were relatively easy to assign based simply on latitude and longitude of site locations. Habitat covered a broad array of submitted information, based on metadata provided and goals of the individual studies.

To visually display the data, maps were made of presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report as well as estuaries with documented presence (Hughes et al. 2014), to represent extent of data coverage and gaps. Average frequency of occurrence (FREQ; # samples present/total) and CPUE were calculated using the most common gear type for each species from the years 1990–2014, using only months that the species were present in each estuary/record to account for different timings across estuaries/latitudes (especially for anadromous species). Estuaries with less than five sampling events were not included. Averages of FREQ and CPUE were summarized into pie charts for each ecoregion by binning values for each estuary into quantiles representing the general range of values (1 to 4, low-high). Gear types used for FREQ and CPUE calculations were based on the most representative gear for each species as follows:

**Beach Seine:** Chinook salmon, coho salmon, Dungeness crab, English sole, Pacific herring, Pacific staghorn sculpin, shiner perch, starry flounder, and steelhead trout.

**Otter Trawl:** Bat ray, bay shrimp, brown rockfish, green sturgeon, California halibut, and leopard shark.

The relationship between species abundance and estuarine stressor was evaluated using generalized additive mixed models (GAMM; Zuur et al. 2009, Wood 2011; Figure 1). We were able to model eight of the 15 species that had suitable data coverage, using beach seine data from the years 1990–2014: Chinook salmon, coho salmon, Dungeness crab, English sole, Pacific herring, shiner perch, staghorn sculpin, and starry flounder (see further descriptions of data coverage in the Results). This data represented 20 West Coast estuaries: Alsea Bay, Chetco River, Columbia River, Coos Bay, Coquille River, Grays Harbor, Hood Canal Basin, Nehalem River, Nestucca Bay, Russian River, Salmon River, San Diego Bay, San Francisco Bay, San Juan Islands and Georgia Strait Basin, Siletz Bay, Siuslaw River, South Central Puget Sound Basin, Tillamook Bay, Whidbey Basin, and Yaquina Bay (also see Figure 3 in the Results section). The GAMM modeling approach was appropriate because the data were non-normally distributed, there were non-linear annual trends in species abundance, and species were repeatedly sampled from the same estuaries.

We included parameters in the model to quantify the influence of estuarine stressor on fish abundance while accounting for differences among sampling protocols. Specifically, we accounted for sampling that varied by time of year, salinity, and net size. The fixed effects used for the models were stressor bin and salinity bin, as described below. We were primarily interested in examining fish and crustacean response to the estuarine stressor level of human impact, and also incorporating salinity which is a major governing factor in species distribution and abundance. We used the stressor scores calculated for each estuary by the 2010 National Assessment (Greene et al. 2015b), which indicated level of human impact to estuarine habitats. We used the composite stressor index (scaled 0 to 1, higher is more impaired) which was developed by combining 43 indicator datasets in four categories: (1) land cover/land use, (2) alteration of river flows, (3) pollution sources, and (4) eutrophication. The only estuary that did not have a specific value for the beach seine data was the Salmon River in Oregon, which we estimated by averaging the neighboring Nestucca and Siletz Rivers (~13km to the north and south, respectively, values of 0.093 and 0.133, average value of 0.103). Our hypothesis was that there would be lower probability of presence or CPUE with higher stressor scores for species that were most estuarine dependent and negatively affected by human impacts. Stressor scores were binned for analysis by segments of 0.2. Scores above 0.6 were pooled into one stressor bin because estuaries with these scores were less common, resulting in four total levels of stressor bins (<0.2, 0.2–0.4, 0.4–0.6, >0.6). Binning stressor scores was appropriate for our mixed modeling approach because it allowed for multiple estuaries to occur at each level of a stressor bin.

The salinity bins used were freshwater tidal (<0.5 ppt), mixing (0.5–25 ppt), and marine (>25 ppt). Salinity bins were assigned based on averaged field measurements from a location. If field data was unavailable, the NOAA 3-Zone Average Annual Salinity Digital Geography layer was used (spatial join w/ 50m buffer). If no field data or NOAA digital data existed, the location was assigned the salinity class of the nearest classified point (nearest neighbor ID) and reviewed by a regional expert.

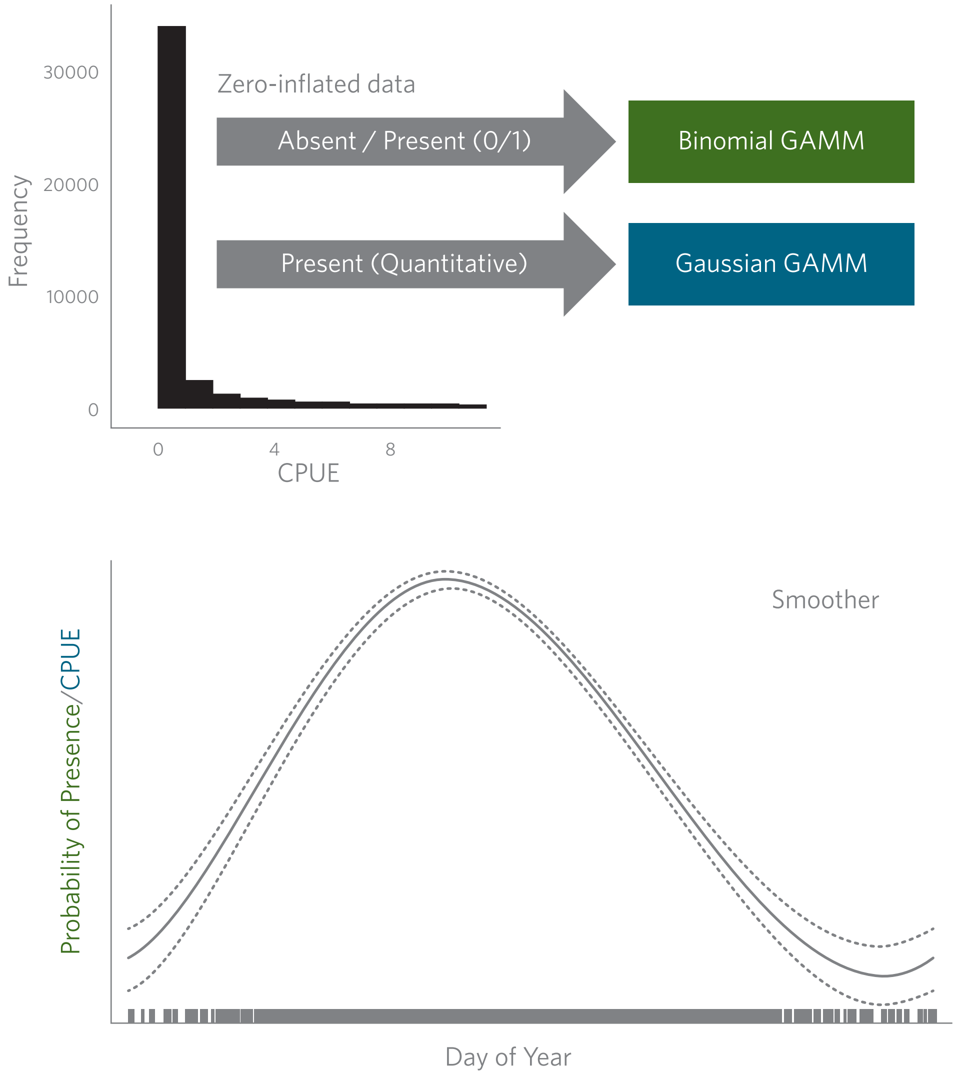
A smoother was used to account for intra-annual variation of species abundance using the day of year (e.g., January 1 = 1, December 31 = 365) as the explanatory variable. Smoothers can be used in additive models to describe non-linear seasonal patterns in data and are created by connecting a series of lines that are defined by functions (e.g., cubic polynomial) joined together at points termed knots. Smoothers were constrained to begin and end at the same point (i.e., connecting December 31 to January 1) and were limited to four knots to avoid overfitting the model (i.e., excessive flexibility in the smoother). These constraints were appropriate given a priori knowledge of annual species abundance trends.

Chinook and coho salmon showed differences in annual timing among salinity bins that were consistent with their anadromous life histories. Models describing these species were fit with a unique smoother describing annual trends in abundance for each salinity bin. Herring data was especially right-skewed, presumably because this species schools in patchily distributed large groups, and was log-transformed prior to analysis. Chinook salmon and herring captured in San Francisco showed unique trends in annual abundances, with peak abundances occurring at different times of the year compared to other estuaries (Figure 2). Data from San Francisco Bay were therefore adjusted to center the peak timing to that of the other estuaries by adding 127 and 150 to the day of year for Chinook salmon and herring, respectively, as determined by visualizing annual time series of the data via local regression.



The first phase of creating the models was to choose an approach that accounted for zero inflation, as there were many zeros in the dataset. Therefore, two models were fit for each species: one describing presence or absence of a species (hereafter: presence/absence model) and the other describing catch per unit effort when a species was present (hereafter: CPUE model). Presence/absence models were fit using a binomial distribution and a logit-link function. CPUE models were fit using a gamma distribution and log-link function. Each estuary was treated as a random effect. The log-transformed length of the net used for sampling was treated as an offset, which is a model parameter that accounts for predictable relationships in the data associated with sampling intensity. We used length of net as an offset because we expect greater fish counts when fishing with a larger net. Model selection procedures typically involve eliminating explanatory variables that do not significantly improve model fit; however, we present the summary statistics for the full models because we were interested in comparing the effects of stressors among a range of species that may vary in their estuarine dependence.

Model output was visualized by calculating relative abundance (probability of presence or CPUE) for each estuary by summing the parameter estimates for stressor bin, estuary intercept (i.e., random intercept), and global intercept, and plotting these values with their corresponding stressor bins. Models were fit in R version 3.2.2 (R Core Team 2015) using the mgcv (Wood 2015b) and gamm4 (Wood 2015a) packages. CPUE models were fit using the gamm function in the package mgcv because it is computationally faster than gamm4. Presence/absence models were fit using the gamm4 function in the package gamm4 because it performs better on binary data than gamm (Wood 2015a).




**Fixed Effects:**
Stressor Bin (Greene et al. 2015b)
- 1 (< 0.2)
- 2 (0.2 – 0.4)
- 3 (0.4 – 0.6)
- 4 (> 0.6)

Salinity Bin
- Tidal Freshwater (< 0.5 ppt)
- Mixing (0.5 – 25 ppt)
- Seawater (> 25 ppt)

**Random Effect:**
Each of the estuaries sampled

**FIGURE 1.** Conceptual diagram describing the structure of the generalized additive mixed models. Data shown is for Chinook salmon.

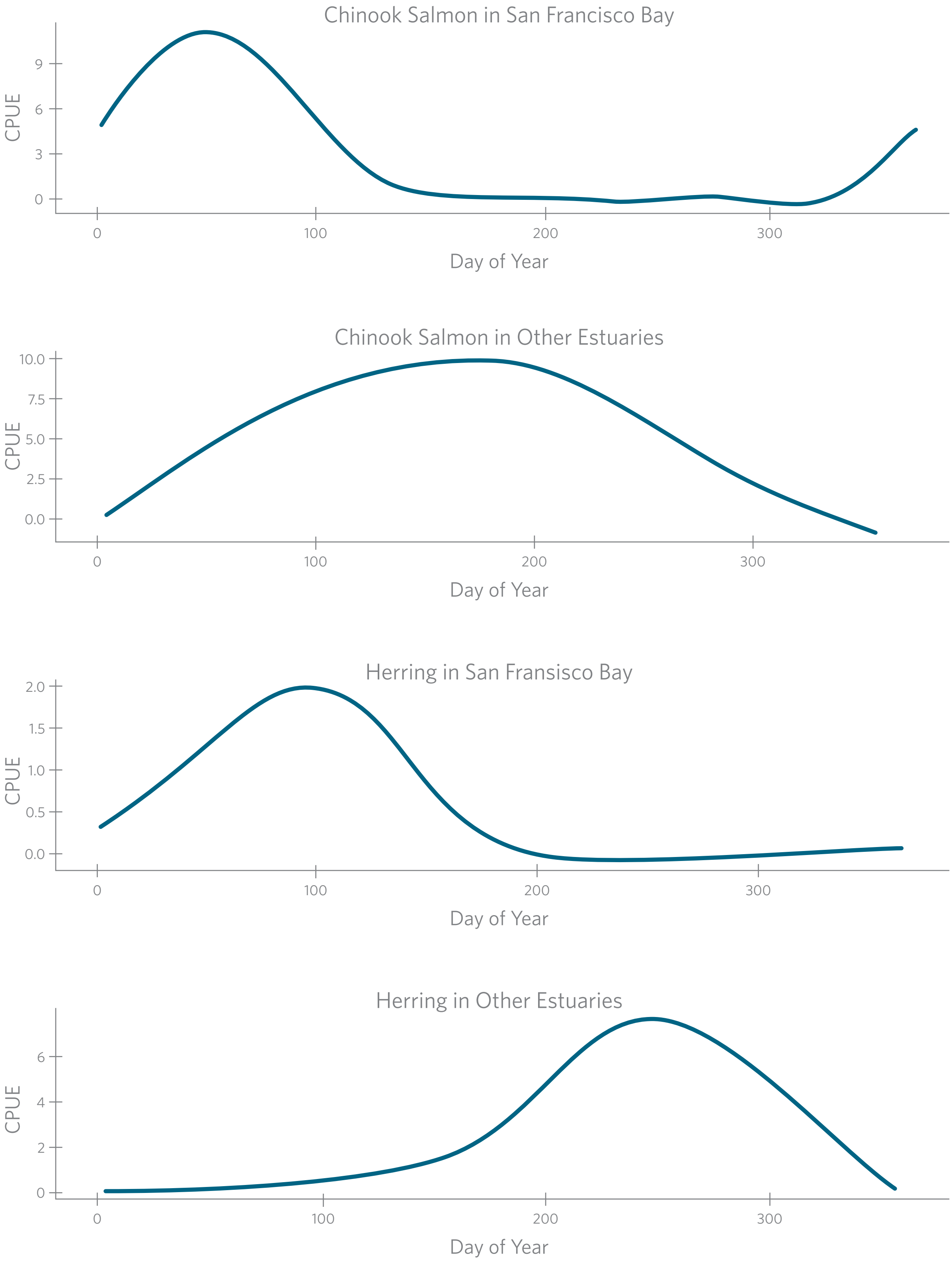



**FIGURE 2.** Annual abundance trends of Chinook salmon (top) and Pacific herring (bottom) comparing San Francisco Bay and all other estuaries combined. Curves are fit by local polynomial regression.

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# RESULTS

### Overall data coverage

We combined data from 34 sampling programs across 47 estuaries, representing 11 estuaries in Washington, 15 in Oregon, and 21 in California (Figure 3). Over 468,000 individual records of the targeted 15 species of juvenile fish and crustaceans were included. There were five main sources of data variability and constraints that contributed to the extent that we could apply our meta-analysis:

1. **Data coverage**—Some estuaries were less sampled than others, not all available data sets were submitted, and we were not able to enter all submitted datasets in the timeframe for this analysis. Therefore, minimal or no data from a particular estuary or location does not necessarily mean the data does not exist; rather, it was not available for our analysis.

2. **Gear types**—18 different gear types were submitted, and comparisons of presence/absence and CPUE across gear types are problematic.

3. **Metrics of abundance**—Precision of catch records occurred across a range of presence/absence, CPUE, and density. Those records with higher precision were fewer than those with lower precision.

4. **Temporal frequency of sampling**—Sampling varied across years, seasons, and months.

5. **Spatial coverage**—Data coverage within each estuary varied, as did the precision of specific measurements of latitude and longitude where sampling occurred.

The majority of studies targeted only certain species or habitats, hindering quantitative assessment if overlap across studies did not exist. Non-target species of a study that focused on one group (e.g., salmonids) were often binned to family (e.g., cottids, flatfish, cancer crabs, crangon shrimp were all very common bins) and therefore could not be incorporated into our species-level assessment. There were five focal species that were particularly lacking in data submissions, for the following reasons:

- Brown rockfish—Juvenile *Sebastes* were typically not identified to species in the datasets submitted, and prefer structured habitats that are difficult to sample.
- Bay shrimp—Shrimp are not typically identified to species in fish surveys, and our network was primarily fish surveyors.
- Green sturgeon—Abundance surveys are rare, and adults and sub-adults are more commonly studied for movement because numbers are so low.
- Leopard shark—Leopard sharks are uncommon in netting surveys, and their range coincides with an area of weaker overall data coverage.

- Bat ray—Bat rays are uncommon in netting surveys, and their range coincides with an area of weaker overall data coverage.

Our original objective was to summarize data by ecoregion, estuary type, and habitat. However, the contributed data did not have the equal representation of ecoregion and estuary type that we envisioned (Figure 4), and habitat type was not consistently represented. Each of the ecoregions had one main estuary type, and none of them had all four estuary types (Figure 4). Also, the estuary types did not proportionally represent those documented in Heady et al. (2014). The lagoonal estuaries in California and Oregon were not sampled as extensively as bay and riverine estuaries. Although lagoonal estuaries are the most common type coastwide, they collectively comprise the smallest cumulative area because of their small size (Heady et al. 2014). Puget Sound was the only component of the sound estuarine type, and because of its large size and complex system, it is unique in that it contains the three other estuarine types, especially several large riverine estuaries (e.g., Skagit and Snohomish in the contributed datasets for the Whidbey Basin of Puget Sound), and therefore represents an accumulation of estuarine types that could be sub-categories. Beach seines were the most representative across ecoregions, and otter trawls were also representative of bays in northern California, mostly San Francisco Bay. Although data from the Southern California Bight represented 14 estuaries, there were not many sampling events compared to other ecoregions, and the most common gear types were pole/river seines and beam trawls.



Habitat type associated with catch data was specified by the data sources when available, and assigned into three broad categories of habitat (e.g., nearshore, intertidal), substrate (e.g., mud, gravel), and vegetation (e.g., eelgrass, aquatic vegetation). Of the 34 sampling programs that submitted data, 11 specified habitat type across 42 different categories, eight specified substrate type across 110 different categories, and 11 specified vegetation type across 216 categories. These were often just notes taken during sampling that would be difficult to accurately interpret and retroactively assign into categories (e.g., "some algae on mud", "cobble/gravel/oyster"). Because of this variation in resolution and lack of consistency, we were unable to make even broad habitat summaries and comparisons across studies.

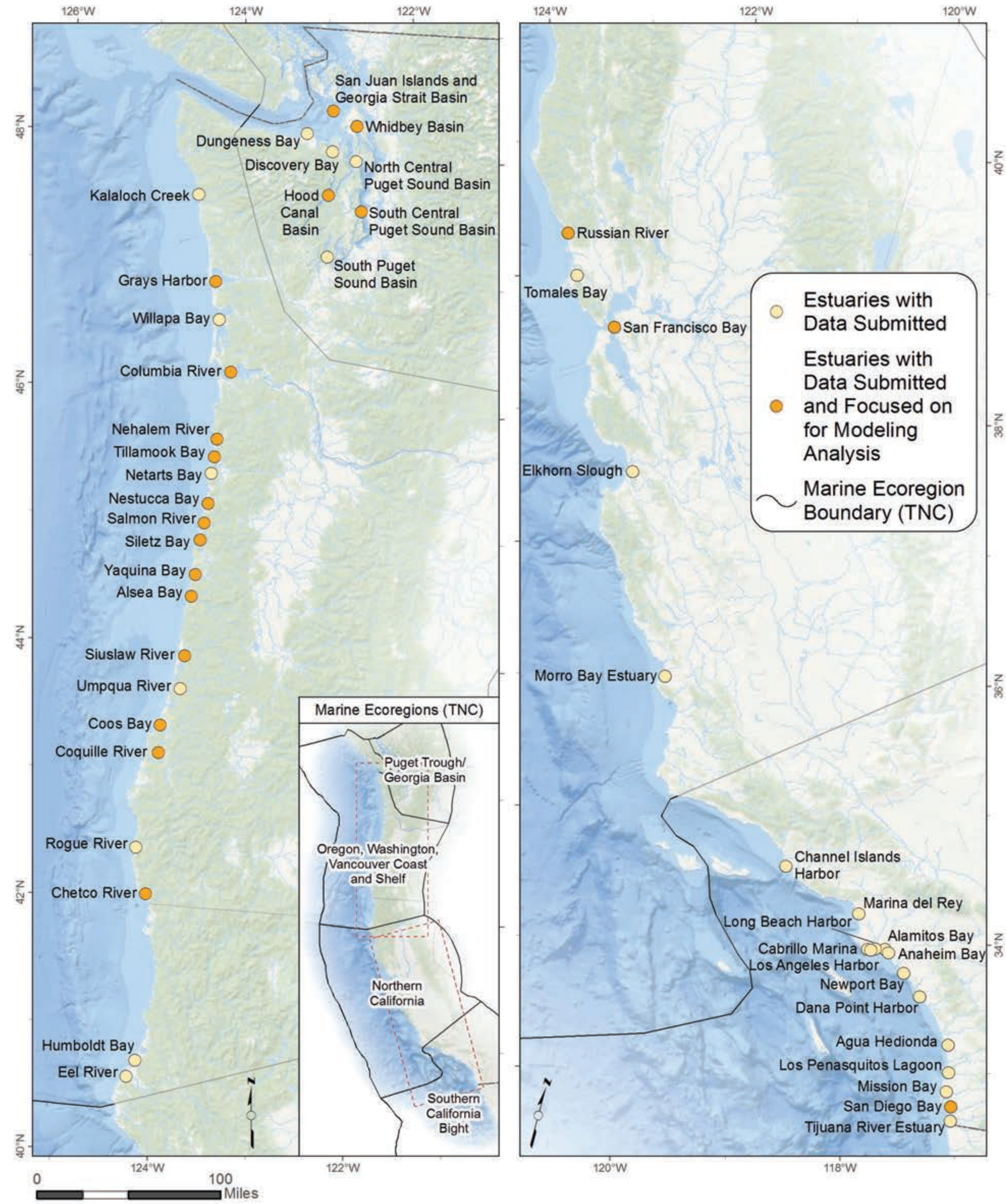


**FIGURE 3.** Map of the 47 estuaries covered by submitted data, with ecoregion boundaries. Highlighted are the 20 estuaries that had extensive beach seine data and were a focus for modeling analysis.

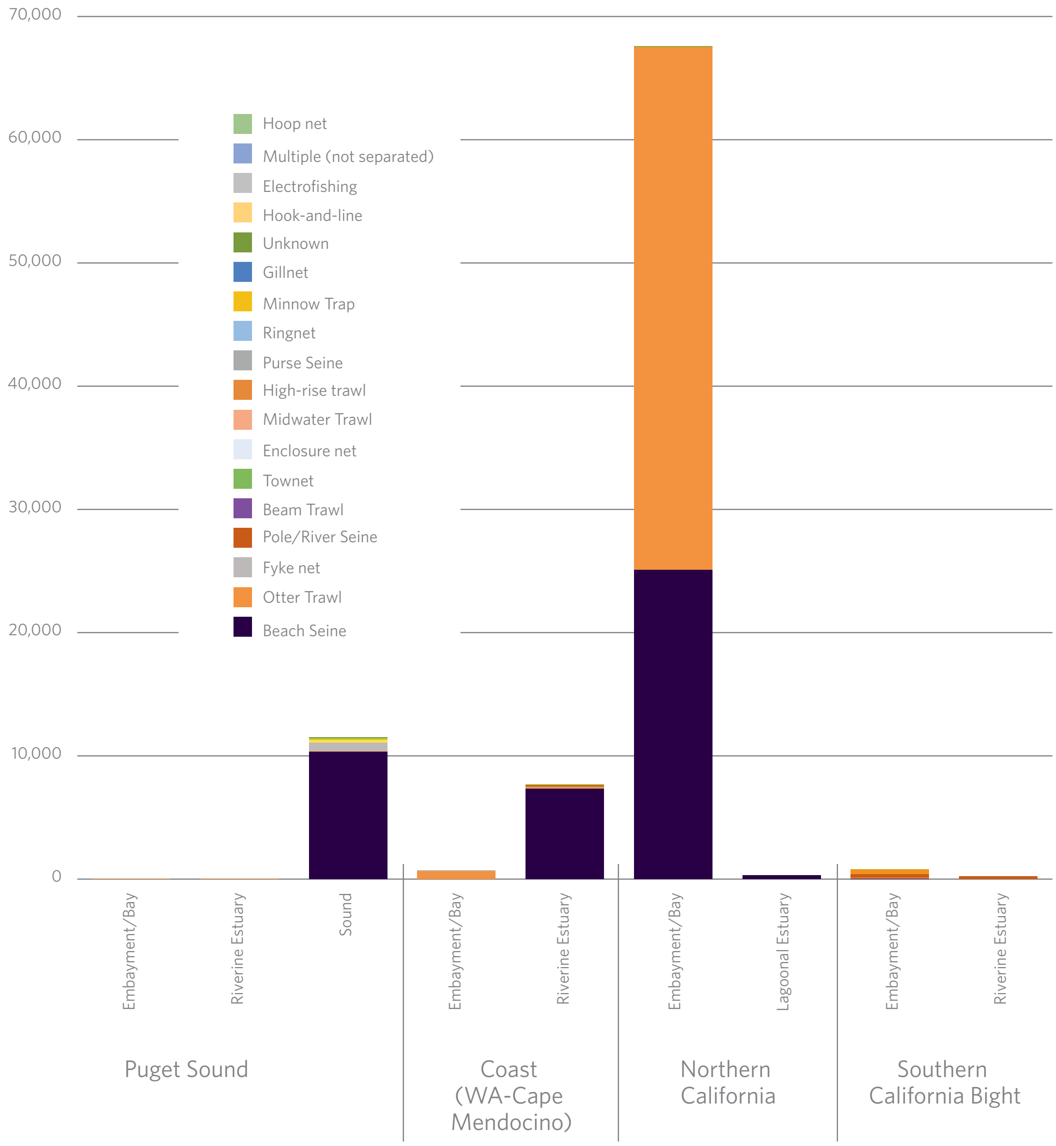


**FIGURE 4.** Number of sampling events in each ecoregion and estuary type, separated by gear type. Gear types are sorted in the legend from most sampling events at the bottom (beach seine) to least at the top (hoop net).

The 47 estuaries varied in representation by the 15 focal species (Figure 5). Some species, such as shiner perch and staghorn sculpin, were fairly ubiquitous, whereas others were more restricted both in their geographic range (Hughes et al. 2014) and in the submitted data. Some species, such as Pacific herring, had a broad geographic range, but were patchily distributed in data submitted. The Southern California Bight ecoregion was different from the other three ecoregions, and was mainly characterized by California halibut. Beach seines were the gear type that had the most numbers for comparison across the eight species that were clearly most abundant in the submitted data, and were subsequently used in the modeling analysis (Figure 6). We also attempted to analyze the otter trawl data for California halibut and the beach seine data for steelhead trout across estuaries, but the data coverage was not extensive enough, with most of the otter trawl sampling occurring in San Francisco Bay (Figure 4). Similarly, we attempted to analyze the otter trawl data for English Sole and Dungeness crab. Although numbers were high (Figure 6), again the bulk of the data submitted was from San Francisco Bay and precluded a cross-estuary comparison.

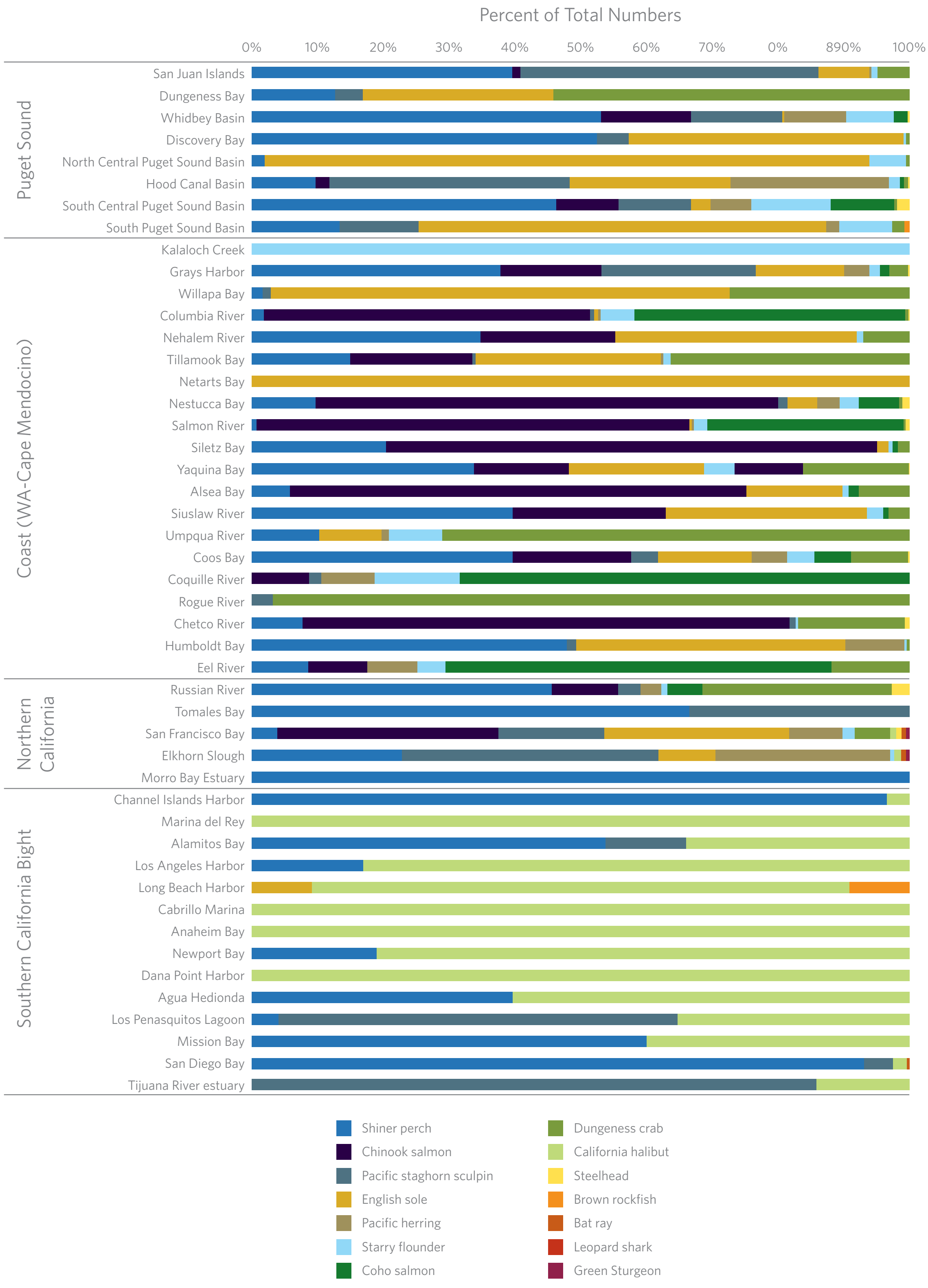


**FIGURE 5.** Species percent of total fish numbers in each estuary. Estuaries are sorted descending by latitude from top to bottom. Species are sorted from most numerous at the left (shiner perch) to least at the right (green sturgeon). California bay shrimp are not included as they were present in very high numbers only from San Francisco.

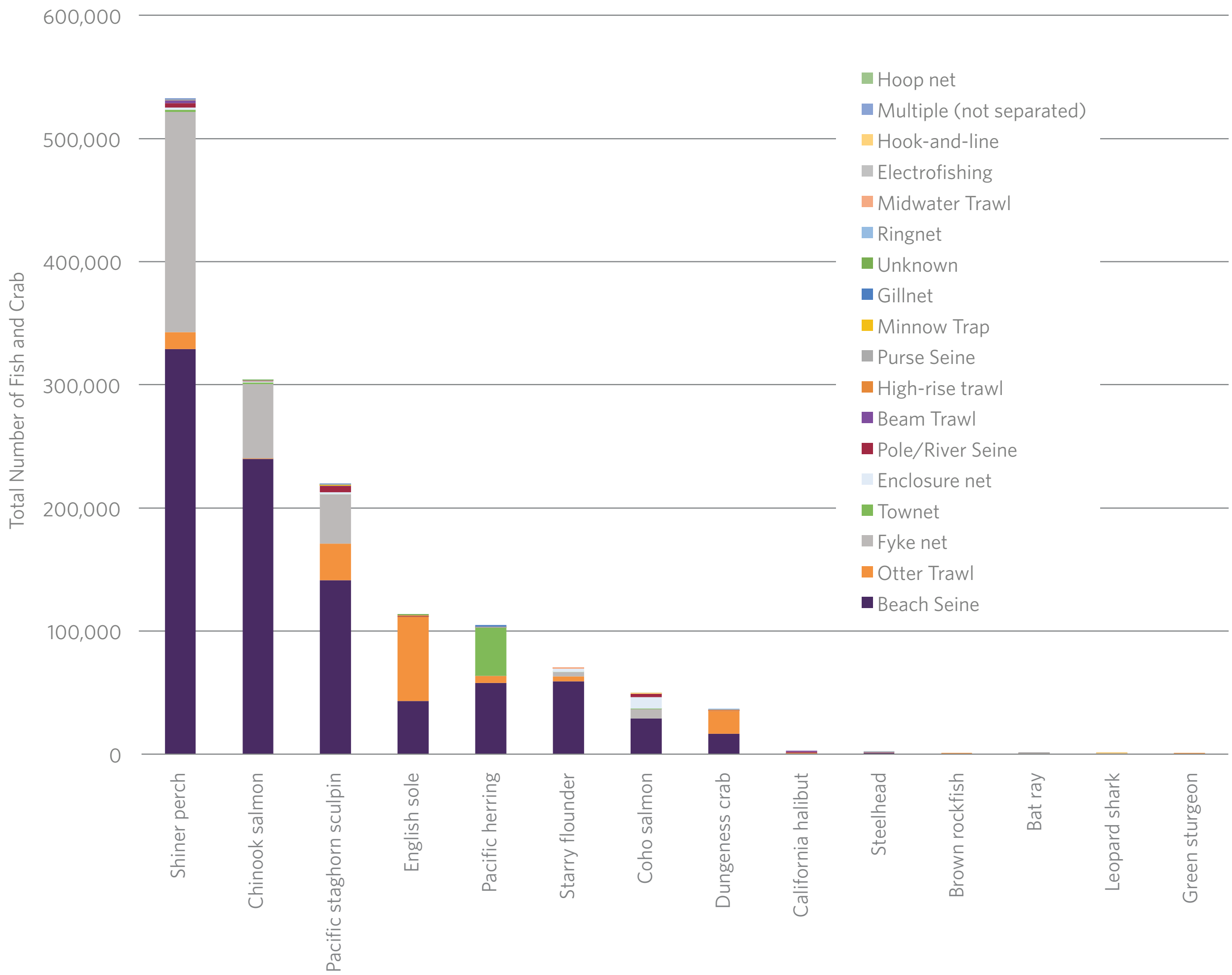


**FIGURE 6.** Total numbers of fish and crab captured by each gear type. Gear types are sorted in the legend from most numbers at the bottom (beach seine) to least at the top (hoop net). California bay shrimp are not represented in the graph, as they had very high numbers almost all from otter trawls.

## Focal species: Maps

Three maps are shown for each of the 15 species, illustrating presence, frequency of occurrence, and catch per unit effort (see Methods section for more details). Species best summarized by beach seine data are presented first (Chinook salmon, coho salmon, Dungeness crab, English sole, Pacific herring, shiner perch, Pacific staghorn sculpin, starry flounder, steelhead trout) followed by otter trawl data (bat ray, bay shrimp, brown rockfish, California halibut, green sturgeon, leopard shark).

Chinook Salmon

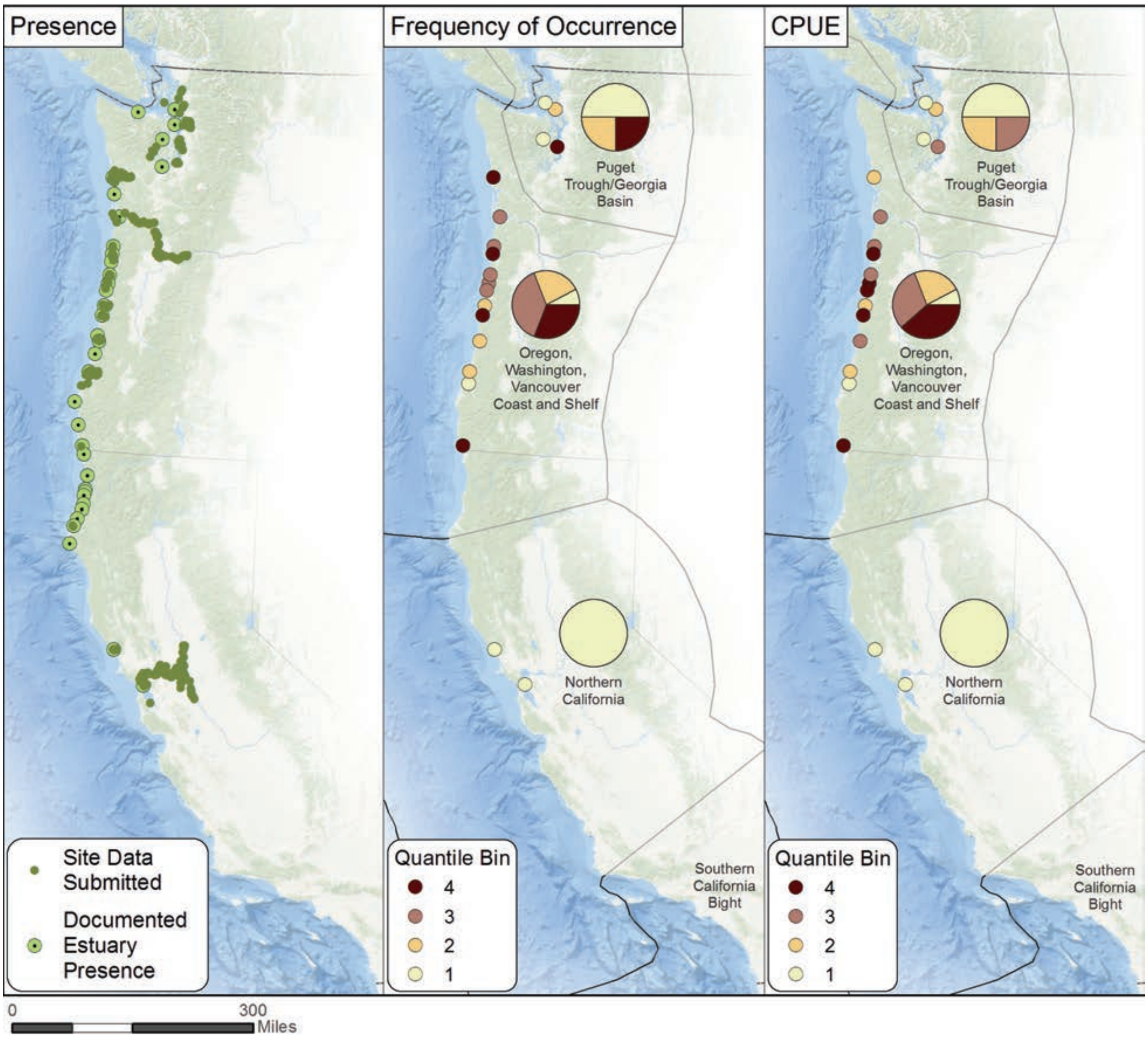


**FIGURE 7.** Maps of juvenile Chinook salmon presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that Chinook were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

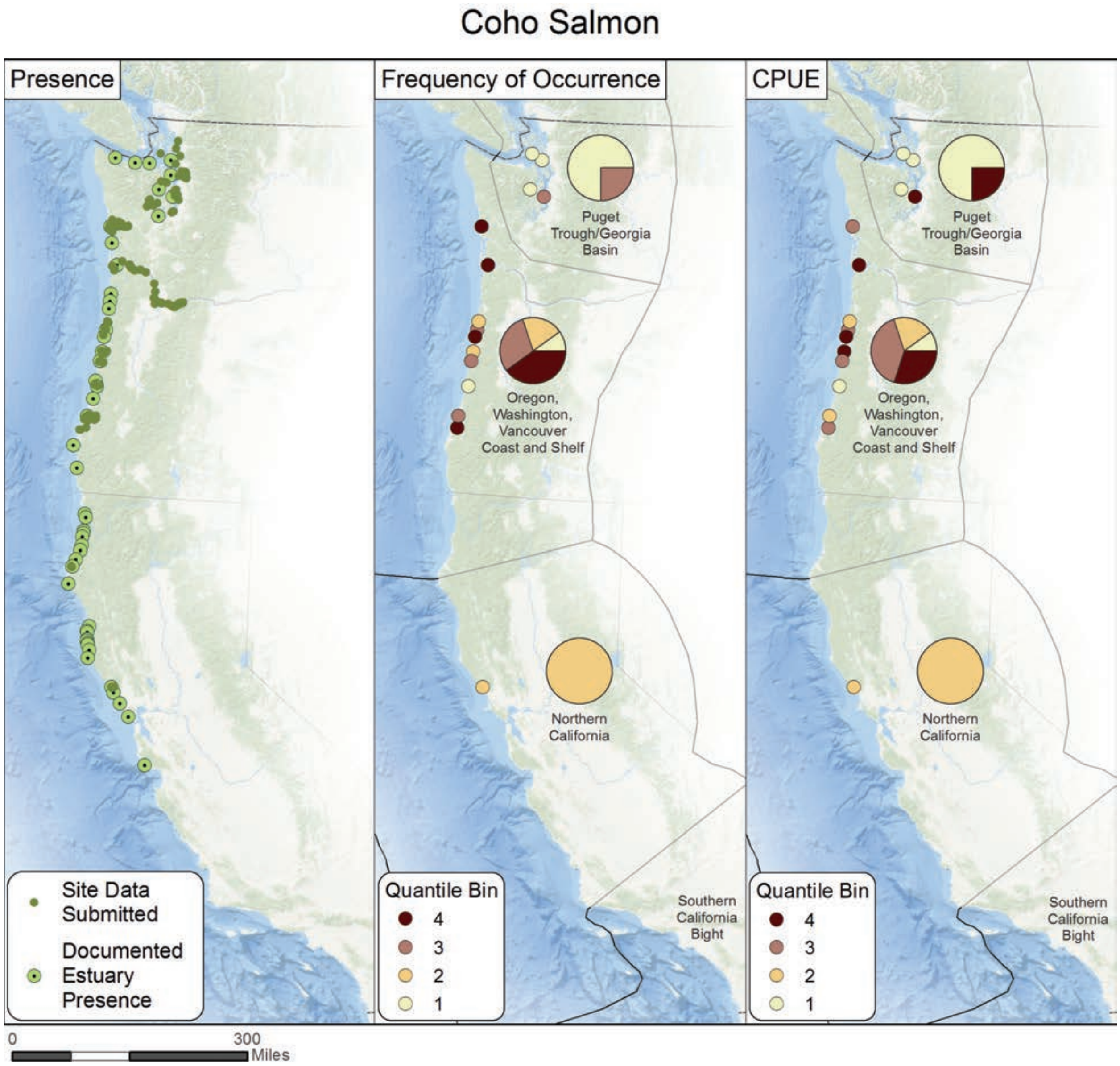


**FIGURE 8.** Maps of juvenile coho salmon presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that coho were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

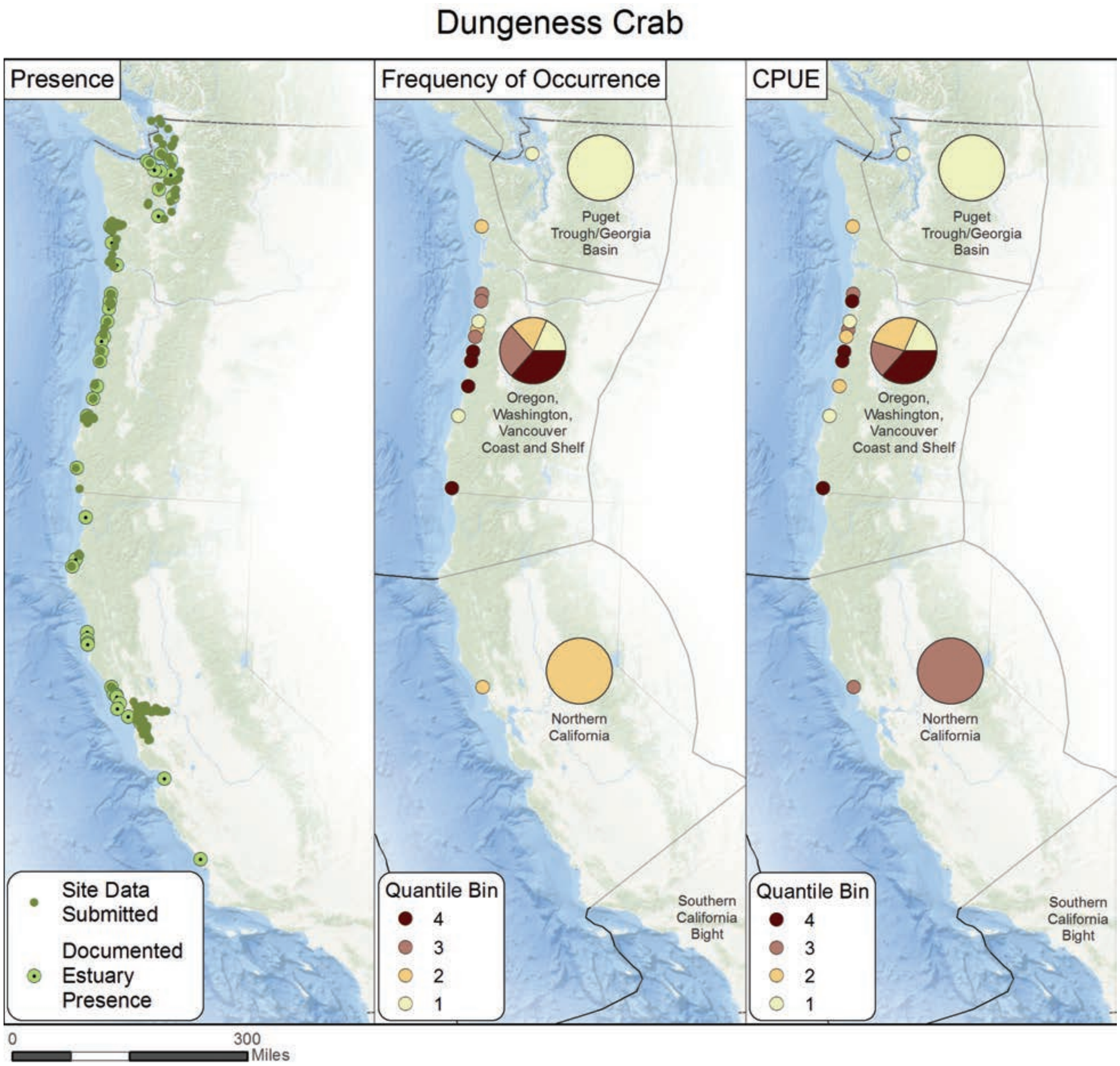


**FIGURE 9.** Maps of juvenile Dungeness crab presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that Dungeness crab were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

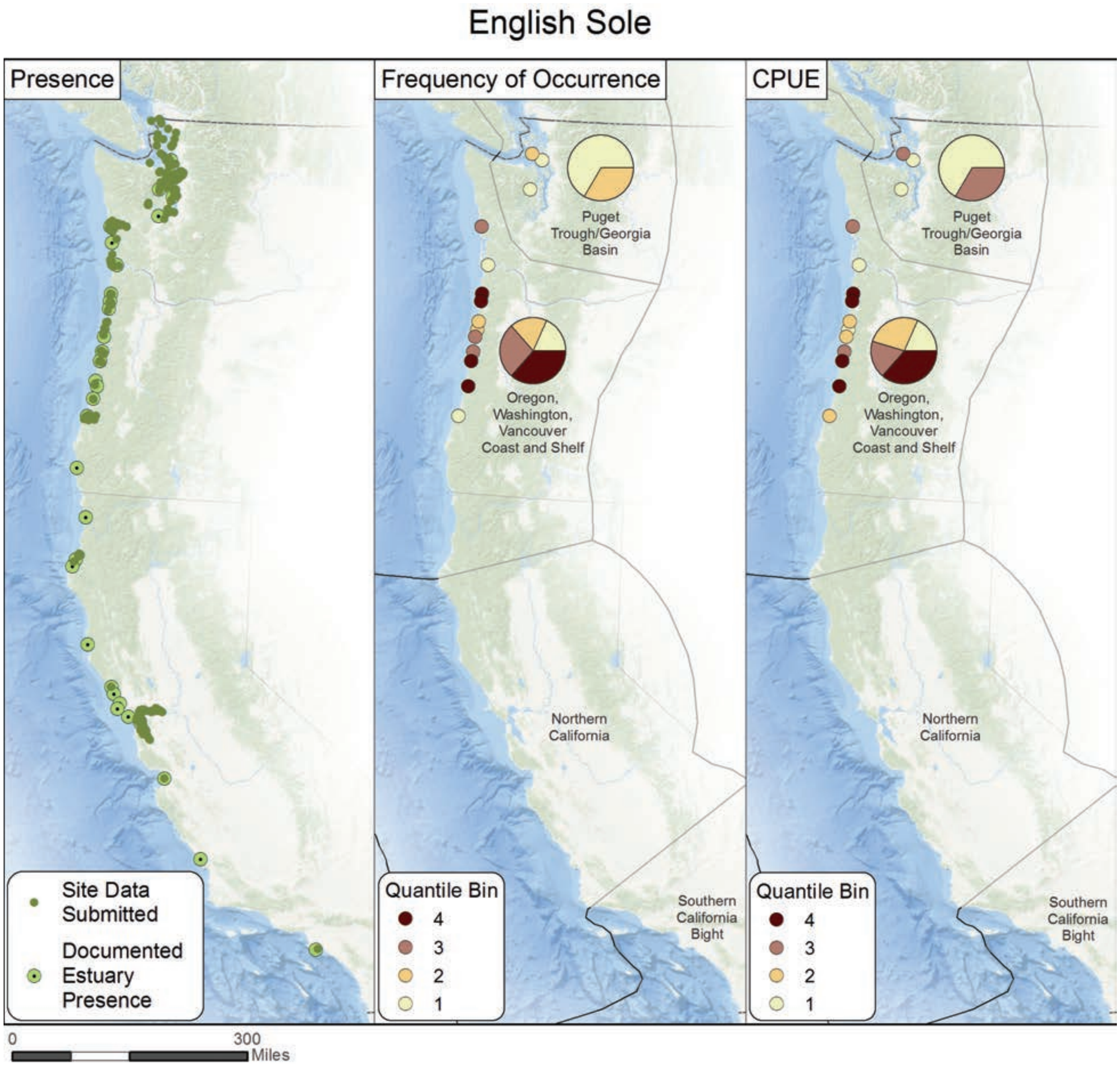


**FIGURE 10.** Maps of juvenile English sole presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that English sole were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

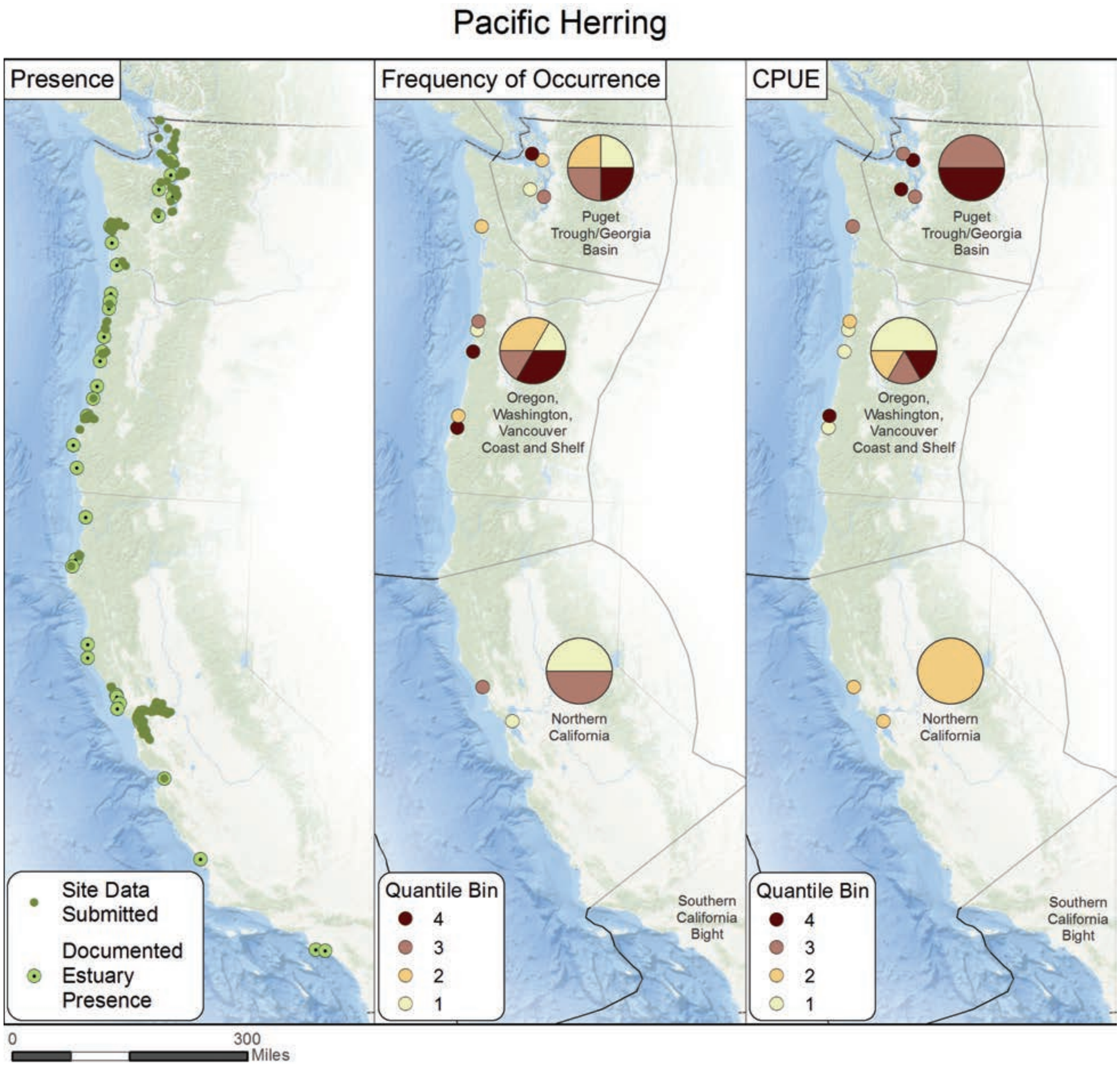


**FIGURE 11.** Maps of juvenile Pacific herring presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that herring were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

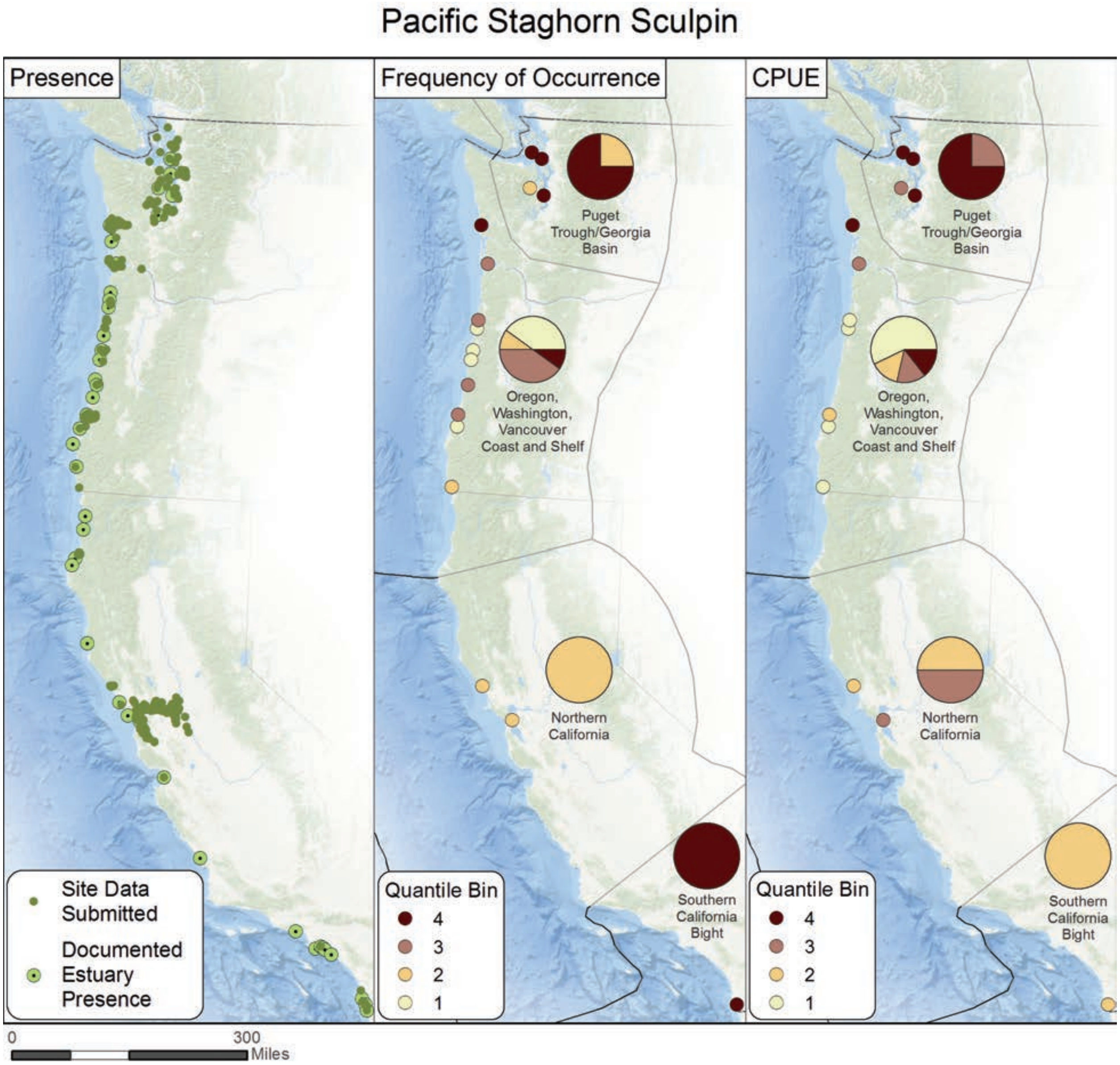


**FIGURE 12.** Maps of juvenile Pacific staghorn sculpin presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that staghorn sculpin were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

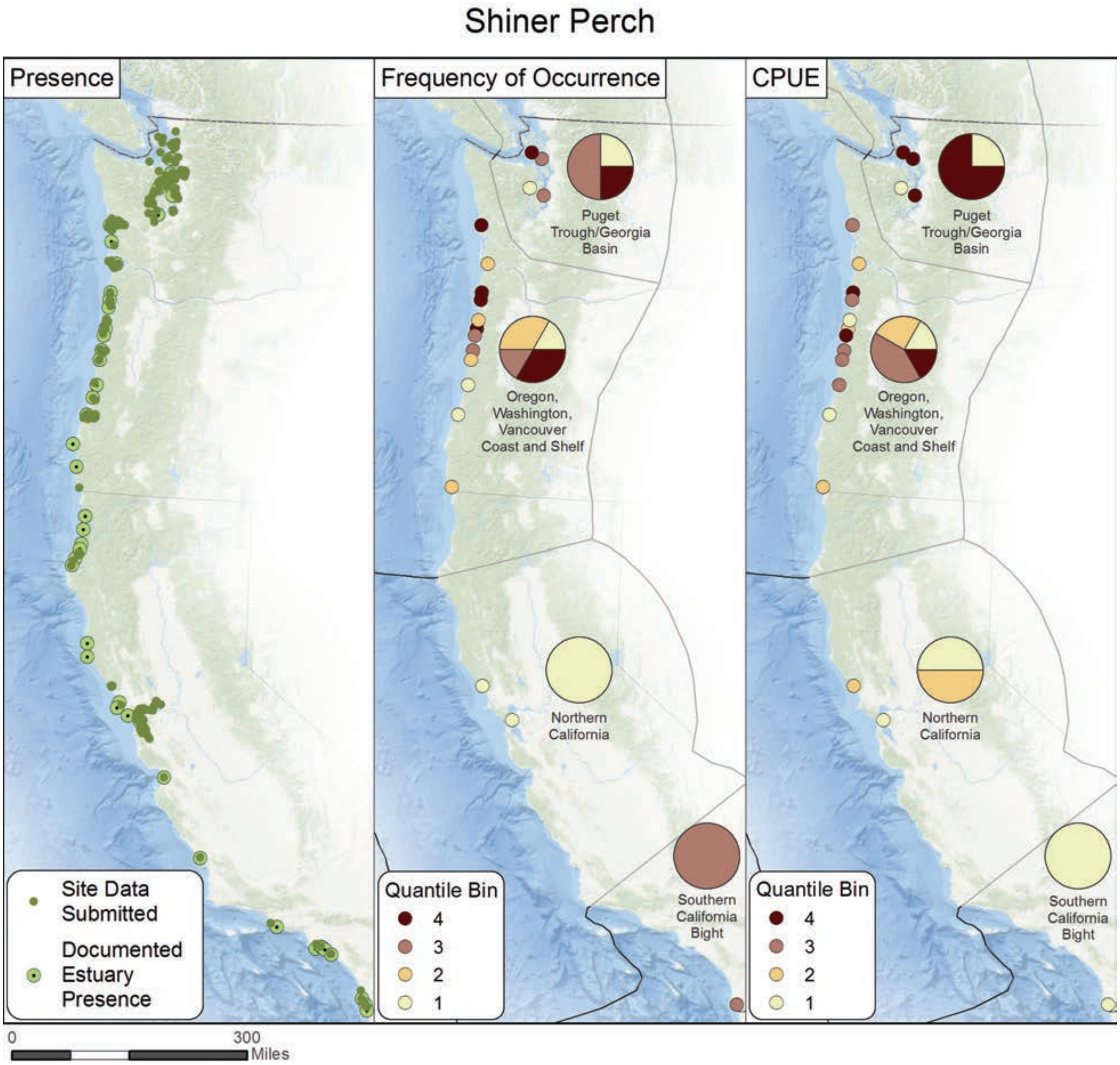


**FIGURE 13.** Maps of juvenile shiner perch presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that shiner perch were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

## Starry Flounder

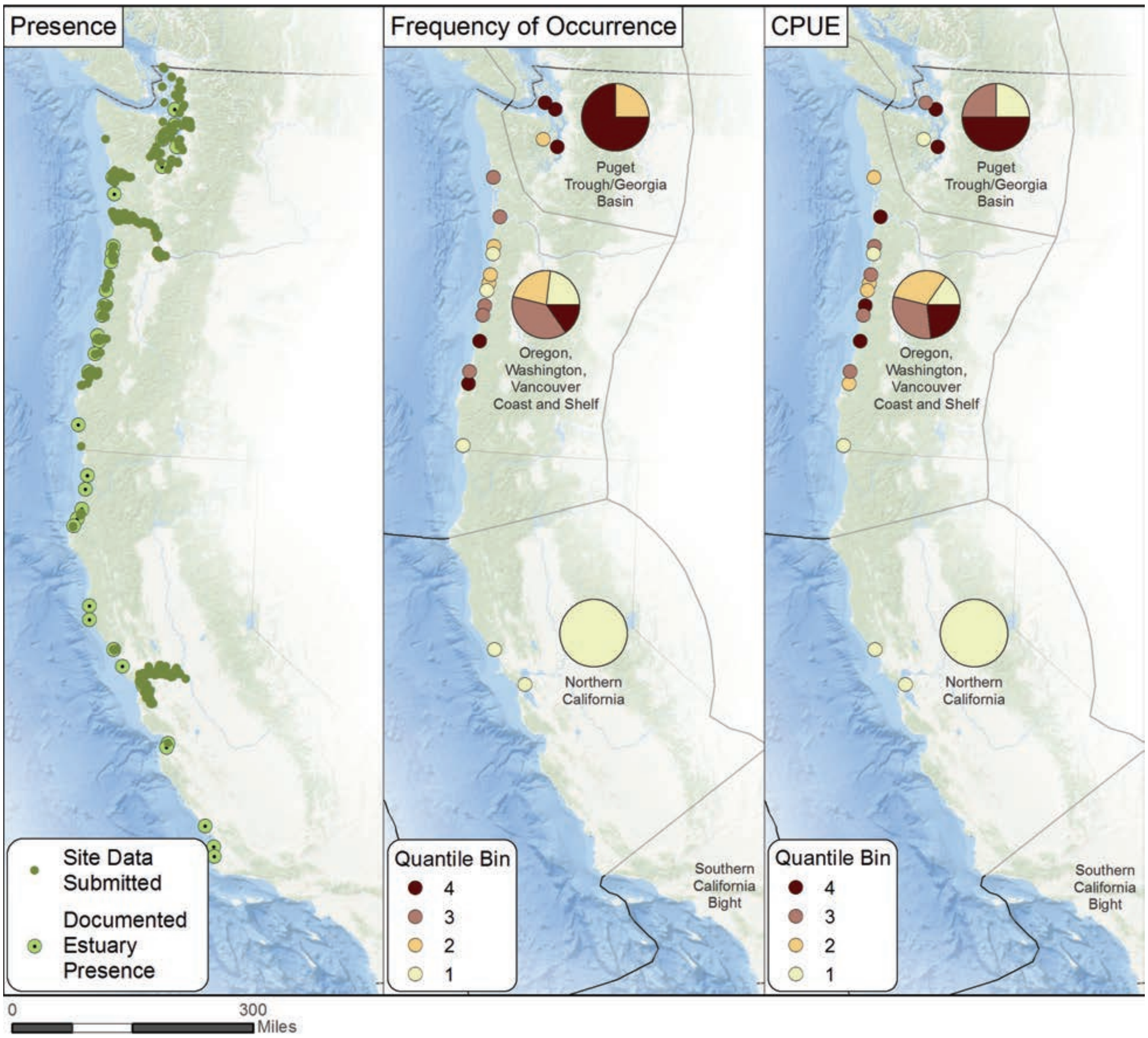


**FIGURE 14.** Maps of juvenile starry flounder presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that starry flounder were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

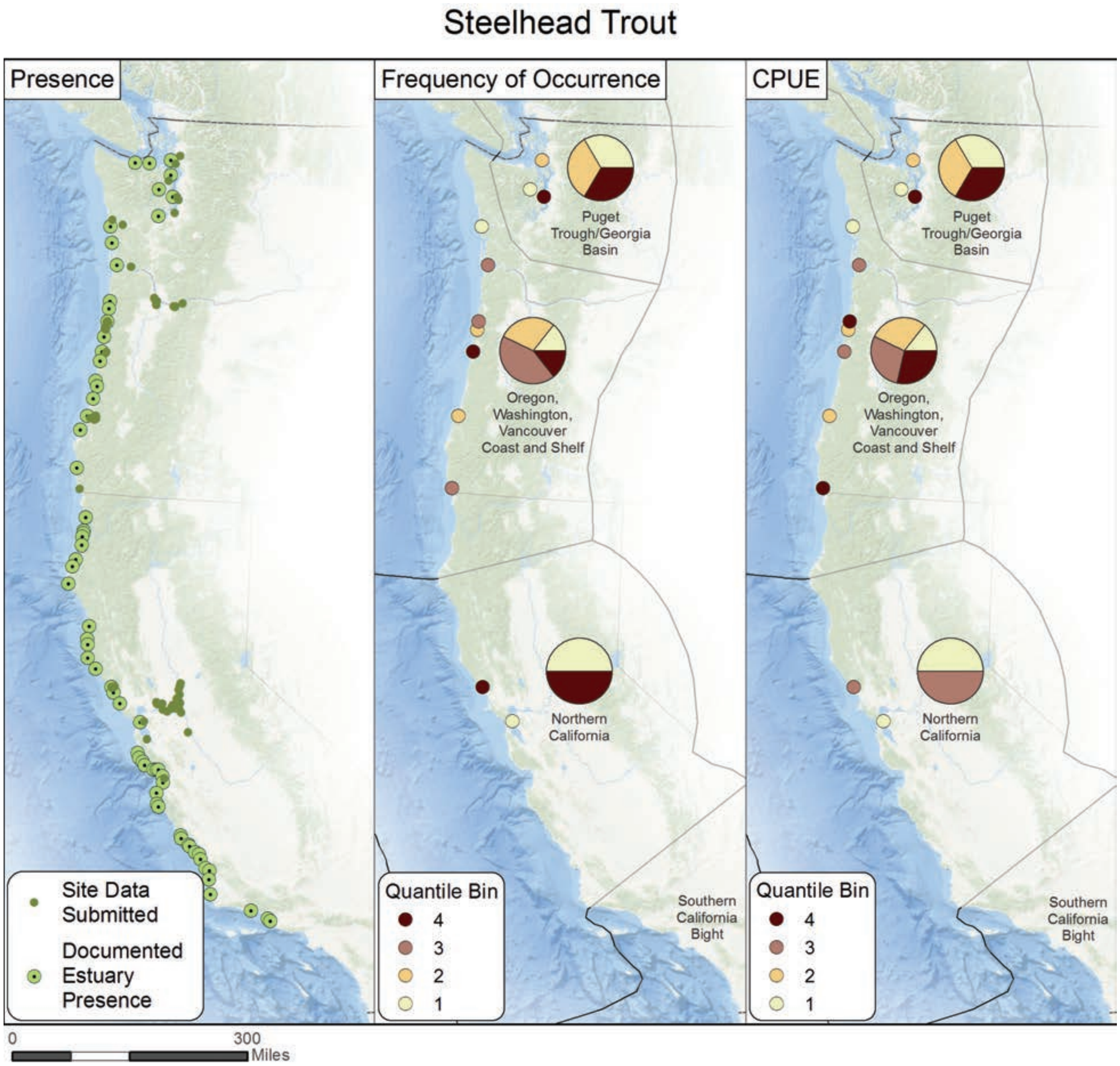


**FIGURE 15.** Maps of juvenile steelhead trout presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using beach seine data from the years 1990-2014, using only months that steelhead were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

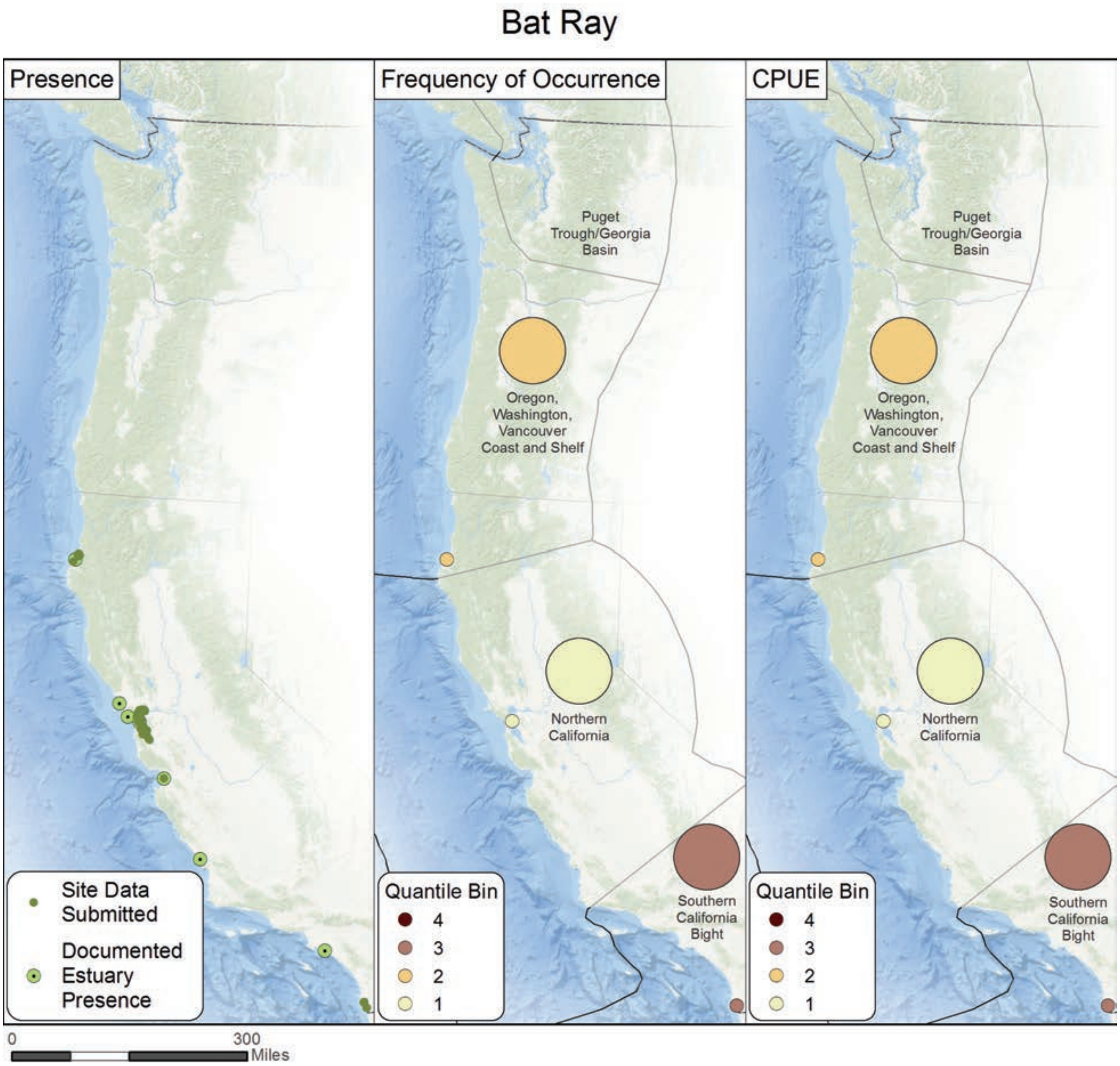


**FIGURE 16.** Maps of juvenile bat ray presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using otter trawl data from the years 1990-2014, using only months that bat rays were present in each estuary/record to account for different timings across estuaries/ latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

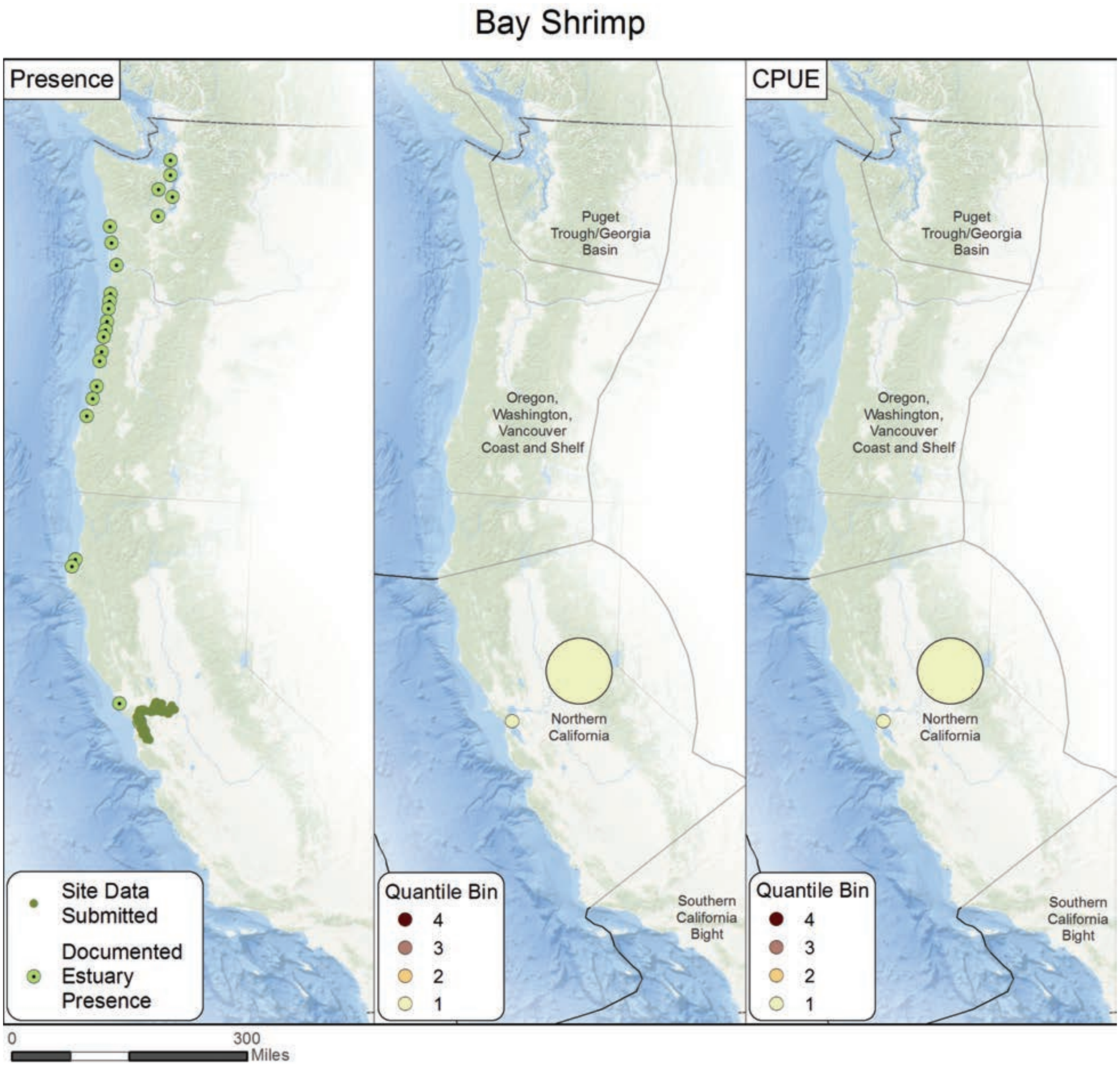


**FIGURE 17.** Maps of bay shrimp presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using otter trawl data from the years 1990-2014, using only months that bay shrimp were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

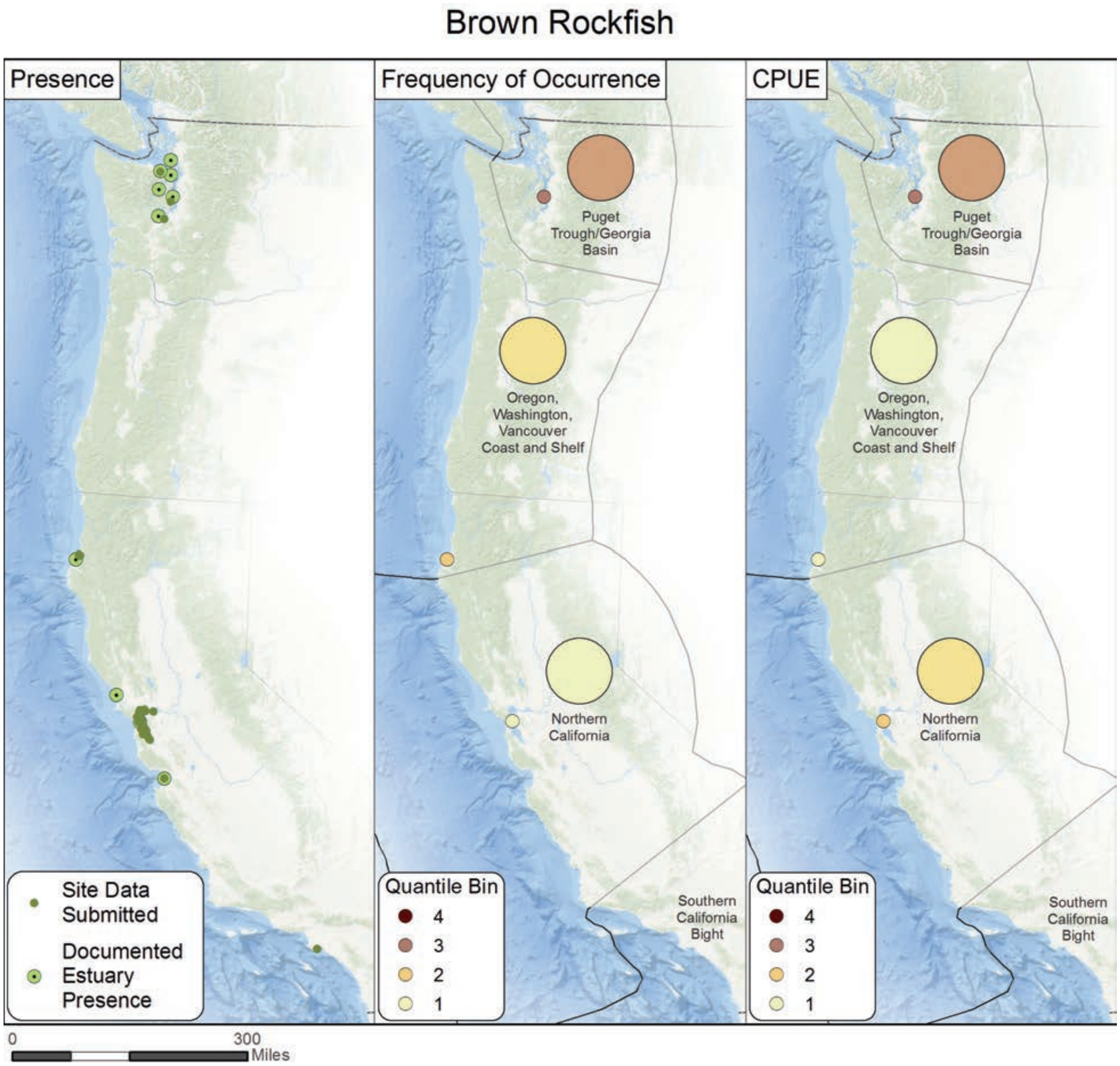


**FIGURE 18.** Maps of brown rockfish presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using otter trawl data from the years 1990-2014, using only months that brown rockfish were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

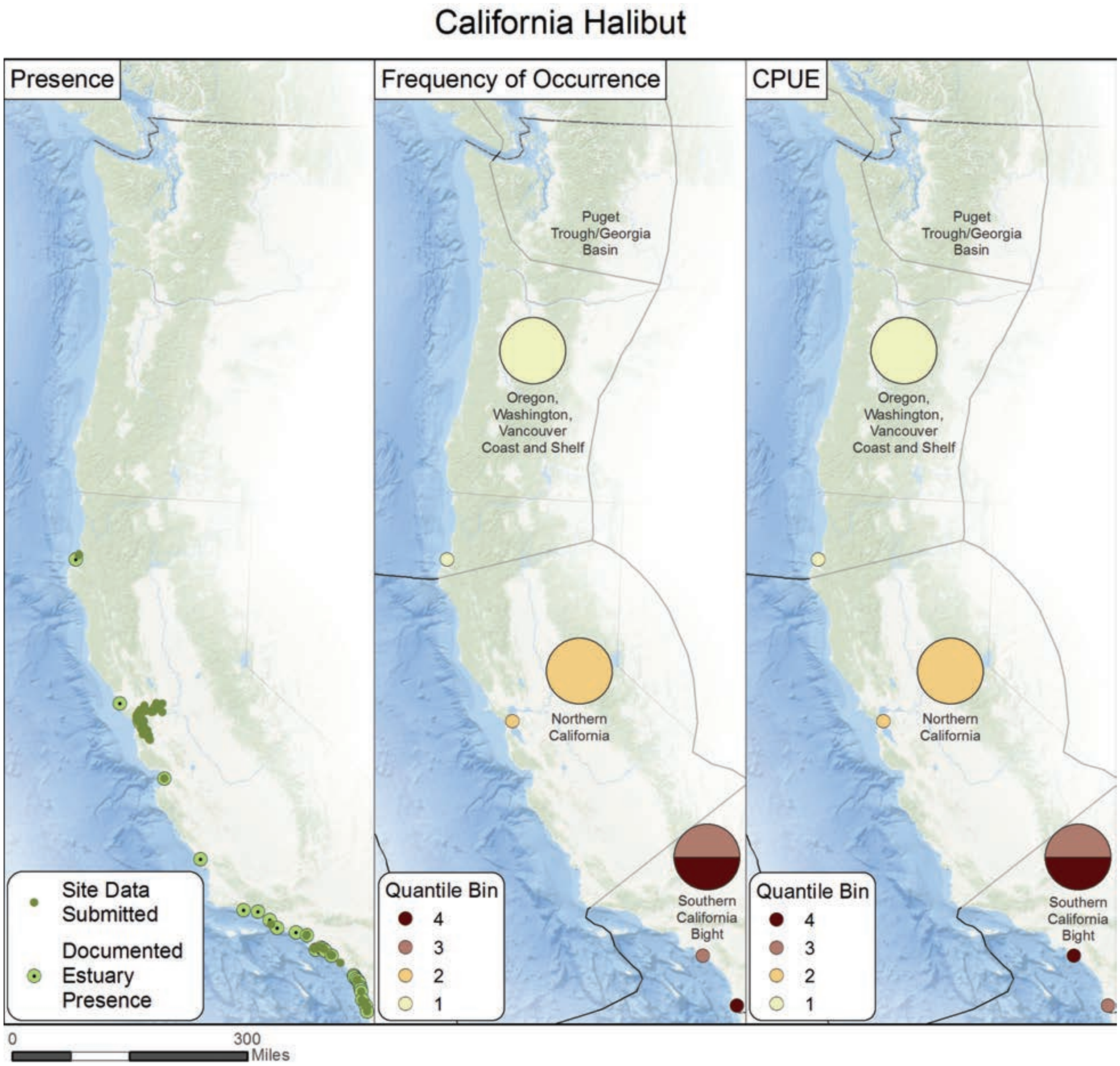


**FIGURE 19.** Maps of California halibut presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using otter trawl data from the years 1990-2014, using only months that halibut were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

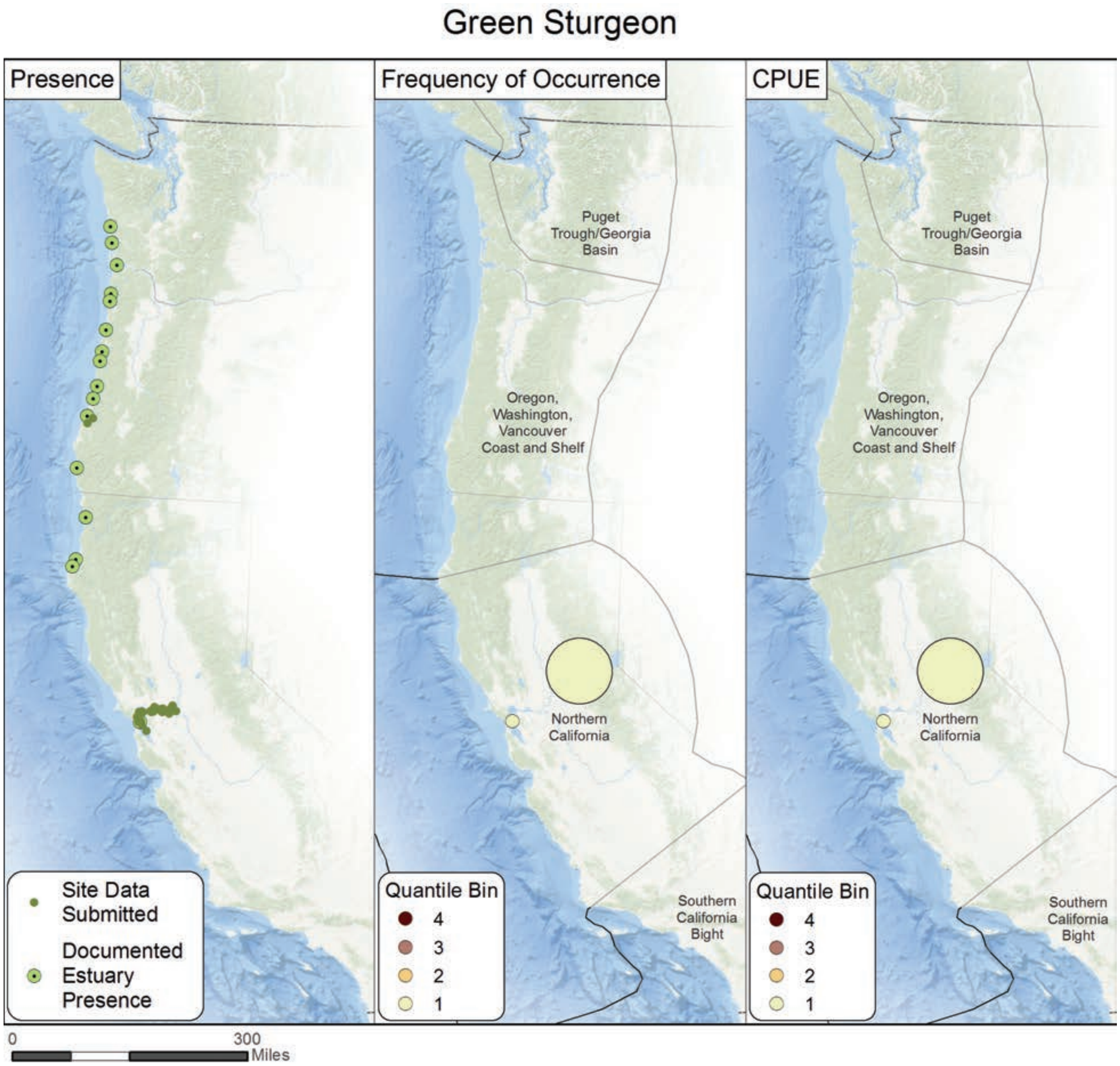


**FIGURE 20.** Maps of green sturgeon presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using otter trawl data from the years 1990-2014, using only months that green sturgeon were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

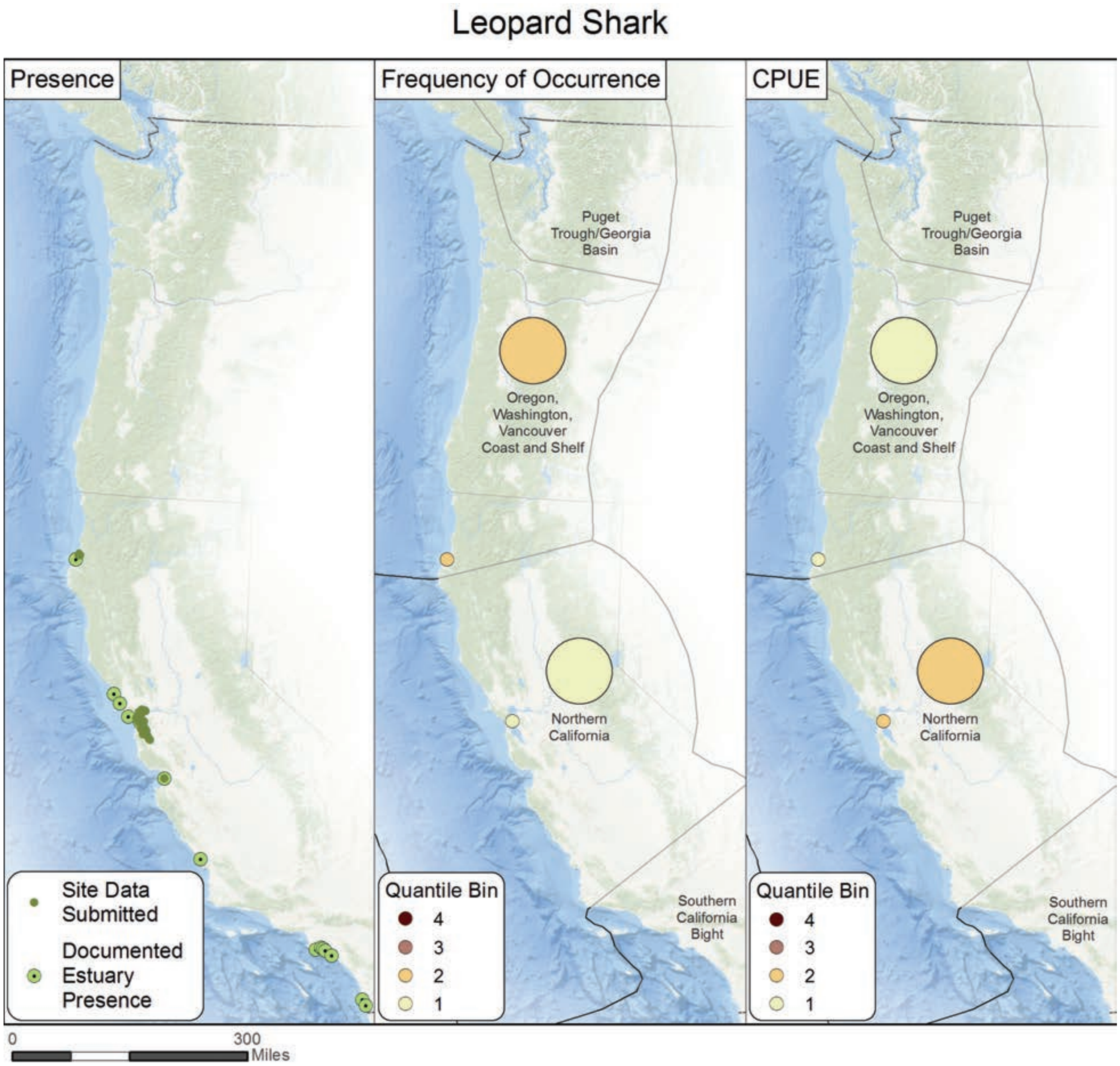


**FIGURE 21.** Maps of leopard shark presence, frequency of occurrence, and catch per unit effort (CPUE). The map of presence represents all gear types and years for site data that were submitted for this report, as well as estuaries with documented presence (Hughes et al. 2014). Average frequency of occurrence (# samples present/total) and CPUE were calculated using otter trawl data from the years 1990-2014, using only months that leopard shark were present in each estuary/record to account for different timings across estuaries/latitudes. Estuaries with less than five sampling events were not included. Averages for each estuary were binned into quantiles (grouped 1 to 4, low to high, respectively) to illustrate general low to high values, and summarized into pie charts for each ecoregion.

### Focal species: Modeling analysis

Presence/absence and CPUE models were fit for beach seine data representing eight species (Table 1). There was a significant effect of stressor bin in the CPUE model for Chinook salmon ($p < 0.01$), indicating lower CPUE of Chinook salmon in estuaries with greater stressor scores. There was also evidence of lower English sole ($p < 0.1$) and Pacific herring ($p = 0.15$) CPUE and coho salmon presence ($p < 0.1$) in estuaries with greater stressor scores. Salinity affected the presence and CPUE of most species, and there were annual trends in abundance for all species.

**TABLE 1.** Summary statistics for models describing the relationship between abundance and stressor bin, salinity bin (baseline: mixing zone), and day of year for each species.

| **Chinook Salmon** | | | |
|---|---|---|---|
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -3.77887 | 0.39725 | 2.00E-16 |
| Stressor Bin | -0.15679 | 0.39725 | 0.417 |
| Salinity Bin (Seawater Zone) | 1.01575 | 0.19334 | 2.00E-16 |
| Salinity Bin (Tidal Fresh Zone) | -0.02347 | 0.07782 | 0.563 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year): Mixing Zone | 1.998 | 1314.4 | 2.00E-16 |
| s( Day of Year): Seawater Zone | 1.99 | 268.1 | 2.00E-16 |
| s(Day of Year): Tidal Fresh Zone | 1.999 | 2478.8 | 2.00E-16 |
| R sq | 0.156 | | |
| **CPUE Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 3.37737 | 0.2747 | 2.00E-16 |
| Stressor Bin | -0.34465 | 0.13174 | 0.0089 |
| Salinity Bin (Seawater Zone) | -0.02644 | 0.13159 | 0.8407 |
| Salinity Bin (Tidal Fresh Zone) | 0.3954 | 0.07549 | 1.65E-07 |
| *Smooth Terms* | *edf* | *F* | *p* |

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| | | | |
|---|---|---|---|
| s(Day of Year): Mixing Zone | 1.926 | 32.03 | 4.03E-15 |
| s( Day of Year): Seawater Zone | 1.917 | 16.08 | 5.44E-08 |
| s(Day of Year): Tidal Fresh Zone | 1.985 | 94.52 | 2.00E-16 |
| R sq | 0.0232 | | |
| **Coho Salmon** | | | |
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -4.7176 | 0.6289 | 6.33E-14 |
| Stressor Bin | -0.5492 | 0.333 | 0.0991 |
| Salinity Bin (Seawater Zone) | -1.2994 | 0.1911 | 1.04E-11 |
| Salinity Bin (Tidal Fresh Zone) | 0.4561 | 0.0965 | 2.28E-06 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year): Mixing Zone | 1.991 | 333.41 | 2.00E-16 |
| s( Day of Year): Seawater Zone | 1.96 | 80.69 | 2.00E-16 |
| s(Day of Year): Tidal Fresh Zone | 1.976 | 227.24 | 2.00E-16 |
| R sq | 0.0697 | | |
| **CPUE Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 2.26477 | 0.32272 | 2.85E-12 |
| Stressor Bin | 0.08092 | 0.18898 | 0.669 |
| Salinity Bin (Seawater Zone) | -0.19838 | 0.19985 | 0.321 |
| Salinity Bin (Tidal Fresh Zone) | -0.10368 | 0.16007 | 0.517 |
| *Smooth Terms* | *edf* | *F* | *p* |
| s(Day of Year): Mixing Zone | 1.82 | 13.141 | 6.10E-07 |

*Continued on the next page*

| | | | |
|---|---|---|---|
| s( Day of Year): Seawater Zone | 1.01 | 1.366 | 0.071 |
| s(Day of Year): Tidal Fresh Zone | 1.571 | 2.91 | 0.0256 |
| R sq | 0.00746 | | |
| **Dungeness Crab** | | | |
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -4.957 | 0.2963 | 2.00E-16 |
| Stressor Bin | -0.1555 | 0.1552 | 0.316 |
| Salinity Bin (Seawater Zone) | 0.2721 | 0.1655 | 0.1 |
| Salinity Bin (Tidal Fresh Zone) | -4.8475 | 0.715 | 1.20E-11 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year) | 1.964 | 153.3 | 2.00E-16 |
| R sq | 0.113 | | |
| **CPUE Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 2.41151 | 0.35299 | 1.59E-11 |
| Stressor Bin | -0.03168 | 0.17915 | 0.859701 |
| Salinity Bin (Seawater Zone) | 0.87048 | 0.24106 | 0.000323 |
| Salinity Bin (Tidal Fresh Zone) | -2.99871 | 1.2429 | 0.016045 |
| *Smooth Terms* | *edf* | *F* | *p* |
| s(Day of Year) | 2.12E-06 | 0 | 0.54 |
| R sq | 0.0111 | | |

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| English Sole | | | |
|---|---|---|---|
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -5.1304 | 0.5628 | 2.00E-16 |
| Stressor Bin | -0.2319 | 0.3364 | 0.491 |
| Salinity Bin (Seawater Zone) | 1.0984 | 0.1241 | 2.00E-16 |
| Salinity Bin (Tidal Fresh Zone) | -5.4745 | 0.7114 | 1.41E-14 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year) | 1.983 | 180.3 | 2.00E-16 |
| R sq | 0.092 | | |
| **CPUE Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 3.1168 | 0.3696 | < 2e-16 |
| Stressor Bin | -0.3416 | 0.201 | 0.089459 |
| Salinity Bin (Seawater Zone) | 0.8599 | 0.2217 | 0.000108 |
| Salinity Bin (Tidal Fresh Zone) | -3.2889 | 1.528 | 0.031484 |
| *Smooth Terms* | *edf* | *F* | *p* |
| s(Day of Year) | 1.943 | 27.48 | 8.57E-13 |
| R sq | 0.0582 | | |
| **Herring** | | | |
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -6.4418 | 0.8169 | 3.14E-15 |
| Stressor Bin | -0.3328 | 0.3512 | 0.343 |

*Continued on the next page*

| | | | |
|---|---|---|---|
| Salinity Bin (Seawater Zone) | 1.4485 | 0.1137 | 2.00E-16 |
| Salinity Bin (Tidal Fresh Zone) | -4.4663 | 0.5087 | 2.00E-16 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year) | 1.979 | 238.3 | 2.00E-16 |
| R sq | 0.0297 | | |
| **CPUE Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 0.73918 | 0.10385 | 2.13E-12 |
| Stressor Bin | -0.06131 | 0.04232 | 0.148 |
| Salinity Bin (Seawater Zone) | 0.06552 | 0.0776 | 0.399 |
| Salinity Bin (Tidal Fresh Zone) | -0.39908 | 0.38764 | 0.304 |
| *Smooth Terms* | *edf* | *F* | *p* |
| s(Day of Year) | 1.895 | 19 | 3.38E-09 |
| R sq | 0.0324 | | |
| **Shiner Perch** | | | |
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -6.7224 | 0.5273 | 2.00E-16 |
| Stressor Bin | 0.1161 | 0.2436 | 0.634 |
| Salinity Bin (Seawater Zone) | 0.5734 | 0.1005 | 1.15E-08 |
| Salinity Bin (Tidal Fresh Zone) | -2.3243 | 0.1149 | 2.00E-16 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year) | 1.998 | 2373 | 2.00E-16 |
| R sq | 0.211 | | |

*Continued on the next page*

| CPUE Model | | | |
|---|---|---|---|
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 4.3238 | 0.4169 | <2e-16 |
| Stressor Bin | -0.1167 | 0.1862 | 0.531 |
| Salinity Bin (Seawater Zone) | -0.2828 | 0.2664 | 0.2886 |
| Salinity Bin (Tidal Fresh Zone) | -0.5315 | 0.3157 | 0.0923 |
| *Smooth Terms* | *edf* | *F* | *p* |
| s(Day of Year) | 1.948 | 24.81 | 1.08E-11 |
| R sq | 0.00537 | | |
| **Staghorn Sculpin** | | | |
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -5.29881 | 0.74594 | 1.22E-12 |
| Stressor Bin | 0.29701 | 0.32008 | 0.353 |
| Salinity Bin (Seawater Zone) | 0.29635 | 0.06053 | 9.81E-07 |
| Salinity Bin (Tidal Fresh Zone) | -2.29505 | 0.05981 | 2.00E-16 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year) | 1.993 | 528.3 | 2.00E-16 |
| R sq | 0.201 | | |
| **CPUE Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 1.970222 | 0.602206 | 0.00107 |
| Stressor Bin | 0.002523 | 0.239821 | 0.99161 |
| Salinity Bin (Seawater Zone) | 0.076362 | 0.091578 | 0.40439 |

*Continued on the next page*

| | | | |
|---|---|---|---|
| Salinity Bin (Tidal Fresh Zone) | -0.856776 | 0.10607 | 7.50E-16 |
| *Smooth Terms* | *edf* | *F* | *p* |
| s(Day of Year) | 1.989 | 214.1 | 2.00E-16 |
| R sq | 0.0167 | | |
| **Starry Flounder** | | | |
| **Presence/Absence Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | -4.50799 | 0.45607 | 2.00E-16 |
| Stressor Bin | -0.23625 | 0.21966 | 0.28214 |
| Salinity Bin (Seawater Zone) | -0.79475 | 0.1016 | 5.37E-15 |
| Salinity Bin (Tidal Fresh Zone) | -0.20295 | 0.06552 | 0.00195 |
| *Smooth Terms* | *edf* | *Chi Sq* | *p* |
| s(Day of Year) | 1.973 | 158.1 | 2.00E-16 |
| R sq | 0.141 | | |
| **CPUE Model** | | | |
| *Parametric Coefficients* | *Estimate* | *SE* | *p* |
| Intercept | 1.3068 | 0.4512 | 0.00379 |
| Stressor Bin | 0.1051 | 0.2126 | 0.62103 |
| Salinity Bin (Seawater Zone) | -0.1465 | 0.2075 | 0.48005 |
| Salinity Bin (Tidal Fresh Zone) | 0.2978 | 0.1304 | 0.02245 |
| *Smooth Terms* | *edf* | *F* | *p* |
| s(Day of Year) | 1.982 | 109.2 | 2.00E-16 |

Relative probability of presence and CPUE compared to stressor bin was visualized for all species (Figures 22 and 23). These visualizations show the data linked by logit and log link functions, which is necessary to preserve the linear relationships that are quantified by the models and why some values are negative. These values should therefore be interpreted relative to one another for each species rather than indicating absolute probability of presence or CPUE. Although stressor bin was statistically significant only in the Chinook salmon CPUE model at an alpha level of 0.05, models with lower p value estimates for stressor bin often showed a negative relationship between abundance and stressor bin.

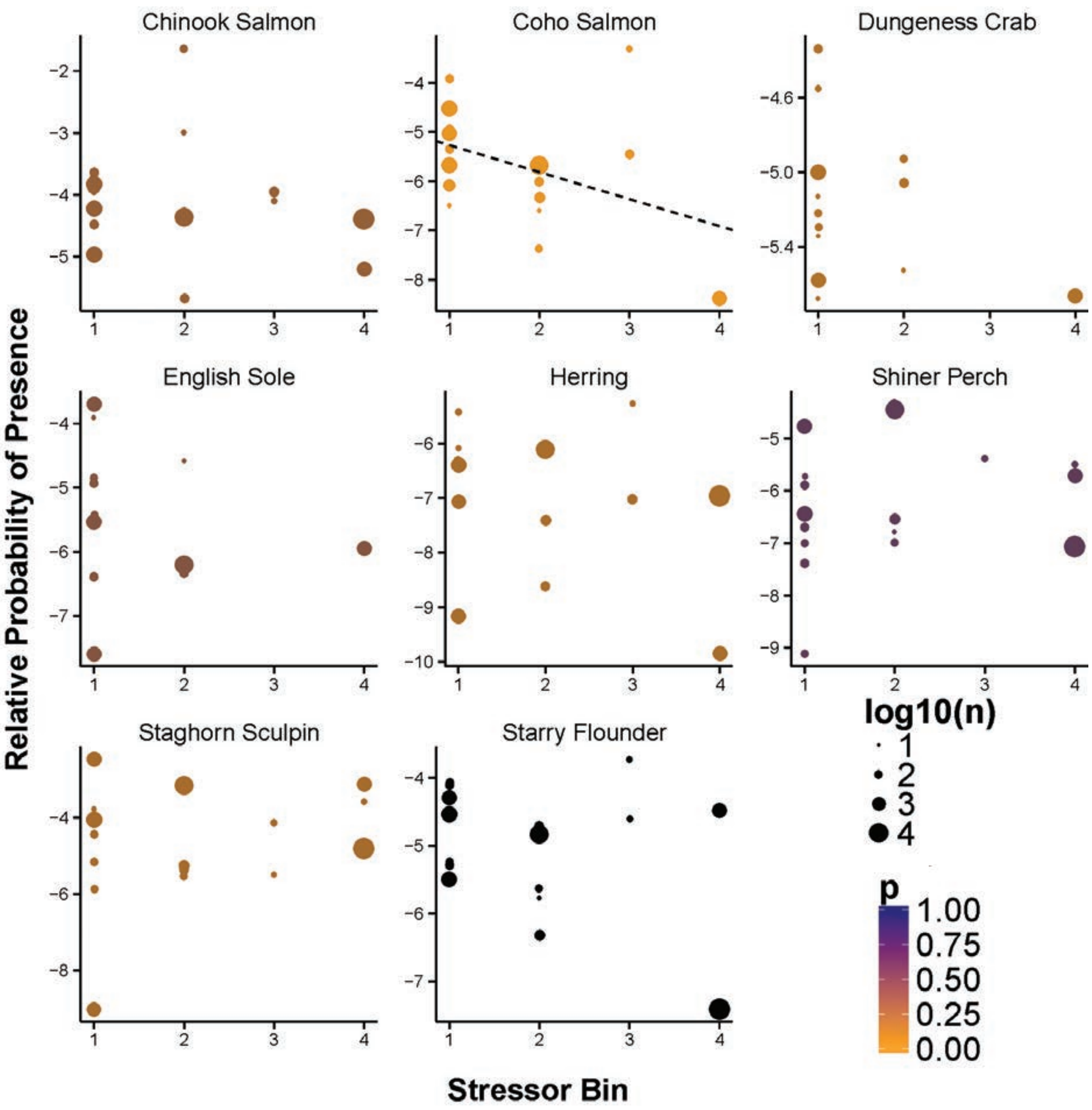


**FIGURE 22.** Modeled values of probability of presence vs. stressor bin for all modeled species. Points indicate values for different estuaries, point size is proportional to the log-transformed sample size (n) of data from that estuary, and color indicates the p value for the parameter estimate of stressor bin for that model. Where appropriate, lines indicate linear relationship between probability of species presence and stressor bin (solid = significant relationship, dashed = marginally insignificant relationship).

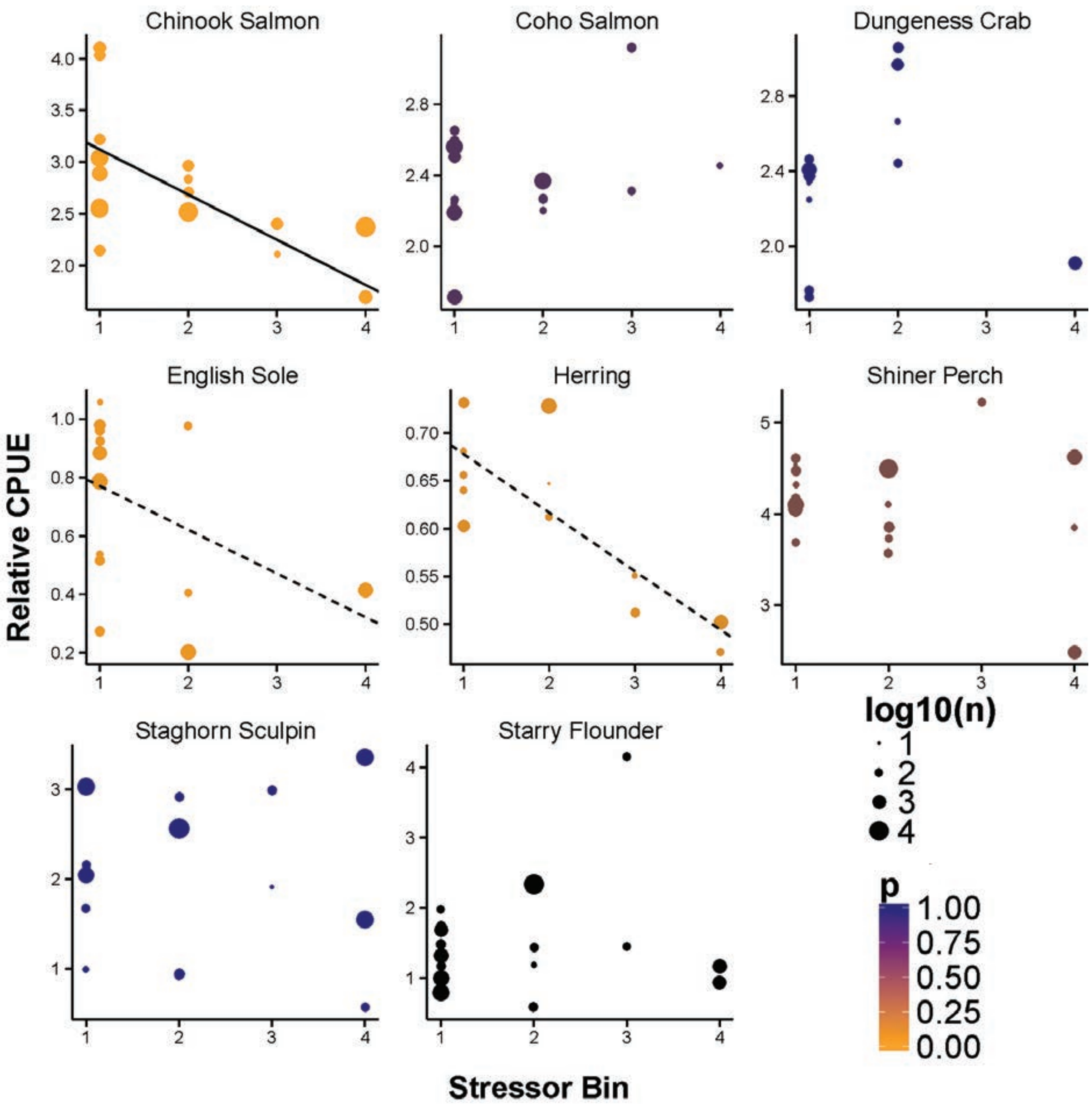


**FIGURE 23.** Modeled values of CPUE vs. stressor bin for all modeled species. Points indicate values for different estuaries, point size is proportional to the log-transformed sample size (n) of data from that estuary, and color indicates the p value for the parameter estimate of stressor bin for that model. Where appropriate, lines indicate linear relationship between CPUE and stressor bin (solid = significant relationship, dashed = marginally insignificant relationship).

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# DISCUSSION

Our analysis has highlighted significant opportunities for learning based on the combined strength of many datasets that cover a broad spatial scale as well as the constraints that could not be addressed and must be informed by more focused field studies and specific data requests. At the estuary level, our analyses that included stressor scores from the NFHP National Estuary Assessment (Greene et al. 2015b) are most informative in helping to guide management decisions on restoration priorities. Juvenile Chinook salmon are the only species that showed a significant decrease in CPUE with increasing stressor score. One plausible explanation for this is that estuaries are a vital transition zone for outmigrating Chinook salmon (Simenstad et al. 1982), which may be more dependent on the estuary as a nursery and more prone to stressors in the estuary than other species. In addition, wild juvenile Chinook salmon have been shown to use estuarine environments more extensively than hatchery Chinook salmon (Rice et al. 2011), emphasizing the importance of these systems for naturally-produced fish.

When planning West Coast restoration actions, we recommend targeting estuaries that have a stressor score above a certain value, with the goal of moving the score downward and toward a more natural state. Additional work would have to be done to target a specific threshold level, but in lieu of that, our analysis would suggest that scores below 0.4 might be an appropriate goal, especially for Chinook salmon. Stressor scores were a composite of 43 indicators representing four categories (land cover, river flow, pollution, and eutrophication; Greene et al. 2015b); further analysis could also seek to pinpoint effects of separate versus multiple stressors. Common types of threats in estuaries to focal fish species are habitat loss, species invasions, hypoxia from eutrophication, pesticides, and climate change, which warrant further analysis especially given that juvenile Chinook salmon were one of the species with the most documented of 19 potential threats (Hughes et al. 2014).

Modeling presence/absence and abundance metrics in relation to environment variables is a continually developing field, and there are many avenues for refinement (Vasconcelos et al. 2013). Few estuaries are unaffected by stress, and developing a regional network with management guidelines will be key to coordinate efforts (Merrifield et al. 2011). There can be differing frameworks for strategizing restoration and preservation actions across a range of relatively intact to highly impacted estuaries, and PMEP is currently developing a prioritization strategy for the West Coast to help guide such a regional network. Fish sampling concurrent with updating of the national assessment would allow for future analysis of any trends, including whether or not increasing or decreasing stressor scores results in increases or decreases in Chinook numbers. Additionally, since there is a general trend of increasing stressor scores in heavily urbanized estuaries in southern California (Greene et al. 2015b), a better data representation of these estuaries in future analyses would be informative.

For the other focal species that did not show a significant effect of estuary stressor score, there were several trends in the data suggesting associations with estuarine nursery function and avenues for future work. English sole, coho salmon, and Pacific herring showed negative trends with increasing stressor bins similar to Chinook salmon, and therefore these four species may receive the largest benefit from restoration efforts in intertidal and shallow subtidal areas that were the focus of beach seine efforts in our analysis. There was comparatively less evidence for a negative effect of stressor bin on staghorn sculpin, shiner perch, starry flounder, and Dungeness crab. These species may be more adaptable to certain characteristics of altered systems, for example by occupying a wider range of available habitats given the human alteration that has already taken place to historic habitats. Staghorn sculpin and shiner perch, in particular, seem not to be as affected by estuarine stressors, as a recent review did not find documentation of threats to their juvenile life-stages in estuaries (Hughes et al. 2014).

Focusing on beach seine data limited the implications of our analysis to intertidal and shallow subtidal areas mainly in Washington and Oregon estuaries, largely because species such as Dungeness crab, English sole, and Pacific herring move to colder deeper waters in the more southern estuaries of their range in California. We attempted to run the presence-absence and CPUE models on otter trawl data for these species and California halibut, but the amount of data we received was too limited to obtain meaningful results. Forage fish CPUE from trawl data has been similarly analyzed using linear mixed effects models over time in Puget Sound and shows a response to anthropogenic stressors (Greene et al. 2015a), further emphasizing that forage fish, such as Pacific herring, should be among the focal species monitored for understanding stressors and restoration potential.

Based on our summary maps of sampling locations, frequency of occurrence, and CPUE, riverine estuaries were the most sampled estuary type represented in the contributed data. The northern region of the West Coast is dominated by riverine estuaries (Heady et al. 2014), and the amount of data received reflected large sampling efforts in those systems. Our summaries show that riverine estuaries are important nursery areas, even though the data resolution did not allow us to focus on specific habitat types. Although California is numerically dominated by lagoonal estuaries, they were not as extensively sampled as larger riverine estuaries and bays because of their small size (Heady et al. 2014, Hughes et al. 2014). Our focus on 15 species precluded an overall assemblage analysis, which would be informative to follow-up on what estuarine groups respond to certain habitat indicators (Monaco et al. 1992). Taken as a whole, riverine estuaries are vital ecosystems containing a diversity of habitat types, and maintaining this natural complexity should be prioritized, especially given increased demands on shorelines due to the combination of sea level rise and coastal development.

There are strengths and weaknesses of any data meta-analysis, and the limitations we encountered give us an opportunity to make informed recommendations for future studies. One complication was the variations in gear types encountered. For example, standard net sizes can be program-specific, resulting in different lengths and mesh sizes of nets used in different regions. Also, nets are often designed specifically to catch target species given the characteristics of the estuaries and habitats sampled, and the size of the target species. If there is flexibility in choosing netting methods, we recommend two simple parameters: in the contributed datasets for our study, the median beach seine length was 37—m, and the median otter trawl tow was 10 minutes. Using these measurements as defaults would help data be more compatible in future analyses.

The power of analysis would have increased had we been able to compare densities across estuaries, because CPUE may not be proportional to abundance (Harley et al. 2001). The data that was submitted included density estimates in only 11 of the 34 sampling programs. Many studies either do not or cannot make accurate density calculations, or may standardize densities by differing surface area or volume measurements of the water sampled. For example, it can be difficult to accurately measure density (number/$m^2$) with beach seines because of variables such as habitat complexity, water flow, and boat maneuverability, but every attempt should be made when possible as this would lead to more precise measurements. For targeted studies, enclosure nets that measure a set area and can hold fish for a few hours as the tide ebbs would also provide improved measurements for not only density but additional metrics such as fish feeding and growth (Rozas and Minello 1997, Minello et al. 2003, Toft et al. 2007, Cordell et al. 2011).

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varying labels of habitats across studies. We recommend that field studies use a standard CMECS classification system so that there can be consistency across studies (Heady et al. 2014, Hughes et al. 2014). Some classifications are common across estuaries and would make suitable targets of meta-analyses, such as emergent tidal marsh, tidal flat, and seagrass bed (e.g., see Minello et al. 2003). Others are unique to certain systems or positions in the estuary, such as specific anthropogenic habitats, and may best be addressed by targeted field studies that may be difficult to replicate across estuaries. Whatever the case, using standard CMECS classifications would provide the level of detail necessary to allow increased overlap of datasets and the potential for more precision in future meta-analyses. Also, our modeling analysis indicates that salinity is important, and field studies should attempt to stratify sampling locations by at least the three main zones of freshwater tidal (<0.5 ppt), mixing (0.5 – 25 ppt), and marine (>25 ppt), which, although coarse in scale, can provide a surrogate for habitat types represented in those zones. Given the frequency of occurrence and spatial distribution of the species represented in the submitted datasets, the eight species with data coverage allowing modeling analyses are good candidates for application of more detailed habitat-level indices via a meta-analysis. Again, this recommendation only applies to the data that was submitted, and best represents beach seine collections from riverine estuaries in Washington and Oregon.

Other recommendations for next steps include a combination of increased resolution of spatial data and increased communication and collaboration across agencies. Improved spatial data on site locations and habitat types would allow future data synthesis efforts to accomplish more precise analyses. There is a temporal component to spatial data as well, and both current and historic habitat types should be a focus, as measurements of historic habitat loss would greatly inform patterns in fish distribution and abundance. Our focus on collected data from 1990-2014 limits the implications to the last few decades, and any further insights from historic datasets would be useful. The technology of information gathering is always improving, and developing standard systems for addressing data management should improve in pace with the technology, leading to more opportunities to merge spatial and temporal components of datasets.

Addressing nursery function of different habitat types was an original goal of our study, and one that could not be addressed because of the limited amount and

To fully characterize and identify priority habitats for focal fish and invertebrate species, a more targeted and complete data set would be required than that which we received in our data call. The lack of cohesion in habitat-specific fish data received for this study precluded our ability to target specific nursery habitat restoration possibilities. To acquire this type of data, we recommend conducting sampling for focal species in an array of representative estuaries that is specifically targeted to identify habitat affinities. This type of data is presently not available, or exists for only a few estuaries and/or species, but is essential for understanding nursery habitat variability across West Coast estuaries and for identifying habitats that may require additional protection or restoration.

A good example of the specificity and types of data that can be used in this way was presented in three papers by Vasconcelos and co-authors (Vasconcelos et al. 2007, 2010, 2011). These studies occurred in eight Portuguese estuaries that were nurseries for a suite of important fish species. In the first paper (Vasconcelos

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et al. 2007), a multi-metric index of 13 anthropogenic pressure components was developed that could be combined into an aggregate index similar to the stressor scores we used from the NFHP National Estuary Assessment (Greene et al. 2015b). The second study (Vasconcelos et al. 2010) used targeted sampling within each of the eight estuaries to identify particular habitat attributes related to the density of each fish species. The species distributions that were generated identified use of areas within the estuaries (e.g., particular salinities, sediments, or invertebrate densities), allowing the identification of important estuarine sites for juveniles of each species. They found considerable variability among estuaries, leading them to conclude that "the individual analysis of multiple estuaries is therefore essential to identify environmental features decisive in structuring important sites for juveniles of each species and to evaluate consistency of intra-estuarine use". The third paper (Vasconcelos et al. 2011) measured the contribution of individual estuaries to marine subpopulations—thus addressing the nursery concept of Beck et al. (2001) and Dahlgren et al. (2006) that a nursery is defined as contributing more to adult populations than other areas. This was measured with "potential" metrics (juvenile density, habitat quantity, juvenile number and habitat quality within estuaries) compared to "effective" metrics (estuarine source of young adults in the marine environment measured via otolith elemental fingerprints). They found that estuaries identified as important nursery and/or effective juvenile habitat (EJH) differed with species and no single estuary was best for all, again highlighting the importance of analyzing multiple estuaries and identifying species-specific regulation of nursery functions.

Anthropogenic modifications and restoration actions are two areas of study that involve management planning and deserve more attention as to their specific contributions to nursery functions, or lack thereof. Are there species that have adapted to the changing shoreline structure of estuarine nursery habitats better than others? What anthropogenic modifications have caused the most harm to which species? How can studies target this that will improve management concerns? These research topics have gained momentum in recent years (Bilkovic and Roggero 2008, Able et al. 2013, Toft et al. 2013, Munsch et al. 2015), but more work is needed to assess broad multiple-scale patterns (Valesini et al. 2014). Given increasing levels of coastal urban growth and projected sea level rise, there is great potential for restoration to not only enhance shoreline health but also better protect coastal communities using more natural approaches (Shepard et al. 2011, Arkema et al. 2013). Incorporating studies that address sea level rise and effect on major habitats, such as percent and area of tidal wetland type, and opportunities for either surface elevation increase or transgressive migration inland (Craft et al. 2007, Schile et al. 2014, Jones 2015), will help us to predict the potential to maintain nursery functions of estuaries given climate change scenarios.

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# APPENDIX A: TIER 1 DATA CALL (*example*)

WHAT KINDS OF DATA WERE COLLECTED AND OVER WHAT TIME PERIOD WAS THE DATA COLLECTED?

| | ONE SEASON | MULTIPLE SEASONS IN ONE YEAR | MULTIPLE YEARS |
|---|---|---|---|
| PRESENCE/ABSENCE | ● | ● | ● |
| CATCH PER UNIT EFFORT (CPUE) | ● | ● | ● |
| DENSITY | ● | ● | ● |
| LENGTHS | ● | ● | ● |
| WEIGHTS | ● | ● | ● |
| MARK/RECAPTURE | ● | ● | ● |
| BEHAVIOR | ● | ● | ● |
| PHYSICAL (e.g., dissolved oxygen, salinity, habitat) | ● | ● | ● |
| SPATIAL (e.g., GIS framework) | ● | ● | ● |

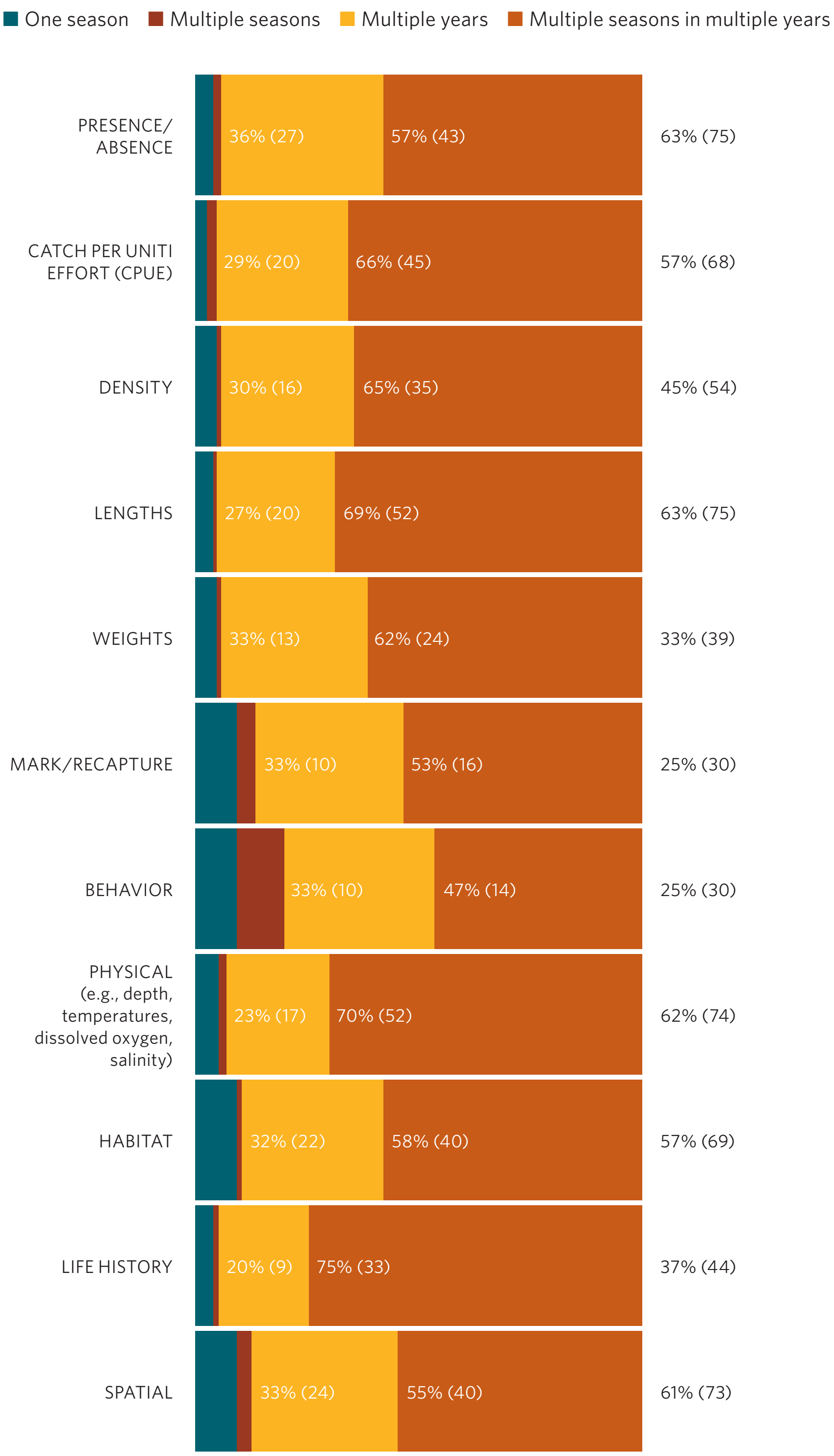
**WHAT ESTUARY OR ESTUARIES WAS THE DATA COLLECTED?**

- ■ SALISH SEA (Washington, Puget Sound to Cape Flattery)
- ■ OREGON/WASHINGTON COAST (Cape Flattery to Cape Mendocino)
- ■ CENTRAL CALIFORNIA (Cape Mendocino to Point Conception)
- ■ SOUTHERN CALIFORNIA BIGHT (California South to Point Conception)
- ■ OR, SPECIFY ESTUARIES ______

**IN WHAT FORMATS ARE YOU WILLING TO SHARE DATA?**

- ■ SUMMARIES (e.g., by habitat type, by year, by location, by species)
- ■ SPREADSHEETS/DATABASE
- ■ GIS DATABASE
- ■ HARD COPIES OF DATA
- ■ OTHER COMMENTS ON DATA SHARING ______

WHAT KINDS OF DATA WERE COLLECTED AND DURING WHAT TIME PERIODS WERE THEY COLLECTED? (Please select the time period that most closely resembles when you collected data.)



# APPENDIX B: TIER 2 DATA CALL

## Pacific Marine and Estuarine Fish Habitat Partnership Data Request

*Assessment Overview:* The overarching goal of the PMEP assessment is to demonstrate how conserving and restoring juvenile fish habitat in estuaries contributes to the overall ecological health and economic sustainability of commercial and recreational fisheries. Our primary deliverable from this assessment is to produce a peer-reviewed report that allows funding agencies to prioritize where key strategic investments could and should be made. In tandem with this call for fish data, PMEP is currently delineating and classifying West Coast estuaries to serve as the underlying GIS framework for a regional analysis of fish use of estuarine nursery habitat. Detailed information is available at http://www.pacificfishhabitat.org.

*What we are looking for:* The Pacific Marine and Estuarine Fish Habitat Partnership (PMEP) is currently compiling fish and shellfish data from California, Oregon, and Washington estuaries. We are focusing on spatially referenced presence, absence, and abundance information 15 focal species (below) sampled within estuarine waters. High priority data has records of fish life stage as well as location, count, and species.

*How the data will be used:* Your data will be standardized to a database owned by PMEP, housed at the Pacific States Marine Fisheries Commission. Use is restricted to PMEP contracted scientists. There are three assessments planned that may use data from this PMEP database: the PMEP Nursery Assessment, the National Fish Habitat Partnership (NFHP) National Estuary Assessment, and NOAA-led Pacific Forage Fish Assessment. Assessments will include both peer-reviewed reports and journal articles. Outside requests to access assessment inputs are reviewed on a case-by-case basis. Your dataset will be acknowledged in all PMEP and NFHP publications that use your data. Publicly available data, as indicated by the data originator, may be shared outside of PMEP provided that end-users acknowledge both PMEP and original source (ODBC-By attribution license). Please let me know if you have any data sharing stipulations; **we are willing to work with you to develop an individual data sharing agreement**.

*15 focal fish and shellfish species for nursery habitat assessment:* The species selected are intended to represent major fish guilds, fish of commercial, recreational, and cultural importance, and fish whose life histories span all or a portion of West Coast estuaries:

- Dungeness crab (*Cancer magister*)
- Bay shrimp (*Crangon franciscorum*)
- Leopard shark (*Triakis semifasciata*)
- Bat ray (*Myliobatis californica*)
- Green sturgeon (*Acipenser medirostris*)
- Steelhead trout (*Oncorhynchus mykiss*)
- Coho salmon (*Oncorhynchus kisutch*)
- Chinook salmon (*Oncorhynchus tshawytscha*)
- California halibut (*Paralichthys californicus*)
- English sole (*Parophrys vetulus*)
- Starry flounder (*Platichthys stellatus*)
- Brown rockfish (*Sebastes auriculatus*)
- Staghorn sculpin (*Leptocottus armatus*)
- Shiner Perch (*Cymatogaster aggregata*)
- Pacific herring (*Clupea pallasi*)

# APPENDIX C: DATA CONTRIBUTOR ACKNOWLEDGEMENTS

We are deeply indebted to the people and organizations who provided data that made this assessment possible. Below are citations of reports from data contributors. We additionally thank the following people for providing datasets valuable to future assessments: Mark Allen (Normandeau Environmental Consultants), Scott Bailey (Tillamook Estuaries Partnership), Hans Daubenberger (Port Gamble S'Klallam Tribe), Alison Dauble (ODFW), Ben Becker and Darren Fong (NPS), Joel Fodrie (UNC), Jordan Gold (Mari-Gold Environmental Consulting), Scott Heppell (OSU), Mike Hudson (USFWS), Matt Kowalski (Skokomish Indian Tribe), Novo Aquatic Sciences, Ann-Marie Osterback (NOAA), Joanne Park (CDFW), Brook Silver (USFWS), Michael Wallace (CDFW), Laurie Weitkamp (NOAA). Additionally, Ole Shelton (NOAA) advised on modeling analysis.

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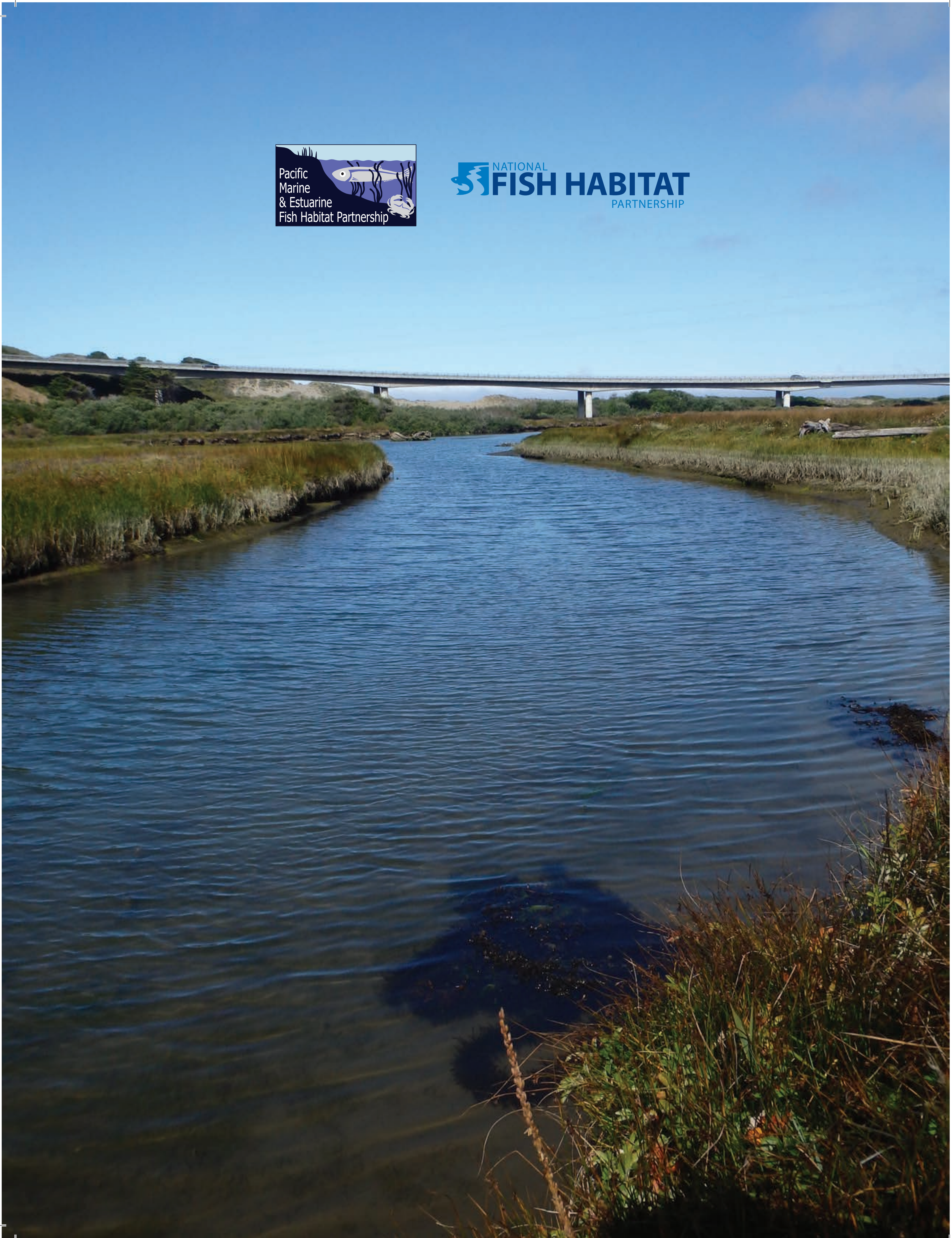
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