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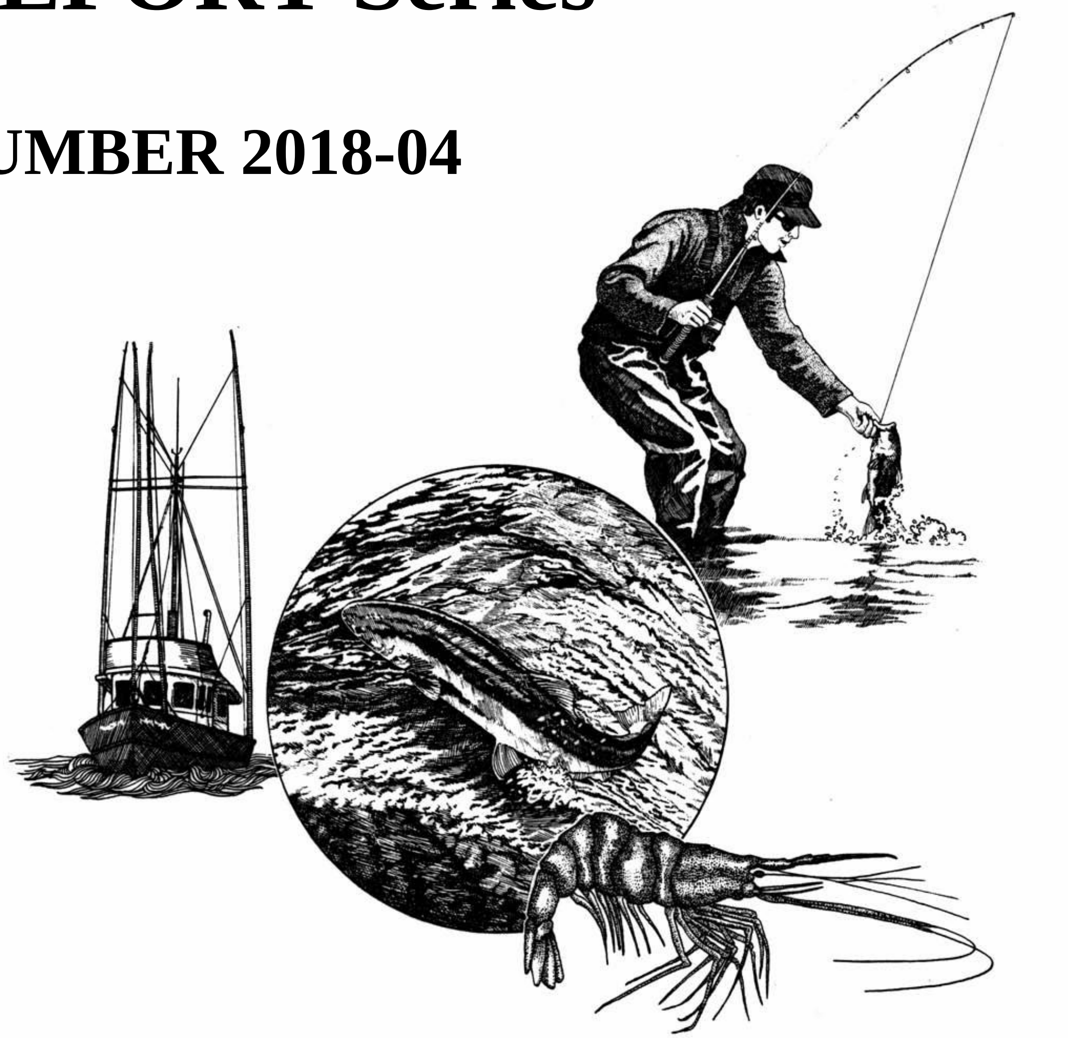

Oregon Department of Fish and Wildlife

Smolt Abundance Estimates for the Oregon Coast Coho Evolutionarily Significant Unit

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ABSTRACT

Analysis of Coho Salmon (*Oncorhynchus kisutch*) smolt abundance can provide insight on freshwater habitat capacity and factors affecting salmonid persistence. To explore these relationships we linked multi-year data sets of overwinter survival rates from three streams within the Oregon Coast Coho Evolutionarily Significant Unit (OCC) to summer parr abundance estimates from calibrated OCC-wide snorkel survey counts to estimate annual Coho Salmon smolt abundance from 2000-2017. Smolt abundance estimates ranged from a low of 0.9 million in 2000 to a high of 4.1 million in 2013 within the OCC. Accuracy of the smolt abundance estimates was tested using two datasets: (i) adult abundance modeled from the corresponding smolt abundance estimate was compared with adult abundance derived empirically from spawning ground surveys and (ii) our smolt abundance estimates were compared with smolt abundance estimates from trapping efforts in select basins within the OCC. Adult abundance modeled from smolt abundance estimates was highly correlated with adult abundance from spawning ground surveys ($r = 0.88$, $p < 0.001$) and smolt abundance estimates correlated with abundance from smolt trapping efforts ($r = 0.81$, $p <0.001$). Graphical relationships between smolt abundance and parental abundance suggest that freshwater productivity may be limited in the OCC by density dependent processes at spawner levels observed since 1998. Additionally, smolt abundance estimates have potential use as a variable in adult forecast models and could be used to assess trends in freshwater productivity and to probe factors of density dependence.

INTRODUCTION

In some cases half of the variability in Coho Salmon (*Oncorhynchus kisutch*) adult recruitment can take place in the freshwater portion of the life cycle (Lawson et al. 2004; Bradford 1995). Smolt abundance estimates can aid the understanding of the variability in freshwater production, freshwater habitat capacity, density dependence, and other factors related to salmonid persistence over time (Nickelson et al. 1992, Sharma and Hilborn 2001, Crawford and Rumsey 2011). Smolt abundance estimates may also have value as a predictive variable in adult forecasts. Here we describe an empirically-based method to estimate Coho Salmon smolt abundance for the Oregon Coast Coho Evolutionarily Significant Unit (OCC ESU, hereafter OCC, Figure 1), developed from the integration of existing monitoring data. Our objective was to provide long term smolt abundance trend data, which can inform management decisions related to Coho Salmon and their freshwater habitat, such as ESA listing evaluations, across this large spatial scale.

The OCC was defined pursuant to the listing of Coho Salmon under the U. S. Endangered Species Act in 1998 (NMFS 2011). The OCC populations extend from the Sixes River in the south to the Necanicum River in the north (Weitkamp et al. 1995) and is supported by nearly 12,000 km of rearing and spawning habitat in freshwater streams (ODFW 2007). The Coast Coho Conservation Plan (ODFW 2007) recognizes the benefit of abundant Coho Salmon in the OCC for economic, cultural, and ecological benefits. In light of these benefits, the ESA listing, and because Coho Salmon are harvested in ocean and river fisheries, several projects to monitor attributes of Coho Salmon and their habitat in the OCC were developed under the Oregon Plan for Salmon and Watersheds (OPSW). The OPSW projects operated by the Oregon Department of Fish and Wildlife (ODFW) include the Oregon Adult Salmonid Inventory and Sampling project (OASIS), the Aquatic Inventories project (AQI), and the Salmonid Life Cycle Monitoring project (LCM). OASIS monitors the abundance and distribution of adults in the entire OCC, AQI monitors the abundance and distribution of parr and freshwater habitat conditions in the entire OCC, and LCM monitors adult and smolt abundance and produces freshwater, marine, and overwinter survival rates from fixed stations in select basins within the OCC.

Coho Salmon in the OCC have a relatively consistent life cycle (Nickelson and Lawson 1998), with the vast majority spending 1.5 years in freshwater and 1.5 years in the ocean (reviewed by Sandercock 2003). The brood year is defined as the calendar year that adult Coho Salmon enter freshwater to spawn, and is the start of the life cycle. Spawning takes place from October through January. Fry emerge in the following spring and parr distribute and rear in streams during the summer, primarily in pools (Hankin and Reeves 1988; Nickelson et al. 1992; Bisson et al. 1997; McMillan et al. 2013). In winter age-1 parr are typically found in slow water pool habitats and in off-channel and secondary channels (Nickelson et al. 1992). A small portion Coho Salmon juveniles may rear in estuary habitats (Jones et al. 2014). At approximate age-1.5 smolts migrate to the ocean from February to June, though fall migration at approximate age-1 may be a common life history variant (Miller and Sardo 2003; Roni et al. 2012; Rebenack et al. 2015). Smolts grow in coastal waters off California, Oregon, and Washington. With the exception of precocial adult males (jacks), the majority (>90%) of adults mature and return to freshwater streams at age 3 to spawn (Sandercock 2003). Coho Salmon only spawn once and die soon after, so in practical terms, the composite Coho Salmon population consists of the cycling of three brood lines, each producing an iteration every three years.

METHODS

Methodology from the OPSW monitoring projects pertaining to estimation and accuracy testing of the SAEs is summarized below. The complete methodologies for AQI salmonid parr monitoring was described by Jepsen and Rodgers (2004), Jepsen and Leader (2007), and Constable and Suring (2017). The complete methodologies for LCM and OASIS were described by Suring et al. (2015) and Sounhein et al. (2015), respectively.

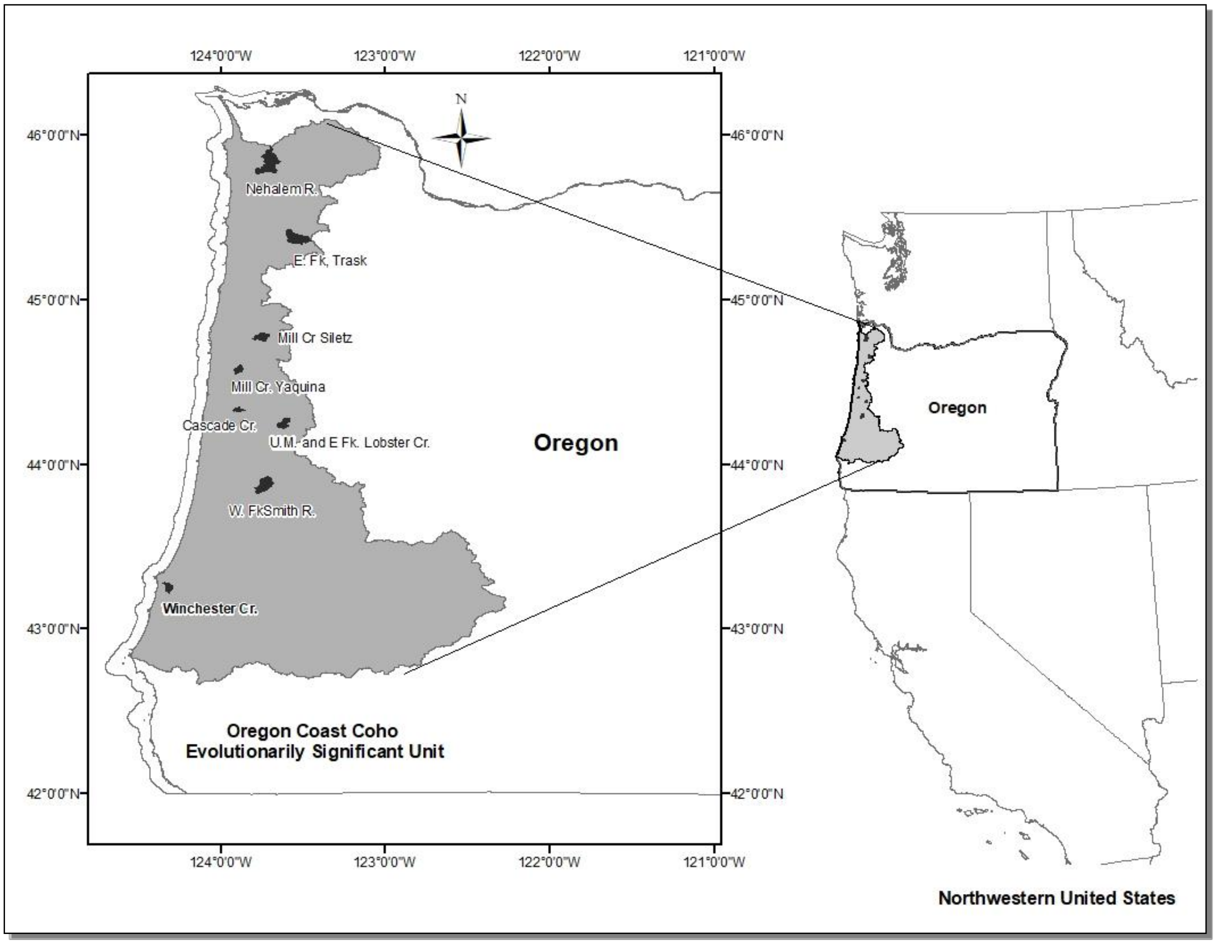

Figure 1. Location of the Oregon Coast Coho ESU, shaded in gray in Western Oregon. Salmonid Life Cycle Monitoring (LCM) basins are the labeled, black polygons.

Parr abundance estimates.— Yearly parr abundance estimates across the ESU have been made since 1998 using snorkel surveys (Rodgers 2000; Constable and Suring 2017). Sample sites for snorkel surveys were selected using a Generalized Random Tessellation Stratified (GRTS) design (Firman and Jacobs 2001; Stevens 2002) from all potential rearing areas within 1^{st} – 3^{rd} order streams. Selected sample sites were surveyed during base flows using daytime snorkeling. Sample sites were one kilometer (km) long and encompassed the GRTS point. All pools ≥40cm deep and ≥6 m^2 in surface area within the sample site were snorkeled and parr within these pools were counted. Sample sites with poor water clarity or quality (<

9% each year) were not sampled. Approximately 160 sample sites in the OCC were surveyed each year from 1998 to 2017. Parr abundance was calculated by multiplying the count of parr per km at each sample site by the sample site weight. Parr per km was the sum of the snorkel count at the sample site divided by the length of the sample site (in km). Sample site weight is the total length of the rearing distribution in the OCC divided by the number of successfully surveyed sample sites. The weighted abundance for each site was then summarized as a total abundance for the OCC using tools developed by the EMAP Design and Analysis Team (EPA 2009) and R (R Core Team 2017).

The bias of snorkel counts for parr in pools was mitigated by applying a calibration factor from Rodgers et al. (1992), who determined that an average of 40% (95%CI = ±4.8%) of the parr abundance in pools is observed by snorkeling. To account for parr abundance in habitats that did not meet snorkeling criteria (glides, riffles, rapids) we applied a second calibration factor derived from Constable and Suring (in prep.), Johnson et al. (2005), and Lorion and Suring (2017). These studies, which estimated Coho Salmon parr abundance during base low flows using a combination of electrofishing and snorkeling across all habitat types, estimated an average of 13% (95%CI = ±2.5%) of the parr abundance was observed in habitats that did not meet snorkeling criteria.

Because the two calibration factors were determined from studies that took place in the OCC and with methods similar to those used by AQI to calculate Coho Salmon parr abundance, we assumed they were applicable to AQI parr abundance estimates. Using these calibration factors, the parr abundance estimate from snorkel surveys was divided by 0.4 and the product was further divided by 0.87 to produce a calibrated parr abundance estimate.

Overwinter survival rates.— Overwinter (parr to smolt) survival rates were applied to the calibrated parr abundance to calculate the yearly SAE. Overwinter survival rates were calculated annually on Mill Creek, a tributary of the Siletz River, (Suring et al., 2015) and the East Fork and Upper Mainstem of Lobster Creek, a tributary of the Alsea River, (Lorion and Suring 2017) by ODFW’s LCM project.

Overwinter survival rates in the Lobster Creek streams were calculated by dividing the estimate of downstream migrating smolts captured in the spring by the estimated parr abundance within the brood (from the previous summer). From 1988-2002, parr abundance estimates were made using the methods of Hankin and Reeves (1988). Counts made by snorkelers in every third pool in the basin were calibrated based on electrofishing estimates in a subset of the snorkeled pools. Electrofishing estimates were also made in a subset of glide, riffle, and rapid habitats using a removal population estimate with two or more passes (Seber and Le Cren 1967). For each habitat type, the mean fish density was multiplied by the surface area of the habitat type in the entire stream (Hankin 1984). In the summers of 2003-2017, counts were made by a snorkeler in every third pool, and expanded using regression equations based on the relationship between uncalibrated snorkel counts and total population estimates from 1991-2002 (Lorion and Suring 2017). Regression equations based on the 1991-2002 data were highly significant for both East Fork Lobster Creek ($r^2 = 0.74$, $p < 0.001$) and Upper Mainstem Lobster Creek ($r^2 = 0.94$, $p < 0.001$).

Overwinter survival rates from Mill Creek were calculated by dividing the estimated number of tagged smolts migrating out of Mill Creek in the spring by the total number of parr tagged in the same brood from the previous fall. Fall tagging occurred at pools throughout the Mill Creek basin that were randomly selected using a GRTS design (Stevens 2002). To estimate the total number of tagged smolts migrating out of Mill Creek in the spring, a smolt trap was operated from the beginning of March until late June. All smolts captured in the trap were scanned for tags and the number tagged smolts was expanded to account for trap efficiency (average = 49.3%) using BTSPAS (Bonner and Schwarz 2014). The number of tagged fish was also corrected for tag loss based on observed tag retention among double-tagged smolts recaptured at the smolt trap.

We assumed that overwinter survival rates from these streams would represent average overwinter survival rate for the OCC, given that results from modeling using the Habitat Limiting Factors Model (HLFM) (Nickelson et al. 1992; Anlauf et al. 2014) shows the quality of winter habitat in LCM project basins is similar to the quality of winter habitat on average in the OCC (Suring and Lewis 2013). The average of the overwinter survival rates from these basins was applied to the calibrated parr abundance estimates to produce a yearly SAE.

Accuracy testing.— We used two datasets to scope the accuracy of the SAEs and the inherent assumptions about calibrated parr estimates and overwinter survival rates. First, SAEs were used to independently estimate spawner abundance using marine survival rates from LCM basins (Suring et al. 2015) applied to SAEs from each corresponding brood. This modeled adult abundance was compared to adult abundance estimates from the OASIS project (Sounhein et al. 2015). OASIS adult abundance was estimated with spawning ground surveys, following procedures described in OASIS (2015) and Sounhein et al. (2015). Approximately 500 sample sites per year were selected within putative Coho Salmon spawning distribution in a spatially balanced and random GRTS design (Firman and Jacobs 2001; Stevens 2002). Sample sites were surveyed within a 10-day rotation for the duration of the spawning season. Surveys included counts of adults at each sample site from which area under the curve (AUC) abundance was calculated. AUC abundance per mile at the sample site was then expanded to abundance for the OCC (Sounhein et al. 2015). Abundance estimates from OASIS are the accepted abundance estimates of adults in the OCC (PFMC, 2015). Spawning surveys also included adult carcass examinations and sampling, from which the percentage of females was determined. The percentage of females was multiplied by total adult abundance to estimate female spawner abundance.

Annual marine survival rates were calculated from LCM basins where both smolt and adult abundance are estimated. LCM smolt and adult abundance estimate methods vary according to basin and were described by Suring et al. (2015). For each LCM basin, marine survival rates were calculated by dividing the female spawner abundance estimate by one half the corresponding smolt abundance estimate, assuming an equal sex ratio among out-migrating smolts. Marine survival rates were then averaged across sites for each year and applied to the SAEs to produce modeled adult abundance estimates. The SAE derived adult estimates were compared to OASIS adult estimates using Pearson correlation analysis to evaluate the relationship and a paired t-test to evaluate bias. Both the modeled and OASIS adult abundance included harvest impacts.

As a second accuracy test we correlated the SAEs with the sum of smolt abundance estimates from LCM basins (Suring et al. 2015) for the corresponding years. Only LCM basins that had smolt abundance estimates in all years from brood years 1998-2014 (smolt migration years 2000-2016) were used in this test, which are all those shown in Figure 1, except the East Fork Trask.

Potential as a monitoring tool.— To evaluate whether SAEs could be used to understand density dependence and habitat capacity, we visually compared plots of parental female spawners abundance estimates to SAEs (recruits). These plots were produced using SigmaPlot (Systat Software, San Jose, CA), which also provided R^2, P-values, and y-intercept equations related to each plot. Female spawner abundance was from OASIS spawning ground surveys, as described above. We also examined the potential use of SAEs as a forecasting variable for adult Coho Salmon. Adult returns in the OCC are currently forecast by the Oregon Production Index Technical Team (OPITT) using an ensemble average of six three-variable generalized additive models (GAM, Rupp et al. 2012b). Only one of the six GAMs includes a direct measure of freshwater abundance, parental adult abundance (log $N_{spawners}$), as well as Pacific Decadal Oscillation (PDO), and the date of spring transition (SPR). We contrasted the predictive power of SAEs by comparing them to parental abundance as a single indicator, in a regression with adult recruits, and as a component of the above GAM, replacing parental abundance with SAE. In the GAM we truncated the time series to the 2000-2017 return years to match the years where smolt abundance was estimated. The R^2 and the Ordinary Cross Validation (OCV) scores were compared (Rupp et al. 2012b).

RESULTS

SAEs ranged from a low of 925,615 in brood year 1998 to a high of 4,144,481 in brood year 2011 (Table 1). Adult abundance modeled from SAEs correlated strongly with empirical adult abundance estimates from OASIS surveys ($r = 0.88$, $p < 0.001$, Figure 2) and there is no evidence for bias in the SAE derived adult abundance ($t = 1.32$, $df = 16$, $p = 0.21$). SAEs also correlated with smolt abundance estimates from LCM trapping basins in corresponding years ($r = 0.81$, $p < 0.001$). The lowest SAE was produced when female spawner numbers were also at their lowest (Figure 3) but there was no apparent linear correlation between female spawner and smolt abundances. The three highest (>3.9 million) SAEs were produced when female spawner abundances were at their second lowest (23k), near average (101k), and at their highest (194k). Likewise, low (<2.6 million) SAEs were produced when female spawner abundances were at their lowest (16k), above average (136k) and at their second highest (192k). When female spawner numbers exceeded 20k, the SAE averaged 2.97 million and ranged from 2.35-4.14 million. High smolt production rates occurred at low female spawner abundances (Figure 4). The number of smolts produced per female spawner averaged 49 and ranged from 168 in brood year 1999 (when female spawner abundance was at its second lowest) to 13 in brood year 2014 (when female spawner abundance was at its second highest).

Regression showed no relationship between parental adult abundance and adult recruit abundance (Figure 5, left panel; $f = 159729.1 + 0.0258x$, $R^2 < 0.01$, p 0.921) and a weak relationship between SAEs and adult recruit abundance (Figure 5, right panel; $f = 2082767 + 3.5322x$, $R^2 = 0.224$, $p = 0.064$). When replacing adult spawners with smolt abundance in one of the model components of the OPITT forecast there was little difference in R^2 or OCV values between the model containing log $N_{spawners}$ and the model containing SAE (Table 2).

Table 1. Smolt abundance estimates for the Oregon Coast Coho ESU. Parr abundance from snorkel surveys is calibrated and the result is multiplied by average overwinter survival rates in the ESU to estimate smolt abundance.

Brood year	Parr sampling year	Parr abundance	Calibrated parr abundance	Overwinter survival rate	Smolt year	Smolt abundance estimate
1998	1999	884,929	2,542,901	0.364	2000	925,616
1999	2000	2,861,072	8,221,472	0.480	2001	3,946,307
2000	2001	2,969,004	8,531,620	0.275	2002	2,346,195
2001	2002	3,355,610	9,642,558	0.272	2003	2,622,776
2002	2003	3,632,891	10,439,342	0.258	2004	2,693,350
2003	2004	3,319,231	9,538,020	0.376	2005	3,586,296
2004	2005	3,086,536	8,869,356	0.352	2006	3,122,013
2005	2006	4,285,481	12,314,600	0.235	2007	2,893,931
2006	2007	4,120,906	11,841,685	0.238	2008	2,818,321
2007	2008	3,097,981	8,902,244	0.366	2009	3,258,221
2008	2009	4,941,814	14,200,615	0.289	2010	4,103,978
2009	2010	3,503,440	10,067,358	0.256	2011	2,577,244
2010	2011	4,393,927	12,626,227	0.226	2012	2,853,527
2011	2012	3,898,052	11,201,299	0.370	2013	4,144,481
2012	2013	4,436,290	12,747,960	0.283	2014	3,607,673
2013	2014	2,944,019	8,459,825	0.335	2015	2,834,041
2014	2015	4,329,397	12,440,796	0.197	2016	2,450,837
2015	2016	3,069,097	8,819,244	0.305	2017	2,689,870

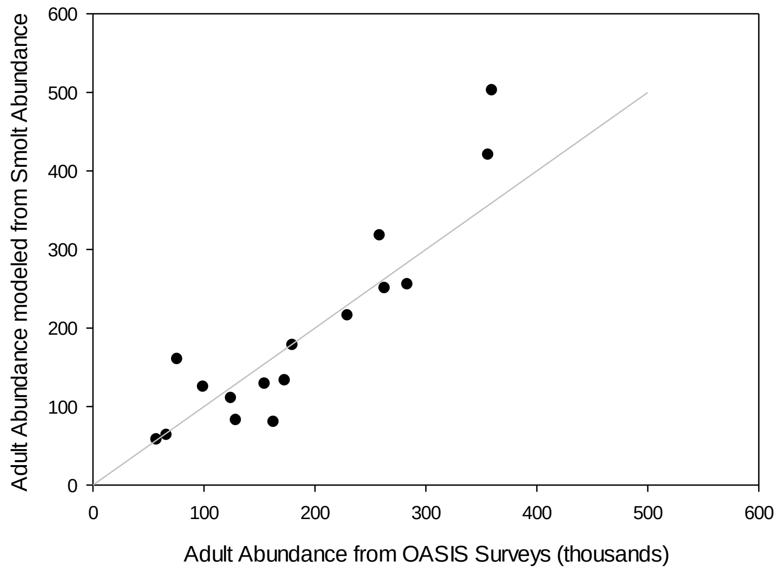

Figure 2. Plot of adult abundance from spawning ground surveys and adult abundance modeled from smolt abundance estimates and a 1:1 line for comparison. Data is from the Oregon Coast Coho Evolutionarily Significant Unit, brood years 2001-2016 (smolt migration years 2000-2015).

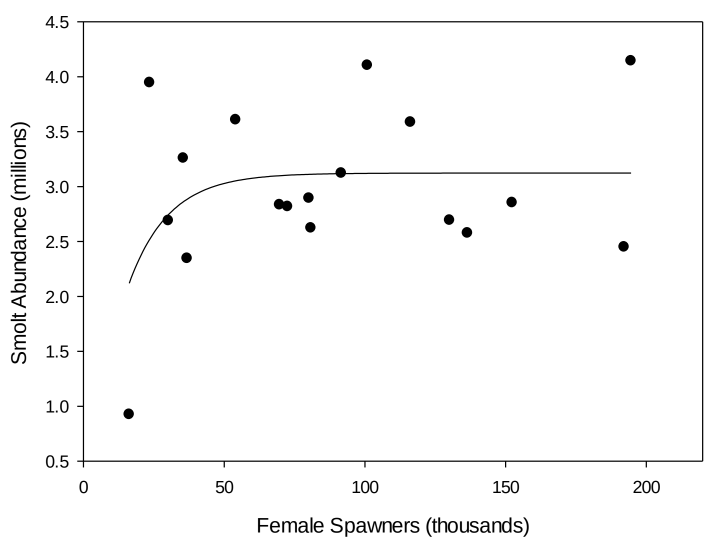

Figure 3. The relationship between parental female spawner abundance and smolt recruit abundance within the same brood in the Oregon Coast Coho ESU, brood years 1998-2015 (smolt migration years 2000-2017). Spawner abundance is from spawning ground surveys.

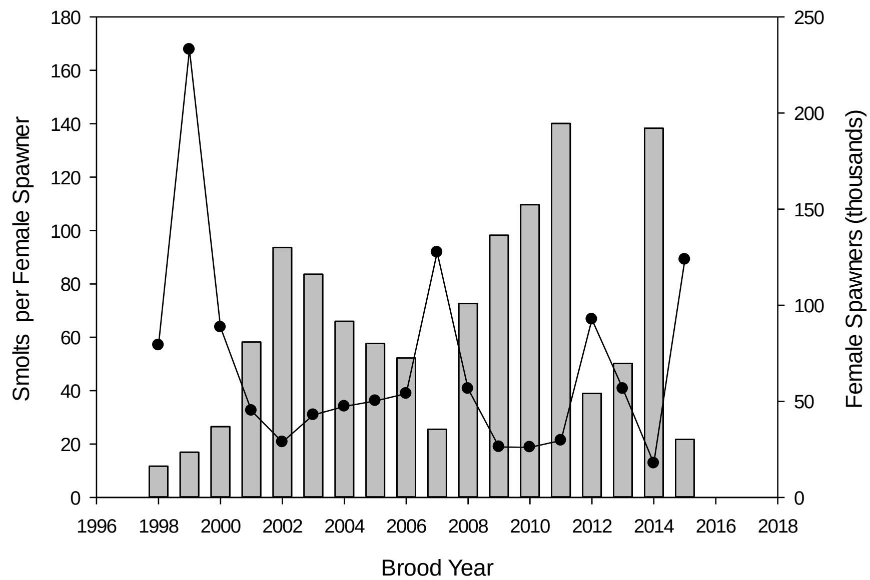

Figure 4. The abundance of Coho Salmon female spawners (gray bars) and the number of smolt recruits produced per female spawner (black dots and black lines) over time in the Oregon Coast Coho ESU. Female spawner abundance is from spawning ground surveys.

Table 2. Comparison of R^2 and OCV values from an OPITT GAM adult forecast sub-model using parental adults as a variable with the same model using smolt abundance as a variable.

	Variable 1	Variable 2	Variable 3	R Squared	Ordinary cross validation (OCV) score
Model Run 1	Pacific Decadal Oscillation	Spring Transition Date	Log $N_{spawners}$	0.47	-0.12
Model Run 2	Pacific Decadal Oscillation	Spring Transition Date	Smolt Abundance Estimate	0.43	-0.05

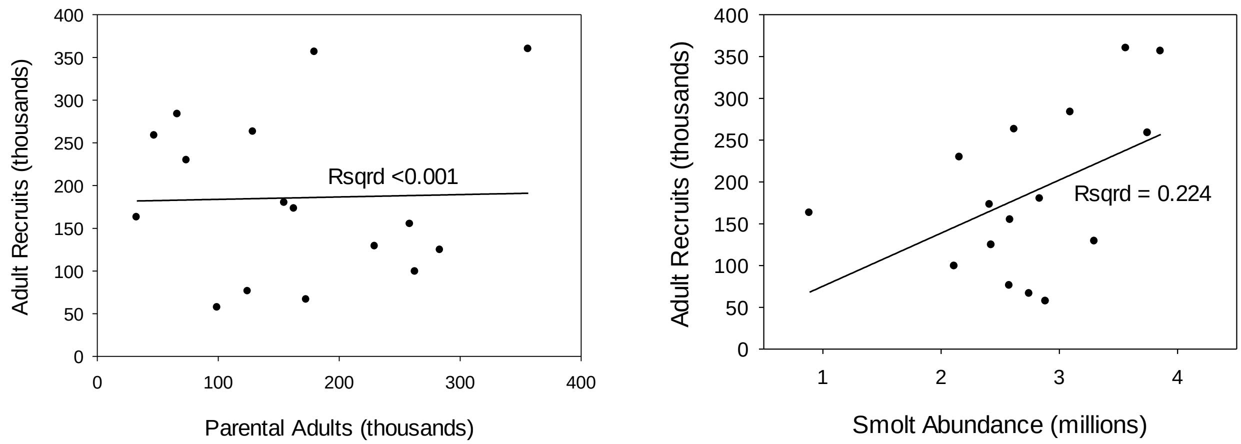

Figure 5. Regressions of parental Coho Salmon and their progeny as adult recruits (left panel) and smolt abundance estimates and adult recruits produced from the smolts (right panel). Data is from the Oregon Coast Coho Evolutionarily Significant Unit for brood years 1998-2013. Parental adult and adult recruit abundance is derived from spawning ground surveys.

DISCUSSION

Smolt abundance at the ESU scale was estimated using existing data from OPSW monitoring projects for brood years 1998-2015. Collection of these ESU-scale supporting data is ongoing. By integrating data from existing monitoring projects, the calculation of SAEs increased the utility of these data with no additional field collection effort. The correlation between adults modeled from SAEs and adults observed on OASIS surveys and between SAEs and LCM smolt abundances suggests our assumptions in calibrating and expanding the parr estimate into a SAE are valid, but the calculation could be improved. Since AQI parr abundance data and LCM data are predominantly collected in 1st-3rd order streams not all Coho Salmon life history variants, such as estuary rearing (described by Jones et al. 2014 and Weybright and Giannico 2017) or rearing in higher order streams (reviewed by Sandercock 2003) were included in AQI and LCM data sets. An accounting of these life history variants should improve the accuracy of ESU-scale parr abundance estimates, marine survival rate calculations, and the accuracy of SAEs. Accounting for inter-annual or geographic variability in snorkel survey bias and percent parr abundance in fastwater habitats (and inter-annual variation in the availability of pool and fastwater habitats) by continued testing of these assumptions could further inform the calculation of the SAEs. As local environmental conditions vary from average environmental conditions in the OCC, additional, spatially representative basins where over-winter survival is estimated may be a priority if increasing the accuracy of SAEs was desired for more accurate smolt abundance trend monitoring or more through evaluations of spawner:parr and density dependent relationships in the OCC. This may be best accomplished by estimating summer parr abundance estimates in more LCM basins where smolt and adult abundance are estimated.

The relationship between female spawner abundance and SAEs provides additional evidence that density dependent processes affect survival of freshwater life stages of Coho Salmon in the OCC (Nickelson and Lawson 1998, Nickelson 2003). Understanding the actionable details of these processes is an important informational step to addressing resource constraints that affect freshwater resilience in the OCC. When spawner abundance is relatively low, there can be a compensatory juvenile survival effect subsequently expressed by a relatively high ratio of smolts per spawner (Wainwright et al. 2008). This can restrain further reductions in spawner abundance. Conversely, when spawner abundance is relatively high, redd displacement and other competition for resources can result in lower juvenile survival rates and can be expressed as a low ratio of smolts per spawner, which can limit future increases in spawner abundance. This was observed in the OCC at current spawner abundances and on smaller scales in LCM basins (Suring et al. 2015). From these observations it seems that in some years that freshwater habitat conditions play a role in limiting juvenile survival relative to the number of available spawners. SAEs and other evaluative tools such as the Habitat Limiting Factors Model (HLFM, Nickelson et al. 1998) can be used to detect variability in freshwater survival over time in the OCC. Such evaluations can aid in determining whether freshwater survival is sufficient to support recovery goals given the range of observed marine survival rates. Monitoring may also detect changes in the smolts per spawner relationship that can inform evaluations of Coho Salmon persistence in the OCC over time.

As a measure of freshwater production smolt abundance may have application as an indicator for predicting brood year adult recruitment. Smolt abundance, which incorporates more proximate information about freshwater survival than parental abundance, has a stronger relationship with subsequent adult returns than parental abundance as a single indicator (Figure 7). When combined with PDO and SPR the comparison is equivocal; the model including smolt abundance has a lower R^2 but higher OCV compared to the model including parental abundance. The oceanographic indicators, while ostensibly tied to marine conditions, may be related to environmental conditions that effect freshwater survival (Lawson et al. 2004). Use of smolt abundance as a component of adult forecasting models would require a more thorough evaluation in line with the original forecast model development.

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