NOAA Technical Memorandum NMFS-NWFSC-162

https://doi.org/10.25923/2bfz-ah24

Juvenile Salmon Ecology in Tidal Freshwater Wetlands in the Lower Columbia River Estuary

January 2021

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northwest Fisheries Science Center

NOAA Technical Memorandum Series NMFS-NWFSC

The Northwest Fisheries Science Center of NOAA's National Marine Fisheries Service uses the NOAA Technical Memorandum NMFS-NWFSC series to issue scientific and technical publications that have received thorough internal scientific review and editing. Reviews are transparent collegial reviews, not anonymous peer reviews. Documents within this series represent sound professional work and may be referenced in the formal scientific and technical literature.

The Northwest Fisheries Science Center's NOAA Technical Memorandum series continues the NMFS-F/NWC series established in 1970 by the Northwest and Alaska Fisheries Science Center, which subsequently was divided into the Northwest Fisheries Science Center and the Alaska Fisheries Science Center. The latter uses the NOAA Technical Memorandum NMFS-AFSC series.

NOAA Technical Memorandums NMFS-NWFSC are available from the NOAA Institutional Repository, https://repository.library.noaa.gov.

Reference this document as follows:
Sol, S. Y., B. Anulacion, D. P. Lomax, P. Chittaro, P. Moran, G. M. Ylitalo, A. Hanson, C. Corbett, and L. L. Johnson. 2021. Juvenile Salmon Ecology in Tidal Freshwater Wetlands in the Lower Columbia River Estuary. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-162.

https://doi.org/10.25923/2bfz-ah24

NOAA FISHERIES

Juvenile Salmon Ecology in Tidal Freshwater Wetlands in the Lower Columbia River Estuary

Sean Y. Sol,[1] Bernadita Anulacion,[1] Daniel P. Lomax,[1] Paul Chittaro,[1] Paul Moran,[2] Gina M. Ylitalo,[1] Amanda Hanson,[3] Catherine Corbett,[3] and Lyndal L. Johnson[1]

https://doi.org/10.25923/2bfz-ah24

January 2021

[1]Environmental and Fisheries Sciences Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

[2]Conservation Biology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

[3]Lower Columbia Estuary Partnership
811 Southwest Naito Parkway #410
Portland, Oregon 97204

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northwest Fisheries Science Center

Contents

Figures

Tables

Executive Summary

The lower Columbia River estuary is an important migratory corridor for threatened and endangered out-migrating juvenile salmonids. The tidal freshwater portion of the estuary provides nurseries for juvenile salmonids transitioning from freshwater to saltwater environments. This study examined the spatial and temporal occurrence of juvenile salmon in the tidal freshwater reaches of the lower Columbia River and characterized their genetic stock, condition, contaminant exposure, and origin (hatchery produced [marked] or presumed wild [unmarked]). Fish were sampled at 19 sites from 2008 to 2016. Chinook salmon (*Oncorhynchus tshawytscha)* were the most abundant species in all reaches; coho (*O. kisutch)*, chum (*O. keta)*, and sockeye salmon (*O. nerka)*, and steelhead (*O. mykiss)* and cutthroat trout (*O. clarkii)* were also observed. Unmarked Chinook salmon juveniles were present throughout the year, while marked juveniles were present primarily from May through July and in highest proportions in the middle and upper reaches. Chinook salmon stocks from both the lower Columbia River and the interior Columbia River basin were present, with interior Columbia River basin stocks most abundant in the upper reaches. Chemical contaminant concentrations were generally lowest in salmon from the upper reaches, upstream of urbanized areas of the estuary. Our results reveal seasonal and spatial patterns in salmon habitat occurrence, provide baseline data for habitat restoration, and comparisons against future changes in anthropogenic conditions and climate.

Acknowledgments

Support for the Ecosystem Monitoring Project was provided by the Bonneville Power Administration, and we gratefully acknowledge the contributions of this agency and its staff to this work. We are also grateful to the many people who assisted with collection and analysis of data for the Ecosystem Monitoring Program. For assistance with fish sampling, we thank David Baldwin, Tiffany Linbo, Keith Marcoe, Mark Myers, Sean Naman, O. Paul Olson, Tony Ramirez, Dana Rudy, Frank Sommers, Julann Spromberg, Carla Stehr, and Maryjean Willis. We thank David Kuligowski for genetic stock analyses and Keri Baugh, Jennie Bolton, Daryle Boyd, Richard Boyer, Ronald Pearce, Catherine Sloan, Karen Tilbury, and Gladys Yanagida for assistance with sample processing and laboratory analyses for salmon lipid content and chemical contaminant concentrations. This manuscript benefited substantially from critical comments and editorial revision by Anna Kagley, Susan Hinton, Nat Scholz, and our anonymous reviewers. We also thank our collaborators on the Ecosystem Monitoring Program, Jina Sagar (formerly of the Lower Columbia Estuary Partnership), Amy Borde (Pacific Northwest National Library), Jennifer Morace (U.S. Geological Survey), Whitney Temple (USGS), Tawnya Peterson (Oregon Health and Science University), and Joe Needobam (OHSU).

Introduction

The Columbia River basin historically supported diverse and abundant populations of fish and wildlife, and was one of the largest producers of Pacific salmon in the world. An estimated 8 to 16 million wild Pacific salmon migrated up the Columbia River system annually to spawn in the mid-1870s (Netboy 1980, Cone 1995). The mid-1800s, however, also saw the beginning of actions in the river such as dredging, diking, infill, urban and industrial development, and the construction of the hydropower system that significantly reduced the quantity and quality of off-channel and floodplain habitat available to fish and wildlife in the Columbia River basin (Sherwood et al. 1990, Bottom et al. 2005b). Such actions also led to changes in river flow, poor water quality, increased chemical contaminants, and the introduction of invasive species altering food web dynamics (Bottom et al. 2005a, Fresh et al. 2005, Hinck et al. 2006, Maier and Simenstad 2009, Johnson et al. 2013). As a result, returns of wild fish have declined to where Columbia River and Snake River populations of Chinook salmon (*Oncorhynchus tshawytscha)*, coho salmon (*O. kisutch)*, and chum salmon (*O. keta)* are all currently listed as threatened or endangered under the Endangered Species Act (ESA; Ford 2011).

The lower Columbia River estuary (LCRE) is a migration corridor for outmigrant juvenile salmon with minimal rearing habitat (Bottom et al. 2005b). Recent studies have established the importance of the saltwater portion of the estuary as critical habitat for juvenile Columbia River Pacific salmon (e.g., Bottom et al. 2005b, Fresh et al. 2005, Roegner et al. 2012, Craig et al. 2014, McNatt et al. 2016). The estuary provides various advantages to juvenile salmon transitioning from freshwater to saltwater environments, including a productive feeding area capable of sustaining increased growth rates, refugia from marine predators, and a physiological transition zone where fish can gradually acclimate to saltwater (Simenstad et al. 1982, Thorpe 1994). Work by Sather et al. (2016) and Johnson et al. (2011) showed patterns of juvenile salmonid habitat use in tidal freshwater areas of the lower Columbia River, suggesting that this portion of the estuary may also provide valuable rearing habitat. However, earlier studies were limited to reaches between river kilometers (RKM) 110–141 and 188–202. The current study expands that earlier work with a comprehensive assessment of the occurrence of juvenile salmon throughout the tidal freshwater portion of the LCRE, from RKM 36–230.

The data presented here are part of a long-term status and trends monitoring effort in the LCRE by the Northwest Fisheries Science Center's Ecosystem Monitoring Program (EMP; Hanson et al. 2015, Sagar et al. 2015). The primary goal of this research program is to characterize how juvenile salmonids utilize the shallow tidal freshwater wetland portion of the LCRE. In this report, we describe seasonal and spatial patterns of salmonid assemblages in emergent marsh habitats in the tidal freshwater wetlands of the lower Columbia River. The specific questions addressed by our analyses include: 1) Does the occurrence of salmonid species vary among reaches in the LCRE? and 2) Do juvenile Chinook salmon of different origin (hatchery vs. naturally produced), genetic stock (ESU), size class, condition, and chemical contaminant exposure differ spatially in the LCRE? Characterization of multiple parameters is important because juvenile salmonids may use tidal freshwater areas extensively as they migrate to saltwater and these data can guide management efforts in the recovery of endangered salmonids in the LCRE.

Methods

Sampling Design

The LCRE is defined as all tidally influenced areas from the mouth of the Columbia River at RKM 0, upstream into freshwater and to the tailrace of Bonneville Dam at RKM 234. The LCRE can be divided into eight major hydrogeomorphic reaches, each with unique characteristics and physical processes (Figure 1; Simenstad et al. 2011). Reach boundaries are based on the Environmental Protection Agency's (EPA) Level IV Ecoregions, which were modified to include important parameters such as salinity intrusion, maximum tide level, upstream extent of current reversal, geology, and major tributaries.

From 2008 to 2016, we sampled 19 sites across six of the eight hydrogeomorphic reaches of the lower Columbia River. These sites ranged in location from the upper limit of the saltwater influence area to the upper limit of the tidal influence area just below the Bonneville Dam (Figure 1). We focused on minimally disturbed, tidally influenced emergent wetland habitats (Sagar et al. 2015). Sites were present in all reaches except Reach D; Reach F had only one site, and we excluded the marine-dominated Reach A.

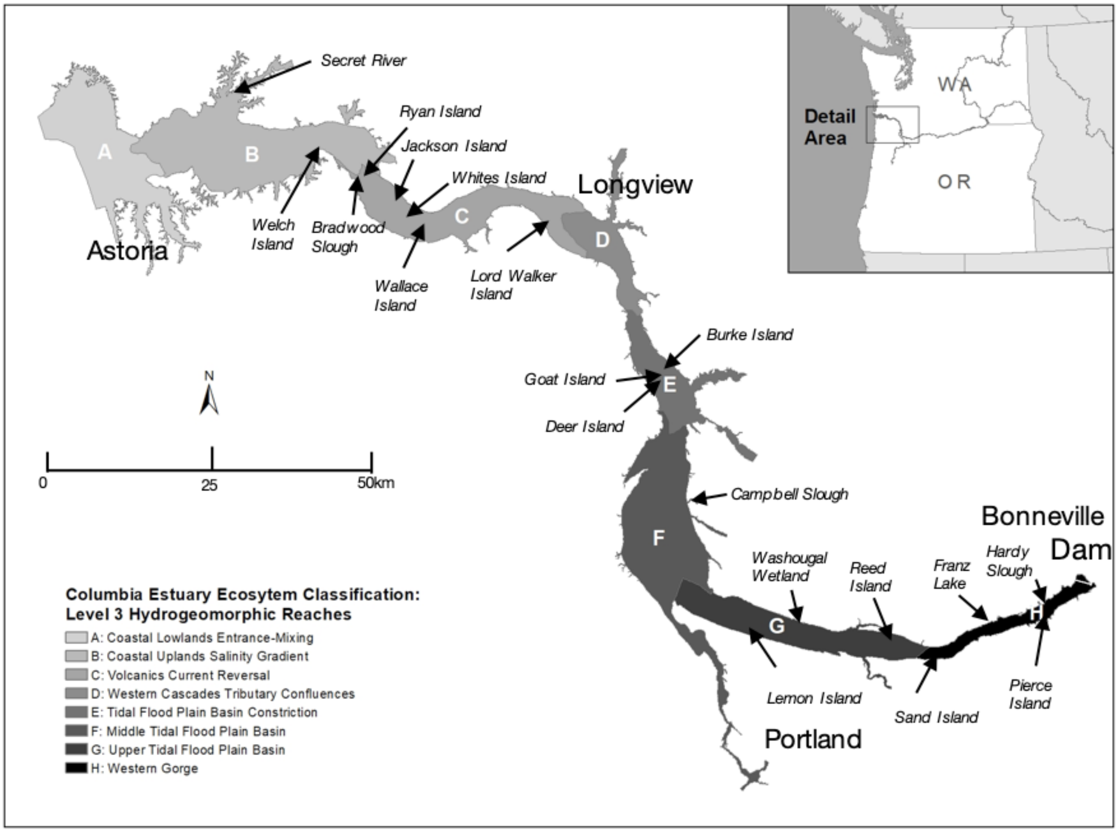

Figure 1. Sampling sites within hydrogeomorphic reaches (A–H) throughout the Lower Columbia River Estuary. Map courtesy of K. Marcoe, Lower Columbia Estuary Partnership.

Each year, three to four "status sites" in a previously unsampled reach were sampled along with the long-term "trend sites" that were sampled for multiple years (Table 1; see Sagar et al. 2015 for a detailed description of EMP study design). From 2008 to 2010, monitoring generally began in April and continued monthly through August or September. Beginning in 2011, the sampling period was expanded to include the fall and winter months, typically beginning in February and extending through December. Sampling was generally not possible in January because of the time needed to renew fish collection permits; at other times it was precluded by extremely high or low water levels (USGS 2020).

Table 1. Site coordinates (in decimal degrees), river kilometers, distance from mainstem (m), and years sampled for 2008–16 sampling sites. RKM 0 is the mouth of the Columbia River; RKM 234 is Bonneville Dam and the height of tidal influence in the river. From 2008–10, sites were sampled from Apr–Sep; from 2011–16, sites were sampled from Jan–Dec. Stars (⋆) denote trend sites, which were sampled for multiple years.

Site Name	Reach	Latitude (°N)	Longitude (°W)	RKM	Years Sampled
⋆ Secret River	B	46.304400	123.690467	37	2011–13
⋆ Welch Island	B	45.783867	122.754850	53	2011–16
Ryan Island	C	46.206600	123.414817	61	2009
Bradwood Slough	C	46.203183	123.447733	62	2010
Jackson Island	C	46.169417	123.350600	71	2010
⋆ Whites Island	C	46.159350	123.340133	72	2009–16
Wallace Island West	C	46.140467	123.283100	77	2009
Lord/Walker Island	C	46.137216	123.040278	99	2009
Burke Island	E	45.938867	122.789683	131	2011
Deer Island	E	45.926917	122.819683	132	2011
Goat Island	E	45.932317	122.815417	131	2011
⋆ Campbell Slough	F	45.783867	122.754850	149	2008–16
Lemon Island	G	45.590233	122.560917	180	2012
Washougal Wetland	G	45.580917	122.039450	195	2012
Reed Island	G	45.555217	122.297517	201	2012
Sand Island	H	45.553350	122.211117	221	2008
⋆ Franz Lake	H	45.600583	122.103067	221	2008–09 2011–16
Pierce Island	H	45.620967	122.010800	228	2008
Hardy Slough	H	45.628217	122.012150	230	2008

Fish Collection Methods

Fish were collected with a 37 × 2.4 m, 10-mm mesh Puget Sound beach seine (PSBS) deployed from a boat or on foot following the recommended guidelines for beach seining in Puget Sound (PSEP 1990). During low water levels (depth of 0.5–1 m), a modified PSBS (7.5 × 2.4 m, 10-mm mesh) was deployed on foot. Under extremely low water conditions (depth <0.5 m), a modified block net (MBN) utilizing the middle portion of the modified PSBS was deployed across the channel or slough and a second, smaller pole-net (2 × 1.5 m, 10-mm mesh) was used as a chase net to corral fish downstream and into the MBN.

Up to three seine sets were deployed at each site and sampling time (i.e., month), as site conditions and sampling permit limits allowed. All fish in each set were identified to the species level and counted, and up to 30 salmonids of each species were measured (to the nearest mm) and weighed (to the nearest 0.1 g). Salmonids were examined for fin clips and coded wire tags to determine the proportions of hatchery (marked) and unmarked fish. While all marked fish are of hatchery origin, unmarked fish can include individuals of both natural and hatchery origin. We recorded the coordinates of the sampling locations, the time of sampling, and water temperature (boat onboard thermometer [depth >1 m] or handheld thermometer [depth <1 m]), as well as estimating the area covered by the gear.

Up to 30 Chinook salmon were sacrificed and their fin clips collected at each site per sampling month for genetic stock identification. Additionally, the individual whole bodies (with stomach contents removed) were then collected for measurement of lipid content and chemical contaminant concentrations. Each whole body was wrapped in precleaned aluminum foil. Samples for lipid content and chemical analysis were held on dry ice during transport and were stored frozen at –80°C until analyses were performed.

Catch Analyses

Different gear types were used to accommodate variable hydrological conditions at the sampling sites. Gear efficiencies can be different across species and for different types of habitats (Bayley and Herendeen 2000, Steele et al. 2006, Hahn et al. 2007). Gear efficiency tests were not performed for this study; therefore, for calculation of fish species richness and density, we used only the data from PSBS, the gear type which provided the greatest amount of data. Data from other gear types were included in the chemical contaminants, lipid contents, and genetic stock identification analyses.

For each set, the number of fish captured was determined, then standardized to the number of fish captured per 1,000 m^2 (Roegner et al. 2009), to provide a measurement of fish density similar to fish densities reported in other studies in the lower Columbia River (Bottom et al. 2008, Johnson et al. 2011, Sather et al. 2016).

Fish Sample Analyses

For all salmonid species, Fulton’s condition factor *K* (Fulton 1902, Ricker 1975) was calculated as an indicator of fish health and fitness, using the formula

$$K = [\text{weight (g)} / (\text{fork length (cm)})^3] \times 100. \tag{1}$$

Chinook salmon were also classified by life stage as fry, fingerlings, or yearlings, following the criteria of Dawley et al. (1986) and Fresh et al. (2005); fish less than 60 mm fork length were classified as fry, 60–120 mm as fingerlings, and >120 mm as yearlings.

Lipid Determination and Chemical Contaminants in Salmon Tissues

For lipid and chemical analyses, individual Chinook salmon whole bodies (with stomach contents removed) were combined to produce composite samples consisting of three to five fish each from the same site, sampling time, genetic stock, and origin (unmarked vs. marked). The amount of total, nonvolatile, extractable lipid (reported as percent lipid) in the body composites was determined by gravimetric analysis as described by Sloan et al. (2014). Lipid classes were determined as described in Ylitalo et al. (2005), and the percent triglycerides contributing to total percent lipid was evaluated. The percent triglycerides provides a measure of the proportion of lipid that is available as an immediate energy source (Torcher 2003, Arkoosh et al. 2011).

Composite body samples (with stomach contents removed) were extracted with dichloromethane using an accelerated solvent extractor. Polar compounds were removed using a gravity flow cleanup column containing alumina/silica, followed by removal of lipids and other biogenic materials with size exclusion liquid chromatography. Samples were analyzed by gas chromatography/mass spectrometry (GC/MS) for PCB and PBDE congeners and for organochlorine (OC) pesticides (including DDTs, hexachlorocyclohexanes [HCHs], chlordanes, aldrin, dieldrin, mirex, and endosulfan I as described in Sloan et al. [2004, 2014]). To adjust for the influence of lipids on toxicity, body contaminant concentrations were lipid-normalized. Lipid-normalized data were primarily used to evaluate potential health effects of contaminants on juvenile salmon.

Genetic Stock Identification

Genetic stock identification (GSI) techniques (see Manel et al. 2005) were used to investigate the origins of juvenile Chinook salmon, as described by Teel et al. (2009, 2014). The stock composition of juveniles was estimated with a regional microsatellite DNA dataset (Seeb et al. 2007) that includes baseline data for spawning populations from throughout the Columbia River basin (described in Teel et al. 2009). The overall proportional stock composition was estimated with the GSI computer program ONCOR (Kalinowski et al. 2007), which implemented the likelihood model of Rannala and Mountain (1997). The same method was used to estimate the probability of origin of individual fish for the following Columbia River Chinook salmon genetic stock groups (Seeb et al. 2007, Teel et al. 2009): Deschutes River fall, West Cascades fall, West Cascades spring, Middle and Upper Columbia spring, Spring Creek Group fall, Snake River fall, Snake River spring, Upper Columbia River summer/fall, and Upper Willamette River spring. Also included was a non-native Rogue River spring Chinook salmon stock (Southern Oregon Coast) that is propagated and released in the lower Columbia River.

Statistical Methods

As described above, we were unable to sample all reaches uniformly by month or year. Because of the unbalanced nature of the data, a complex statistical analysis accounting for the influence of multiple factors on fish abundance measures (e.g., fish densities) was considered inappropriate. Therefore, fish abundance data are presented primarily in a descriptive manner (e.g., without explicitly including factors such as year × reach interactions).

Statistical comparisons were applied to other types of data. Analysis of variance and multiple regression techniques were used to examine the effects of fish type (unmarked vs. marked) and reach and month of capture on length, weight, condition factor, and tissue concentrations of DDTs, PCBs, and PBDEs in Chinook salmon. Additionally, we compared tissue residue values associated with toxicant injury (Meador et al. 2002, Beckvar et al. 2005, Arkoosh et al. 2010, 2015). Differences among means were evaluated with the Tukey–Kramer Honestly Significant Difference Test (Tukey–Kramer HSD). Chi-square analysis was used to compare stock and size class composition by reach and month. Statistical analyses were conducted with the JMP statistical package, with values considered significantly different at $\alpha = 0.05$.

Results

Juvenile Salmon Occurrence

A) Chinook salmon

Chinook salmon were the most abundant salmon species found throughout our sampling area, comprising 2.3% of the total fish catch (salmonids and nonsalmonids) collected between 2008–16, and 82% of the salmonid catch (Figure 2). Nearly all of the Chinook salmon caught in Reaches B, C, and E were unmarked, but in Reaches F–H, substantial proportions of marked Chinook salmon were also present (Figure 2).

Both marked and unmarked Chinook salmon were present in the LCRE from February through August, though marked Chinook salmon were rare in February and March, presumably due to hatchery release timing (Figure 3). A small number of Chinook salmon were caught in September and none were caught in October, but unmarked Chinook were observed again in November and December in Reaches G and H (Figure 3). Density of Chinook salmon varied by month for both marked and unmarked fish, with the highest mean density in May and June.

Higher densities of unmarked Chinook salmon were found in Reaches B, C, G, and H than in Reaches E and F (Figure 4). Density of marked Chinook salmon tended to be higher in Reaches F and G (Figure 4).

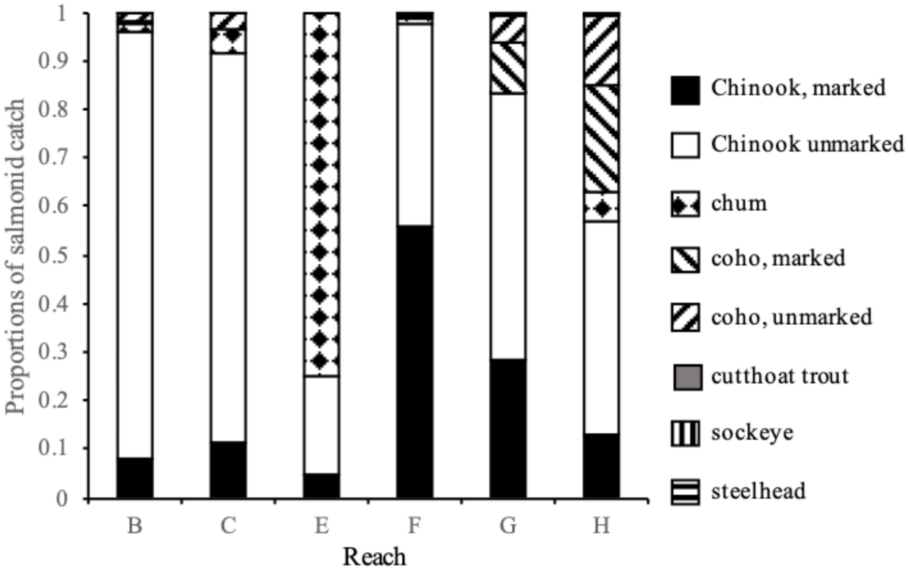

Figure 2. Proportions of salmon species (and numbers of individuals) by hydrogeomorphic reach. Samples were collected from 2008 to 2016.

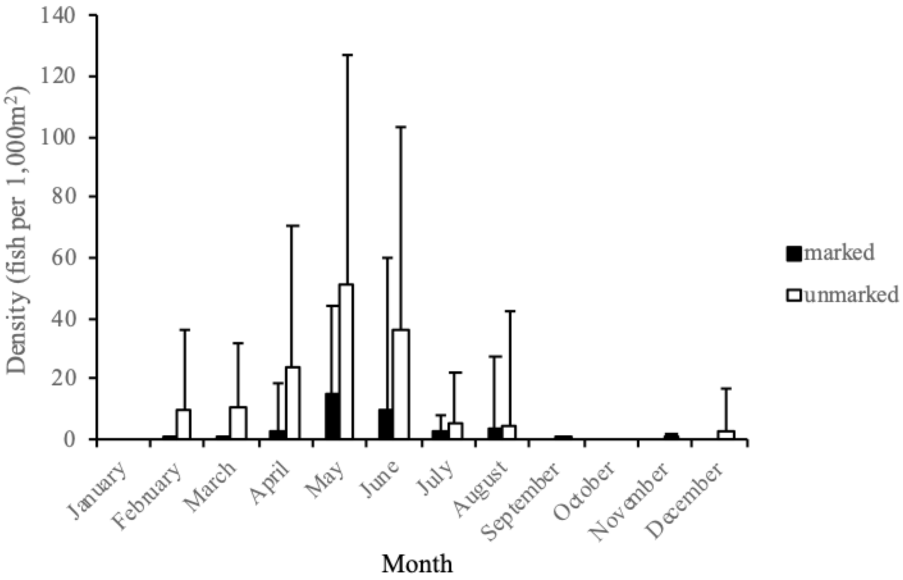

Figure 3. Mean (SD) Chinook salmon density (fish/1,000 m²) by sampling month (all reaches and years combined). Black and white bars indicate marked and unmarked fish. Sites were sampled from 2008 to 2016 with PSBS.

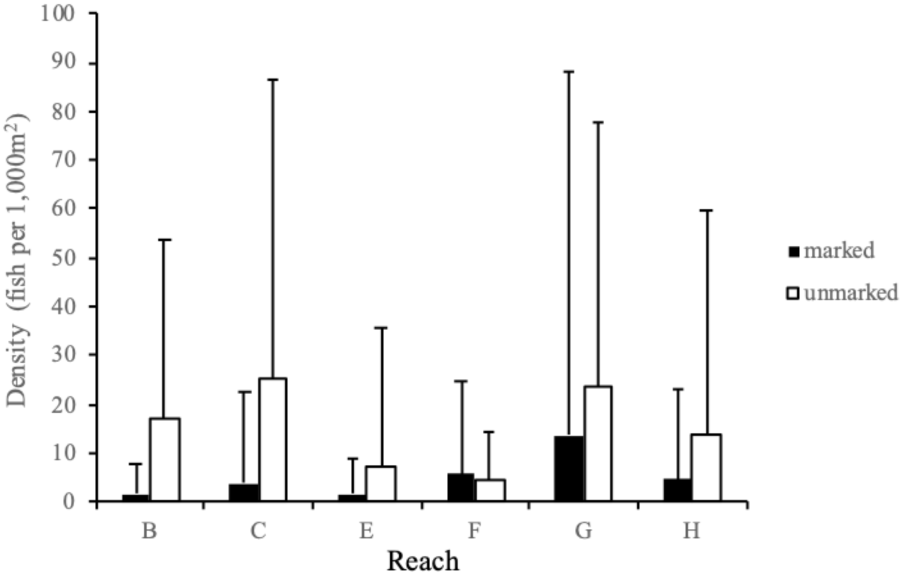

Figure 4. Mean (SD) Chinook salmon catch per unit effort (fish/1,000 m²) by hydrogeomorphic reach. Black bars indicate marked Chinook salmon, white bars indicate unmarked fish. Data are from sites sampled from 2008 to 2016 with PSBS.

B) Coho salmon

Coho salmon, especially unmarked coho salmon, were generally less abundant than Chinook salmon, with an average density over the sampling season of 1.6 unmarked fish and 1.3 marked fish per 1,000 m^2. Coho salmon made up 0.27% of the total fish catch collected between 2008–16, and 5.9% of the salmonid catch. Coho salmon were seldom encountered in Reaches B–F, but the percentages were higher in Reaches G and H (including both marked and unmarked coho salmon; Figure 2).

Unmarked coho salmon were observed more frequently than marked coho salmon (unmarked coho salmon were not observed in March, September, or October, while marked coho salmon were not observed in January, March, July, August, October, or November). The highest densities of unmarked coho salmon were recorded in May and August (Figure 5), while the highest density for marked coho salmon was observed in May (Figure 5). The highest densities of both marked and unmarked coho salmon were found in Reaches G and H (Figure 6), with unmarked coho salmon also present in notable numbers in Reaches B and C (Figure 6).

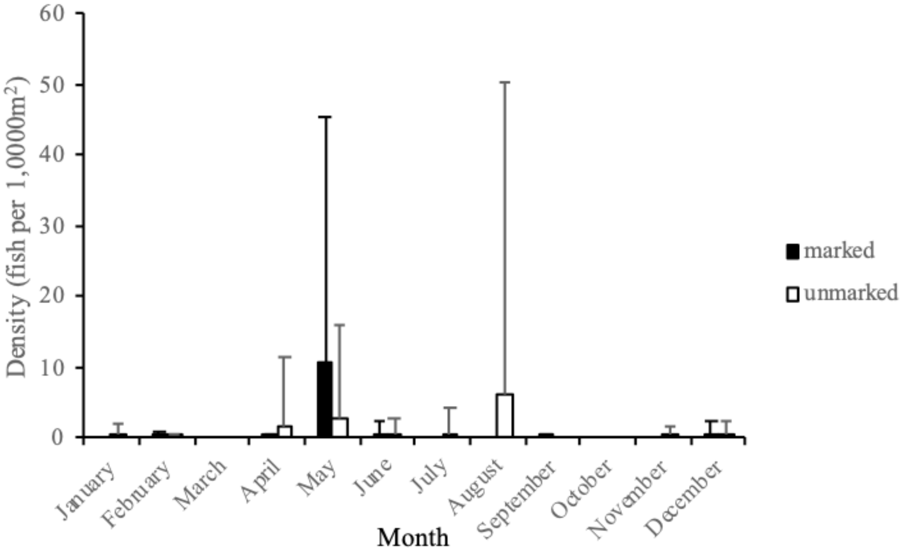

Figure 5. Mean (SE) coho salmon density (fish/1,000 m^2) by sampling month. Black bars indicate marked coho salmon, white bars indicate unmarked coho salmon. Data are from sites sampled from 2008 to 2016 with PSBS.

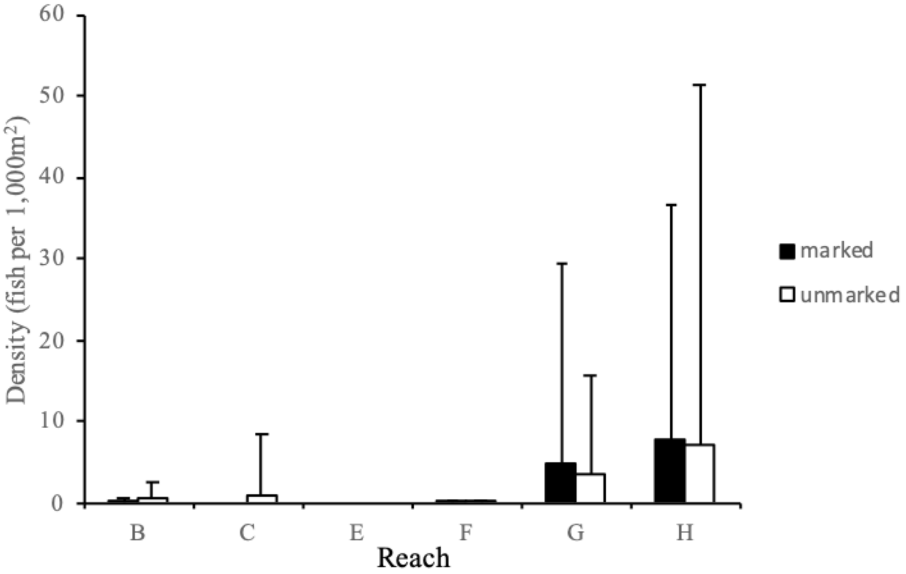

Figure 6. Mean (SE) coho salmon catch per unit effort (fish/1,000 m^2) by hydrogeomorphic reach. Black and white bars indicate marked and unmarked fish, respectively. Data are from sites sampled from 2008 to 2016 with PSBS.

C) Chum salmon

Chum salmon, all unmarked, made up 0.21% of the total fish assemblage collected from 2008–16, and 7.6% of the salmonid catch. They were present in the LCRE at an average density of 2.7 fish per 1,000 m^2 (Tables 2 and 3). Chum salmon were found in all sampled reaches, but were most abundant in Reach E (Table 2). They were found frequently from February through June, with highest densities in April and May, but rarely seen during the rest of the year (Table 3).

Table 2. Chum salmon, cutthroat, rainbow trout/steelhead, and sockeye salmon density (expressed as number of fish/1,000 m^2) by hydrogeomorphic reach. Data are from sites sampled from 2008–16. *n* indicates the total number of sampling events.

Reach	*n*	Chum	Cutthroat	Rainbow trout / Steelhead	Sockeye
B	123	0.52 ± 2.40	0.03 ± 0.37	0	0.04 ± 0.39
C	199	1.18 ± 5.10	0	0.10 ± 0.16	0.13 ± 1.78
E	17	61.70 ± 251.58	0	0	0
F	120	0.16 ± 0.87	0.01 ± 0.12	0	0.13 ± 0.15
G	31	0.14 ± 0.57	0.09 ± 0.51	0.05 ± 0.27	0.05 ± 0.30
H	78	1.77 ± 9.73	0.05 ± 0.41	0.14 ± 0.72	0.60 ± 0.50
Total	568	2.66 ± 43.80	0.02 ± 0.26	0.02 ± 0.29	0.06 ± 1.09

Table 3. Chum salmon, cutthroat, rainbow trout/steelhead, and sockeye salmon density (expressed as number of fish/1,000 m^2) by sampling month. Data are from sites sampled from 2008 to 2016. *n* indicates the total number of sampling events.

Month	*n*	Chum	Cutthroat	Rainbow trout / Steelhead	Sockeye
January	8	0	0	0	0
February	26	0.43 ± 2.20	0	0.16 ± 0.10	0
March	39	0.97 ± 2.87	0	0	0
April	80	3.98 ± 11.04	0.10 ± 0.53	0.11 ± 0.57	0.06 ± 0.50
May	67	16.82 ± 126.78	0.06 ± 0.49	0	0.48 ± 3.11
June	73	0.23 ± 1.96	0	0.03 ± 0.27	0
July	97	0	0	0	0
August	75	0	0	0	0
September	35	0	0	0	0
October	13	0	0	0	0
November	31	0	0	0	0
December	24	0	0	0	0.07 ± 0.34
Total	568	2.66 ± 43.79	0.02 ± 0.26	0.20 ± 0.29	0.07 ± 1.09

D) Sockeye salmon

Sockeye salmon, all unmarked, were found in all reaches except Reach E, but only in small numbers (Table 2), making up a negligible proportion of the total fish catch, and only about 0.3% of the salmonid catch. Sockeye salmon density was very low (an average of 0.07 fish per 1,000 m^2) (Tables 2 and 3). They were found in April, May, and December (Table 3).

E) Trout species

Although rainbow trout/steelhead (*Oncorhynchus mykiss)*, all unmarked, were observed in Reaches C, G, and H (Table 2), they were rarely encountered, accounting for <0.1% of the total salmonid catch. Overall steelhead density was low, averaging 0.03 fish per 1,000 m^2 (Tables 2 and 3). Steelhead were captured in February, April, and June (Table 3).

Cutthroat trout (*O. clarkii)*, also all unmarked, were observed in Reaches B, F, G, and H, but only in very small numbers (Table 2), accounting for <0.01% of the total salmonid catch. Cutthroat density was low, averaging 0.02 fish per 1,000 m^2 (Tables 2 and 3). Cutthroat trout were captured in April and May (Table 3).

Chinook Salmon Genetic Stock of Origin

Of the ten Chinook salmon stock groups present in the Columbia River, eight were observed in the tidal freshwater habitats sampled in this study. Those not identified were Snake River spring and Middle and Upper Columbia spring Chinook salmon. Stock composition varied temporally and spatially, as well as by marked vs. unmarked fish (Figures 7 and 8).

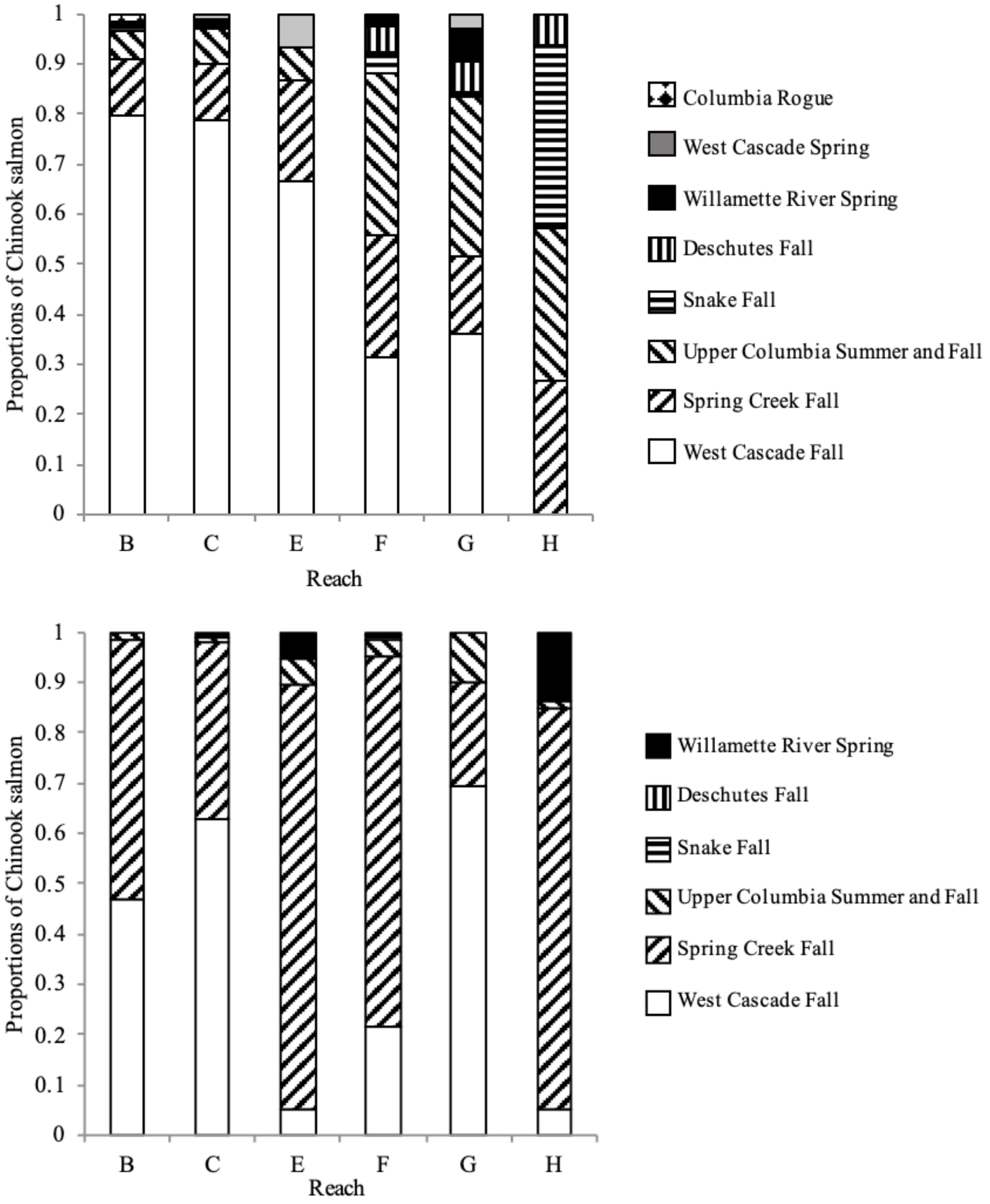

Figure 7. Percent genetic stock assignments for (top) unmarked and (bottom) marked juvenile Chinook salmon collected at sampling sites from 2008–15 across hydrogeomorphic reaches. Figures include data from all sampling gear types.

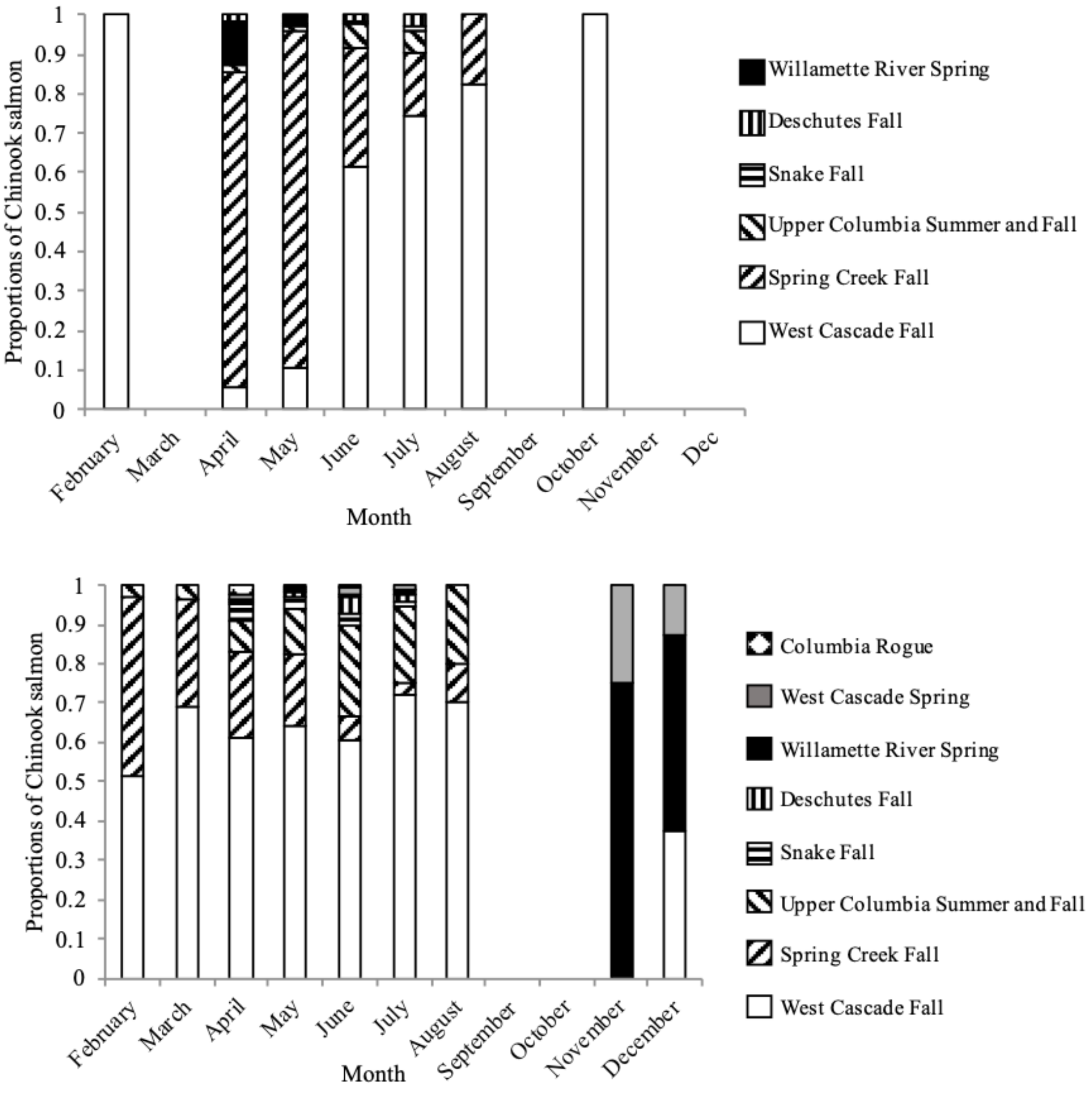

Figure 8. Percentage of different Chinook salmon stocks observed by month in (top) unmarked and (bottom) marked juveniles from 2008–15. Figures include data from all sampling gear types.

A) Stock composition by reach

The genetic stock composition of unmarked Chinook salmon differed by reach (contingency table and chi-square analyses, $P < 0.01$; Figure 7, top). In Reaches B through E, West Cascades fall Chinook salmon were the predominant stock, accounting for 70–80% of Chinook salmon analyzed from these reaches. In Reaches F and G, the predominant stocks were West Cascades fall, Spring Creek Group fall, and Upper Columbia summer/fall, with each group accounting for 25–30% of the Chinook salmon analyzed from these reaches. In Reach H, the major stocks present were Spring Creek Group fall, Upper Columbia River summer/fall, and Snake River fall. Other stocks identified included Deschutes River fall (present in all reaches except Reach E), Willamette River spring (present in Reaches C, F, and G), West Cascades spring (present in all reaches except Reach H), and Columbia Rogue River (present in Reaches B and F).

The stock composition of marked Chinook salmon (Figure 7, bottom) also differed by reach (contingency table and chi-square analyses, $P < 0.01$). In Reaches B, C, and G, West Cascades fall Chinook salmon were the predominant stock, while Spring Creek Group fall were more common in Reaches E, F, and H. Other stocks identified included Upper Columbia summer/fall (present in all reaches), Snake River fall (present in Reach F), Willamette River spring (present in Reaches C, E, F, and H), and West Cascades spring Chinook (present in Reaches B, C, F, and G).

B) Genetic stock composition by month

For both marked and unmarked Chinook salmon, stock composition varied by sampling month ($P < 0.01$ for both groups; Figure 8). West Cascades fall Chinook salmon predominated throughout most of the year. From February through May, primary unmarked Chinook salmon stocks were West Cascades fall and Spring Creek fall (Figure 8, top). Upper Columbia summer and fall Chinook salmon were present from February to August, peaking in June. Unmarked Chinook salmon were not present in September or October, and only a small number of fish were collected in November and December (identified as Upper Willamette spring, West Cascades spring, or West Cascades fall).

Marked Chinook salmon were present primarily from April through August (Figure 8, bottom). Spring Creek fall was the most abundant stock in April and May, while West Cascades fall dominated catches in June through August. From April through July, other stocks, including Snake River fall and West Cascades spring, were also present in small numbers. The marked Chinook salmon collected in October and February were West Cascades fall.

Chinook Salmon Size and Condition Factor

Marked and unmarked Chinook salmon were sampled from 2008 to 2016 for size class distributions, length, weight, and condition factor by month (Table 4). Due to the limited numbers of other salmonids (coho salmon, chum salmon, sockeye salmon, and steelhead) captured during our study, we did not assess their spatial or temporal patterns of length, weight, or other measures of condition.

Table 4. Chinook salmon mean ± SD of length (mm), weight (g), Fulton's condition factor (*K*), and percent size class distribution by sampling month. *n* indicates number of fish from each reach.

Month	***n***	**Length**	**Weight**	***K***	**% fry**	**% fingerlings**	**% yearlings**
Unmarked Chinook salmon							
February	81	40 ± 2	0.5 ± 0.2	0.81 ± 0.17	100	0	0
March	128	42 ± 4	0.6 ± 0.2	0.78 ± 0.15	100	0	0
April	491	46 ± 9	1.1 ± 1.3	0.91 ± 0.22	93.5	6.5	0
May	750	57 ± 11	2.2 ± 1.4	1.04 ± 0.19	65.3	34.7	0
June	579	62 ± 10	2.7 ± 1.5	1.05 ± 0.14	47.7	52.3	0
July	176	70 ± 10	4.1 ± 1.9	1.15 ± 0.13	17.6	82.3	0
August	11	76 ± 9	5.1 ± 1.8	1.12 ± 0.10	0	100	0
September	1	99	9.3	0.96	0	100	0
October	0	—	—	—	—	—	—
November	4	105 ± 16	11.0 ± 4.2	0.94 ± 0.09	0	75	25
December	26	105 ± 12	11.1 ± 3.3	0.93 ± 0.07	0	92.3	7.7
Marked Chinook salmon							
February	1	108	12.6	1.00	0	100	0
March	4	168 ± 19	40.1 ± 14.4	0.81 ± 0.06	0	0	100
April	58	87 ± 26	9.1 ± 11.4	0.99 ± 0.17	1.7	86.2	12.1
May	281	83 ± 14	6.4 ± 5.0	1.02 ± 0.08	0.4	95.4	4.3
June	118	79 ± 9	5.3 ± 1.8	1.05 ± 0.15	0.8	99.2	0
July	83	81 ± 8	6.1 ± 2.1	1.11 ± 0.10	0	100	0
August	19	87 ± 8	6.4 ± 2.4	1.07 ± 0.11	0	100	0
September	0	—	—	—	—	—	—
October	0	—	—	—	—	—	—
November	0	—	—	—	—	—	—
December	0	—	—	—	—	—	—

For unmarked Chinook salmon, fork length of individual fish ranged from 30 to 127 mm, and weight from 0.2 to 18.2 g, with fry and fingerlings being the most abundant size classes. Size class distribution varied with sampling month, with fry early in the sampling season and fingerlings becoming more abundant by June or July. A small number of yearlings were collected in November and December. Both length and weight increased over the sampling season. Fish condition (*K*) also varied with sampling month, ranging from a low of 0.81 in February and March to a high of 1.15 in July, and declining to 0.93–0.94 in November and December.

Marked Chinook salmon were primarily fingerlings, though some fry and yearlings were also caught. Size class distribution of marked Chinook salmon varied with sampling month: yearlings in the spring, and fingerlings as the season progressed. The fork length of individual fish ranged from 51 to 187 mm, and weight from 1.3 to 5.6 g. Both length and weight varied by month, with highest mean lengths and weights in February and March when yearlings were present. Fish condition (*K*) also varied with sampling month, with low average values in March and April and higher values in July and August.

Table 5. Chinook salmon mean ± SD of length (mm), weight (g), Fulton's condition factor (*K*), and percent size class distribution by sampling reach. *n* indicates number of fish from each reach.

Reach	***n***	**Length**	**Weight**	***K***	**% fry**	**% fingerlings**	**% yearlings**
Unmarked Chinook salmon							
B	611	53 ± 13	1.8 ± 1.6	0.95 ± 0.20	73.6	26.4	0
C	980	57 ± 11	2.2 ± 1.5	1.02 ± 0.18	62.4	37.6	0
E	56	56 ± 11	2.0 ± 1.4	0.98 ± 0.22	73.2	26.8	0
F	216	66 ± 14	3.6 ± 2.4	1.10 ± 0.18	33.8	66.2	0
G	181	60 ± 24	3.2 ± 4.0	0.94 ± 0.17	68.0	30.4	1.6
H	203	50 ± 11	1.5 ± 1.2	1.00 ± 0.19	82.3	17.7	0
Marked Chinook salmon							
B	34	87 ± 31	9.6 ± 13.1	1.08 ± 0.23	0	88.2	11.8
C	61	82 ± 14	6.5 ± 6.5	1.08 ± 0.13	0	98.4	1.6
E	22	80 ± 4	4.4 ± 0.5	1.01 ± 0.15	0	100	0
F	255	83 ± 9	5.9 ± 2.4	1.02 ± 0.12	0	98.8	1.2
G	121	81 ± 16	6.3 ± 5.7	1.05 ± 0.11	2.5	95.0	2.5
H	71	90 ± 24	9.9 ± 9.7	1.00 ± 0.15	0.5	95.4	4.1

Chinook salmon size class distributions, length, weight, and *K* for marked and unmarked Chinook salmon by hydrogeomorphic reach are shown in Table 5. Fish from Reach F tended to be larger and heavier, and fish from Reach G smaller and lighter than other reaches. In the case of *K*, higher values were found in fish from Reaches F and H than in the other reaches, and the lowest values in Reach G. Size class distribution also varied by reach, with fingerlings making up a higher proportion of Chinook salmon catches in Reach F than in other reaches. For marked fish, the largest and heaviest fish were in Reach H; however, condition factor, *K*, did not vary greatly among reaches. Size class distribution also varied by reach, with yearlings most predominant in Reaches B and H.

Chinook Salmon Lipid and Triglyceride Content

Body lipid content (% lipid) and percentage of lipids occurring as triglycerides (% triglyceride) were analyzed from Chinook salmon collected from the sampling sites between 2008 and 2015. Overall, neither % lipid nor % triglyceride were different between marked and unmarked Chinook salmon ($P > 0.05$; Figure 9). In unmarked Chinook salmon, % lipid varied by sampling month ($P < 0.01$), with lowest values in February and March and highest values in May (Figure 9, top). Percent triglyceride also varied by sampling month ($P < 0.01$; Figure 9, bottom), with the lowest values in February and March and the highest values in August. In marked Chinook salmon, sampling month had an influence on lipid content ($P < 0.01$), with mean lipid content significantly higher in April than in other months, and lowest in August (Figure 9, top). Percent triglyceride also varied by month, with lower values in fish collected in August compared to other months ($P < 0.05$; Figure 9, bottom).

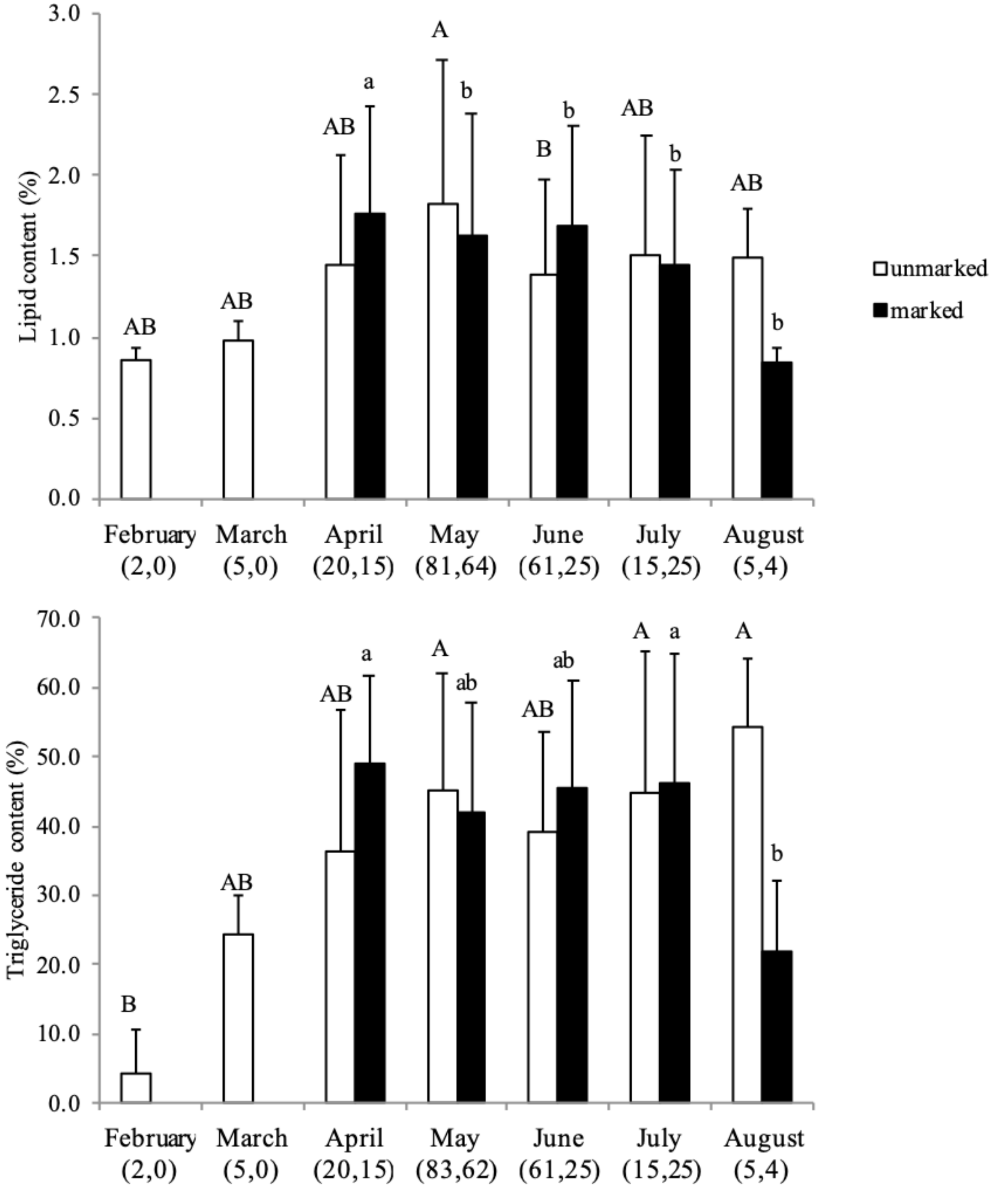

Figure 9. (top) Percent body lipid content and (bottom) % triglyceride of marked (black bars) and unmarked (white bars) juvenile Chinook salmon from sampling sites, by sampling month. Sample sizes are in parentheses. Data are from juvenile Chinook salmon collected at the sampling sites from 2008–15. Differences for unmarked fish are shown in capital letters; differences for marked fish are shown in lower-case letters (ANOVA, Tukey–Kramer HSD, $P < 0.05$). Figures include data from all sampling gear types.

With sampling month taken into account, both lipid content ($P < 0.01$) and % triglyceride ($P < 0.01$) varied significantly by reach in unmarked Chinook salmon (Figure 10). Lipid content in samples from Reach F were higher than in those from Reaches E and G, while % triglyceride was higher in samples from Reach F than in samples from Reaches B, C, E, and G. In contrast, neither % lipid nor % triglyceride varied by reach in marked Chinook salmon once sampling month had been taken into account ($P > 0.05$; Figure 10).

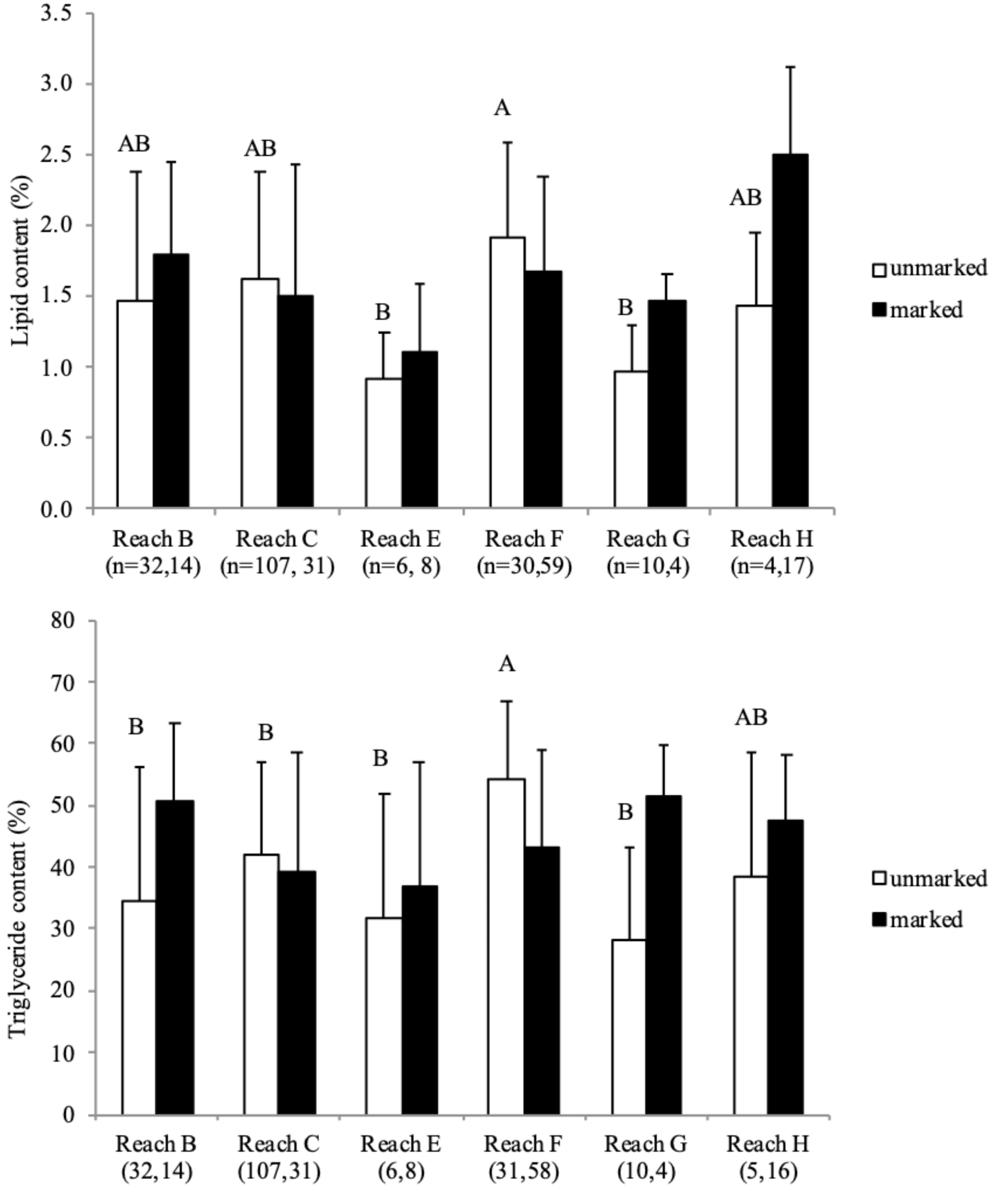

Figure 10. (top) Percent body lipid content and (bottom) % triglyceride of marked (black bars) and unmarked (white bars) juvenile Chinook salmon from the sampling sites, by hydrogeomorphic reach, 2008–15. Sample sizes are in parentheses. Differences for unmarked fish are shown in capital letters (ANOVA, Tukey–Kramer HSD, $P < 0.05$), after adjusting for the influence of sampling month. Figures include data from all sampling gear types.

Contaminants in Chinook Salmon

Overall, lipid-normalized concentrations of DDTs and PCBs did not differ between marked and unmarked Chinook salmon ($P > 0.05$; Figure 11, top and middle); however, PBDEs (ng/g lipid) varied by marked vs. unmarked status ($P < 0.05$; Figure 11, bottom). The mean PBDE concentration in unmarked fish was approximately double the mean value in marked fish. Concentrations of PCBs, DDTs, and PBDEs in Chinook salmon did not vary significantly based on month of capture ($P > 0.05$).

Among reaches, lipid-normalized concentrations of DDTs in marked fish (Figure 11, top) were highest in Reach E and lowest in Reach H, but did not vary across reaches for unmarked fish ($P > 0.05$). Lipid-adjusted concentrations of PCBs (Figure 11, middle) varied by reach in both marked and unmarked fish ($P < 0.05$). In marked fish, concentrations were highest in Reach E and lowest in Reach H, while in unmarked fish they were highest in Reach G and lowest in Reach H. Concentrations of PBDEs (Figure 11, bottom) also varied significantly by reach in both marked and unmarked fish ($P < 0.01$). In both marked and unmarked fish, concentrations were highest in Reach E and lowest in Reach H.

Concentrations of organochlorine pesticides other than DDTs were very low in both marked and unmarked salmon from all hydrogeomorphic reaches, typically <1 ng/g wet weight (ww). Aldrin, mirex, endosulfan I, and HCHs were less than the lower limit of quantitation (LOQ) in almost all samples analyzed. Mean concentrations of HCB ranged from 0.2 ng/g ww in Reach H to 0.4 ng/g ww in Reach C; mean concentrations of dieldrin ranged from 0.04 ng/g ww in Reach H to 0.2 ng/g ww in Reach E; and mean concentrations of chlordanes ranged from 0.5 ng/g ww in Reach H to 0.9 ng/g ww in Reach G.

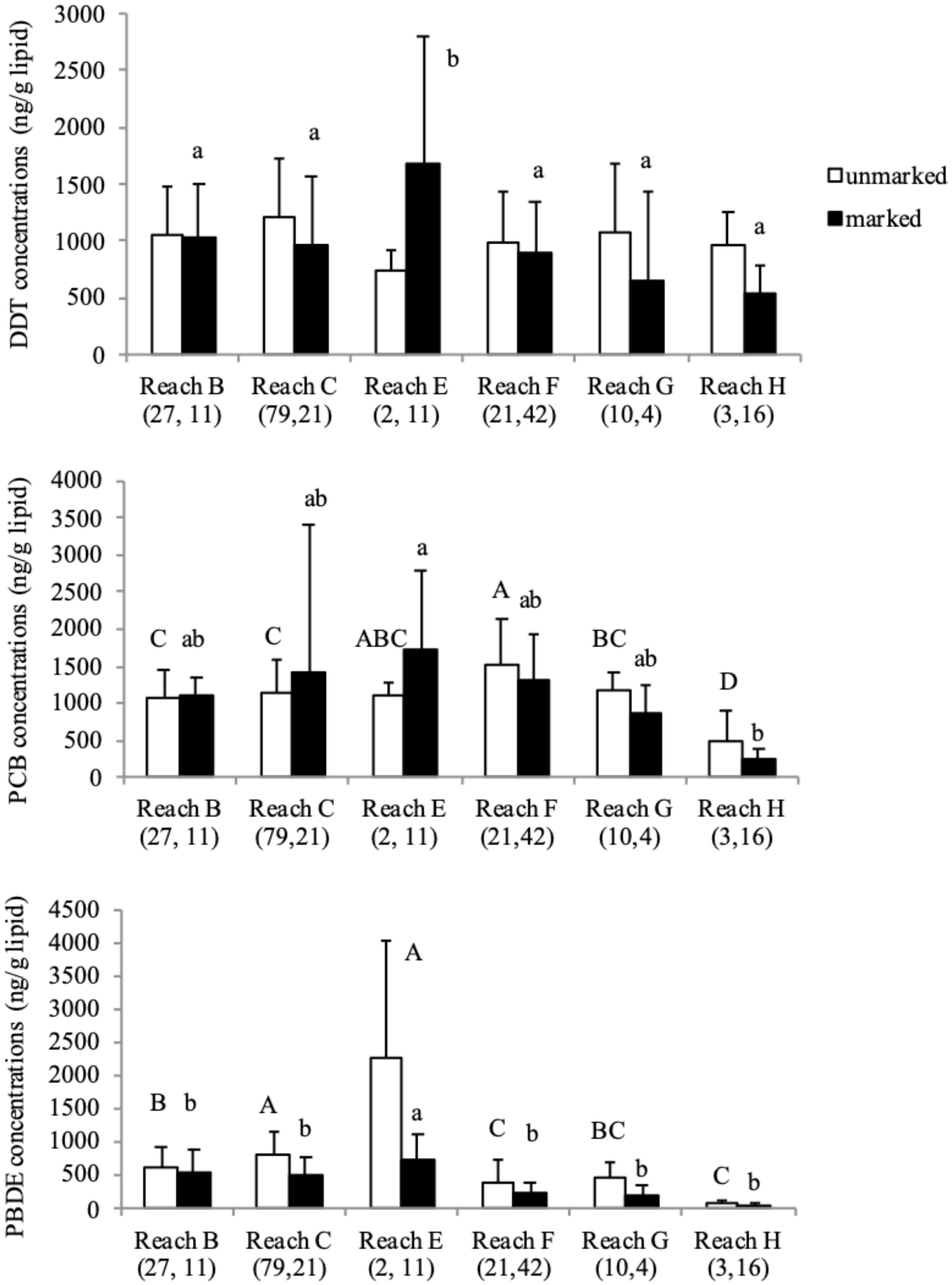

Figure 11. Mean concentrations (SD) of (top) DDTs, (middle) PCBs, and (bottom) PBDEs (ng/g lipid) in marked (black bars) and unmarked (white bars) juvenile Chinook salmon whole bodies from tidal freshwater hydrogeomorphic reaches in the lower Columbia River estuary. Capital letters indicate significant differences by reach for unmarked salmon, while lower-case letters indicate significant differences by reach for marked salmon (ANOVA, Tukey–Kramer HSD, $P < 0.05$). Sample sizes are in parentheses. Data include sampling from 2008–13, all sampling gear types.

Discussion

The data presented in this study were collected as part of a long-term monitoring program that began in 2005. The aim of the program was to assess the status and track trends in the overall condition of the LCRE, with a particular focus on tidal freshwater juvenile salmon rearing habitats. The intent was to describe baseline or reference conditions within the estuary, in sites that were among the least-disturbed in the sampling areas. The synthesis of results presents a detailed picture of the status of juvenile salmon ecology at some of the least-impacted freshwater emergent wetland sites, from the various hydrogeomorphic reaches of the LCRE.

With the importance of the lower reaches of the estuary (Reaches A–C) as critical rearing habitat for juvenile salmon clearly established in previous studies (Bottom et al. 2005b, 2005a, Fresh et al. 2005, Roegner et al. 2010, 2012), our findings show that tidal freshwater habitats throughout the LCRE are also used for migration and rearing by several species of salmonids, including spring and fall Chinook salmon, coho salmon, chum salmon, and, to a lesser extent, sockeye salmon and steelhead. We observed distinct patterns of salmon occurrence and condition by hydrogeomorphic reach, as well as by season. For Chinook and coho salmon, we also observed differences between marked and unmarked fish, consistent with the assumption that unmarked fish are more representative of natural populations. It was estimated that in 2015, 90% of hatchery-origin lower Columbia River fall Chinook were marked (NMFS 2015), so it is likely many of the unmarked Chinook salmon we sampled are in fact of natural origin.

Seasonal Patterns of Salmon Occurrence

Of the salmon species we encountered, Chinook salmon were the most widely distributed and abundant, followed by coho and chum salmon. Sockeye salmon and steelhead were observed in low numbers. Each of these salmon species showed distinct seasonal patterns of occurrence. We caught chum salmon almost exclusively in April and early May, consistent with their expected outmigration (Myers 1982, Salo 1991, Johnson et al. 1997), and supported by recent reports on chum salmon occurrence in the lower Columbia River and estuary (Roegner et al. 2008, Johnson et al. 2011). Sockeye salmon were also most frequently present in March and May, and steelhead most consistently present from April through June. These sockeye salmon and steelhead patterns of seasonal occurrence were similar to other reports from the region (Dawley et al. 1986, Burgner 1991, Gustafson et al. 1997, Quinn 2005).

For Chinook and coho salmon, both marked and unmarked fish were observed, and the two groups had different seasonal patterns of occurrence. For both marked and unmarked Chinook salmon, densities were highest in May and June, but unmarked Chinook salmon were present throughout the sampling season, whereas marked Chinook salmon were found only from April through August. Similarly, smaller unmarked coho salmon, likely subyearlings (Johnson et al. 1997), were present throughout the sampling season. Larger unmarked, as well as marked, coho salmon were most abundant in May, the established time for coho salmon smolt migration in the Columbia River (Weitkamp et al. 1995). Times when marked Chinook and coho salmon were present coincided with hatchery releases (Columbia River DART[1] 2012), consistent with reports by others (Bottom et al. 2008, Roegner et al. 2008, Johnson et al. 2011, Sather et al. 2016).

---

[1] http://www.cbr.washington.edu/dart/hatch.html

Seasonal patterns were also evident in Chinook salmon stock composition. Among unmarked Chinook salmon, Lower Columbia ESU stocks (West Cascades fall and Spring Creek fall) were generally predominant, but as the season progressed through summer, the Interior Columbia stocks (Upper Columbia summer/fall, Snake River fall, Deschutes fall) increased while Spring Creek fall declined. The increased proportion of interior stocks later in the season may reflect the extended migration these stocks must undertake to reach the lower Columbia River and estuary. In late fall and winter, spring Chinook salmon stocks (West Cascades spring and Upper Willamette River spring) were more predominant, likely representing spring Chinook salmon overwintering prior to their migration in early spring. Among the marked Chinook salmon, West Cascades fall and Spring Creek fall were the predominant stocks, with Spring Creek fall dominating in April and May and West Cascades fall more prevalent as the season progressed. Other studies report temporal patterns in stock composition in the LCRE similar to those we observed (Johnson et al. 2011, Teel et al. 2014, Sather et al. 2016).

Unmarked Chinook salmon were present in a diverse range of size classes (Fresh et al. 2005), including fry (<60 mm) and fingerlings or subyearling smolts (60–100 mm), as well as a small number of larger yearling-size fish (>120 mm). These larger fish were observed in November and December, presumably overwintering prior to migration in the spring. The diversity of life history strategies in unmarked juvenile Chinook salmon has also been reported by Bottom et al. (2005a, 2008) and Roegner et al. (2008, 2010) in the saltwater portion of the estuary, and by Sather et al. (2009, 2016) and Johnson et al. (2011) at tidal freshwater sites. Further, both length and weight increased in unmarked fish as the sampling season progressed, consistent with feeding and rearing in the estuary. In contrast to the unmarked Chinook salmon, marked Chinook salmon were generally within the fingerling size range, and showed only modest increases in size over the sampling season similar to observations by Bottom et al. 2008 and Johnson et al. 2011. An exception to this were a small number of larger marked yearlings encountered, coinciding with hatchery releases of this life stage (Columbia River DART). This size pattern in marked fish is consistent with relatively rapid migration through the estuary following their hatchery release.

Spatial Patterns of Salmon Occurrence

Our study showed distinctive patterns in salmon species occurrence among reaches, which might reflect the relative importance of the habitats that characterize those reaches. Chinook salmon were the dominant salmon species in all reaches except Reach H, where a fair number of coho salmon were also present. However, Chinook salmon densities varied from reach to reach, with peak densities of unmarked Chinook salmon ranging from 23 fish per 1,000 m^2 in Reach F to 160 fish per 1,000 m^2 in Reach G. These ranges are very similar to those observed by others. For example, Johnson et al. (2011) reported peak seasonal densities for unmarked Chinook in the 50 to 250 fish per 1,000 m^2 range in the Sandy River Delta (Reach G), whereas at tidal wetland sites in Reaches B–C, Bottom et al. (2008) reported seasonal peak densities for subyearling Chinook salmon ranging from <10 to 170 fish per 1,000 m^2. In the Salmon River and Oregon Coast estuaries, the reported range for peak seasonal juvenile Chinook salmon densities is 20 to 110 fish per 1,000 m^2 (Cornwell et al. 2001, Bottom et al. 2005a).

Densities of unmarked Chinook salmon were especially high in Reaches B and C, and relatively high in Reaches E and G, suggesting that these may be important areas for natural production. Reaches B and C, which were sampled most often and showed this trend most consistently, had fewer piscivorous predators and non-native species, as well as slightly lower summer water temperatures than other reaches (Hanson et al. 2015, Sagar et al. 2015). Both factors could make these reaches more favorable habitat for juvenile salmon. The highest densities of marked hatchery Chinook salmon were found in Reaches E–G. There are several hatcheries releasing Chinook salmon in these areas, including Spring Creek, Little White Salmon, and Cascade hatcheries in the Columbia Gorge, and Washougal and Bonneville hatcheries, which could be a source of marked fish in Reaches G and H and possibly Reach F. Several hatcheries are also located on the Lewis River near Reaches E and F (Columbia River DART 2012).

Chinook salmon from multiple stocks were documented in all of the sampled reaches. While the majority of fish were Spring Creek Group fall and West Cascade fall, a significant proportion of fish were from interior Columbia River stocks (i.e., Upper Columbia fall, Snake River fall, and Deschutes River fall), and some Upper Willamette spring and West Cascades spring were also present. The highest proportions of interior Columbia River stocks were found in Reaches F–H, although they were also present in other reaches. Similarly, Johnson et al. (2011) and Sather et al. (2016) found that in the Sandy River delta, located in Reach H, Upper Columbia summer/fall and a variety of other stocks were present, in addition to the common Spring Creek Group fall Chinook salmon. At our Reach C sites, genetic stock composition was very similar to that reported by Bottom et al. (2008) for sites near the mouth of the estuary, with West Cascades fall being the most prevalent.

In comparison to Chinook salmon, other salmon species were observed less consistently in the emergent marsh habitats sampled, a finding supported by other researchers (Roegner et al. 2008, Johnson et al. 2011, Sather et al. 2016). Coho salmon were found primarily in Reaches G and H, where both unmarked and marked fish were present, and to a lesser degree in Reach C, where only unmarked fish were observed. While it is uncertain why higher numbers of coho salmon were found in these reaches, there are natural coho populations in the Cowlitz and Lewis Rivers and in Mill, Abernathy, and Germany Creeks that could be a source of fish in Reach C. In addition, natural populations in the upper Columbia Gorge could be a source of fish observed in Reaches G and H (Good et al. 2005). Several federal and state-run hatcheries that release coho salmon are located near Reaches G and H (Columbia River DART), and are a likely source for marked coho salmon.

Chum salmon typically made up 1–5% of the salmonid catch, and were found at the highest densities in Reaches C and H, which is consistent with the fact that the two extant spawning populations of chum salmon are in the Columbia River Gorge and Grays River estuary (Good et al. 2005). Columbia River Gorge subpopulations are found in Hamilton Creek and Hardy Creek (Good et al. 2005), are in close proximity to the Reach H sampling sites. Sockeye salmon and steelhead are in all tidal freshwater reaches of the LCRE with the exception of Reach E, but only at very low densities. Steelhead density was highest in Reaches G and H, while sockeye density was highest in Reach C.

Indicators of Salmon Health and Fitness

Fish fitness data (condition factor, lipid content) collected for fall Chinook salmon were generally within the normal range reported for subyearlings in all reaches (Barnam and Baxter 1998, Biro et al. 2004). Overall, there was no significant difference in lipid content or condition factor between marked and unmarked fish, though they did show somewhat different spatial and seasonal patterns in condition factor and lipid and triglyceride content.

For both marked and unmarked fish, condition factor was low in February and March, increased through spring and summer, and then declined again in fall and winter, as expected with seasonal changes in temperature and prey availability. Roegner and Teel (2014) observed a similar pattern of increasing condition from winter through summer in Lower Columbia fall Chinook salmon fry, with increases coinciding with the spring freshwater phytoplankton bloom in the lower Columbia River and estuary (Roegner et al. 2011) and the onset of the wetland plant growing season.

Although seasonal changes in condition were similar between marked and unmarked fish, lipid and triglyceride content patterns were different. Lipid and triglyceride content were measured only from April through August, and, during most of this time, levels in marked fish were high relative to those of unmarked fish. For reasons that are unclear, unmarked fish lipid and triglyceride levels remained high in August, but declined significantly in marked fish. It is unlikely that these declines in marked fish were due to spatial or genetic factors, as all marked and unmarked fish sampled in August were collected in Reach C and were predominantly from the Lower Columbia ESU (i.e., West Cascades fall or Spring Creek fall Chinook salmon). The decline in marked fish lipid content may be reflective of the stress of outmigration, which typically takes place more rapidly in hatchery-origin fish, allowing them less opportunity for use of nearshore habitats for feeding (Bottom et al. 2005). Such declines in lipid content during outmigration are not uncommon in hatchery fish. For example, in spring Chinook salmon released from Snake River basin hatcheries, Arkoosh et al. (2011) observed a decline in lipid content from 3–5% to less than 1% during outmigration from the hatcheries near Bonneville Dam. Simpson et al. (2009) noted that "the condition of most hatchery salmonids has been shown to deteriorate after release, accompanied by acute post-release mortality due to inability to recognize food, decreases in foraging time, and poor feeding efficiency." Marked fish might also be more sensitive than wild fish to the higher water temperatures common in tidal freshwater habitats in August, and less able to compensate for the increased metabolic demand by increasing food consumption (Roegner and Teel 2014). Additionally, if the larger hatchery-origin fish were beginning to undergo smoltification, this may account for their reduced lipid content, as this process is energetically demanding (Sheridan 1989, Beckman et al. 2000). Other studies have found indications of greater energy loss during outmigration, as measured by changes in condition in larger hatchery-reared Chinook salmon migrating primarily through the main channel than in smaller subyearlings that migrated more slowly and made more extensive use of off-channel habitats (Connor et al. 2004, Hanson et al. 2012).

In August, the decline in lipid and triglyceride content in marked fish was accompanied by only a slight decline in condition factor. This discrepancy could be because the composite samples included only a subset of the fish measured for length, weight, and condition factor, although previous studies have shown that while condition index and lipid content are often related, the indices are not always congruent (MacFarlane 2010, Schloesser and Fabrizio 2016).

Despite this sampling program being focused on relatively undisturbed areas, chemical contaminant exposure was evident in Chinook salmon from a number of sites. Concentrations of persistent organic pollutants (i.e., PCBs, DDTs, and PBDEs) in juvenile Chinook salmon bodies were generally higher in fish from Reaches B though G than in those from Reach H. This pattern of contaminant accumulation is reflective of high industrial and urban development in Portland, Oregon, and Vancouver, Washington, which are adjacent to Reach G and upstream of Reaches B–F. Sewage and industrial outfalls are also present in the vicinity of St. Helens and Columbia City, Oregon, and Longview, Washington, potentially affecting sites in Reaches B–E. The presence of PBDEs in Chinook salmon, which were found in the highest concentration in Reaches C–E, indicates exposure to other wastewater compounds with which PBDEs are typically associated, including pharmaceuticals and personal care products (Morace 2012). The fact that some sections of the Columbia River or its tributaries in these reaches are listed as impaired water bodies for bacteria (ODEQ 2012) provides further evidence that these types of sewage-related chemicals are likely to be present.

Although contaminant concentrations at the study sites were generally low in comparison to maximum levels found in fish from other areas in the lower Columbia River region (LCEP 2007, Sloan et al. 2010, Johnson et al. 2013), lipid-normalized concentrations of PCBs and PBDEs in some samples from Reaches C, E, F, and G were above the estimated threshold for toxicant-related injury (Meador et al. 2002, Arkoosh et al. 2010, 2015, O'Neill et al. 2015). For example, in 8% of the samples collected in Reach C, 31% of the samples collected in Reach E, 13% of the samples collected in Reach F, and 14% of the samples collected in Reach G, concentrations of PCBs were above the effect threshold of 2,400 ng/g lipid proposed by Meador et al. (2002). For PBDEs, Arkoosh et al. (2010, 2015; see also O'Neill et al. 2015) indicate that the risk of immune dysfunction in juvenile Chinook salmon increases at body concentrations of 470 ng/g lipid, and the risk of alterations in thyroid function increases at 1,500 ng/g lipid. We found significant proportions of Chinook salmon samples that exceeded these thresholds, with major differences among reaches. Overall, 48% of samples in the study were above the immunosuppression threshold (54% of samples in Reach B, 77% in Reach C, 77% in Reach E, 11% in Reach F, and 21% in Reach G). A smaller but still substantial number of samples (5%) were at or above the level associated with thyroid dysfunction (4% of samples in Reach C, 8 % in Reach E, and 2% in Reach F).

Summary and Conclusions

Overall, our findings indicate that tidal freshwater emergent wetland habitats throughout the lower Columbia River and estuary support a variety of salmon species, with especially high densities of subyearling Chinook salmon. We also found that Chinook salmon stocks from both the lower Columbia River and the interior Columbia River basin were present in these areas, with the various reaches showing distinct patterns of salmon species and stock occurrence. Both marked and unmarked Chinook salmon were found throughout the Columbia River system, with the highest proportions of marked hatchery fish in the middle and upper reaches. Marked and unmarked Chinook salmon were distinct in stock composition, seasonal occurrence, and size distribution, in ways that were generally consistent with hatchery vs. natural origin, though the sources of the unmarked fish are not certain. Although the sampled sites were relatively undisturbed in comparison to other areas of the LCRE, there were still anthropogenic influences such as diking and channelization, hydropower impacts on river discharge volume and timing, and the presence of chemical contaminants in juvenile Chinook salmon. These findings are generally consistent with other studies that focused on specific reaches of the LCRE, and provide useful baseline information for salmon habitat restoration in multiple reaches of the lower Columbia River and estuary.

~

References

Arkoosh, M. R., D. Boylen, J. Dietrich, B. F. Anulacion, G. Ylitalo, C. F. Bravo, L. L. Johnson, F. J. Loge, and T. K. Collier. 2010. Disease susceptibility of salmon exposed to polybrominated diphenyl ethers (PBDEs). Aquatic Toxicology 98(1):51–59.

Arkoosh, M. R., S. A. Strickland, A. L. Van Gaest, G. M. Ylitalo, L. L. Johnson, G. K. Yanagida, T. K. Collier, and J. P. Dietrich. 2011. Trends in Organic Pollutants in Juvenile Snake River Spring Chinook Salmon with Different Outmigrating Histories through the Lower Snake and Middle Columbia Rivers. Science of the Total Environment 409:5086–5100.

Arkoosh, M. R., A. L. Van Gaest, S. A. Strickland, G. P. Hutchinson, A. B. Krupkin, and J. P. Dietrich. 2015. Dietary exposure to individual polybrominated diphenyl ether (PBDE) congeners, BDE-47 and BDE-99, alters innate immunity and disease susceptibility in juvenile Chinook salmon. Environmental Science and Technology 49:6974–6981.

Barnam, C., and A. Baxter. 1998. Condition factor, *K*, for salmonid fish. Fisheries Notes FN005. State of Victoria Department of Primary Industries, Melbourne, Australia.

Bayley, P. B., and R. A. Herendeen. 2000. The efficiency of a seine net. Transactions of the American Fisheries Socieity 129(4):901–923.

Beckman, B. R., D. A. Larsen, C. Sharpe, B. Lee-Pawlak, C. B. Shreck, and W. W. Dickhoff. 2000. Physiological status of naturally reared juvenile spring Chinook salmon in the Yakima River: Seasonal dynamics and changes associated with smolting. Transactions of the American Fisheries Society 129:727–753.

Beckvar, N., T. M. Dillon, and L. B. Read. 2005. Approaches for linking whole-body fish residues of mercury or DDT to biological effects thresholds. Environmental Toxicology and Chemistry 24:2094–2105.

Biro, P. A., A. E. Morton, J. R. Post, and E. A. Parkinson. 2004. Over-winter lipid depletion and mortality of age-0 rainbow trout (*Oncorhynchus mykiss)*. Canadian Journal of Fisheries and Aquatic Sciences 61:1513–1519.

Bottom, D., G. Anderson, A. Baptista, J. Burke, M. Burla, M. Bhuthimethee, L. Campbell, E. Casillas, S. Hinton, K. Jacobson, D. Jay, R. McNatt, P. Moran, C. Roegner, C. Simenstad, V. Stamatiou, D. Teel, and J. Zamon. 2008. Salmon life histories, habitat, and food webs in the Columbia River estuary: An overview of research results, 2002–2006. Report of the National Marine Fisheries Service Northwest Fisheries Science Center to the U.S. Army Corps of Engineers and Bonneville Power Administration, Portland, Oregon.

Bottom, D. L., K. K. Jones, T. J. Cornwell, A. Gray, and C. A. Simenstead. 2005a. Patterns of Chinook salmon migration and residency in the Salmon River estuary (Oregon). Estuarine, Coastal and Shelf Science 64:79–93.

Bottom, D. L., C. A. Simenstad, J. Burke, A. M. Baptista, D. A. Jay, K. K. Jones, E. Casillas, and M. H. Schiewe. 2005b. Salmon at river's end: The role of the estuary in the decline and recovery of Columbia River salmon. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-68.

Burgner, R. L. 1991. Life history of sockeye salmon *Oncorhynchus nerka.* Pages 3–117 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. University of British Columbia Press, Vancouver, Canada.

Columbia River DART. 2012. DART River Environment Graphics and Text. Available: www.cbr.washington.edu/dart/river.html (March 2017).

Cone, J. 1995. A Common Fate: Endangered Salmon and the People of the Pacific Northwest. Henry Holt and Company, Inc. New York.

Connor, W. P., S. G. Smith, T. Andersen, S. M. Bradbury, D. C. Burum, E. E. Hockersmith, M. L. Schuck, G. W. Mendel, and R. M Bugert. 2004. Post release performance of hatchery yearling and subyearling fall Chinook salmon released into the Snake River. North American Journal of Fisheries Management 24:545–560.

Cornwell, T. J., D. L. Bottom, and K. K. Jones. 2001. Rearing of juvenile salmon in recovering wetlands of the Salmon River estuary. Oregon Department of Fish and Wildlife, Information Reports 2001–05, Portland, Oregon.

Craig, B. E., C. A. Simenstad, and D. L. Bottom. 2014. Rearing in natural and recovering tidal wetlands enhances growth and life-history diversity of Columbia Estuary tributary coho salmon *Oncorhynchus kisutch* populations. Journal of Fish Biology 85:31–51.

Dawley, E. M., R. D. Ledgerwood, T. H. Blahm, C. W. Sims, J. T. Durkin, R. A. Kirn, A. E. Rankis, G. E. Monan, and F. J. Ossiander. 1986. Migrational characteristics, biological observations, and relative survival of juvenile salmonids entering the Columbia River estuary, 1966–1983. Report to the Bonneville Power Administration, Project DACW57-85-F-0623, Portland, Oregon.

Ford, M. J., editor. 2011. Status review update for Pacific salmon and steelhead listed under the Endangered Species Act: Pacific Northwest. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-113.

Fresh, K. L., E. Casillas, L. L. Johnson, and D. L. Bottom. 2005. Role of the estuary in the recovery of Columbia River basin salmon and steelhead: An evaluation of the effects of selected factors on salmonid population viability. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-69.

Fulton, T. Rate of growth of sea fishes. Scientific Investigations of the Fisheries Division of Scotland 20:1035–1039.

Good, T. P., R. S. Waples, and P. B. Adams. 2005. Updated status of federally listed ESUs of West Coast salmon and steelhead. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-66.

Gustafson, R. G., T. C. Wainwright, G. A. Winans, F. W. Waknitz, L. T. Parker, and R. S. Waples. 1997. Status review of sockeye salmon from Washington and Oregon. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-33.

Hahn, P. K. J., R. E. Bailey, and A. Ritchie. 2007. Beach seining. Pages 267–324 *in* D. H. Johnson, editor. Salmonid field protocols handbook: Techniques for assessing status and trends in salmon and trout populations. American Fisheries Society, Bethesda, Maryand.

Hanson, K. C., K. G. Ostrand, and R. A. Glenn. 2012. Physiological characterization of juvenile Chinook salmon utilizing different habitats during migration through the Columbia River estuary. Comparative Biochemistry and Physiology Part A 163:343–349.

Hanson, A. C., A. B. Borde, L. L. Johnson, T. D. Peterson, J. A. Needoba, S. A. Zimmerman, M. Schwartz, C. L. Wright, P. M. Chittaro, S. Y. Sol, D. J. Teel, G. M. Ylitalo, D. Lomax, C. E. Tausz, H. L. Diefenderfer, and C. A. Corbett. 2015. Lower Columbia River Ecosystem Monitoring Program Annual Report for Year 10 (October 1, 2013 to September 30, 2014). Prepared by the Lower Columbia Estuary Partnership for the Bonneville Power Administration, Portland, Oregon.

Hinck, J., C. J. Schmitt, V. S. Blazer, N. D. Denslow, T. M. Bartish, P. J. Anderson, J. J. Coyle, G. M. Dethloff, and D. E. Tillitt. 2006. Environmental contaminants and biomarker responses in fish from the Columbia River and its tributaries: Spatial and temporal trends. Science of the Total Environment 366:549–578.

Johnson, G. E., A. Storch, J. R. Skalski, A. J. Bryson, C. Mallette, A. B. Borde, E. Van Dyke, K. L. Sobocinski, N. K. Sather, D. Teel, E. M. Dawley, G. R. Ploskey, T. A. Jones, S. A. Zimmerman, and D. R. Kuligowski. 2011. Ecology of Juvenile Salmon in Shallow Tidal Freshwater Habitats of the Lower Columbia River, 2007–2010. PNNL-20083, Pacific Northwest National Laboratory, Richland, Washington.

Johnson, L. L., B. F. Anulacion, M. R. Arkoosh, O. P. Olson, C. A. Sloan, S. Y. Sol, J. A. Spromberg, D. J. Teel, G. K. Yanagida, and G. M. Ylitalo. 2013. Persistent organic pollutants in juvenile Chinook salmon in the Columbia Basin: Implications for stock recovery. Transactions of the American Fisheries Society 142:21–40.

Johnson, O. W., W. S. Grant, R. G. Kope, K. Neely, F. W. Waknitz, and R. S. Waples. 1997. Status review of chum salmon from Washington, Idaho, Oregon, and California. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-32.

Kalinowski, S. T., K. R. Manlove, and M. L. Taper. 2007. ONCOR: A computer program for genetic stock identification. Montana State University Department of Ecology, Bozeman, Montana. Available: www.montana.edu/kalinowski/software/oncor.html (December 2020).

LCEP (Lower Columbia Estuary Partnership). 2007. Lower Columbia River and Estuary Ecosystem Monitoring: Water Quality and Salmon Sampling Report. Lower Columbia Estuary Partnership, Portland, Oregon.

MacFarlane, R. B. 2010. Energy dynamics and growth of Chinook salmon (*Oncorhynchus tshawytscha*) from the Central Valley of California during the estuarine phase and first ocean year. Canadian Journal of Fisheries and Aquatic Sciences 67:1549–1565.

Maier, G. O., and C. A. Simenstad. 2009. The role of marsh-derived macrodetritus to the food webs of juvenile Chinook salmon in a large altered estuary. Estuaries and Coasts 32:984–998.

Manel, S., O. E. Gaggiotti, and R. S. Waples. 2005. Assignment methods: Matching biological questions with appropriate techniques. Trends in Ecology and Evolution 20:136–142.

McNatt, R. A., D. L. Bottom, and S. A. Hinton. 2016. Residency and movement of juvenile Chinook salmon at multiple spatial scales in a tidal marsh of the Columbia River estuary. Transactions of the American Fisheries Society 145:774–785.

Meador J. P., T. K. Collier, and J. E. Stein. 2002. Use of tissue and sediment-based threshold concentrations of polychlorinated biphenyls (PCBs) to protect juvenile salmonids listed under the U.S. Endangered Species Act. Aquatic Conservation: Marine and Freshwater Ecosystem 12:493–516.

Morace, J. L. 2012. Reconnaissance of contaminants in selected wastewater-treatment-plant effluent and stormwater runoff entering the Columbia River, Columbia River basin, Washington and Oregon, 2008–10: U.S. Geological Survey Scientific Investigations Report 2012–5068, Reston, Virginia.

Myers, K. W., and H. F. Horton. 1982. Temporal use of an Oregon estuary by hatchery and wild juvenile salmon. Pages 377–392 *in* V. S. Kennedy, editor. Estuarine Comparisons. Academic Press, New York.

Netboy, A. 1980. The Columbia River salmon and steelhead trout, their fight for survival. University of Washington Press, Seattle.

NMFS (National Marine Fisheries Service). 2015. Estimation of Percentages for Listed Pacific Salmon and Steelhead Smolts Arriving at Various Locations in the Columbia River Basin in 2015. Memorandum from NMFS Northwest Fisheries Science Center to NMFS Office of Protected Resources, Seattle.

O’Neill, S. M., A. J. Carey, J. A. Lanksbury, L. A. Niewolny, G. Ylitalo, L. Johnson, and J. E. West. 2015. Toxic contaminants in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) migrating through estuary, nearshore, and offshore habitats of Puget Sound. October 2015. Washington Department of Fish and Wildlife Publication Number FTP 16-02, Olympia, Washington.

ODEQ (Oregon Department of Environmental Quality). 2012. Oregon 2012 Integrated Water Quality Report and 303(d) Listing. Available: www.deq.state.or.us/wq/assessment/rpt2012/search.asp (May 2017).

PSEP (Puget Sound Estuary Program). 1990. Recommended guidelines for sampling soft-bottom demersal fishes by beach seine and trawl in Puget Sound. Final Report for Contract No. 68–D8–0085 by PTI Environmental Services for U.S. EPA, Region 10, Seattle.

Quinn, T. P. 2005. The Behavior and Ecology of Pacific Salmon and Trout. University of Washington Press and American Fisheries Society, Seattle.

Rannala, B., and J. L. Mountain. 1997. Detecting immigration by using multilocus genotypes. Proceedings of the National Academy of Sciences 94:9197–9201.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191:1–382.

Roegner, G. C., and D. J. Teel. 2014. Density and condition of subyearling Chinook salmon in the lower Columbia River and estuary in relation to water temperature and genetic stock of origin. Transactions of the American Fisheries Society 143:1161–1176.

Roegner, G. C., A. M. Baptista, D. L. Bottom, J. Burke, L. A. Campbell, C. Elliot, S. A. Hinton, D. A. Jay, M. Lott, T. A. Lundrigan, R. A. McNatt, P. Moran, C. A. Simenstad, D. J. Teel, E. Volk, J. E. Zamon, and E. Casillas. 2008. Estuarine habitat and juvenile salmon current and historical linkages in the lower Columbia River and estuary, 2002–2004. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Portland, Oregon.

Roegner, G. C., E. W. Dawley, M. Russell, A. Whiting, and D .J. Teel. 2010. Juvenile salmonid use of reconnected tidal freshwater wetlands in Grays River, lower Columbia River basin. Transactions of the American Fisheries Society 139:1211–1232.

Roegner, G. C., H. L. Diefenderfer, A. B. Borde, R. M. Thom, E. M. Dawley, A. H. Whiting, S. A. Zimmerman, and G. E. Johnson. 2009. Protocols for monitoring habitat restoration projects in the lower Columbia River and estuary. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-97.

Roegner, G. C., R. A. McNatt, D. J. Teel, and D. L. Bottom. 2012. Distribution, size, and origin of juvenile Chinook salmon in shallow water habitats of the lower Columbia River and estuary, 2002–2007. Marine and Coastal Fisheries 4:450–472.

Roegner, G. C., C. Seaton, and A. M. Baptista. 2011. Climatic and tidal forcing of hydrography and chlorophyll concentrations in the Columbia River estuary. Estuaries and Coasts 34:281–296.

Sagar, J. P., A. B. Borde, L. L. Johnson, T. D. Peterson, J. A. Needoba, K. H. Macneale, M. Schwartz, A. Silva, C. A. Corbett, A. C. Hanson, V. I. Cullinan, S. A. Zimmerman, R. M. Thom, P. M. Chittaro, O. P. Olson, S. Y. Sol, D. J. Teel, G. M. Ylitalo, M. A. Maier, and C. E. Tausz. 2015. Juvenile Salmon Ecology in Tidal Freshwater Wetlands of the Lower Columbia River and Estuary: Synthesis of the Ecosystem Monitoring Program, Trends (2005–2013) and Food Web Dynamics (2011–2013). Prepared by the Lower Columbia Estuary Partnership for the Bonneville Power Administration, Portland, Oregon.

Salo, E. O. 1991. Life history of chum salmon, *Oncorhynchus keta.* Pages 231–309 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. University of British Columbia Press, Vancouver, Canada.

Sather, N. K., G. E. Johnson, A. J. Storch, D. J. Teel, J. R. Skalski, T. A. Jones, E. M. Dawley, S. A. Zimmerman, A. B. Borde, C. Malette, and R. Farr. 2009. Ecology of Juvenile Salmon in Shallow Tidal Freshwater Habitats in the Vicinity of the Sandy River Delta, Lower Columbia River, 2008. Annual Report PNNL-18450. Prepared for the Bonneville Power Administration by the Pacific Northwest National Laboratory, Richland, Washington.

Sather, N. K., G. E. Johnson, D. J. Teel, A. J. Storch, J. R. Skalski, and V. I. Cullinan. 2016. Shallow tidal freshwater habitats of the Columbia River: Spatial and temporal variability of fish communities and density, size, and genetic stock composition of juvenile Chinook salmon. Transactions of the American Fisheries Society 145:734–753.

Schloesser, R. W., and M. C. Fabrizio. 2016. Temporal dynamics of condition for estuarine fishes in their nursery habitats. Marine Ecology Progress Series 557:207–219.

Seeb, L. W., A. Antonovich, M. A. Banks, T. D. Beacham, M. R. Bellinger, S. M. Blankenship, M. R. Campbell, N. A. Decovich, J. C. Garza, C. M. Guthrie III, T. A. Lundrigan, P. Moran, S. R. Narum, J. J. Stephenson, K. T. Supernault, D. J. Teel, W. D. Templin, J. K. Wenburg, S. F. Young, and C. T. Smith. 2007. Development of a standardized DNA database for Chinook salmon. Fisheries 32:540–552.

Sheridan, M. A. 1989. Alterations in lipid metabolism accompanying smoltification and seawater adaptation of salmonid fish. Aquaculture 82:191–203.

Sherwood, C. R., D. A. Jay, R. B. Harvey, P. Hamilton, and C. A. Simenstad. 1990. Historical changes in the Columbia River Estuary. Progress in Oceanography 25:299–352.

Simenstad, C. A., J. L. Burke, J. E. O'Connor, C. Cannon, D. W. Heatwole, M. F. Ramirez, I. R. Waite, T. D. Counihan, and K. L. Jones. 2011. Columbia River Estuary Ecosystem Classification—Concept and Application. U.S. Geological Survey Open-File Report 2011-1228, Reston, Virginia.

Simenstad, C. A., K. L. Fresh, and E. O. Salo. 1982. The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: An unappreciated function. Pages 343–364 *in* V. S. Kennedy, editor. Estuarine Comparisons. Academic Press, New York.

Simpson, W., K. Benjamen, and K. Ostrand. 2009. Seasonal foraging and piscivory by sympatric wild and hatchery-reared steelhead from an integrated hatchery program. Environmental Biology of Fishes 86:473–482.

Sloan, C. A., B. F. Anulacion, K. A. Baugh, J. L. Bolton, D. Boyd, R. H. Boyer, D.G. Burrows, D. P. Herman, R. W. Pearce, and G. M. Ylitalo. 2014. Northwest Fisheries Science Center's analyses of tissue, sediment, and water samples for organic contaminants by gas chromatography/mass spectrometry and analyses of tissue for lipid classes by thin layer chromatography/flame ionization detection. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-125.

Sloan, C. A., B. F. Anulacion, J. L. Bolton, D. Boyd, O. P. Olson, S. Y. Sol, G. M. Ylitalo, and L. L. Johnson. 2010. Polybrominated Diphenyl Ethers in Outmigrant Juvenile Chinook Salmon from the Lower Columbia River and Estuary and Puget Sound, Washington. Archives of Environmental Contamination and Toxicology 2:403–414.

Sloan, C. A., D. W. Brown, R. W. Pearce, R. H. Boyer, J. L. Bolton, D. G. Burrows, D. P. Herman, and M. M. Krahn. 2004. Extraction, cleanup, and gas chromatography/mass spectrometry analysis of sediments and tissues for organic contaminants. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-59.

Steele, M. A, S. C. Schroeter, and H. M. Page. 2006. Experimental evaluation of biases associated with sampling estuarine fishes with seines. Estuaries and Coasts 29:1172–1184.

Teel, D. J., C. Baker, D. R. Kuligowski, T. A. Friesen, and B. Shields. 2009. Genetic stock composition of subyearling Chinook salmon in seasonal floodplain wetlands of the Lower Willamette River. Transactions of the American Fisheries Society 138:211–217.

Teel, D. J., D. L. Bottom, S. A. Hinton, D. R. Kuligowski, G. T. McCabe Jr., R. A. McNatt, G. C. Roegner, L. A. Stamatiou, and C. A. Simenstad. 2014. Genetic identification of Chinook salmon in the Columbia River estuary: Stock-specific distributions of juveniles in shallow freshwater habitats. North American Journal of Fisheries Management 34(3):621–641.

Thorpe, J. E. 1994. Salmonid fishes and the estuarine environment. Estuaries 17:76–93.

Torcher, D. R. 2003. Metabolism and functions of lipids and fatty acids in teleost fish. Reviews in Fisheries Science 11:107–184.

USGS (United States Geological Survey). 2020. USGS 14128870 Columbia River Below Bonneville Dam, OR. National Water Information System. Available: waterdata.usgs.gov/or/nwis/uv?site_no=14128870 (May 2020).

Weitkamp, L. A., T. C. Wainwright, G. J. Bryant, G. B. Milner, D. J. Teel, R. G. Kope, and R. S. Waples. 1995. Status review of coho salmon from Washington, Oregon, and California. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-24.

Ylitalo, G. M., G. K. Yanagida, L. C. Hufnagle Jr., and M. M. Krahn. 2005. Determination of lipid classes and lipid content in tissues of aquatic organisms using a thin layer chromatography/flame ionization detection (TLC/FID) microlipid method. Pages 227–237 *in* G. K. Ostrander, editor. Techniques in Aquatic Toxicology. CRC Press, Boca Raton, Florida.

Recently published by the Northwest Fisheries Science Center

NOAA Technical Memorandum NMFS-NWFSC-

161 **Clarke, M. E., E. L. Fruh, A. Powell, J. Anderson, J. C. Taylor, and C. E. Whitmire. 2020.** Autonomous Underwater Vehicle (AUV) Survey at The Footprint and Piggy Bank in the Southern California Bight, 2011. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-161. https://doi.org/10.25923/mfq8-6773

160 **Harvey, C., N. Garfield, G. Williams, N. Tolimieri, K. Andrews, K. Barnas, E. Bjorkstedt, S. Bograd, J. Borchert, C. Braby, R. Brodeur, B. Burke, J. Cope, A. Coyne, D. Demer, L. deWitt, J. Field, J. Fisher, P. Frey, T. Good, C. Grant, C. Greene, E. Hazen, D. Holland, M. Hunter, K. Jacobson, M. Jacox, J. Jahncke, C. Juhasz, I. Kaplan, S. Kasperski, S. Kim, D. Lawson, A. Leising, A. Manderson, N. Mantua, S. Melin, R. Miller, S. Moore, C. Morgan, B. Muhling, S. Munsch, K. Norman, J. Parrish, A. Phillips, R. Robertson, D. Rudnick, K. Sakuma, J. Samhouri, J. Santora, I. Schroeder, S. Siedlecki, K. Somers, B. Stanton, K. Stierhoff, W. Sydeman, A. Thompson, D. Trong, P. Warzybok, B. Wells, C. Whitmire, M. Williams, T. Williams, J. Zamon, S. Zeman, V. Zubkousky-White, and J. Zwolinski. 2020.** Ecosystem Status Report of the California Current for 2019–20: A Summary of Ecosystem Indicators Compiled by the California Current Integrated Ecosystem Assessment Team (CCIEA). U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-160. https://doi.org/10.25923/e5rb-9f55

159 **Hartley, M. L., D. M. Schug, K. F. Wellman, B. Lane, W. T. Fairgrieve, and J. A. Luckenbach. 2020.** Sablefish Aquaculture: An Assessment of Recent Developments and Their Potential for Enhancing Profitability. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-159. https://doi.org/10.25923/cb0y-n468

158 **Richerson, K. E., J. E. Jannot, Y.-W. Lee, J. T. McVeigh, K. A. Somers, V. J. Tuttle, and S. Wang. 2020.** Observed and Estimated Bycatch of Green Sturgeon in 2002–17 U.S. West Coast Groundfish Fisheries. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-158. https://doi.org/10.25923/sn5z-w384

157 **Holland, D. S. 2020.** An Analysis of the Pacific Groundfish Trawl Individual Fishing Quota (IFQ) Quota Pound (QP) Market Through 2019. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-157. https://doi.org/10.25923/sxdw-kb49

156 **Zabel, R. W., and C. E. Jordan, editors. 2020.** Life Cycle Models of Interior Columbia River Basin Spring/Summer-run Chinook Salmon Populations. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-156. https://doi.org/10.25923/phfm-wq72

155 **Anderson, L., and J. Hilger. 2020.** A Discrete Choice Experiment Data Collection of U.S. West Coast Saltwater Anglers, 2017: Methodology and Response. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-155. https://doi.org/10.25923/ge3e-vc58

NOAA Technical Memorandums NMFS-NWFSC are available from the NOAA Institutional Repository, https://repository.library.noaa.gov.

U.S. Secretary of Commerce
Wilbur L. Ross, Jr.

Acting Under Secretary of Commerce
for Oceans and Atmosphere
Dr. Neil Jacobs

Assistant Administrator for Fisheries
Chris Oliver

January 2021

fisheries.noaa.gov

OFFICIAL BUSINESS

National Marine
Fisheries Service
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112