EVALUATION OF TRAWL SAMPLING FOR THREATENED EULACHON (THALEICHTHYS PACIFICUS) IN THE LOWER COLUMBIA RIVER DURING JANUARY–MARCH 2013

Authors: Zamon, Jeannette E, Hinton, Susan A, Bentley, Paul J, and Langness, Olaf P

Source: Northwestern Naturalist, 102(3) : 179-195

Published By: Society for Northwestern Vertebrate Biology

URL: https://doi.org/10.1898/1051-1733-102.3.179

EVALUATION OF TRAWL SAMPLING FOR THREATENED EULACHON (*THALEICHTHYS PACIFICUS*) IN THE LOWER COLUMBIA RIVER DURING JANUARY–MARCH 2013

JEANNETTE E ZAMON, SUSAN A HINTON, PAUL J BENTLEY

National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, Pt. Adams Research Station, PO Box 155, Hammond, OR 97121-0155 USA; jen.zamon@noaa.gov

OLAF P LANGNESS

Washington Department of Fish and Wildlife, Region 5, 5525 11th Street, Ridgefield, WA 98642 USA

ABSTRACT—The population of Eulachon (*Thaleicthys pacificus*) spawning in the Columbia River and its tributaries is thought to be the largest in the world. Eulachon historically supported indigenous, commercial, and sport harvests, but were listed as threatened under the US Endangered Species Act in 2010. This study tested the use of a small research trawl and 38-kHz echosounder to provide new, fishery-independent data for Columbia River Eulachon. During January–March 2013, we used a semi-balloon shrimp trawl and an uncalibrated 38-kHz downward-looking echosounder to sample estuarine and tidal freshwater habitats. Eulachon were present in the estuary on every sampling day. Direct mortality in the trawl was very low (<0.1%). We observed sex ratios closer to 1:1 than previously reported for the Columbia River, and trawl-caught Eulachon were longer and heavier than Eulachon caught with the same gear in the same season during 1980–1981. The largest catches occurred after 11 February 2013, when midwater estuary temperature warmed and remained above 5.5°C. Tributary spawning began in mid-March after estuary warming and continued for at least 2 wk. Observations suggested that Eulachon occurred in low densities and remained dispersed in deeper waters of the estuary for at least 2 mo before upstream migration. The estuary may therefore serve as an important staging area prior to upstream migration and subsequent spawning. Catch data and qualitative acoustic images suggest that a combination of trawl and acoustic surveys could provide direct estimates of adult biomass. If Eulachon populations are to recover from the threat of extinction, additional data will be needed to resolve uncertainties regarding spawner condition, adult spawning-stock biomass, and variation in run timing relative to river and estuary conditions. We recommend implementation of systematic surveys for adult Eulachon in the Columbia River to further understand how environmental factors drive variation in run size and run timing for this species.

Key words: acoustics, Columbia River Estuary, Eulachon, run timing, spawning, *Thaleichthys pacificus*

Pacific Eulachon (*Thaleichthys pacificus*) are anadromous schooling fish endemic to the northeast Pacific Ocean with a historical freshwater spawning distribution that extends from northern California, through British Columbia, and north to the coastal southeastern Bering Sea in Alaska (Gustafson and others 2010, 2012). Adults reach sizes of 150–250 mm, among the largest of the smelt family Osmeridae. Mature adults are extremely lipid-rich, containing up to 15–25% fat (Iverson and others 2002). Annual spawning migrations to coastal rivers occur during winter, a time when other lipid-rich food resources for predators, including humans, are scarce (Lewis and Clark 1806; Mitchell and Donald 2001; Sigler and others 2004; Reynolds and Romano 2013). For many indigenous peoples in the Pacific Northwest, Eulachon were a staple trade and diet item, second in importance only to Pacific salmon as a marine food resource (Mitchell and Donald 2001). In addition, Eulachon supported significant commercial and sport fisheries. The Columbia River is thought to support the largest Eulachon population in the world (Hay and McCarter 2000). Adult fish return to the river and its tributaries between December and May, with peak spawning typically occurring during February and March (Gustafson and others 2010). However, in the 1990s, synchronous and severe declines in commercial catches and larval abundance were observed in the southern portion of the species range (California, Oregon, Washington, and southern British Columbia). In 2010, the US National Marine Fisheries Service (NMFS) recognized all Eulachon spawning populations from California, Oregon, Washington, and British Columbia up to and including the Skeena River as vulnerable to extinction, and the US portion of these populations was listed as threatened under the Endangered Species Act (ESA; Gustafson and others 2010; NMFS 2010). Similarly, in 2011, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) listed all vulnerable Eulachon populations in British Columbia, Canada, as threatened or endangered (COSEWIC 2011). Threatened populations recognized by NMFS and Canada are collectively referred to as the Southern Distinct Population Segment (DPS) to distinguish them from unlisted Eulachon populations in the Nass River, British Columbia and Alaska, which consist of at least 1, and perhaps more, DPS units (Flannery and others 2013). The most severe threats to listed populations of Eulachon are climate change effects on marine and freshwater habitat, but also include effects of bycatch in shrimp fisheries, predation, dams, and water quality (NMFS 2017).

The NMFS Final Recovery Plan for Eulachon highlights annual in-river spawning-stock biomass (SSB) estimates as a high priority for tracking population trends over time (NMFS 2017). At present, the Columbia River is still the largest contributor to the Southern DPS, yet available SSB estimates for the Columbia River derive from indirect methods based on egg-larval abundance (Hay and others 2002; Langness and others 2018), where SSB is back-calculated from egg and larval density observed in the river using data on the sex ratio, sex-specific body mass, and fecundity of adult spawners. Availability of adult spawners required for this estimation method is limited to a narrow time period associated with commercial gill-net and recreational dip-net fishery openings (typically $\leq$2 wk in late February or early March), as there is no systematic, fishery-independent sampling program for adult spawners. There is concern (Moffitt and others 2002; James and others 2014) that adult length-weight and sex ratio data from such narrow sampling windows may not be representative of the entire run and could introduce bias into SSB estimates. To better represent adult sizes and sex ratios during the spawning run, it would be ideal to sample adult spawners over a longer period and in the lower river prior to arrival of fish on the spawning grounds.

We had a one-time opportunity in 2013 to do a preliminary evaluation of a small research trawl and a 38-kHz downward-looking echosounder for sampling Columbia River Eulachon during January through March of 2013. Given the absence of both commercial and recreational fishery openings in 2013, the overall goal was to determine whether direct sampling and acoustic observation could provide samples of adult Eulachon size and sex ratios necessary for estimates of 2013 adult spawning-stock biomass (SSB), as well as provide preliminary information on occupancy of and conditions in estuary and tidal freshwater habitats during the spawning run. Our study objectives were to (1) determine whether a downward-looking echosounder and small research trawl could successfully locate and sample adult Eulachon in the Columbia River; (2) compare Eulachon trawl catches between estuarine and tidal freshwater habitats; and (3) construct a timeline of the 2013 Eulachon spawning migration based on field observations of Eulachon and its predators within the study period.

Methods

Study Area

All acoustic observations for this work took place in the lower Columbia River downstream from its confluence with the Cowlitz River (river kilometer [rkm] 109), and all trawling took place near or downstream of Wauna, Oregon (rkm 66, Fig. 1). Both estuarine and freshwater portions of this region of the Columbia River are influenced by mixed diurnal and semi-diurnal tides. Mean tidal influence diminishes to $<$0.2 m above Vancouver, Washington (rkm 171), but can be discerned as far upstream as Bonneville Dam (rkm 234–235; Kukulka and Jay 2003). At our furthest downstream working area near Ham-

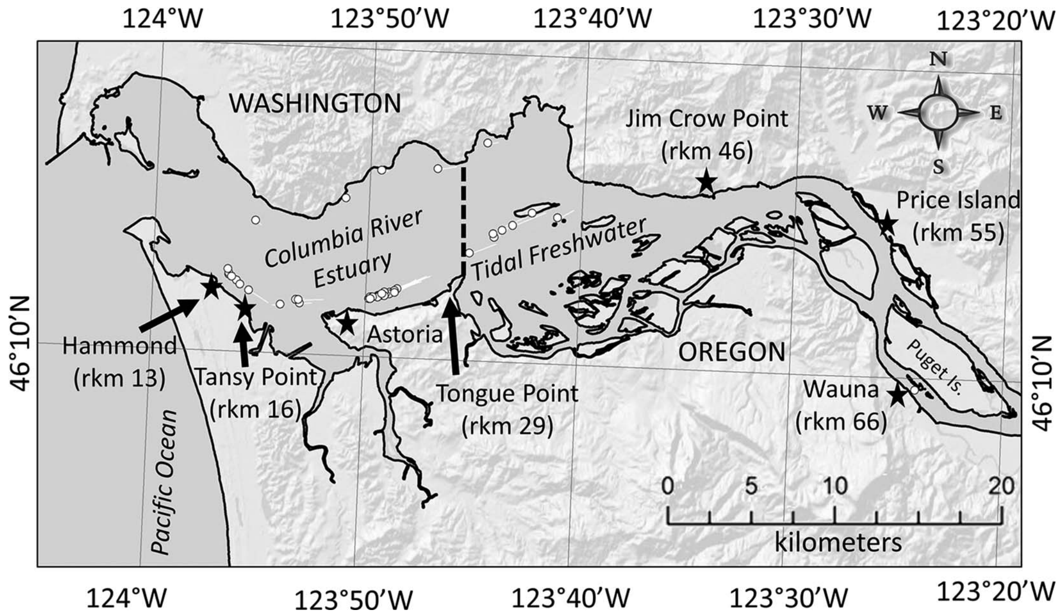

FIGURE 1. Study area and trawl locations in the lower Columbia River and estuary. Trawl start positions are indicated by a white dot, with the length of the trawl shown as a fine white line. The dotted line running north-to-south from Tongue Point, Oregon, is the boundary between estuary habitat downstream and tidal freshwater habitat upstream.

mond, Oregon (rkm 13), mean tidal range was 1.94 m. In contrast, tidal range was 1.01 m at the furthest upstream area near the Cowlitz River (rkm 109). Mean high water for these 2 locations was 2.54 m and 1.22 m, respectively.

Salinity intrusion in the Columbia River is driven by seasonal interactions between ocean tides, river flows, and topography. Salt can be detected as far as 45 km upstream from the mouth during low-flow periods (<5000 m^3 s^{-1}), but this typically occurs from August to October (Jay and Smith 1990). We classified trawl locations as occurring in either the estuary or tidal freshwater based on their respective locations downstream or upstream from approximately 123°45.5′ W. This line of longitude extends across the river from Tongue Point, Oregon, (rkm 29) to Grays Point, Washington (dashed line in Fig. 1). We chose this boundary based on climatological models of mean maximum salinity intrusion from January to March of 1999–2011, which show winter salt penetration is almost always confined to locations downstream of rkm 29 (CMOP 2013). For purposes of this study, we use the term "estuary" to refer to waters where there is measurable salt penetration into the river, and the term "tidal freshwater" to refer to waters where there is no measurable salt penetration into the river.

Qualitative Acoustic Operations

Observations of objects in the water column, including fish, were made from an 8.5-m research vessel with an uncalibrated, downward-looking 38-kHz split-beam Simrad echosounder. The echosounder had a 12° beam width and was hull-mounted 0.5 m below the surface. During operation, the ping rate was 5 pings s^{-1}, transmitting at 1000 W with a 1.024-millisecond pulse width. Echograms (visual images of echo return intensity) were displayed as scattering volume (S_v) in real time on a computer screen, and echogram images were saved in digital files. A conservative minimum threshold for echogram display was set at –65 dB because scattering less than –65 dB was assumed too weak to represent Eulachon targets (Gauthier and Horne 2004; Stables and others 2005).

The day before trawling, the acoustic vessel conducted surveys of the ship channel from rkm 13 to rkm 109 to look for evidence of large, tightly packed fish schools. Detection of such schools was assumed to be an indicator that Eulachon had initiated upstream migration. On the day of trawling, the acoustic vessel accompanied the trawl vessel to trawl locations and recorded images no more than 500 m ahead but on the same track line as the trawl vessel fished, or within less than 100 m to one side of the of the trawl-vessel track line, to obtain a qualitative, visual representation of target distribution in the immediate trawl area.

Trawl Operations

Trawl sampling took place between Hammond, Oregon (rkm 13) and Wauna, Oregon (rkm 66). Estuary trawl sites were located in or near the ship channel, along known migration paths and near sites where Eulachon had been caught in previous winter trawl studies (Fig. 1; Ebel and others 1981; Bottom and Jones 1990). All tows were completed during daylight hours between 11 January and 12 March 2013. Estuarine habitats where depths were <5 m at mean low water (for example, large areas of shallow sand flats in the central part of the estuary such as Desdemona Sands) were too shallow for trawling and were not sampled.

We towed a modified semi-balloon shrimp trawl at 1.5–2 m s^{-1} from a 12.5-m, diesel-powered research vessel. The trawl net had a 7.9-m headrope and a mouth opening approximately 5.6 m wide by 0.46 m deep and was connected to a wire bridle attached to two 0.5 $\times$ 1-m wooden doors (Bottom and Jones 1990; McCabe and others 1993). The net was constructed of 38-mm stretched mesh in the body and 10-mm unstretched mesh in the codend. Fishing depth for the net was estimated by using wire length deployed and the wire angle at the surface to calculate the depth of the haul. Bottom depth during the trawl was determined from the trawl vessel's depth sounder. Trawls were classified as (1) bottom trawls, in which the net fished on or up to 3 m above the river bed; (2) midwater trawls, in which the net fished on targets more than 3 m above the riverbed; or (3) combination trawls, in which the net fished both the bottom and midwater during the same deployment. We note here that because all trawls were oblique hauls (sampling continuously from depth to the surface), individual estuary trawls sampled within both the salt wedge and the freshwater surface layer; therefore trawl sampling could not resolve whether fish were captured within the salt wedge versus the freshwater surface layer.

Average time between net deployment and retrieval was 13 min, with full deployment periods varying from 3 min during limited fishing on extremely dense targets to 21 min during longer hauls on sparsely distributed midwater targets. Catch-per-unit-effort (CPUE) for each haul was calculated as follows: CPUE $=\log_{10}(x+1)$, where x is the number of Eulachon caught per minute of trawling.

Trawl contents were processed on board immediately following net retrieval. We separated Eulachon from other fish species as rapidly as possible and placed Eulachon into 55-gallon dark plastic cylindrical holding tanks that received flow-through river water from an intake depth of approximately 1 m. We then identified and counted all other fish species captured before returning these fishes immediately to the river. For extremely numerous catches of any species other than Eulachon, we sub-sampled individuals with a pair of 14-cm diameter sieves, counted all fish in those 2 sieves, and then extrapolated total counts by measuring the total number of additional full sieves plus any remaining fishes from a partially full sieve. When time allowed, we measured lengths of up to 30 individuals for each non-Eulachon fish species for use in a separate study of winter fish communities. Macroinvertebrates, if present, were noted but not enumerated.

We counted, measured, and sexed all Eulachon from each trawl except for the trawl that had 7,060 Eulachon in it. For that sample, we took a random subsample of 200 to determine sex ratio and we continued to sort males and females after these initial 200 fish until we had sex-specific length measurements for at least 100 males and 100 females. The random sample for sex ratio was taken by dipping a small hand net into the recovery tanks, pulling 200 fish out and holding them in smaller buckets, then continuing to dip fish from the holding tanks for the sex-specific length sample. All remaining Eualchon in this sample were counted and released. Field identification of male and female Eulachon was accomplished by application of gentle abdominal pressure to extrude, if possible, a very small amount of male (milt) or female (eggs) gametes. In cases where gentle pressure produced no gametes, we classified the fish as female. We chose to classify this way because males during the spawning run will easily produce gametes with gentle pressure, but females who are gravid but not yet ready to spawn may not do so. We recorded fork length (FL) in mm for males and females separately, up to a total of 100 lengths for each sex. We released Eulachon only after ensuring that no potential predators were observed within approximately 30 m of the vessel.

On each sampling day, we retained up to 10 female Eulachon from 3 pre-determined size classes for separate use in the Washington Department of Fish and Wildlife (WDFW) egg counts used for spawning-stock biomass estimates (<160 mm, 160–175 mm, and >175 mm FL; James and others 2014). Fish were gently euthanized in a water bath containing tricaine methanesulfonate (MS-222), then placed on ice until weighed later the same day in the laboratory. Individual fish were blotted dry before wet weight was measured to the nearest 0.1 gm using an electronic balance. Specimens were packed on ice and sent to WDFW for egg counting. Preliminary results from egg counts were used for fecundity analyses reported separately by James and others (2014).

To assess whether Eulachon size differed between our 2013 estuary trawl samples and those captured in January to March 1980–1981 with an identically-configured trawl net (Bottom and Jones 1990; S Hinton, unpubl. data), we used Mann-Whitney rank-sum test on natural-logarithm transformed FL and weight data.

Environmental Conditions

To compare mean daily CPUE of Eulachon with temperature, salinity, flow, and turbidity, we used hydrographic records collected from 1 January to 31 March 2013 (CMOP 2013; USGS 2013). We used observations of temperature and salinity from midwater at Tansy Point (8.3 m depth, rkm 16), a representative estuary monitoring station within 11 km of all estuarine trawl locations (CMOP 2013), to plot trends for estuary temperature and salinity. To examine changes in freshwater flow and turbidity in the lower river, we used daily observations from the Beaver Army Terminal station (rkm 86.5; USGS 2013). We plotted daily mean flow ($m^3\ s^{-1}$) and daily provisional median turbidity (formazin nephelometric units, FNU) without any additional averaging or filtering of data.

Timeline of Eulachon and Eulachon Predator Activity

We compiled a timeline of all verifiable reports of Eulachon sightings, spawning activity, and large predator aggregations during our study period to reconstruct a record of migration timing. We used information from our own field notes as well as from e-mail or phone reports from field personnel of the Oregon and Washington Departments of Fish and Wildlife and the Cowlitz Indian Tribe who were also working in the lower river during our study period. An observation was considered a "verifiable report" if it included first-hand observations by biologists or vessel operators able to correctly identify Eulachon and Eulachon predators, or if it included second-hand but confirmed observations reported directly to field biologists by private citizens.

RESULTS

Qualitative Acoustic Operations

The acoustic vessel logged 15 d on the water between 10 January and 20 March 2013 working between rkm 13 and rkm 109. During this time, we observed daytime acoustic targets (displayed as scattering volume, S_v) exhibiting 4 qualitative types of echo distributions (Fig. 2). Distribution types were classified by increasing intensity and spatial continuity of acoustic scattering. Type I echograms showed few or no aggregated targets; Type II, dispersed midwater targets; Type III, mixed, non-continuous midwater and bottom targets; and Type IV, large, continuous, bottom-oriented or midwater shoals >50 m in length.

During January and February, we saw few or no aggregated targets (Type I echograms) in tidal freshwater reaches upstream from Tongue Point (rkm 29). Dispersed midwater targets and mixed midwater and bottom targets (Type II and III echograms) were common during January, February, and March throughout the estuary downstream of rkm 29, but Type II and III echograms were not observed upstream of rkm 29 in tidal freshwater. We first saw Type IV echograms with large, continuous, bottom-oriented shoals near Upper Clifton Channel and Wauna (rkm 64–68) in tidal freshwater. Type IV echograms were also observed during the 2nd week of March within and adjacent to the ship channel between the

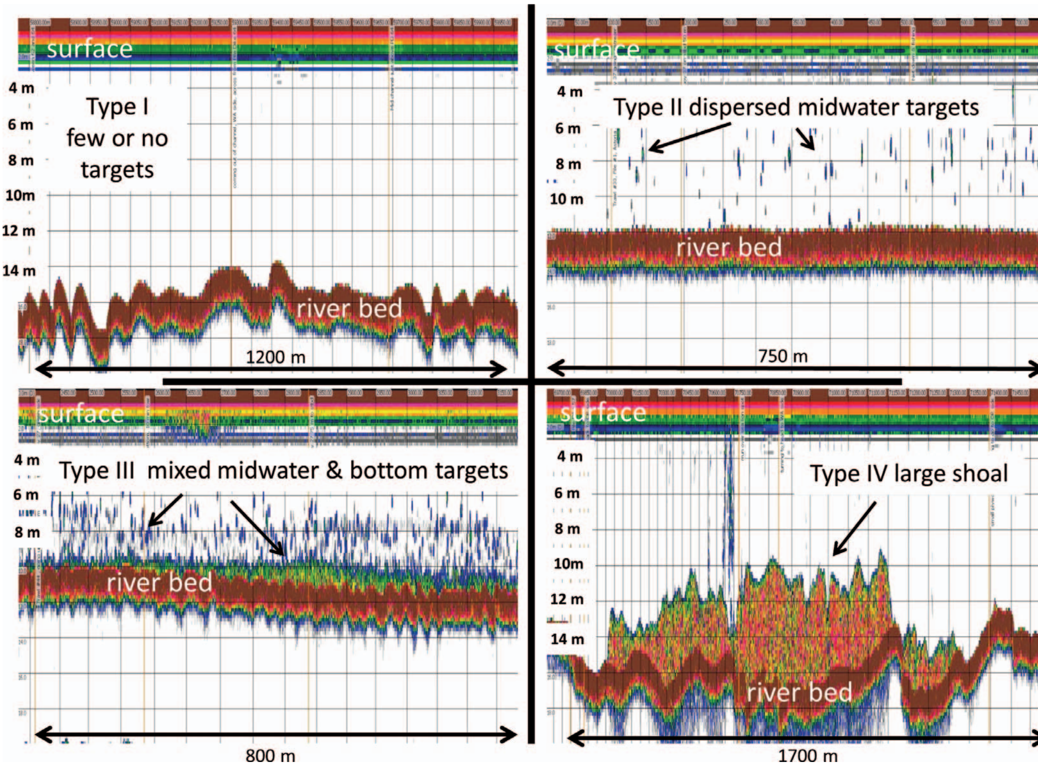

FIGURE 2. Typical echogram image types seen during qualitative acoustic surveys of the lower Columbia River and estuary, January–March 2013. Scattering volume (S_V) is shown from –65 dB (light gray and blue, weak acoustic reflection) to –25 dB (dark red, strong acoustic reflection). Gridlines divide images into 50 m long by 2 m deep cells. Rainbow bands at the top of each image indicate noise in the near-field of the transducer. The Type I echogram is from 7 March, in the ship channel near Pile Dike 64 (rkm 73); Type II echogram 11 February, near Buoy 37 on the Astoria Anchorage (rkm 27); Type III echogram 25 February, near Buoy 27 off Tansy Point (rkm 16); Type IV echogram 7 March, in the ship channel near Wauna, Oregon (rkm 66).

Astoria-Megler Bridge (rkm 22) and Tongue Point (rkm 29). Given trawl catch composition (see next section), all echograms that occurred in the estuary were associated with mixed-species targets (including some Eulachon). However, the continuous shoals seen in Type IV echograms from tidal freshwater appeared to be composed entirely of Eulachon.

Trawl Operations

We included a total of 47 trawls on 11 different sampling days between 11 January and 12 March 2013 in our final analysis; we excluded 6 trawls in which the net snagged or tore, or tow cables or doors became fouled. Holding tanks were very effective in preventing immediate, direct mortality of Eulachon captured in the trawl net; we observed mortality in only 7 of 7776 individuals (<0.1%) that died during the period of trawl retrieval, catch sorting, and Eulachon release. Eulachon released in groups from the holding tank immediately schooled together and swam rapidly away from the surface within a few seconds. We did not observe any near-surface predation events on Eulachon that we released nor did the release appear to attract predators from a distance.

Trawl information and Eulachon presence-absence data are presented in Table 1. Eulachon were not equally present across the three trawl types. Eulachon presence occurred less often than expected in midwater trawls that did not sample near the bottom, more often than expected in trawls sampling near the bottom, and slightly more often than expected in combination trawls where both near-bottom

TABLE 1. Summary of trawl effort, Eulachon (*Thaleichthys pacificus*) occurrence, and water depth, January–March 2013.

Trawl type	n	Eulachon occurrence			Water depth (m)			
		Present (n)	Absent (n)	Frequency of occurrence (%)	Min	Mean	Median	Max
ESTUARY								
Bottom	25	16	9	64.0	5.5	15.5	12.8	18.6
Midwater	7	1	6	14.3	7.6	12.9	13.4	16.2
Combination	6	4	2	66.7	9.4	12.3	12.3	15.8
TIDAL FRESHWATER								
Bottom	3	2	1	66.7	11.6	13.2	11.6	16.5
Midwater	6	0	6	14.3	6.1	10.9	11.0	15.2
Combination	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a

and mid-water depths were sampled (goodness-of-fit test, $\chi^2 = 6.13$, 2 *df*, $P = 0.02$). Eulachon did not appear to be present more often in estuarine trawls than in freshwater trawls, although we note that our sample size for tidal freshwater is small and our ability to resolve estuary-freshwater differences is therefore limited (goodness-of-fit test, $\chi^2 = 1.60$, 1 *df*, $P = 0.14$).

Numerical species composition data are presented in Table 2. In estuary trawl samples ($n = 38$), we captured a total of 344 male and 371 female Eulachon as well as 21 other fish species. Eulachon were the 4th-most numerically abundant component of estuary catches, occurring in 60.5% of all trawls and comprising 3% of total numerical catch. Juvenile American Shad (*Alosa sapidissima*), Longfin Smelt (*Spirinchus thaleicthys*), and Threespine Stickleback (*Gasterosteus aculeatus*) were the 3 most commonly caught pelagic fishes in the estuary, together accounting for 92.8% of estuary catch and co-occurring with Eulachon more than 85% of the time. Two benthic species, Starry Flounder (*Platichthys stellatus*) and Pacific Staghorn Sculpin (*Leptocottus armatus*) occurred in over 55% of the estuary samples and co-occurred with Eulachon more than 76% of the time. The co-occurrence of Eulachon, American shad, Longfin Smelt, and Threespine Stickleback was consistently associated with sites where echogram images showed midwater or mixed midwater and bottom targets (echogram Types II and III, Fig. 2).

In tidal freshwater samples ($n = 9$), we captured a total of 7061 Eulachon but only 6 other fish species in the trawl. All but 1 individual Eulachon were captured in a single sample taken on 7 March 2013 from an area where a series of acoustically detected aggregations formed layers up to 10 m thick on the river bottom between Upper Clifton Channel and the entrance to Westport Slough (rkm 64–70). One section formed a continuous layer 2 km long. Hundreds of predators (birds and pinnipeds) were actively foraging in this region. Because we suspected the dense acoustic signals represented primarily Eulachon and we sought to avoid unnecessary take of large numbers of this endangered species, we decided to fish on only 1 smaller bottom-oriented shoal less than 100 m in diameter and separated from the much larger 2-km-long aggregation. We fished the net only at the top of this aggregation, completing net deployment and retrieval in 3 min. This rapid "dip" into the top of the school captured 7060 Eulachon and no other fish species. Sex ratio subsamples of Eulachon in this sample contained 130 males and 71 females.

Only 1 Eulachon was captured during the other 8 tows made in tidal freshwater where there were acoustic images of very few or no targets (Type I echograms) in the water column. Threespine Stickleback dominated numerical species composition in tidal freshwater, occurring in all 8 trawls and accounting for 96.4% of the numerical fish composition. Starry Flounder occurred in low densities across 5 samples. One haul included 385 juvenile American Shad, but no other hauls contained American Shad. All other species captured in tidal freshwater (Longfin Smelt, Pacific Staghorn Sculpin, and juvenile Chinook Salmon *Oncorhynchus tshawytscha*) occurred in only 1 or 2 samples of <20 individuals per haul.

We calculated the overall sex ratio from a grand total of 916 Eulachon across all trawls (716 captured in 22 trawls, plus the subsample of 200 from the single trawl containing 7,060 individuals); of those fish, 886 were also measured for

TABLE 2. Numerical fish species composition of trawl samples in the estuary and tidal freshwater, January–March 2013. See text for scientific names. Ten additional fish species we captured represented by <10 individuals total included: Pacific Lamprey (*Entosphenus tridentatus*), River Lamprey (*Lampetra fluviatilis*), Pacific Sandfish (*Trichodon trichodon*), Prickly Sculpin (*Cottus asper*), a snailfish (*Liparis adiostolus*), Saddleback Gunnel (*Pholis ornata*), Sturgeon Poacher (*Podothecus accipenserinus*), Surf Smelt (*Hypomesus pretiosus*), Whitebait Smelt (*Allosmerus elongatus*), and Yellow Perch (*Perca flavescens*). Nineteen unidentified juvenile smelt (Osmeridae) were also captured. Although benthic macroinvertebrates such as Dungeness Crab (*Cancer magister*) and bay shrimp (*Crangon* spp.) were captured in some trawls, we did not enumerate macroinvertebrates.

	Estuary trawls (n = 38)				Tidal freshwater trawls (n = 9)			
Species	n	Proportion of catch (%)	Frequency of occurrence (%)	Frequency of co-occurrence w/Eulachon (%)	n	Proportion of catch (%)	Frequency of occurrence (%)	Frequency of co-occurrence w/Eulachon (%)
American Shad (juvenile)	12,152	50.8	84.2	90.5	385	<0.1	11.1	0.0
Longfin Smelt	5827	24.4	73.7	95.2	34	<0.1	22.2	0.0
Threespine Stickleback	4204	17.6	85.9	85.7	204,506	96.4	88.9	11.0
Eulachon	715	3.0	60.5	100.0	7061	3.3	22.2	100.0
Starry Flounder (juvenile)	256	1.1	65.8	81.0	72	<0.1	55.6	11.0
English Sole (juvenile)	242	1.0	31.6	33.3	0	0.0	0.0	0.0
Pacific Staghorn Sculpin	240	1.0	55.3	76.2	1	<0.1	11.1	11.1
Snake Prickleback	64	0.3	26.3	33.3	0	0.0	0.0	0.0
Sand Sole (juvenile)	61	0.3	15.8	19.0	0	0.0	0.0	0.0
Pacific Tomcod (juvenile)	59	0.3	15.8	28.6	0	0.0	0.0	0.0
Chinook Salmon (juvenile)	36	0.2	26.3	23.8	12	<0.1	11.1	0.0
Other fish species	53	< 0.3	n/a	n/a	1	<0.1	0.0	n/a

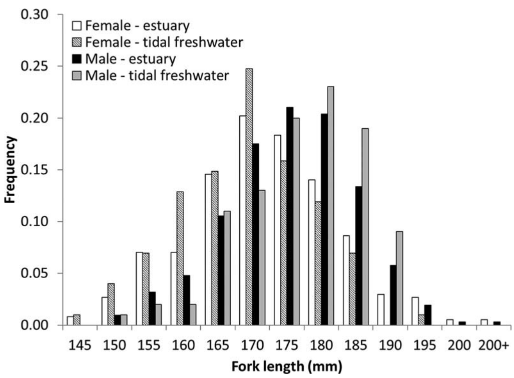

FIGURE 3. Length-frequency histograms for Eulachon (*Thaleichthys pacificus*), January–March 2013. Data are subdivided by sex and habitat type.

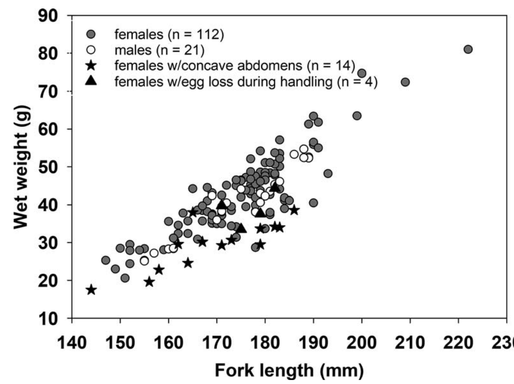

FIGURE 4. Sex-specific length-weight data for Eulachon (*Thaleichthys pacificus*), January–March 2013.

sex-specific fork length (Fig. 3). There were 474 males and 442 females in the pooled sample, exhibiting a male:female sex ratio very close to unity (1:0.93). Overall, mean length of males was slightly longer than that of females (173.9 mm vs. 169.6 mm; *t*-test, $P < 0.0001$). There was no difference in male mean lengths between estuary and tidal freshwater samples (173.5 mm vs. 174.9 mm, respectively; *t*-test, $P = 0.20$), but females from estuary samples were slightly longer than those from tidal freshwater (170.3 mm vs. 167.2 mm, respectively; *t*-test, $P = 0.01$).

Over the entire study period, we retained 151 Eulachon for weight measurements in the laboratory. The sample retained was intentionally highly biased toward females ($n = 130$) over males ($n = 21$) because the WDFW egg-count analyses for spawning-stock biomass estimates required only females and we sought to minimize lethal take. In 14 cases, females exhibited concave abdomens that were visually clearly different from those of other females retained from the same trawl. We believe these individuals had spawned or otherwise extruded significant quantities of gametes before we measured them. Another 4 females lost small numbers of eggs during handling. We therefore excluded all 18 females with suspected or observed gamete loss from weight measurements.

Mean weight was significantly higher for females captured in the estuary (43.5 g) than for those captured in tidal freshwater reaches (37.4 g; *t*-test, $P = 0.01$). Mean weight of males in the estuary was 41.7 g; no male weights from tidal freshwater were measured (Fig. 4).

Empirical length-weight regression equations are provided presented in logarithmic form: (1) males: $\log_{10}(\text{weight in g}) = 3.596 \cdot \log_{10}(\text{fork length in mm}) - 6.462$, $R^2 = 0.91$; (2) females: $\log_{10}(\text{weight in g}) = 3.115 \cdot \log_{10}(\text{fork length in mm}) - 5.367$, $R^2 = 0.76$.

We found that although there was no statistically significant difference in log-transformed lengths between 2013 and 1980–1981 samples of Eulachon (median 175.9 vs. 169.0 mm, Mann-Whitney rank sum test, $P = 0.37$), there was a significant difference in log-transformed weights (median 43.8 vs. 27.0 g, Mann-Whitney rank sum test, $P < 0.001$).

Environmental Conditions

Mean daily CPUE data relative to environmental conditions in the lower Columbia River are presented in Table 3. Daily CPUE displayed what resembled a threshold response, being relatively low (<0.06) prior to 12 February and relatively high (>0.2) after that date. During the period of 1 January through 31 March 2013, estuary temperatures varied between 3.7 and 10.9°C (Fig. 5), a temperature range encompassing the tidal dynamics between ocean and river water. During the initial period of low CPUE, minimum daily temperatures in the estuary were all <6°C, and spring-neap tidal oscillations in estuary temperature were evident. After 12 February, daily minimum temperatures remained ≥5.5°C, and by 27 February a distinct warming trend became evident, with minimum temperatures thereafter consistently exceeding 6°C. Spring-neap oscillations in temperature

TABLE 3. Mean daily CPUE (log_{10} [count+1] per minute of trawling) of Eulachon (*Thaleichthys pacificus*) and river conditions for trawling efforts, January–March 2013. FNU = formazin nephelometric units.

Date	Trawls (n)	Mean daily CPUE	Minimum daily estuary temperature (°C)	Daily estuary salinity range	Mean daily flow ($m^3 s^{-1}$)	Median provisional turbidity (FNU)
11 Jan	6	0.052	5.0	0.0–24.3	8297	8.2
14 Jan	7	0.049	4.2	0.0–22.9	7674	7.0
15 Jan	6	0.005	4.3	0.0–20.8	7476	7.4
27 Jan	7	0.028	3.8	0.0–23.3	6485	13.0
28 Jan	4	0.054	3.8	0.0–19.7	6541	14.0
11 Feb	4	0.041	5.5	0.0–25.7	6116	2.9
12 Feb	5	0.436	5.5	0.0–25.8	6088	2.8
25 Feb	1	1.140	5.8	0.0–22.1	5635	2.9
07 Mar	1	3.372	6.7	0.0–19.6	5607	4.0
11 Mar	3	0.683	6.7	0.0–24.3	5040	3.9
12 Mar	3	0.218	6.9	0.0–24.8	4927	3.4

were damped out and freshwater discharge began to dominate the temperature signal during this primarily monotonic warming trend. The 3 highest daily CPUEs for Eulachon occurred during this later period of estuary warming.

Salinity at 8.3 m in the estuary near Tansy Point (rkm 16) exhibited regular spring-neap tidal oscillations between 0 and 29.3 throughout the entire study period and showed no visible pattern in relation to the 2 periods of low versus high Eulachon CPUE (Table 3; daily salinity data not shown). River flow during the study period was low to moderate, varying between 4587 and 8636 $m^3 s^{-1}$, with a mean flow of 6365 $m^3 s^{-1}$ (Fig. 6). Flow was generally lower than historical records of mean daily winter flow (7370 $m^3 s^{-1}$, 1969–2013, January through March). Flow during the period of low Eulachon CPUE was generally higher (>6100 $m^3 s^{-1}$) than during the period of high Eulachon CPUE (<6100 $m^3 s^{-1}$).

Median provisional daily turbidity (range: 2–15 FNU; mean: 5.3 FNU) was lower than available historical records for January through March during 2001–2009 (range: 5.6–35.5 FNU; mean: 14.7 FNU). After 5 February turbidity declined, varying between 2 and 4.4 FNU for the rest of the study period (Fig. 6). With one exception (29 January), the period of low Eulachon CPUE was associated with turbidity values ≥4.9 prior to 5 February, and the period of high Eulachon CPUE was associated with the

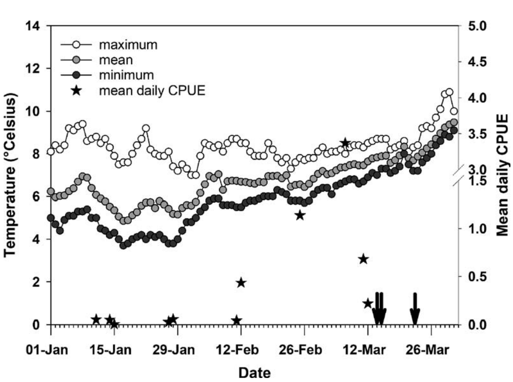

FIGURE 5. Estuary temperature variation vs. mean daily CPUE Eulachon (*Thaleichthys pacificus*), January–March 2013. Small black arrows point to dates on the horizontal axis when Eulachon spawning was first confirmed in the Grays, Cowlitz, and Sandy rivers, respectively.

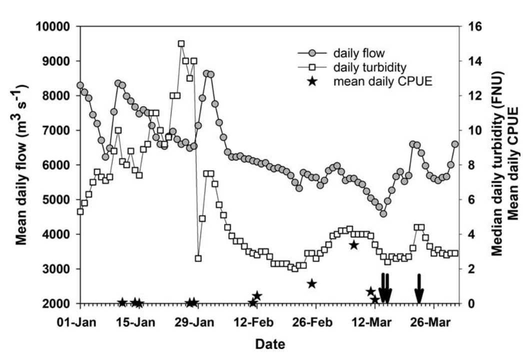

FIGURE 6. Daily river flow and turbidity in tidal freshwater versus mean daily CPUE Eulachon (*Thaleichthys pacificus*), January–March 2013. Small black arrows point to dates on the horizontal axis when Eulachon spawning was first confirmed in the Grays, Cowlitz, and Sandy rivers, respectively.

period of more stable, lower turbidity values between 2.0 and 4.3.

Timeline of Eulachon and Eulachon Predator Activity

We received 15 verifiable reports of Eulachon or Eulachon predators between 14 February and 23 March 2013. Initial sightings of predator aggregations feeding in the estuary or tidal freshwater occurred during 14–17 February near the Washington side of the Astoria-Megler Bridge (rkm 22) and Price Island (rkm 55). By 23 February, hundreds of feeding sea lions with thousands of gulls were reported in the tidal freshwater mainstem between Altoona (rkm 39) and Jim Crow Point (rkm 46). However, Cowlitz Tribe biologists monitoring fyke nets in the Cowlitz River reported no Eulachon on the spawning grounds during February (C. Olds, Cowlitz Indian Tribe Natural Resources Department, Longview, WA, pers. comm.).

On 4 March, biologists working at Westport Slough (rkm 70) reported "sea lions everywhere" and took photos to confirm high densities in the area. On 5 March, the acoustic vessel encountered a large aggregation of Eulachon predators for the first time from Upper Clifton Channel to Wauna, Oregon (rkm 64–66). Visual estimates of predator abundance included several hundred gulls (*Larus* spp.), 9 Harbor Seals (*Phoca vitulina*), at least 120 California Sea Lions (*Zalophus californianus*), and 1 Steller Sea Lion (*Eumatopias jubatus*), as well as dozens of Bald Eagles (*Haliaeeatus leucocephalus*). The majority of predators were actively flying, swimming, and diving. We observed gulls consuming Eulachon in Clifton Channel (rkm 64). The echosounder detected a very large (>50 m in length), continuous target aggregation in the lower half of the water column within and adjacent to the area of predator activity. This type of target distribution (Type IV) had not been seen on previous acoustic surveys in either the estuary or tidal freshwater. Few predators and few acoustic targets were seen downstream (Tongue Point and Price Island, rkm 29–55) or upstream (Lord Island and Cowlitz River mouth, rkm 100–109) of the predator aggregations. The same level and location of predator-Eulachon activity was seen on 7 March by both the acoustic and trawl vessel.

Fertilized Eulachon eggs were first documented on 14 March in the Grays River, Washington (approximately rkm 34), where prior surveys on 1 and 6 March had observed neither eggs nor adults. Eulachon were first reported entering the Cowlitz River spawning grounds (rkm 109) on 15 March, when a large school entered the Cowlitz River from the mainstem of the Columbia River at approximately 14:30 h. Subsequent sampling by the Cowlitz Indian Tribe on 16–18 March captured fish in fyke nets and a boat followed a 3 m wide by 30 km long "ribbon" of fish to the Castle Rock boat ramp. On 20 March we observed 1000s of gulls picking moribund Eulachon from the surface waters just inside the Cowlitz River mouth (rkm 109). Members of the general public observed Eulachon entering the Sandy River, Oregon (rkm 200) spawning grounds on 23 March, evidence that some portion of spawners continued upstream past the Cowlitz River.

DISCUSSION

Effectiveness of Research Sampling of Eulachon in the Columbia River

Acoustic and trawl methods were successful in locating and sampling adult Eulachon in both estuarine and tidal freshwater habitats of the lower Columbia River. A downward-looking 38-kHz echosounder system successfully detected mixed-species, dispersed targets in the estuary, although it was not possible to filter targets by species with our uncalibrated, single-frequency acoustic system. These targets were identified by trawl sampling as containing primarily juvenile American Shad (50.2%), Longfin Smelt (24.1%), and Threespine Stickleback (17.4%), as well as Eulachon (3%). Acoustics also documented a period in January–February when very few pelagic targets appeared to be occupying tidal freshwater habitat upstream of rkm 29, a result corroborated by the fact that freshwater trawls through these regions captured only very small Threespine Stickleback (mean = 41.2 mm FL, which because of their small size would be poor reflectors of sound transmitted at 38 kHz), only 1 school of American Shad, and few other fishes. In early March, acoustics subsequently detected large, bottom-oriented shoals of fish appearing in tidal freshwater between Upper Clifton Channel and Wauna (rkm 64–68) as well as in the estuary between the Astoria-Megler Bridge and Tongue Point (rkm 22–29), which trawl sampling and observations of predators foraging confirmed to be composed of Eulachon. Large shoals were successfully observed with the echosounder over the course of at least 3 d (5–7 March). These remained relatively stationary despite continuous predation pressure from hundreds of pinnipeds and birds observed eating Eulachon. Eulachon may have remained stationary because they were actively spawning in or near Upper Clifton Channel, or because they were waiting for some environmental cue, such as temperature, to continue moving upstream. Regardless, acoustic images revealed that predation pressure did not cause fish to avoid the area near Wauna and Clifton Channel or trigger them to disperse into lower densities. Echograms therefore provided insight into run timing and behavior by identifying the dates when Eulachon moved out of the estuary and coalesced into shoals that migrated upstream.

Trawl surveys successfully captured Eulachon in the lower Columbia River during January, February, and March; there was no sampling day on which trawl efforts failed to catch adult Eulachon in the estuary. Some Eulachon were therefore present in the Columbia River Estuary for at least 2 mo before spawning was observed in upstream tributaries. This is a longer period of estuary occupancy than the approximately 1 mo reported for pre-spawning staging for northern Eulachon populations in the glacially fed Berners Bay estuary in Alaska (Sigler and others 2004), and our results imply that the Columbia River Estuary is likely to provide important staging habitat for populations of Eulachon in the Columbia River.

Eulachon in the estuary and tidal freshwater were captured more frequently in bottom trawls than midwater trawls, an observation that supports oral reports by commercial fishers that Eulachon are bottom oriented in the estuary during daytime. Differences between midwater and bottom capture may be due to Eulachon actively avoiding net capture by diving to escape; diving would be an effective avoidance behavior in midwater but ineffective when fish are near the bottom. Camera deployments on the trawl would be necessary to document possible net avoidance behaviors for Eulachon.

Comparisons of mean CPUE for Eulachon with environmental conditions showed that CPUE increased after minimum temperatures consistently exceeded 5.5°C and there were reductions in river flow and turbidity. These observations support historical assertions by commercial fishers that at least some Eulachon are present in the lower Columbia River throughout the winter, where they hold in deeper areas of the estuary before warming water temperatures stimulate them to gather in schools for the upstream spawning migration (The Oregonian 1891, 1955, 1985; Lampman 1943; Smith and Saalfeld 1955; Stockley and Ellis 1970; Martin 1994). Hypotheses regarding the exact combination of environmental or biological cues that trigger Eulachon in the estuary to begin their upstream spawning migration remain to be tested. For example, it is not known whether Eulachon respond to absolute or relative changes in water temperature, river flow, turbidity, the density of conspecifics, or some combination of these factors. Eulachon responses in more precipitation-driven river systems occupied by the southern DPS may be quite different from responses of Eulachon in northern populations, which spawn in glacially fed rivers. As with more well-studied anadromous species such as salmon (Keefer and others 2008), developing an understanding of how Eulachon respond to temperature and river flow will be necessary to predict how run timing might respond to climate-driven or other anthropogenic changes in temperature and flow in the Columbia River. Ideally, as for salmon, studies would include direct observations of adult run timing over the course of 5 or more years.

Timeline of the 2013 Spawning Migration

Trawl samples, acoustic images, reports of Eulachon with sightings of Eulachon predators, and egg-larval surveys reported by WDFW (James and others 2014) all converged on a common timeline for the 2013 spawning migration. If a simple measure of CPUE provides an index of relative abundance for Eulachon in the lower estuary, then Eulachon were present but dispersed in low densities throughout the estuary during January through mid-February. Sometime between mid-February and the 1st week of March, fish density in the estuary began to increase, and later large Eulachon shoals were found in the Columbia River mainstem accompanied by large aggregations of actively feeding predators. This implies that predators only aggregate on Eulachon after large, monospecific Eulachon shoals coalesce and move out of their dispersed estuary distribution into tidal freshwater, as we did not observe predator aggregations in the estuary even though the trawl consistently caught Eulachon throughout the estuary in low numbers. Our observations of predator response to Eulachon support the hypothesis of Marston and others (2002) that the spawning runs of Eulachon play a critical role in supporting winter and spring predator energy demands in coastal ecosystems of the Pacific Northwest.

We believe the large shoals of Eulachon associated with predators observed during the 1st week of March included fish that eventually entered the Cowlitz (rkm 109) and Sandy (rkm 200) rivers. If egg hatch occurs 21–28 d after spawning, as reported in prior studies (Smith and Saalfeld 1955), then we would expect to see an increase in mainstem larval densities about 3–4 wk after 15 March, the date when we first received verifiable reports of fish on the Cowlitz River (109 km) spawning grounds. James and others (2014) reported increases in egg and larval densities and flow after the week of 8 April at index sites near rkm 55 and rkm 64, supporting our hypothesis that at least some portion of Eulachon we observed in shoals between rkm 34–66 moved upstream to spawn in the Cowlitz and Sandy rivers (rkm 200). Definitive tests of this hypothesis would require regularly scheduled trawl or acoustic surveys to track school movement or the use of small tags such as passive integrated transponders or active hydroacoustic tags to follow individual fish movements onto spawning grounds upstream. As our compilation of verifiable reports of Eulachon and sightings of Eulachon predators demonstrates, a formal system for compiling future verifiable qualitative reports, such as agency or citizen-science reporting of predator aggregations or Eulachon sightings through a web- or app-based system, would be helpful in documenting events related to run timing, especially in the absence of systematic surveys of adult fish.

Comparison with Historical Data Sets

Differences between trawl data from this study and previously collected data on Eulachon in the lower Columbia River demonstrate the need to update and evaluate present-day population information on Columbia River Eulachon. For example, the male-to-female sex ratio we report from trawls is very near 1:1. This sex ratio is similar to that reported for the Fraser River in British Columbia (Hay and others 2002) but different from male-biased sex ratios reported in earlier literature for the Columbia River (Smith and Saalfeld 1955; Stockley and Ellis 1970). Different sex ratios in the Columbia River may reflect sample bias relative to sample method (gillnet and recreational dip net vs. trawl), run timing, and possible behavioral or distributional differences between males and females (Gustafson and others 2010). Sex-specific differences in migration timing have been observed in Alaska, where the 2nd half of the Copper River Eulachon run is male-biased (Moffitt and others 2002). Because sex ratio is a key parameter for population viability models and for estimation of adult spawning-stock biomass (SSB) with the egg-larval method, accurate estimates of sex ratio are important to fishery management and recovery planning. At present, sex-ratio estimates are derived from fish captured from very short-duration (approximately 2-wk) commercial or recreational openings for Eulachon and thus they are not representative of the entire run. If fisheries are closed (as they were in 2013 when this study took place), there may be no sex-ratio estimates available for SSB at all unless research sampling of adults is in place. Weekly or biweekly estuary and tidal freshwater trawl sampling over the entire course of the Columbia River run, for several different years, would allow biologists to determine the extent to which sex-ratio variation occurs within or between runs and would improve the quality of information available for SSB estimation and environmental triggers for spawning migration.

When comparing 2013 length-weight data to data from estuary trawl samples from January–March 1980–1981 (Bottom and Jones 1990; S Hinton, unpubl. data), we found no significant difference in lengths between 2013 and 1980–1981 samples (175.9 vs. 169.0 mm, Mann-Whitney rank sum test, $P = 0.37$), although we found a significant difference in weights. Fish from 1980–1981 tended to weigh less at a given length compared to fish from 2013 (Fig. 7). The weight difference cannot be entirely explained by less precise measurement in the historical data ($\pm$1.0 g) compared to our data ($\pm$0.1 g).

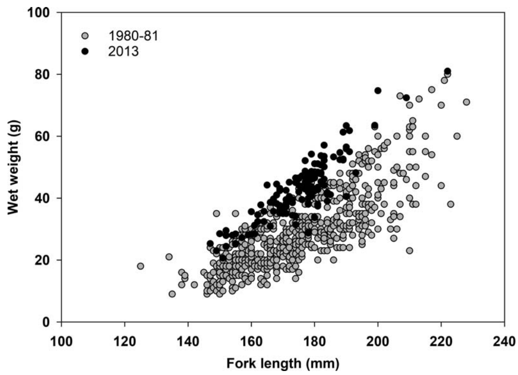

FIGURE 7. Comparison of length-weight distributions for trawl-caught Eulachon (*Thaleichthys pacificus)* in January–March, 1980–1981 versus 2013. Historical data were collected using the same semi-balloon shrimp trawl as used in 2013.

Sex-specific comparisons could not be made because 1980–1981 catches were not sexed. We suspect the older data set may have included some proportion of spawned-out specimens; this could explain most, but not all, of the difference. Whether changes in length-frequency and length-weight represent a change in spawner age distribution or spawning condition is unknown. Analysis of individual age at spawning from otoliths was beyond the scope of this study (e.g., Clarke and others 2007), but otoliths have been saved so that otolith microchemistry techniques could be applied in the future. Whatever the cause, it is evident that the size structure of 2013 Eulachon was likely not identical to that reported from the same winter months 3 decades earlier. We conclude that measures of sex ratio and fish size used to calculate SSB should be based on contemporary data from the year of the run in question rather than rely on the few historical data available.

Compared to recent estimates of Eulachon SSB, 2013 appeared to be a year of relatively strong contemporary returns. Although 2014 and 2015 also appeared to have strong returns, Langness and others (2018) report declines in estimated mean SSB from 5000 metric tons in 2015 (an estimated return similar to 2013) to 170 metric tons in 2018 (their figure 32 and tables 4–7). This monotonic decline of 2 orders of magnitude is occurring during a period of 3 years (2016–2018) with record-high global temperatures, yet there is no mechanistic explanation for which factors most influence mortality.

Potential Applications to Eulachon Conservation

If Eulachon populations are to recover from the threat of extinction, additional data on population status and run-timing response to environmental variation are needed. Differences we observed between historical and contemporary population parameters like sex ratio and size distribution, and our lack of understanding of what mechanisms are responsible for such differences, emphasize the need to update and expand our knowledge of the ecology of this species. Regularly scheduled trawl surveys over the course of the spawning season (mid-November to April) could be implemented to quantify data on distribution, relative abundance, sex ratio and sex-specific length-weight relationships, habitat use, and migration timing for Columbia River Eulachon relative to variation in factors such as estuary and river temperatures, river flow, and turbidity. Trawling provides a way to survey the run without causing prespawning mortality necessarily associated with traditional gill nets or bobber nets used in test fisheries—as we demonstrated, the majority of trawl-caught fish can be released alive. Our observation that trawl-caught specimens remain in good condition is a result consistent with Stockley and Ellis (1970), who reported that Eulachon captured in a similar trawl tested for commercial use not only survived capture but also survived transport to laboratory aquaria. Trawl capture of live specimens also opens possibilities for tagging studies during migration, non-lethal genetic sampling, physiological and behavioral studies in the laboratory, as well as evaluation of sex ratio, size-at-age structure, and reproductive condition for individual fish throughout the run. Trawl data would provide key information about adult condition used to indirectly estimate adult SSB (James and others 2014) and would fill data gaps identified in population recovery plans for this species (NMFS 2017).

Based on our combined acoustic and trawl results, we conclude that distribution, run timing, and SSB for Eulachon in the Columbia River can be estimated directly using conventional echo-integration techniques, given development of proper acoustic target-strength relationships in the field (for example, Gauthier and Horne 2004; Stables and others 2005) with trawl information to ground-truth species identification and length distributions. This information could also be used to construct model simulations of future Eulachon distribution and abundance in response to climate change scenarios for estuary conditions. Acoustic methods have been used successfully in short-term field studies of Eulachon in Alaska (Sigler and others 2004) and British Columbia (Stables and others 2005). Specifically, applying acoustic methods in tidal freshwater will have a high probability of success in documenting run timing and estimating Columbia River SSB for 3 reasons. First, our acoustic echograms showed that Eulachon formed large, well-defined, bottom-oriented aggregations after entering tidal freshwater; these echograms were visually distinct from all other acoustic images seen during the study period (Fig. 3). This type of bottom-oriented daytime distribution, if typical migration behavior, would make Eulachon amenable to downward-looking acoustic surveys. It would be difficult to use alternative technologies such as video on unmanned aerial vehicles (for example, drones) because these fish remain at depth and there is low water-column transparency except in shallow-water spawning areas. Second, from trawl sampling and predator observations these acoustically detected aggregations, when seen in tidal freshwater, are likely to be composed entirely of Eulachon, as we caught no other species but Eulachon in our sample of the Type IV shoal. This greatly simplifies biomass estimates because complex filtering algorithms do not need to be developed to remove echo returns from other fish species in the data files. Third, the topography of several tidal freshwater areas downstream from known Eulachon spawning grounds would naturally funnel migrating Eulachon into a relatively deep, narrow section of the river. The placement of survey lines in areas of topographic funneling could ensure that Eulachon from a major portion of the Columbia River run are well sampled in 1 or 2 strategic locations, providing efficient monitoring of run timing and SSB with either mobile or fixed-site acoustics. Acoustic measures of run timing and run strength in the Columbia River would provide new information that is presently unavailable to assess links between run timing, river temperature, and river flow, as well as within-season management of fishery openings for indigenous, commercial, and sport harvests. Systematic trawl and acoustic surveys would provide new, direct, and relatively non-intrusive measures of the distribution, relative abundance, fish condition, and run timing for adult Eulachon during estuary staging and active migration in tidal freshwater to the spawning grounds. They might also provide an independent but direct estimate of adult SSB for comparison with indirect estimates of SSB from the egg-larval method currently used to assess population trends. At present, within-season information on adult fish from the Columbia River run and data on how Eulachon runs respond to environmental variation are not available to biologists and managers trying to assess the effects of climate change on spawning migration behavior and who must make decisions about balancing fishery opportunities with effective recovery actions.

ACKNOWLEDGMENTS

The authors thank R Gustafson, T Wainwright, K Fresh, J Butzerin, and 5 anonymous reviewers for critique which greatly improved the manuscript. This work was made possible by funding from the NOAA Fisheries Office of Protected Resources in Portland, OR. We thank S Rumsey, NOAA Protected Resources Division Branch Chief, for recognizing the need to act quickly so resources could be in place for this sampling effort. Additional appreciation goes to R Anderson of NOAA Fisheries Regional Office and P Dionne of WDFW, who on very short notice expedited completion of the permits required for this work. We are grateful to all Point Adams Research Station staff that supported this work and facilitated gear-up for vessel operations: Station Chief R. Emmett, G McCabe, T Cross, J Holcomb, and B Fite, and especially vessel operators B Kelly, R/V *Murrelet* and R/V *Quinnat*, and C Neace, R/V *Magister*. We thank B Cady, B James, S Schade, and C Wagemann of WDFW who also assisted with preparation, discussions, and fieldwork. B Sylvander of NOAA generated our map figures. We acknowledge C Olds of the Cowlitz Indian Tribe and J Watts of ODFW for sharing information about their Eulachon and predator sightings during winter 2012–2013; that information significantly improved the overall picture of events during the 2012–2013 spawning run. Finally, we wish to honor the memory of our colleague the late Dr. Robert Emmett, who devoted his 36-y career with the National Marine Fisheries Service to increasing scientific knowledge of food webs and pelagic fish species in the marine and estuarine environments of the Pacific Northwest.

Literature Cited

Bottom DL, Jones KK. 1990. Species composition, distribution, and invertebrate prey of fish assemblages in the Columbia River Estuary. Progress in Oceanography 25:243–270.

Clarke AD, Lewis A, Telmer KH, Shrimpton JM. 2007. Life history and age at maturity of an anadromous smelt, the Eulachon *Thaleicthys pacificus* (Richardson). Journal of Fish Biology 71:1479–1493.

[CMOP] Center for Coastal Margin Observation and Prediction. 2013. Collaborative model and datasharing center of the Oregon Health & Science University, Oregon State University, University of Washington, and National Science Foundation. Available online at www.stcmop.org (accessed 14 April 2020).

[COSEWIC] Committee on the Status of Endangered Wildlife in Canada. 2011. COSEWIC assessment and status report on the Eulachon, Nass/Skeena Rivers population, Central Pacific Coast population and Fraser River population *Thaleichthys pacificus* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa. Available online at species-registry.canada.ca/index-en.html#/documents/2292 (accessed 23 December 2020).

*Ebel WJ, Durkin JT, Blahm T, McCabe GT, Coley T, McConnell R, Emmett RL, Muir WD. 1981. Columbia River Estuary Data Development Program Report: Salmonid and non-salmonid fish, 1981. Report to the Pacific Northwest River Basins Commissions. Hammond, OR.

Flannery BG, Spangler RE, Norcross BL, Lewis CJ, Wenburg JK. 2013. Microsatellite analysis of population structure in Alaska Eulachon with application to mixed-stock analysis. Transactions of the American Fisheries Society 147:1036–1048.

Gauthier S, Horne JK. 2004. Acoustic characteristics of forage fish species in the Gulf of Alaska and Bering Sea based on Kirchhoff-approximation models. Canadian Journal of Fisheries and Aquatic Sciences 61:1839–1850.

Gustafson RG, Ford MJ, Teel DJ, Drake JS. 2010. Status review of Eulachon (*Thaleichthys pacificus*) in Washington, Oregon, and California. US Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-105.

Gustafson RG, Ford MJ, Adams PB, Drake JS, Emmett RL, Fresh KL, Rowse M, Spangler EAK, Spangler RE, Teel DJ, Wilson MT. 2012. Conservation status of Eulachon in the California Current. Fish and Fisheries 13:121–138.

Hay DE, McCarter PB. 2000. Status of the Eulachon *Thaleichthys pacificus* in Canada. Canadian Stock Assessment Secretariat, Fisheries and Oceans Canada, Research Document 2000/145, Ottawa, ON.

Hay DE, McCarter PB, Joy R, Thompson MW, West K. 2002. Fraser River Eulachon biomass assessments and spawning distribution: 1995–2002. Canadian Stock Assessment Secretariat, Fisheries and Oceans Canada, Research Document 2002/117, Ottawa, ON.

Iverson SJ, Frost KJ, Lang SLC. 2002. Fat content and fatty acid composition of forage fish and invertebrates in Prince William Sound, Alaska: Factors contributing to among and within species variability. Marine Ecology Progress Series 241:161–181.

*James BW, Langness OP, Dionne PE, Wagemann CW, Cady BJ. 2014. Columbia River Eulachon spawning stock biomass estimation. Report A. In: Mallette C, editor. Studies of Eulachon Smelt in Oregon and Washington. p 1–59. Prepared for NOAA Fisheries Protected Species Conservation and Recovery, Washington, DC by the Oregon Department of Fish and Wildlife and the Washington Department of Fish and Wildlife.

Jay DA, Smith JD. 1990. Circulation, density distribution, and neap-spring transitions in the Columbia River Estuary. Progress in Oceanography 25:81–112.

Keefer ML, Perry CA, Caudill CC. 2008. Migration timing of Columbia River spring Chinook salmon: Effects of temperature, river discharge, and ocean environment. Transactions of the American Fisheries Society 137:1120–1133.

Kukulka T, Jay DA. 2003. Impacts of Columbia River discharge on salmonid habitat: 1. A nonstationary fluvial tide model. Journal of Geophysical Research–Oceans 108:1–20.

Lampman HS. 1943. Rods, ripples, rifles. The Oregonian, February 21:3.

*Langness OP, Lloyd LL, Schade SM, Cady BJ, Heironimus LB, James BW, Dionne PE, Claiborne AM, Small MP, Wagemann C. 2018. Studies of Eualchon in Oregon and Washington: Designed to guide implementation of a monitoring program to track coast-wide status and trends in abundance and distribution. Project Completion Report July 2015–July 2018, Fish Program Report Nubmer FPT 18-07 for NOAA Fisheries Protected Species Conservation and Recovery Grant Number NA14NMF4720009, Ridgefield, WA.

Lewis M, Clark W. 1806. The journals of the Lewis and Clark Expedition. Journal entries from 24 February 1806. University of Nebraska Press/University of Nebraska-Lincoln Libraries-Electronic Text Center. Available online at lewisandclarkjournals.unl.edu (accessed on 8 November 2014).

Marston BH, Willson MF, Gende SM. 2002. Predator aggregations during Eulachon *Thaleichthys pacificus* spawning runs. Marine Ecology Progress Series 231:229–236.

* Unpublished

MARTIN I. 1994. Legacy and testament: The story of the Columbia River gillnetters. Pullman, WA: Washington State University Press.

MCCABE GT, EMMETT RL, HINTON SA. 1993. Feeding ecology of juvenile White Sturgeon (*Acipenser transmontanus*) in the Lower Columbia River. Northwest Science 67:170–180.

MITCHELL D, DONALD L. 2001. Sharing resources on the North Pacific Coast of North America: The case of the Eulachon fishery. Anthropologica XLIII:19–35.

MOFFITT SD, MARSTON B, MILLER MG. 2002. Summary of Eulachon research in the Copper River delta, 1998–2002. Regional Information Report No. 2A02-34. Anchorage, AK: Alaska Department of Fish and Game, Division of Commercial Fisheries.

[NMFS] NATIONAL MARINE FISHERIES SERVICE. 2010. Endangered and threatened wildlife and plants: Threatened status for Southern Distict Population Segment of Eulachon. Federal Register 64(228):13012–13024.

[NMFS] NATIONAL MARINE FISHERIES SERVICE. 2017. Recovery plan for the southern distinct population segment of Eulachon (*Thaleichthys pacificus*). National Marine Fisheries Service, West Coast Region, Protected Resources Division, Portland, OR, 97232. Available online at https://www.westcoast.fisheries.noaa.gov/publications/protected_species/other/Eulachon/final_Eulachon_recovery_plan_09-06-2017-accessible.pdf (accessed 24 July 2019).

REYNOLDS ND, ROMANO MD. 2013. Traditional ecological knowledge: Reconstructing historical run timing and spawning distribution of Eulachon through tribal oral history. Journal of Northwest Anthropology 47:47–70.

SIGLER MF, WOMBLE JN, VOLLENWEIDER JJ. 2004. Availability to Steller Sea Lions (*Eumetopias jubatus*) of a seasonal prey resource: A prespawning aggregation of Eulachon (*Thaleichthys pacificus*). Canadian Journal of Fisheries and Aquatic Sciences 61:1475–1484.

SMITH WE, SAALFELD RW. 1955. Studies on Columbia River smelt *Thaleichthys pacificus* (Richardson). Washington Department of Fisheries Fisheries Research Papers 1:3–26.

STABLES T, PERRIN CJ, ROSENAU ML. 2005. Acoustic and trawl surveys to locate Eulachon aggregations in the lower Fraser River, British Columbia. North American Journal of Fisheries Management 25:675–688.

*STOCKLEY CE, ELLIS IE. 1970. Otter trawl trials for Columbia River smelt with associated notes and recommendations. Columbia River Investigations Supplemental Progress Report, Seattle, WA: Washington Department of Fisheries/US Bureau of Commercial Fisheries.

THE OREGONIAN. 1891. Goes down after them. December 14:5.

THE OREGONIAN. 1955. Gillnet group in dissolution, smelt marketing dispute blamed. February 19:16.

THE OREGONIAN. 1985. Trawlers get go-ahead to net Columbia smelt. March 2:B1.

[USGS] US GEOLOGICAL SURVEY. 2013. USGS National Water Information System. Water resource data collection and dissemination network. Available online at waterdata.usgs.gov/or/nwis (accessed 14 Apr 2020).

Submitted 16 April 2020, accepted 5 January 2021.
Corresponding Editor: James Orr.