Managing Uncertainty: Forecasting Ocean Abundance of Klamath River Fall-Run Chinook Salmon (*Oncorhynchus tshawytscha*)

Capstone Project
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"How many fish are in the ocean, and where they are going to be at any one point in time, are the confounding questions of fisheries management."

-Ronnie M. Pierce, M.S., 1998.

Abstract

In 2011, when assessing the environmental impacts of allowing a minimal fishery during years of lower Chinook salmon abundance, the National Marine Fisheries Service noted that Pacific salmon preseason forecasts of ocean abundance, although variable, were unbiased over the long-term, with underestimates offsetting overestimates (PFMC 2011). Recent error in preseason forecasts of a critical Pacific salmon stock, the Klamath River Fall Chinook (KRFC), suggests that they are no longer unbiased. This project reviews the accuracy of forecasts of KRFC ocean abundance between 1985 and 2021 and arrives at four principal findings. First, overforecasts of ocean abundance have increased in frequency and magnitude. Second, KRFC salmon are maturing earlier in their life cycle. Third, increased maturation rates in ages 2 and 3 fish are predictive of increased error rates in ages 3 and 4 fish, respectively. Fourth, by using more recent brood years, we were able to achieve more accurate forecasts. These findings can inform potential modifications to the KRFC salmon forecasting model. They also highlight that salmon management approaches must be able to adapt to future changes in maturation timing.

Introduction

Chinook salmon (*Oncorhynchus tshawytscha*) are integral to the economic and cultural fabric of coastal and tribal communities on the West Coast (Satterthwaite et al. 2020; Winsor et al. 2021). The Klamath River Basin (Basin) (Figure 1) drains an area of 40,632 km comprising two main rivers, the Klamath and Trinity Rivers. The Klamath River straddles the border of Southern Oregon and Northern California, while the Trinity River lies to the south and in California only. The Klamath River is the second largest river in California (PFMC 2008; Quinones et al. 2014) and was historically among the most productive salmon rivers on the West Coast.

Indigenous Peoples in the Basin have depended on salmon abundance since time immemorial (Pierce 1998). An apt metaphor used by the United States Supreme Court to describe access to salmon fisheries for tribes in the Pacific Northwest, that applies equally to tribes in the Basin, is that salmon were "not much less necessary to [their] existence… than the atmosphere they breathed".[1] Tribal members in the Basin are painfully aware of the decline in salmon abundance over the last several decades. In 2021, the Yurok tribal allotment was ~6,500 fish, which is effectively one fish per tribal member for the year. During an abundant season, between smoking, canning, and eating, some families utilize three to five salmon per week (Parker 2022).

> "I feel at this point, our elders don't even get their basic allotment that they need, … as much like all the people, but I mean, it was always a thing that you when you fish, your first fish, you … make sure your elders were taken care of, and they had enough salmon. But yeah, it's significantly declined. In my lifetime. I can, I would

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[1] United States v. Winans, 198 U.S. 371, 381 (1905).

say it was probably in the 80s, is when I noticed it, probably mid-80s. Just a decline."

-Fawn Murphy, Chairperson, Resighini Rancheria (Murphy 2022).

"It's like gold if you can get some."

-Moonchay Dowd, Vice-Chairperson, Resighini Rancheria (Dowd, M. 2022).

When salmon numbers in the Basin are depressed, fishing interests and coastal communities in northern California and southern Oregon also suffer financially (PFMC 2008). In 2020, the California commercial salmon fishery, which is currently composed solely of Chinook salmon, generated ~$13.9 million from sales at the dock.[2] The same year, there were 105 charter boats in northern California participating in the ocean recreational salmon fishery (PFMC 2022c). Many reside on the coasts specifically to have the opportunity to fish for salmon or work in industries that support the recreational salmon fisheries (Yarnall 2022). The opportunity to bond with a parent or child and receive or pass along a livelihood and enjoyment of fishing is invaluable.

"But if you go from Monterey, all the way up to Crescent City in California, even Morrow Bay, having a salmon barbecue on the Fourth of July, or labor day …that's part of this culture of smoking salmon, giving away smoked salmon for gifts… and sharing it with your neighbors that can't go out and fish. That's part of the coastal communities' culture, and there's not an economic price on that. How do you put a price on dad taking his young daughter, like the picture I showed, out there and having them catch a big fish… that's why you live in a coastal community. And it's tough to put an economic price on that. You can't."

-Jim Yarnall, California sport fisheries representative to PFMC Salmon Advisory Subpanel (Yarnall 2022).

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[2] https://www.fisheries.noaa.gov/foss/f?p=215:200:1927708574888::NO:RP:: (last visited June 6, 2022)
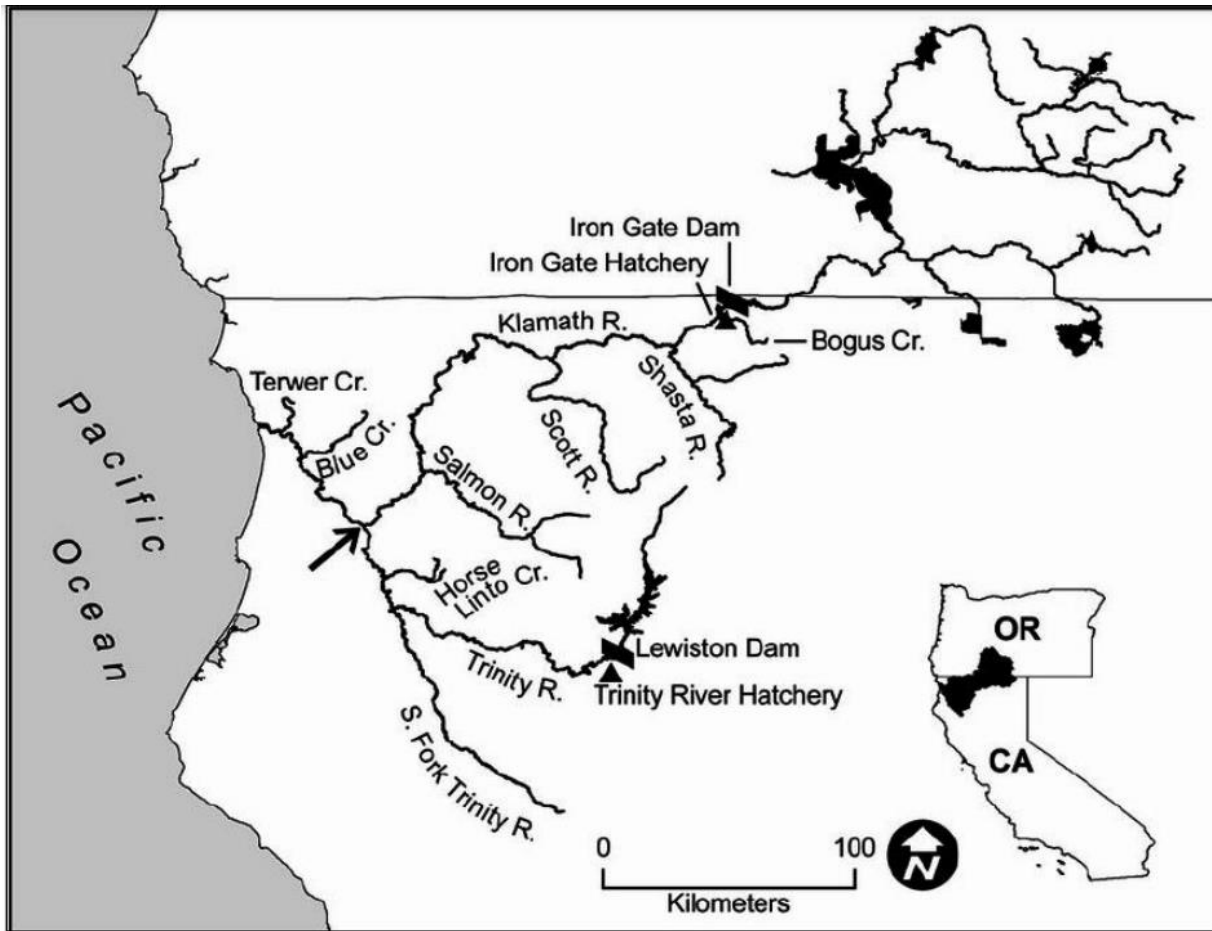
Figure 1. Klamath River Basin map (PFMC 2019b)

As anadromous fish, Chinook salmon contribute ecological value "by providing food for predators, scavengers, and decomposers, and nutrient transport for forest ecosystems" (PFMC 2008; Ohlberger et al. 2016). Because of their large size – historically Chinook salmon frequently weighed as much as 80 lbs. – their carcasses contribute substantial amounts of marine-derived nutrients to terrestrial ecosystems (Dowd, K. 2022; Parker 2022).

> "...if you take a map of the Pacific Northwest of all the conifer forests, especially redwood trees, and you overlay all the salmon return rivers, you'll see how they overlap. That's by design, because over millions of years, these conifer forests, like these coastal redwood trees outside my window right now, depend upon the return of the salmon every year to absorb those marine-derived nutrients."
>
> - Keith Parker, Sr. Fisheries Biologist, Yurok Tribe (Parker 2022).

Klamath River Fall Chinook Salmon and Declining Abundance

Today, the largest Chinook stock in the Basin is the fall-run, referred to as the Klamath River Fall Chinook (KRFC).[3] A "stock" is a group of reproductively isolated interbreeding individuals

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[3] Historically, it was the spring run that constituted the largest run in the Basin. It was the first run that returned from the oceans and, due to higher river water levels in the spring, Spring Chinook were able to

(Nehlsen 1991).[4] The KRFC stock is composed of fish of varying ages that inhabit a variety of natal streams. A significant portion of the stock is composed of fish from the Iron Gate and Trinity River hatcheries. Within the Basin are two distinct Evolutionarily Significant Units (ESUs); the Southern Oregon - Northern California Coastal (SONCC) and the Upper Klamath – Trinity River (UKTR) ESUs. The SONCC fish inhabit the lower Klamath River and tributaries from the ocean to the confluence of the Trinity River. The UKTR fish inhabit the Upper Klamath River and all of the Trinity River Basin (Kinziger 2013).

KRFC salmon have retained genetic diversity associated with many wild populations. This contrasts with the genetic structure of Chinook salmon in the California Central Valley, which has been homogenized by hatchery supplementation (Kinziger et al. 2013). There also remains a significant genetic distinction between the spring and fall runs of Klamath River Chinook salmon, including a run with heterozygotes that contain both the spring and fall-run alleles (Thompson et al. 2018).

Anadromous salmon throughout California have experienced severe declines in abundance over the last century, which has negatively impacted commercial, sport, and subsistence fisheries (CDFW 2020). In 2012, scientists predicted that, should the then-observable trends in population declines continue, 78% of all salmonid taxa (including steelhead and trout) will no longer exist in California within the coming decades (Katz et al. 2012). Historically, the Basin was home to 55 separate taxa of salmonids, but now chum salmon (*O. keta*) and pink salmon (*O. gorbuscha*) face local extinction, as do spring Chinook salmon (Quinones et al. 2014).

Among the primary pressures that have resulted in Chinook salmon decline are habitat degradation, adverse effects of hatchery supplementation, fishing, and exacerbation of these pressures by climate change (Katz et al. 2012; Okey et al. 2014).

> "Without Chinook salmon, all the habitat issues on the inland side would be swept
> under the rug, I'm afraid."

> - Jim Yarnall, California sport fisheries representative to PFMC Salmon Advisory
> Subpanel (Yarnall 2022).

Access to former salmon habitat in the upper reaches of the Klamath River Basin has long been blocked on the Klamath River by the construction of the Copco Dam #1 (1917) and the Iron Gate Dam (1962), and on the Trinity River by the Lewiston Dam (1963). Four dams in the Klamath River in California and Oregon are scheduled to be removed in 2023 (ODFW 2021). In addition to providing access to historic habitats, the dam removal should result in a greater volume and rate of water flow (ODFW 2021). Due to these dam removals and associated habitat restoration plans,

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travel hundreds of miles upriver to spawn in the headwaters. Spring Chinook salmon have higher fat content than other runs. (Parker 2022). Wild stocks of the spring run have dwindled to the point that, between 1981-2011, the average count of spring Chinook on the South Fork Trinity River was 253 fish (CBD 2011).

[4] Because salmon have adapted to the local conditions of their natal streams, the loss of a stock undermines genetic diversity. For this reason, management focuses on sustaining the population of salmon stocks (Nehlsen 1991).

Klamath River stocks may be well-positioned to recover some extent of historic abundance (Quinones et al. 2014; Yarnall 2022).

Fisheries for Chinook salmon from the Basin have become increasingly dependent on production from hatcheries constructed adjacent to the Iron Gate and Lewiston dams (Quinones et al. 2014; Katz et al. 2012).[5] Hatchery fish may compete with natural-origin fish for food in the ocean, especially during times of low productivity. Offspring of hatchery fish have lower survival rates than natural spawners (Katz et al. 2012). Proportions of natural origin fall Chinook have significantly decreased concurrently with increases in hatchery returns (Quinones et al. 2014).

> "if we don't have relief on the Klamath, either through climate change or through water usage, then salmon populations will further decline and it'll be higher and higher … reliance on hatchery fish."

> - Jim Yarnall, California Sport Fisheries representative to PFMC Salmon Advisory Subpanel.

Fishing often results in the selective removal of older and larger Chinook salmon, which can lead to less resilience and greater sensitivity to changing ocean conditions (Okey et al. 2014). One explanation for this phenomenon is the size-selective harvest of larger fish associated with gill net mesh size (Law 2000).

Influence of Ocean Conditions on Chinook Salmon

Due to their extended ocean residency, ocean conditions play an important role in Chinook salmon cohort abundance. Chinook salmon spawn and rear in freshwater, migrate to the ocean as juveniles, spend one to four years in the ocean and return to freshwater to spawn and die (Satterthwaite 2019). Natural origin KRFC salmon hatch between February and March, spend seven to eight months in freshwater, and enter the estuary and ocean between June and the end of September (PFMC 2019b). Conditions in the few first months of ocean migration are critical for the recruitment of California's Central Valley Chinook salmon (Macfarlane 2010). In the California Current Ecosystem, juvenile Chinook salmon largely stay close to coastal waters near their natal rivers (Hassrick et al. 2016). The ocean distribution of Chinook salmon is influenced by the presence of cooler water and the accompanying higher nutrient levels that make for prime conditions for their prey, such as northern, lipid-rich krill (Wells et al. 2012).

Physical ocean conditions can serve as indicators of Chinook salmon abundance. For example, the Pacific Decadal Oscillations (PDOs) are associated with recruitment, with greater marine survival occurring during periods of cool PDOs and poorer survival occurring during periods of warm PDOs (Mantua et al 1997; Peterson et al. 2014). With warming surface water temperatures in the Eastern Pacific Ocean, it is projected that the ocean distribution of adult Central California Chinook will shift southward, with increasing abundance in ocean waters adjacent to Central California. In contrast, Northern California fall runs, such as the KRFC, are expected to shift their

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[5] As of 2013, these hatcheries were producing about 10 million juvenile Chinook salmon annually (Kinziger 2013).

ocean distribution farther north and be found in lower abundance adjacent to northern California coastlines (Shelton et al. 2019).

Chinook Salmon Age of Maturity

The age at which salmon reach reproductive potential and return to their natal rivers to spawn is called the age of maturity. Age of maturity is highly heritable (Carlson & Seamons 2008) and modifiable by selective harvest (Okey et al. 2014). Progressive deterioration of the genetic basis for maturation at an older age has been observed (Ricker 1980). Heritability of maturation age suggests that significant genetic variation for this trait may help salmon adapt to local conditions (Vähä et al. 2008). Variability based on sex has been observed, with females maturing, on average, later than males (Fleming 1996). Hatchery fish mature at an earlier age than natural-origin fish. Harvest intensity magnifies this trait (Davison and Satterthwaite 2017). Fishing also limits the capacity of Chinook from delaying maturity to benefit from more favorable environmental conditions (Fujiwara 2008).

Management of Chinook Salmon Fisheries

The KRFC fishery management process combines science-based stock prediction with policy-based management decisions. Under the Magnuson-Stevens Fishery Conservation and Management Act, the objective of the management process is to maintain harvest at levels that meet legal requirements and preserve long-term stock productivity (PFMC 2008). The Pacific Fishery Management Council (PFMC) is the lead entity responsible for managing all salmon fisheries on the West Coast.

Forecasting ocean abundance is broadly used as the starting point for setting harvest controls for a variety of salmon species along the West Coast (Haeseker et al. 2008; Satterthwaite et al. 2020). Each year the Pacific Fishery Management Council's Salmon Technical Team (STT) forecasts total KRFC ocean abundance by performing linear regressions on estimates of age-specific ocean abundance and river runs of the same cohorts. This method is a variation of the "sibling model", in which age-specific estimates of freshwater returns for a cohort are used to forecast the ocean abundance of the same cohort in the next year (Winship et al. 2015). From the ocean abundance forecast, the STT forecasts, in the absence of fishing, the escapement, which is the number of salmon that will reach natural areas to spawn (PFMC 2022a).

The KRFC salmon fishery is managed by targeting a number of adults that will escape mortality and spawn in natural areas, often referred to as spawner "escapement targets" (PFMC 2022a). Escapement targets and exploitation rates for all salmon under PFMC jurisdiction are outlined in the Pacific Coast Salmon Fishery Management Plan (Salmon FMP). For KRFC salmon, the Salmon FMP allows for a maximum exploitation rate of 68%, also known as the maximum fishing mortality threshold (MFMT) (PFMC 2021, § 3.3.6). When total KRFC salmon ocean abundance is predicted to sustain an escapement, in the absence of fishing, of between 54,300-127,200, the MFMT varies between 25% and 68% of total spawning adults. The KRFC spawner escapement target (S_{MSY}) is 40,700 and corresponds to the natural area escapement associated with maximum

sustainable yield ("MSY").[6] This escapement target, and higher targets in times of greater abundance, are referred to as the KRFC "conservation objective". (PFMC 2021).
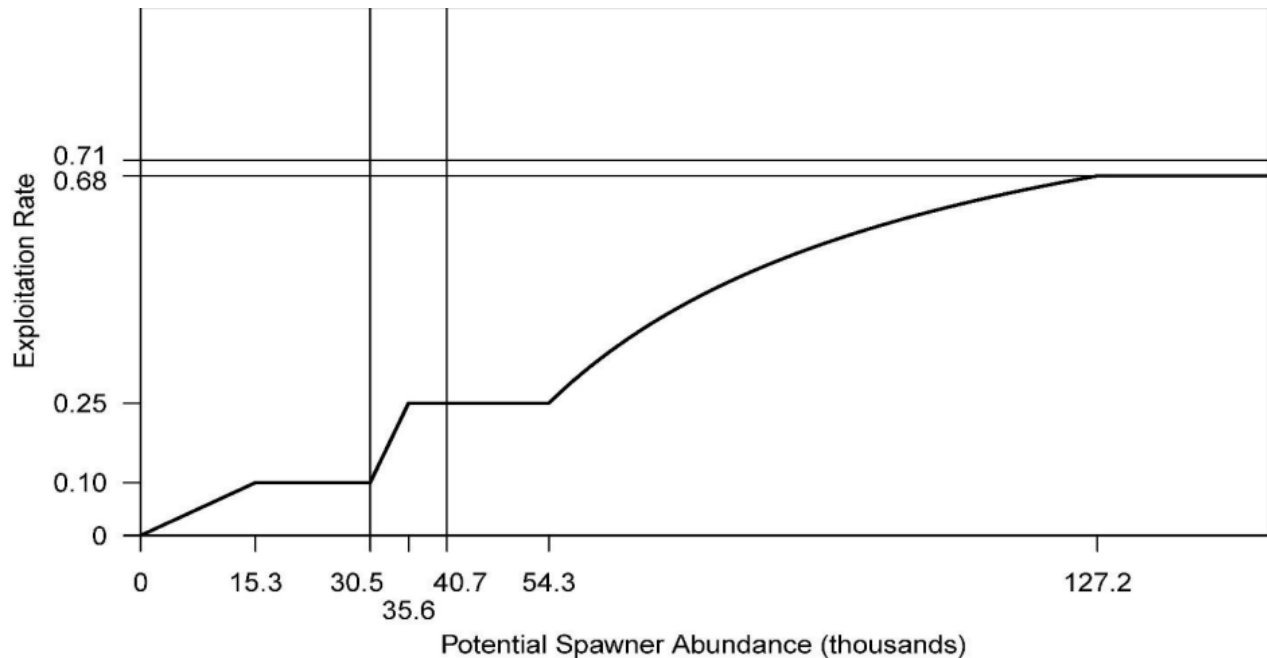

Figure 2 (PFMC 2019b, Figure 2.2.4.a). Klamath River Fall Chinook control rule. Potential spawner abundance is the predicted natural-area adult spawners in the absence of fisheries.

The Salmon FMP includes a rule that allows for a very limited harvest of KRFC salmon during periods of low abundance. Before 2005, when total ocean abundance was forecast to be insufficient to support the escapement floor, fisheries were closed (PFMC 2003). After several closures of portions of the commercial and recreational fishery, in 2008, the National Marine Fishery Service adopted an Amendment to the Salmon FMP called the "de minimis fishery rule". The purpose of the rule was to "provide some low level of economic relief for fisheries-dependent communities without significantly impacting the long-term productivity of KRFC" (PFMC 2008). When projected escapement to natural areas is between 35,600 and 30,500, the MFMT declines rapidly from 25% to 10% of spawners, and subsequently declines to 0% at projected escapement of below 15,300 (Figure 2) (PFMC 2008). De minimis fishing for KRFC salmon has been permitted several times in recent years (PFMC 2022b).

Once an escapement target is identified, the STT projects the allowable ocean harvest rate using the Klamath Ocean Harvest Model (KOHM) (Prager and Mohr 2001). The KOHM is a planning tool for establishing annual commercial and recreational ocean fishery seasons for the zones within PFMC jurisdiction. From ocean abundance estimates, historical fishery exploitation patterns, and

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[6] The current KRFC Salmon escapement floor of 40,700 natural area spawners is an increase from the 35,000-escapement floor set by the Klamath River Technical Team (KRTT) in 1986. When the KRTT adopted the 1986 floor, it concluded that this number of natural area spawners was half that required to achieve maximum sustainable yield. (PFMC 2008).

a combination of effort estimates and quotas, the KOHM predicts ocean fishery impacts on KRFC salmon (PFMC 2011).

Management of ocean salmon fishing focuses on achieving the conservation and allocation objectives for "weak stocks"; that is, those most at risk of overharvest in a given season. (PFMC 2008). For example, in 2008 and 2009, the Sacramento River fall Chinook experienced relatively low abundance while the KRFC salmon experienced a period of relatively higher abundance. As a result, during this period the constraining factor in setting season length was achieving sufficient Sacramento River fall Chinook escapement. Over the last several years, the constraining factor has been achieving sufficient KRFC escapement (2003 FMP, Table 3-1; PFMC 2008; PFMC 2022b).[7]

For the river harvest, the management authorities are the California Department of Fish and Wildlife (CDFW) and the Yurok and Hoopa Valley tribes. Federal law recognizes the Yurok and Hoopa Valley tribes reserved right to no less than 50% of the total salmon fishery (U.S. Solicitor General 1993). However, it fails to recognize a similar right for any other Klamath River tribes, despite their members' culture and health being no less dependent on continued access to salmon.

Missed Escapement Targets and Preseason Forecasts of Ocean Abundance

In 2018, low escapement in the years 2015-2017 resulted in KRFC salmon being declared to be "overfished", which means that the stock's productivity and sustainability are at risk (PFMC 2019b). Low abundance of KRFC salmon resulted in continuing closures of the commercial fishery in the Klamath Management Zone (KMZ), relatively limited commercial and recreational seasons south of the KMZ, and the complete closure of the Yurok salmon river fisheries in 2017 (PFMC 2019a; Parker 2022). The STT concluded that river habitat conditions, including below-average flows and high temperatures that coincided with a high incidence of disease for a portion of the critical broods (2011-2014), contributed to the low KRFC salmon escapement.

But it also identified another cause of the missed escapement targets – overforecasts of KRFC ocean abundance (PFMC 2019b). Inaccurate preseason forecasts were also identified as a principal causative factor of missed conservation objectives in 1990, 1992, and 2008 (Pierce 1998; PFMC 2008). The 2018 overfished declaration, another overforecast the same year, and in 2019, the highest overforecast on record (Figure 3), triggered a renewed urgency to understand potential causes of forecasting error.[8]

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[7] Often, it is age-4 KRFC salmon, which are a proxy for the health of the endangered California Coastal Chinook stock ("CCC"), that causes this constraint (PFMC 2022b).

[8] For all historic preseason forecasts and postseason estimates of ocean abundance, and forecasting accuracy ratios, see Preseason Report I, Stock Abundance Analysis and Environmental Assessment Part 1 for 2022 Ocean Salmon Fishery Regulations (PFMC 2022a) (https://www.pcouncil.org/documents/2022/03/2022-preseason-report-i.pdf/).
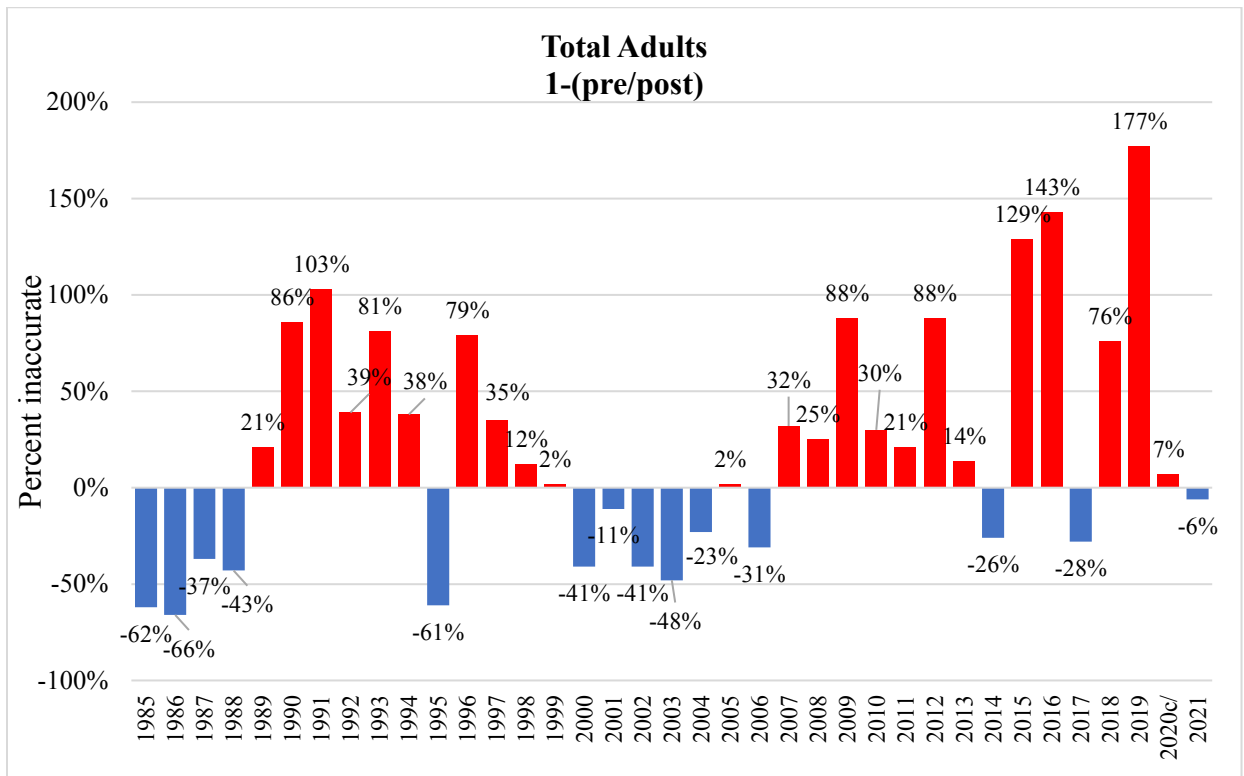
Figure 3. Percentage of the inaccuracy of preseasons forecasts of total adults (ages 3, 4, and 5) KRFC ocean abundance.

Research into forecasting errors of west coast salmon stocks includes attempts to identify physical and biological ocean indicators of changing abundance. Coastal ocean upwelling has been found useful in predicting 1-year-ahead forecasts of Snake River spring and summer Chinook salmon (Scheuerell and Williams 2005). However, larger-scale indicators of sea surface temperature were found to be more predictive than coastal upwelling for adult spring Chinook salmon in the Columbia River (Burke et al. 2013). Overall, results have been mixed and, after early promising performances, many environmental-based forecast methods have been discontinued (Wainright 2021).

Due to similar problems with inaccuracy, potential modifications to the forecasting model for Sacramento River fall Chinook salmon were recently explored (Winship et al. 2015). A model that employed temporally autocorrelated errors and models that directly incorporated information on environmental conditions such as sea surface temperature and upwelling strength were shown to have promise. However, concerns were expressed about changes in the long-term predictive strength of these variables, along with the complexity of incorporating them into models (Winship et al. 2015). Specific to KRFC salmon, recent research found no single ocean indicator that explained more than 17% percent of the error in forecasting ocean abundance (Satterthwaite et al. 2020).

This project explores the hypothesis that changing maturation rates are causing increased forecasting error in KRFC salmon, and attempts to answer the following questions:

1) Has inaccuracy of preseason forecasts of ocean abundance increased since 1984?

2) Have age-specific maturation rates increased since 1984?

3) If there is an increase in age-specific maturation rates, is there a relationship between changing maturation rates and increased forecasting inaccuracy?

4) Could the accuracy of the forecasting model be improved if, instead of relying on brood year data from 1979 to the present, it relied only on data from more recent brood years?

Methodology

The STT provided all data, which included 1) preseason forecasts and postseason estimates of age-specific and total adults ocean abundance (FY1985-2021), 2) a ratio of preseason forecasts to postseason estimates for ages, 3, 4, and 5, and total adults (FY1985-2021), 3) maturation rates for ages 3, 4 and 5 (FY1985-2022), and 4) run size and ocean abundance data for ages 2-5 (FY1982-2022). Using R (R Core Team 2021), changes in forecasting error (FY1985-2021), maturation rates (FY1984-2021), and abundance (FY1983-2021) were analyzed by performing linear regression models. Similarly, the relationship between age-specific maturation rates and forecasting accuracy was analyzed using linear regression models, with maturation rates as the independent variable.

In the context of calculating ocean abundance, three distinct "years" are frequently referenced: Brood Year, Run Year, and Forecast Year.

> Brood Year (BY) is the year when eggs of a certain cohort were deposited in the gravel (Ohlberger 2019a).

> Run Year (RY) is the year in which a brood of Chinook salmon returns from the ocean to its natal river to spawn.

> Forecast Year (FY) is the year in which the forecast is conducted and used to set fishing regulations.

Preseason Forecasts of Ocean Abundance and Accuracy

Computing preseason forecasts in year "y" involves linear regressions of historical post-season ocean abundance estimates for ages 3, 4, and 5 fish, against the post-season run size estimates for ages 2, 3, and 4 fish, respectively, in year "y-1". The regression is constrained to the origin, as a river run size of zero predicts an ocean abundance remainder of zero for the same cohort. (PFMC 2022a). For each forecast year, the linear regression is performed using brood year data from 1979 forward. For example, in 2022, the linear regression was performed on brood year data on ocean abundance and run size from 1979 to 2018 (PFMC 2022c). The generated regression slope coefficient (β) is multiplied by the run size for that brood year.

Put another way, the number of three-year-old fish left in the ocean is calculated from the number of two-year-old fish of that brood's population that matured and returned to the river to spawn. Similarly, the ocean abundance of four-year-olds is calculated from the three-year-olds of the same brood year that matured (Pierce 1998). For example, to forecast age-4 ocean abundance in 2022,

β was 1.192, which was then multiplied by the 2021 age-3 run size of 36,248, resulting in a preseason estimate of 43,211 (Figure 4).
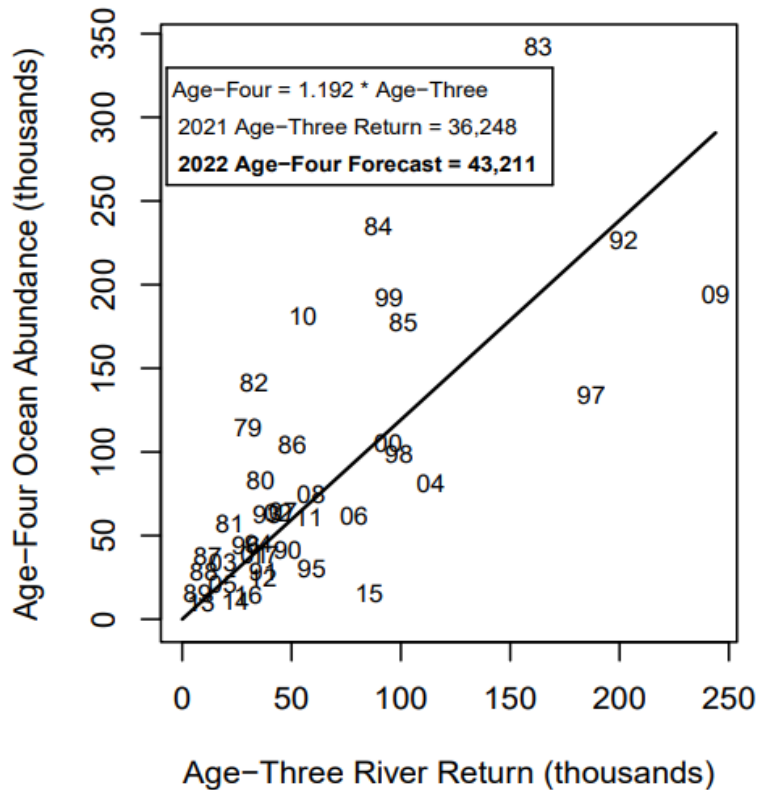

Figure 4. Regression estimators for Klamath River Fall Chinook ocean abundance (September 1) based on that year's river return of the same cohort. Numbers in the plot denote brood years (PFMC 2022a; Fig. II-3).

Each year, the CDFW Ocean Salmon Project generates "postseason estimates" of age-specific and total KRFC ocean abundance using cohort reconstruction methods. Identifying potential errors in the data supporting postseason estimates was beyond the scope of this project, therefore only a brief overview of the data used to generate postseason estimates and the cohort reconstruction method follows.[9]

The cohort reconstruction method starts with sampling estimates of coded-wire-tagged hatchery fish and surveys of actual adults that return to natal streams and hatcheries to spawn (KRTT 2022). To these counts are added estimated harvest, mortality from other causes in the ocean and rivers, and fish that have not yet matured. These estimates are calculated from a mix of collected data, such as from harvest reports and escapement surveys (e.g., carcasses on riverbanks), extrapolations from that data, and assumptions about natural mortality rates. This process is completed for ages 3, 4, and 5 salmon (PFMC 2022c; Mohr 2006).

Age-specific contributions to Klamath Basin returns are estimated by the Klamath River Technical Team (KRTT) using scale analyses (KRTT 2022). Estimation of age composition is performed by

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[9] For a full description of the data that underlies the cohort reconstructions, see Goldwasser (2001).

two trained scale readers, whenever possible, on random samples of scales collected from harvested salmon and fish recovered in hatcheries and natural spawning areas. The KRTT uses age information collected from caught hatchery fish and statistical methods to correct for bias (KRTT 2022). A diagram showing a sample reading of a Chinook salmon scale is attached as Appendix A.

At the end of each season, the accuracy of KRFC salmon ocean abundance forecasting is calculated using the ratio of preseason forecasts to postseason estimates of ocean abundance (PFMC 2022a).

> Accuracy = pre/post

Ratios that exceed 1.0 indicate that the forecast exceeded the postseason estimate – an "overforecast". Ratios less than 1.0 indicate that the forecast was less than the postseason estimate – an "underforecast". Error in the numerator (preseason forecasts), the denominator (postseason estimates), or both, can affect the pre/post ratio.[10]

Maturation Rates

To determine the age-specific maturity rate (M_a) of a brood year, the STT compares the age-specific river run size against age-specific ocean abundance at the time maturation occurred. For example, in 2021 it was estimated that 36,348 of 82,218 age-3 fish in the ocean returned to their natal rivers and creeks to spawn (river run). Therefore, the 2021 age-3 maturity rate was 44% (36,348/82,218).

> $M_a = R_a/O_a$

- O_a – age-specific ocean abundance determined by cohort reconstruction.
- R_a – run size at age determined from in-river surveys.

Alternative Forecasting Model Evaluation

To evaluate whether there were systematic changes in the ratio of ocean abundance to run size for ages 3 and 4 fish, using run years 1981-2021 a linear regression and a general additive model (using the R package 'gam') analysis were performed between the ratio (dependent variable) and year (independent variable). A generalized additive model (GAM) is a non-parametric, regression technique unrestricted by linear relationships between the dependent and independent variables (Wang et al. 2009).[11] After discovering that the ratio changed after 1990 (see Results), two alternative data sets (Models 1 and 2) were identified and tested for performance.

Model 1. For FY2004-2021, alternative forecasts of ocean abundance for ages 3 and 4 fish were calculated using brood year data from 1990 forward. Each new forecast was based on the brood year data that would have been available in that forecast year, except for data from BY1979-1989.

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[10] There are many potential errors in the data supporting the cohort reconstruction method, including in sampling methodology, extrapolations from sampled populations, and assumptions about stray rates, natural mortality, and proportions of spawners in natural areas (Mohr 2006). For this project, it was assumed that postseason estimates are accurate.

[11] GAMs have been used to evaluate Chinook salmon forecasts, it has been used to evaluate forecasts of Queets River Coho salmon and the predictive strength of ocean indicators for Chinook salmon ocean abundance forecast accuracy (Wang et al. 2009; Satterthwaite et al. 2020).

New regression coefficients were generated using the linear regression model. The new coefficients were then multiplied by the run size in the year preceding the forecast year, resulting in new forecasts of ocean abundance.

Model 2. For FY1993-2021, alternative forecasts of ocean abundance for ages 3 and 4 fish were calculated using data limited to the 10 most recent brood years and the same preseason forecasting methodology described above (using the R package 'slider'). A three-year moving average method has been applied to other forecasts and was recently found to have some success in predicting Oregon Chinook (McCormick and Falcy 2015). In selecting a 10-year range, a balance of the risk of overfitting the model against the risk of using obsolete maturation rates was generally considered.[12] New regression coefficients were generated by applying the linear regression model to the 10-year datasets. The new coefficients were then multiplied by the run size in the year preceding the forecast year, resulting in new forecasts of ocean abundance.

Each new forecast generated by Models 1 and 2 was compared to the postseason estimate to generate a new pre/post ratio. The resulting ratios for each model were then compared to the existing pre/post ratios. To evaluate model performance, commonly used performance measures to characterize the central tendency and variability were used, including mean raw error ("MRE"), mean absolute error ("MAE"), mean percentage error ("MPE"), and root mean square error ("RMSE") (Haeseker et al. 2008).[13] To evaluate the significance of changes in pre/post, MRE, and MAE, between Models 1 and 2 and the original forecasts, paired t-tests were performed using the R package 'tidyverse'.

To obtain MRE, the raw errors were averaged over the number of years (*n*) forecasted. The MRE reflects the overall bias of the forecasts. In contrast, the MAE reflects the magnitude of forecasting error regardless of the direction of the error. The RMSE was used to measure the forecast error variance and can be used to construct confidence intervals in forecasts (Haeseker et al. 2008).

Results

Total abundance for all age classes declined over the analysis period (AP), FY1985-2021. Average abundance between the periods 1985 to 2000 and 2000 to 2022 declined for ages 3, 4, and 5 fish by 39%, 30%, and 31% respectively. As of 2021, age 3 fish are the majority of adult KRFC ocean abundance; age 3 (77.2%), age 4 (21.5%), and age 5 (1.3%).

Overforecasts Have Increased in Frequency and Magnitude Since 1985

During FY1985-2021, overforecasts become more frequent and increased in magnitude for age 4 fish (p = 0.026), age 5 fish (p = 0.01) and total adults (p = 0.02944). Age 3 forecasts did not significantly change through time (p = 0.27). Plots generated from linear regressions of forecasting accuracy for all ages and total adults are attached in Appendix B.

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[12] A five-year moving average was also examined, but did not appear to perform markedly better than a 10-year moving average (Appendix G).

[13] Raw Error = predicted abundance (x_i) - observed abundance (x); Absolute Error (Δx) = $|x_i - x|$; Percent Error = $\Delta x / x$; Root Mean Square Error = $\sqrt{\Sigma_{i=1}^{n}(P_a - O_a)^2/n}$.

Age-3 forecasts fluctuated between periods in which either overforecasts or underforecasts predominated. During the ten years spanning 1989 and 1998, nine overforecasts occurred, three by greater than 150%. During the following ten years (1999-2008) eight underforecasts occurred, three by more than 100%. During the following 13 years (2009-2021) ten overforecasts occurred, five by 100% or more. The standard deviation from complete accuracy (1.0) was 0.81.

For age-4 KRFC salmon, of the 39 forecast years, eight were underforecast (pre/post ratios ranging from 0.37 to 0.95), two were precise (pre/post of 1.00), and 29 were overforecast (ranging from 1.03 to 6.07). Over the 37-year AP, the average age 4 pre/post ratio was 1.48, or an overforecast of approximately 48%. The standard deviation from complete accuracy (1.0) was 1.17.

For age-5 fish, between FY1985 and FY2000, precise forecasts or underforecasts occurred in 12 of 16 (75%) years. Then overforecasts became dominant; during FY2001 to FY2020, overforecasts occurred in 12 of 20 (40%) years. Seven forecasts exceeded postseason estimates by more than 100%.

Total adult KRFC (ages 3, 4, and 5) resembled the patterns of the most abundant age-class – age-3 fish. The 1990s had periods in which overestimates dominated, then in the 2000s underestimates became more common. Between 2007-2021 overestimates again became the most frequent occurrence. Between FY2015-2021, on average, total adult ocean abundance was overestimated by 71%. Unlike for age-3 fish, the trend of increasing pre/post ratios for total adults was statistically significant (p-value 0.018445).
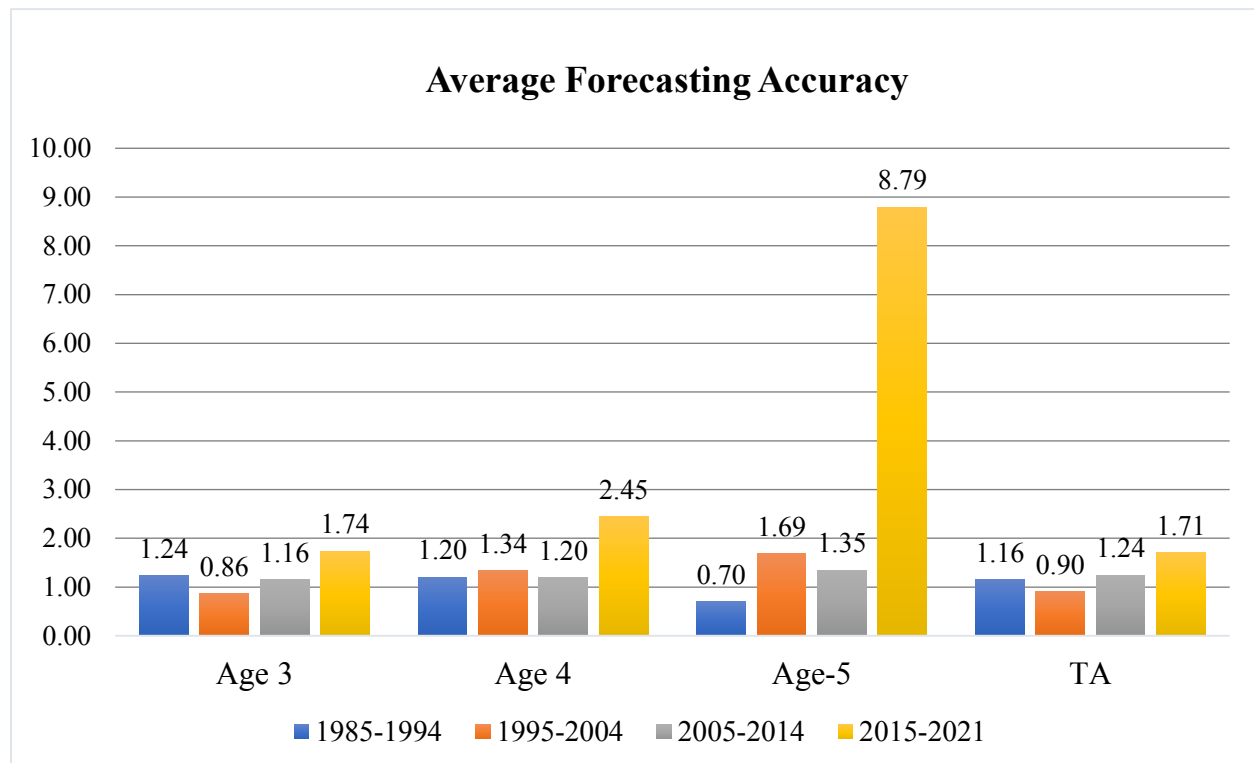

Figure 5. Average forecasting accuracy by 10-year intervals, FY1985-2021. Pre/post ratios are shown on the y-axis; ratios > 1.0 are overforecasts and ratios < 1.0 are underforecasts.

Maturation Rates Have Increased Since 1983

Age-2 (p = 0.02344), age-3 (p = 9.045e-06) and age 4 (p = 0.003304) maturation rates increased systematically over the AP. Age-5 rates did not (p = 0.9421). Maturation rates of age-2 (jacks) fish exhibited the strongest fluctuations (R^2 = 0.1077), followed by rates of age 4 (R^2 = 0.1892) and age 3 (R^2 = 0.3929) fish. Charts of linear regressions of maturation rates are at Appendix C.

Age 2 maturation rates ranged from 2% (1983) to 17% (2014), with a mean value of 5.9%. Average rates started at 4% in the 1980s and then dropped to 2% in the 1990s. In the early 2000s, average rates crept back up to close to 4% and, between 2000 and 2010, they jumped to an average of 8.5%. The highest age-2 maturation rates occurred in 2015 (17%), 2016 (16%), and 2019 (12%).

Age 3 maturation rates ranged from 19% (1985) to 85% (2018), with a mean value of 44%. Between 1982 and 1991 rates were consistently less than 40%, whereas between 1992 and 2021 rates in 24 of 30 years exceeded 40%. Age-3 maturation reached unprecedented rates of 70%, 85% and 68% in 2017, 2018 and 2019 respectively (Figure 6).

Age 4 maturation rates ranged from 61% (1986) to 100% (2019), with a mean value of 90%. Age-4 maturation rates in the 1980s averaged less than 80%, then between 1990-1999, average rates increased to just over 90% and remained there until 2009. Between 2010 and 2021, average rates increased further to 94% (Figure 6). Maturation in 2017, 2018 and 2019 reached unprecedented rates of 99%, 96% and 100% respectively.[14]

Although average maturation rates for ages 2, 3, and 4 fish all increased substantially during the AP, the timing of increases varied.[15] Whereas average maturation rates of Age-2 fish decreased in the 1990s, before they increased in the 2000s, average maturation rates of ages 3 and 4 fish both increased significantly in the 1990s and systematically thereafter. Over the last 12 years, average maturation rates for Age-2 fish have reached 9% (compared to 4% in the 1980s), average rates for Age-3 fish have reached 53% (compared to 28% in the 1980s) and average rates for age-4 fish have reached 94% (compared to 78% in 1980s) (Figure 6).

Similarly, peak maturation rates among age classes did not temporally align. Age-2 fish reached 17% in 2015 and stayed at 16% in 2016, they dropped to 6% by 2021. Age 3 and 4 fish reached their highest average rates of 74% and 98%, respectively, between 2018-2020.[16]

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[14] Age 5 fish generally matured at a 100% rate over the AP, with the exceptions of 1992 (96%), 2002 (99%), 2005 (99%) and 2013 (97%).

[15] Maturation rates of age 5 KRFC salmon have generally stayed at 100%, consistent with the description of KRFC age-class structure in the 1990s (Goldwasser 2001).

[16] Relatedly, estimates of ocean abundance of age-5 fish in 2019 and 2020, dropped to extremely low levels - 220 and 24, respectively.
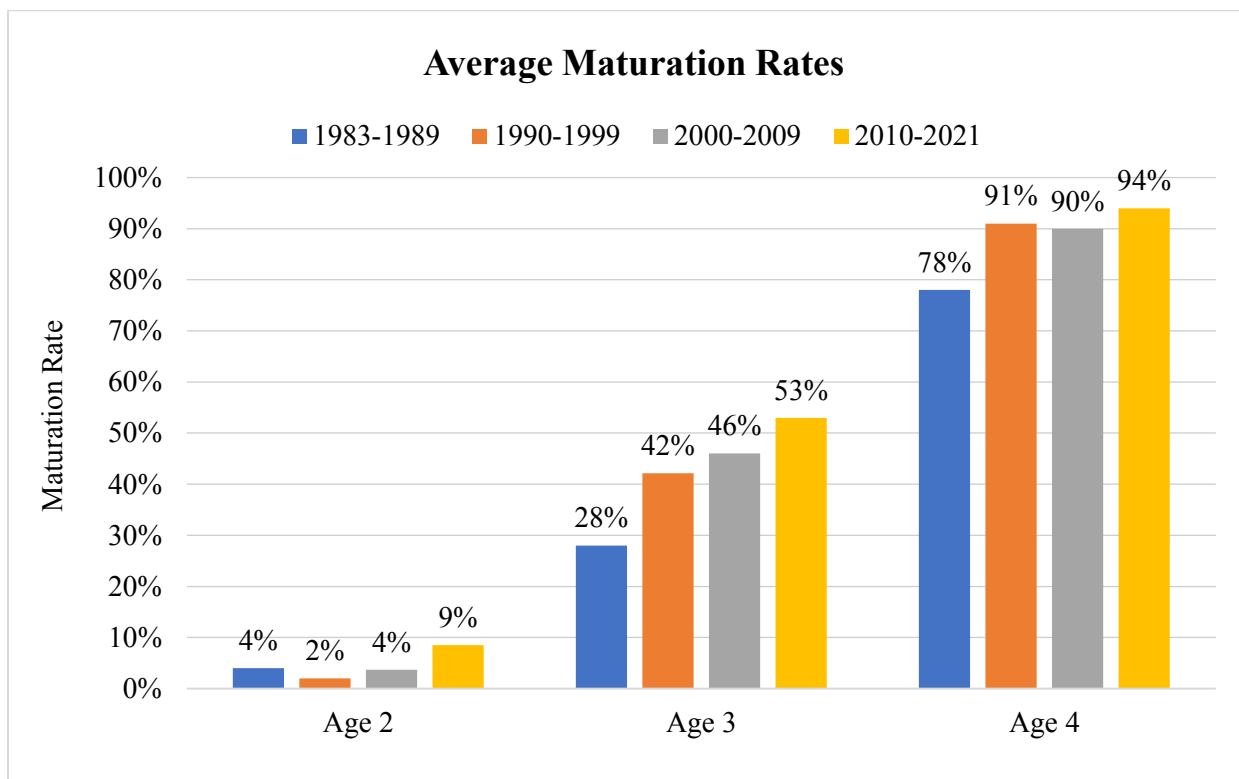
Figure 6. Age-specific average maturation rates by decade, FY1983-2021. Maturation rates, or the percentage of fish that returned to the river to spawn, are shown on the y-axis.

Changes in Maturation Rates Are Predictive of Forecasting Error

The relationships between age-2 maturation rates and age-3 forecasting accuracy (Figure 7) ($p = 4.94e-11$) and age-3 maturation rates and age-4 forecasting accuracy (Figure 8) ($p = 1.476e-07$) was significant. The relationship between maturation rates in age-4 fish and forecasting accuracy for age-5 fish was not statistically significant ($p = 0.3262$). Although forecasting accuracy for two years, 2018 and 2020, were anomalously different (pre/posts of 16.00 and 29.17), even without those years, the relationship remained insignificant.
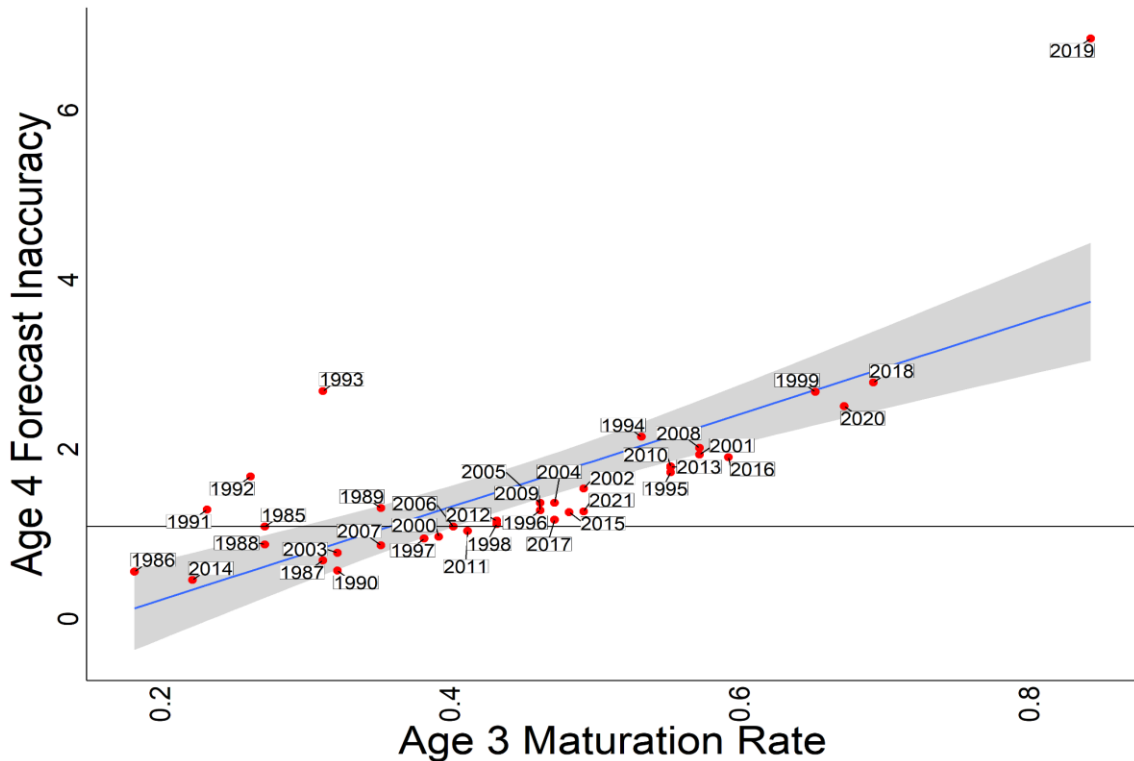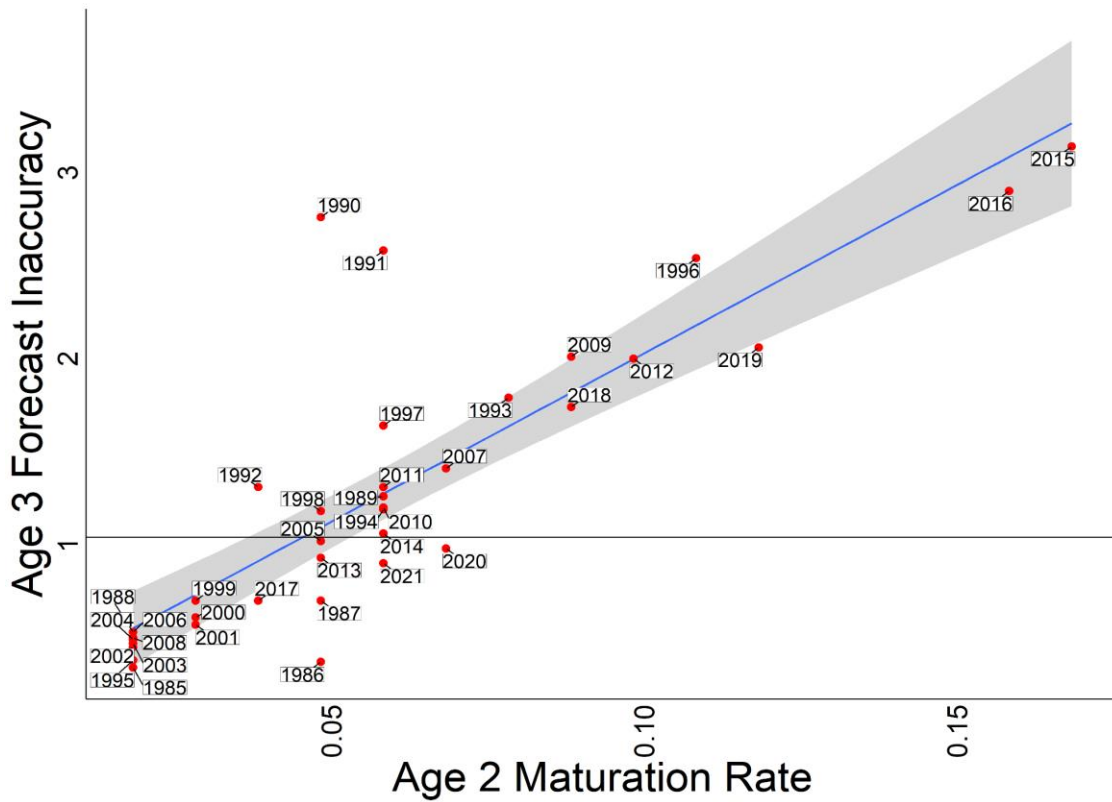
Figure 7. Linear regressions of age-2 maturation rates with Age-3 accuracy rates and of age-3 maturation rates with age-4 accuracy rates. The blue lines are the best fit and the grey areas are the confidence intervals. The black line is the 1.0 pre/post ratio; <1.0 indicates an underforecast and > 1.0 indicates an overforecast.

Limiting Ocean Abundance and Run Size Data to Post-1990 Brood Years Decreased the Magnitude and Frequency of Overforecasts in FY2004-2021

The strong relationship between increasing maturation rates and the increasing frequency and degree of overforecasts led to the hypothesis that older brood years with lower maturation rates may be impairing forecasting accuracy. Indeed, other Chinook salmon preseason forecasts rely on data from more recent brood years, including the Columbia River fall and summer Chinook (PFMC 2021a).

The first step in testing this hypothesis was to identify a year in which the relationship between ocean abundance and run size changed, which was accomplished using a GAM. Relative to the linear model, the GAM reduced variation and resulted in a better score under the Akaike Information Criterion:

	R^2	AIC
Linear Model	0.41	93
Generalized Additive Model	0.51	88

In other words, the GAM produced the best fit line that more closely tracked variation in the ratio of ocean abundance to run size (Appendix D). A visual inspection of the GAM model revealed a steeper slope for brood years 1979-1989 than 1990-2017 (Appendix D). After 1989, the ratio of ocean abundance to run size became more stable.

Recreated regression slopes, forecasts of abundance, and pre/post ratios generated for Model 1 are shown in Appendix E, and for Model 2 are shown in Appendix F. A comparison of regression slopes generated by the existing data set with slopes generated by Models 1 and 2 is shown in Figure 9.
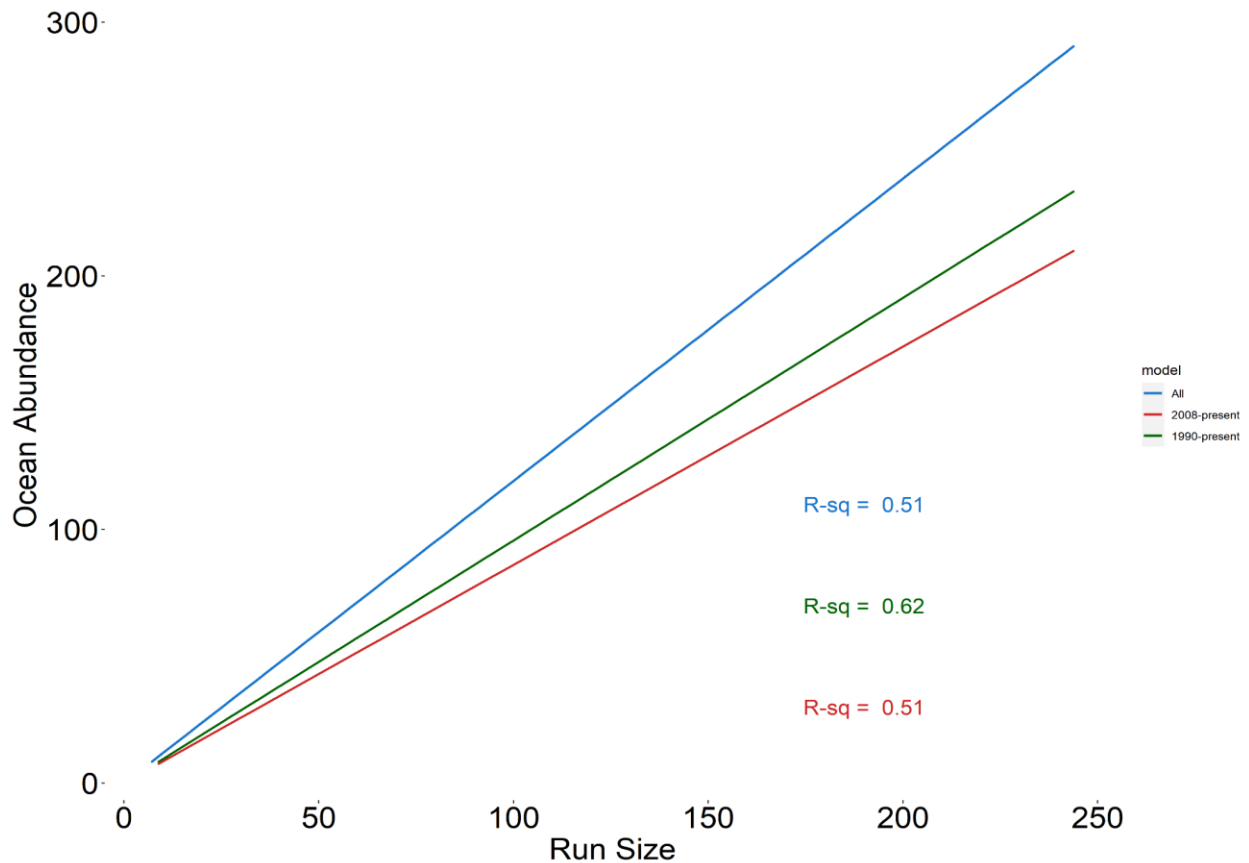
Figure 8. Regression slopes for the 2022 forecast of age-4 KRFC salmon were created by the existing model (blue), Model 1 (green), and Model 2 (red). The lesser grade of slopes generated by Models 1 and 2 is due to smaller slope coefficients.

For age-3 fish, the null hypothesis that the existing data set generated more accurate age-3 forecasts than Model 1 cannot be rejected. Model 1 resulted in an insignificant decrease of the average pre/post from 1.34 to 1.24 (t = 1.59; p = 0.1303). Model 2 resulted in an insignificant decrease of the average pre/post from 1.21 to 1.13 (t = 0.94707; p = 0.3569). However, for the most recent 10-year period (FY2012-2021), Model 1 generated a significant decrease of 0.30 (t = 5.4711, p = 0.0003947) and Model 2 resulted in significant decrease of 0.44 (t = 4.3824, p = 0.001765) (Appendix H).

In contrast, for age-4 fish, the null hypothesis that the existing data set would have generated more accurate forecasts can be rejected. Model 1, age-4 forecasts resulted in a significant decrease in the pre/post ratio from 1.69 to 1.32 (t = 5.7339; p = 2.43e-05). Model 2, age 4 forecasts resulted in a significant decrease in the pre/post ratio from 1.63 to 1.27 (t = 5.1926, p = 7.339e-05).

Changes in MRE, MAE, and RMSE that result from both models are shown in Appendix H. The two models performed similarly in decreasing pre/post ratios:

Average pre/post (2004-2021)

	Original	Model 1	Model 2
Age 3	1.34	1.28	1.24
Age 4	1.69	1.32	1.27

Concerning underestimates, Model 1 performed slightly better. For age-3 fish, out of the 17 forecast years, Model 1 generated fewer underestimates (8 v. 15) and underestimates of a lesser degree (mean 0.68 v. 0.4). For age-4 fish, they both generated 11 underestimates. But Model 2 generated underestimates of a slightly lesser degree (mean 0.83 v. 0.78).

Concerning overestimates, Model 2 performed significantly better. For age-3 fish, out of the 17 forecast years, Model 2 generated only three overestimates, with an average of 1.25. Model 1 generated 10 overestimates with an average of 1.69. For age-4 fish, the models performed similarly with Model 2 generating one more overestimate than Model 1, but the average overestimates were almost the same (2.16 [M1] v. 2.18 [M2]).

Discussion

Forecasting the ocean abundance of KRFC salmon is the first step in the development of annual ocean and river fishing regulations for many stocks of salmon. Errors in forecasts can result in erroneous forecasts of escapement, which in turn can prevent the development of regulations that achieve harvest and conservation objectives. If the mechanism of increased error in forecasting ocean abundance can be identified, adjustments to the model that may result in better performance can be evaluated.

This project examines trends in the accuracy of forecasting the ocean abundance of KRFC salmon and evaluates a hypothesis that overforecasts have become more common due to a change in maturation rates. The hypothesis was tested by running linear regressions on data for forecasting accuracy and maturation rates between the years 1982-2021. Both the frequency and absolute error of overforecasts of KRFC salmon have increased. This trend may be partially explained by changing maturation rates. Finally, two alternative data sets were tested and discovered to generally improve the accuracy of the model used to forecast KRFC ocean abundance.

Forecasting Accuracy

Accurately forecasting ocean abundance is a management challenge common to most, if not all, salmon stocks. Forecasting errors can be substantial (Winship et al. 2015) and accuracy varies widely among stocks the PFMC manages (PFMC 2022a). One explanation for forecasting variability is that their utility breaks down when certain thresholds are crossed (Satterthwaite et al. 2020).

Underestimates of ocean abundance can lead to overly restrictive harvest controls. It has been suggested that, for fisheries that protect weak stocks, errors in times of high abundance may cause little to no lost harvest or conservation opportunity (Satterthwaite et al. 2020). Regardless, with

the frequency and severity of underestimates lessening over the AP, the risk of overly restrictive harvest controls also lessened.

In contrast, as the frequency and severity of overforecasts of age-specific and total adult KRFC ocean abundance increased over the AP, the risk of missed conservation objectives also increased. Overforecasts of ocean abundance can lead to harvest controls that fail to achieve escapement targets (Winship 2015; FISHBIO 2020). Even small errors in forecasts can result in a failure to achieve the escapement floor (PFMC 2008). Because of the de minimis harvest rule, the room for error on ocean abundance forecasts is even less and may jeopardize, at least in the short term, the attainment of conservation objectives (PFMC 2008). Failure to attain conservation objectives can lead to declining abundance, which can cause further restrictions on recreational and commercial seasons (Woodson 2013). Further, due to the stepped design of the harvest control rule for KRFC, even a small overforecast can result in substantial overharvest (Satterthwaite et al. 2020).

> "The more accurate the forecasts can be in the ocean abundance, then it'll allow managers to effectively set the desired seasons, so there isn't an over catch of the desired amount. At the same time, there's not an under-catch of the available fish []. And so that would be beneficial for all users []."
>
> - Jim Yarnall, California Sport Fisheries representative to PFMC Salmon Advisory Subpanel.

Overforecasts may also result in ignoring policies designed to protect stocks from becoming "overfished" (Haeseker et al. 2008). When the two most recent postseason estimates and the current preseason forecast of spawning escapement are below the minimum stock size threshold, the Council is required to structure the fisheries to "avoid the stock from becoming overfished and to mitigate the effects on the stock status." (PFMC 2021, § 3.1.3.1). Forecasts of spawning escapement are calculated from the forecasts of total adult ocean abundance (PFMC 2022a). Successful implementation of this protective policy depends on the accuracy of preseason forecasts.

Due to the many variables that affect ocean abundance, accurate forecasting is challenging for most, if not all, salmon stocks on the West Coast (PFMC 2022a; ADFG 2022; Potter 2004), including sockeye and chum (Haeseker et al. 2008) and the KRFC salmon's California cousin, the Sacramento River fall Chinook salmon (Wainright 2015). Of the 16 Chinook salmon stocks in PFMC jurisdiction for which pre/post data is maintained, the average pre/post for total adult KRFC salmon of 1.40 is the 13th largest (FY2004 to FY2021). In other words, it is among the worst-performing models.[17]

Mortality during outmigration is unlikely significantly contributing to KRFC forecast inaccuracy. If, for example, an outbreak of parasite *Ceratonova Shasta* infects a brood of juvenile fish, the lower survival rates would unlikely alter forecast accuracy, as the forecasts are only based on data collected after the fish have spent a year or more in the ocean. However, if such effects

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[17] The PFMC maintains pre/post data on five Chinook stocks in the Columbia River Basin and 10 Chinook stocks in Puget Sound. This author did not uncover comparable data for California Central Valley Stocks.

systematically alter demographic parameters (maturation, survival) for a cohort beyond age 2, this may not be the case (O'Farrell 2022; McHugh 2022).

The strong relationship between increasing maturation rates and increasing forecast error is a product of the formula used to calculate preseason forecasts. To forecast ocean abundance at age y by run size at age y-1, the STT uses the regression coefficient (OA/RS Slope) of the ratio of ocean abundance to run size for brood years 1979-2021. For example, if the OA/RS Slope in y was 1.2 and the age-3 run size in y-1 was 50,000, the age-4 forecast would be approximately 60,000 (1.2 x 50,000). In other words, the OA/RS Slope described a historic maturity rate of age-3 KRFC of approximately 45% (50,000/110,000). As 50,000 of 110,000 age-3 salmon matured, the remaining 60,000 stayed in the ocean and "aged" into age-4 salmon the following year, which number becomes the target of forecasting efforts for age-4 ocean abundance the next season.

The shift towards earlier maturation has disrupted the premise of stable maturation rates on which the accuracy of the forecasting model depends. Although rates can vary annually, the existing forecasting model implicitly assumes they are relatively stable over the long term. When maturation rates change significantly, directly, and abruptly, the linear regression fails to capture the current relationship between ocean abundance and run size. In other words, maturation rates of older brood years slow the responsiveness of the OA/RS Slope, and model accuracy cannot catch up until sufficient new data inform the changing relationships.

An examination of the 2019 age-4 overforecast of 6.76 reveals how spikes in maturation rates can cause unusually large overforecasts. The age-3 brood years used to generate the OA/RS Slope for FY2019 were 1980-2016, for which the average maturation rate was 42%. In contrast, the 85% maturation rate for age-3 fish in 2019 was more than twice that average rate, and close to the historic maturation rates for age-4 fish. Yet, the brood year data generated an OA/RS Slope of 1.22, much larger than that used for age-4 fish. If the OA/RS Slope used in the 2019 forecast had instead been 0.15, an OA/RS Slope closer to that derived from age-4 maturation rates, the 2019 forecast would have been 12,824 age-4 fish. When compared to the postseason estimate of 15,685 age-4 fish, that forecast would have resulted in a much more accurate pre/post of 0.82 (the perfect forecast is 1.0).

Maturation Rates

The null hypothesis that maturation rates for ages 2, 3 and 4 KRFC salmon did not increase between 1982-2021 can be rejected. If maturation rates continue on their current trajectory, age-4 rates may soon reach 100% maturity and age-3 average rates could soon reach 70-80%. This would result in the disappearance of all age-5 fish and drastically decrease the abundance of age-4 fish.

These maturation trends could also jeopardize the stock's sustainability by causing lower recruitment rates. Older fish are generally larger, and larger fish are associated with greater fecundity and stronger egg health. Declines in average size can result in lower offspring survival as smaller salmon may not be able to dig redds deep enough to withstand scouring (Ohlberger et al. 2018). Increased maturation rates may also result in less variation in KRFC age-class structure. Variation in spawning age buffers populations from genetic diversity loss following catastrophic environmental events via the "portfolio effect" (Satterthwaite et al., 2017). Further, life history

variation reduces interannual variability in adult returns and the frequency of fishery closures (Waters et al. 2021).

Fishing could partially explain this trend towards earlier maturation. Generally, by selecting older and slower-growing fish, fishing selects for earlier maturation (Law 2000). The average ocean harvest of KRFC salmon between 1986 and 1990 was 214,660 fish. Between 2010 and 2017, no annual commercial harvest exceeded 60,000 fish and, in 2017, the harvest dropped to 1,685 fish. This decline in commercial harvest may negatively correlate with increases in KRFC maturation rates. However, higher harvest levels in the late 1980s more closely align with the shift towards earlier maturation in ages 3 and 4 fish. Further, although harvest declined rapidly starting in the 1990s, it is unsurprising that removal of fishing pressure did not result in maturation shifting back to earlier rates (Law 2000).

Another potential cause of earlier maturation could be a change in the ocean ecosystem. Increased maturation rates after 1990 generally coincided with a period for which there is evidence of a potential regime shift in the California Current Ecosystem. Regime shifts are "dramatic, abrupt changes in the community structure that are persistent in time, encompassing multiple variables, and including key structure species—independently from the mechanisms causing them" (Peabody et al. 2018). The basin-scale atmosphere and surface ocean variability associated with the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) changed after 1988/1989, weakening relationships with many regional physical and biological variables, including salmon populations (Litzow et al. 2020). This shift may have caused the abundance of coho salmon from the Canadian Fraser River to decrease in the 1990s (Beamish et al. 1997). Marked population declines across multiple levels of southern California fish assemblage occurred around 1989 or 1990 (Koslow et al. 2015). A potential 1989 regime shift in the North Pacific Ocean aligns with a decline in productivity of California chinook fisheries (Hare and Montua 2000). The California Central Valley Chinook ESU experienced a significant decline in run size abundance after the 1980s (Tolmieri and Levin 2004).

Changing maturation rates may also be the result of increased mortality of immature, slow-growing juveniles. Age 2 KRFC salmon that are growing faster are likely to mature at an earlier age (Vollestad et al. 2004). Larger salmon are also less likely to be exposed to predators, such as harbor seals, that prefer smaller fish (Ohlberger et al. 2019b). After entering the ocean as smolts, Chinook salmon are exposed to two critical causes of high mortality; the first is predation and the second is a related failure to achieve sufficient metabolic requirements. When ocean conditions are poor, juveniles may experience greater competition for food. Juveniles that fail to achieve the size required to maintain a critical level of metabolism may experience endocrine dysfunction, stunted growth, and eventually death by predation or organ failure (Beamish and Mahnken 2001). If marine mortality in slow-growing juveniles increases due to poor ocean conditions, that could result in selective survival of faster-growing juveniles (Woodson et al. 2013). As faster-growing fish are likely to mature earlier, selective mortality of slow-growing fish would be reflected in higher maturation rates in younger years.

In contrast, stage-based life cycle modeling suggests earlier maturation can also be caused by predation later in life (Manishin et al. 2021). Killer whales in the Eastern Pacific Ocean are estimated to consume Chinook salmon at levels that exceed current levels of harvest in

commercial, recreational, and subsistence fisheries. Because they feed largely on the oldest and largest Chinook, killer whale predation may have resulted in evolutionary shifts towards smaller maximum size and faster early growth, which results in earlier maturation. Overlapping ocean distribution between killer whales and KRFC salmon may, however, be too limited to explain changes in KRFC age-class structure (Ohlberger et al. 2019b).

Parentage also influences maturation rates in young male Chinook (jacks). Families sired by jacks mature earlier than families sired by adults (Vollestad et al. 2004). If increasing numbers of jacks are maturing earlier, and a greater proportion of spawners are jacks, that could result in a feedback loop of earlier age-2 maturation.

Hatchery contributions can affect the maturation rates of mixed stocks because hatchery jacks generally mature faster than wild jacks (Winsor et al. 2021). If the ratio of hatchery to wild KRFC salmon is increasing, that could result in earlier maturation rates in the combined stock. The long-term average contribution of hatchery fish to natural area spawners was 24% before 2015, and then it dropped to 9% from 2015 to 2017 (PFMC 2019b). It may be worth exploring whether hatchery fish contributions grew in the late 1980s or early 1990s when age-3 fish maturation rates grew significantly.

Increased prey availability for juveniles under cooler water temperatures has also been found to accelerate maturation rates. Coastal upwelling events (the rise of large, nutrient-rich bodies of cold water to the surface layer) are associated with providing the necessary nutrients for increased primary production (Wells et al. 2012). This increased production of phytoplankton results in greater amounts of zooplankton, such as copepods and krill, that are favored prey of juvenile Chinook (Quinones et al. 2014). A high abundance of favored prey leads to faster growth and earlier maturation (MacFarlane 2010; Vollestad et al. 2004). However, Chinook salmon slow their growth when food is scarce and competition is greater, and slower-growing individuals mature later (Ohlberger et al. 2019b).

Fujiwara and Mohr (2007) found a strong correlation between the rate of coastal upwelling in the spring before the maturation of Klamath River Chinook. They further surmised that the additional food productivity generated by coastal upwelling may influence fertility by increasing fecundity and/or signaling favorable conditions for offspring survival. Wells et al. (2007) similarly found a significant relationship between the run size of age-3 fish and conditions experienced during the spring before their third year at sea. However, later research on wild Chinook Salmon from an Oregon tributary of the Columbia River found no evidence that ocean productivity influences age of maturity and, to the contrary, suggested that age of maturity may be largely determined once smolts leave freshwater (Tattum et al. 2016).

It is unclear whether changes in ocean conditions could explain recent spikes in maturation rates. Between 2014 and 2016, when these fish entered the ocean, sea surface temperature was abnormally warm and conditions were unproductive. There were fewer lipid-rich copepods and greater lipid-poor copepods and krill in waters just north of the Klamath River. But local upwelling and ichthyoplankton presence suggested favorable conditions for KRFC prey (PFMC 2019b). If overall conditions were poor for KRFC juvenile prey and yet they still matured earlier, that

suggests a more dominant offsetting factor, such as strong river conditions or mortality of older fish by predation or harvest, was at play.

Changing Maturation Rate as a Predictor of Forecasting Inaccuracy

Persistent fluctuations in maturation rates suggest that the recent reprieve from overforecasts will be brief. In 2020 and 2021, age-2 maturation rates of 6% and 7% coincided with slight underforecasts of age-3 fish (pre/posts of 0.94 and 0.87, respectively). But as recently as 2018, a 9% maturation rate in age-2 fish coincided with a substantial overforecast of age-3 fish (pre/post of 1.70). It is reasonable to expect further overforecasts of age-3 fish soon if age-2 maturation rates again reach or exceed 9%. Since the average age-2 maturation rate between 2010-2021 was 9%, rates will likely reach 9% again soon. Overforecasts of age-4 fish are likely to reoccur if age-3 maturation rates reach or exceed 50%, which is also a likely scenario since between 2010-2021, the average age-3 maturation rate was 53%.

There may be a trend in maturation rates that could be used to anticipate overforecasts in age-4 fish. Since 2007, there have been at least four instances in which a significant age-3 overforecast was followed by a significant age 4 overforecast in the following year:

	FY	Pre/post	FY	Pre/post	FY	Pre/post	FY	Pre/post
Age 3	2007	1.37	2009	1.97	2012	1.96	2018	1.70
Age 4	2008	1.93	2010	1.71	2013	1.70	2019	6.76

This pattern may reflect increasing maturation rates within the same brood, which makes sense biologically.[18] A sudden ocean condition trigger, such as atypically strong ocean conditions, could shift maturation rates to earlier years for succeeding age classes of an affected brood.

Shorter Datasets May Reduce Future Forecasting Error (Models 1 and 2)

Excluding older brood years from the linear regression may generate more accurate forecasts, as those broods matured substantially slower. If maturation rates stay at or near average rates for the last decade, either Models 1 or 2 should generate more accurate forecasts. The lagging performance of the models for age-3 forecasts may be due to the gradual change in age-2 maturation rates throughout the 1990s (in contrast to the more abrupt increase in age-3 maturation rates after 1990). As a result, the models do not decrease the overforecast magnitude for age-3 fish until broods that matured earlier start to dominate the data, which pattern begins with FY2012.

If avoiding overforecasts is the goal, Model 2 may be preferable. It generated fewer overforecasts of age-3 fish and total adults. As it uses a shorter, moving data set, Model 2 can also more quickly incorporate further changes in maturation timing.

Because spikes and valleys in maturation rates consistently generate large forecast errors, it is important to continue to search for conditions that predict their occurrence. Neither model corrects the problem of years in which there are large pre/post errors, such as 2019, when the pre/post for age-4 fish was 6.76 (Appendix E). 2019 was a poor year for sea surface temperature and copepod

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[18] The statistical significance of this pattern was not tested in this project.

biomass within the southern California Current Ecosystem.[19] However, that was also true in 2015-2017, when the age-4 overforecasts were much less (1.17, 1.82, 1.08). Therefore, there may not be a single ocean indicator that significantly explains KRFC forecasting error (Satterthwaite et al. 2020) or changing maturity rates.

Next Steps

As the PFMC pursues a solution to KRFC forecasting inaccuracy, one option is to continue exploring models that anticipate changes in maturation rates. Regarding model methodology, a recent investigation into Oregon Chinook salmon forecasts concluded that sibling regression models continue to perform as well as, if not better than, non-traditional models such as principal component analysis, less absolute shrinkage and selection operator, and artificial neural networks (McCormick and Falcy 2015). Data on marine survival variability from nearby populations have been shown useful for escapement-based management of coho salmon (Ohlberger et al. 2019a). A "separate reconstruction method" may tease out differences in juvenile and adult natural mortality rates (Allen et al. 2016).

A potential ocean indicator of maturation may be prey availability. Greater krill abundance is correlated with the improved condition of juvenile central California Chinook, which is correlated with higher maturation rates in the same cohort the following year (Wells et al. 2012). Although a single ocean indicator was not found to predict KRFC forecasting error (Satterthwaite et al. 2020), it may be worth searching for a suite of indicators, like the method being used to predict Oregon Coastal Natural Chinook salmon abundance north of Cape Blanco (PFMC 2022a).

Forecasting model modifications alone may not be a satisfactory solution. Simple linear relationships struggle to capture the environment's overall influence on salmon abundance (Winship et al.2015). Reactive tweaks to models may never result in high forecasting precision (Wainright 2021; Mantua and Francis 2004). Further, it is unclear that increasing forecast accuracy will necessarily result in an increased frequency of meeting escapement targets (Rupp et al. 2012).

If ocean conditions are causing earlier maturation, climate change may make accuracy forecasting an even greater challenge. Between 2012 to 2016, the percentage of global oceans experiencing strong or severe heat waves increased from 30% to 70% (Suryan et al. 2021). Modeling suggests that marine heat waves that affect the CCE will occur more frequently under anthropogenic climate change (Jacox et al. 2018). Generally, there is a 10- to 20-year lag between regime shifts and their detection in the ecosystem. (Peabody et al. 2020). Therefore, it's not only possible but likely, that the marine heat waves of 2014-2016 and 2019 may have resulted in changes to the ocean ecosystem that has yet to be detected (Suryan et al. 2021). That could mean another shift in maturation timing to which ocean abundance forecasting methods will need to be able to adapt.

Ultimately, it may be that policymakers need to adapt to and embrace uncertainty (McCormick and Falcy 2015; Wainright 2021). The PFMC Habitat Committee noted in 2006 that, in the face of forecasting inaccuracies of 50% or greater, "a precautionary approach is called for" (Supplemental Habitat Committee Report, 2006). Considering this recent bout of overforecasts,

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[19] https://media.fisheries.noaa.gov/2022-03/2021-Ocean-Indicators-and-Salmon-Forecasting-trend-all-no-numbers-030322.png (last visited May 10, 2022)

many of which were more than 50% inaccurate, a precautionary management approach remains merited (Ohlberger et al. 2018). Such an approach may have benefits beyond fishery sustainability, as even small adjustments in escapement targets can result in substantial ecological benefits, greater access to salmon for cultural and subsistence purposes, and reduced risk of extirpation of weak stocks (Munsch et al. 2020).

> "Almost every recreational fisherman that I've spoken with wants conservation of the resource. So they can pass that same fishing opportunity on to their kids and their grandchildren that they had the opportunity to have. And if that means short-term curtailments or restrictions, they would much rather do that and preserve the fishery, as opposed to, we're going to catch every last fish now here."

> - Jim Yarnall, California Sport Fisheries representative to PFMC Salmon Advisory Subpanel.

> "If we're gonna make an error, I would much rather see us make an error where we under forecast right, I would much rather see a situation where we under predict the amount of fish and then more fish actually are in the ocean. And then, you know, our quotas wouldn't be that impactful to allow enough fish to return to meet the fisheries requirements"

> -Keith Parker, Sr. Fisheries Biologist, Yurok Tribe (Parker 2022).

Conclusion

Although Chinook salmon have proven capable of overcoming a variety of pressures on their survival, their resilience is being tested. The loss of wild Chinook salmon in the Basin would not be felt equally and would have social justice implications. Like other tribes, the Yurok "has always managed our fishery responsibly, prioritized conservation of the resource for long-term productivity over short-term exploitation, so that future generations of Yurok people will benefit."[20] For tribes in the Basin, identity, culture, and spirituality are inextricably intertwined with continued access to Chinook salmon (Parker 2022).

Accurately forecasting salmon ocean abundance is a vexing problem, exacerbated by changing ocean conditions and increasing maturation rates. Greater caution may be warranted in relying on forecasts when setting harvest control rules. Relying on shorter, more recent datasets on ocean abundance and run size in forecasting may be part of the solution. Doing so may reduce forecasting error and the accompanying risk of overharvesting during times of low abundance.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[20] Letter from Thomas O'Rourke, Chairman of Yurok Tribe, to Rod McInnis, Regional Administrator, NMFS SW Region, Nov. 17. 2011, Exhibit to Final Environmental Assessment of Amendment 16 to Salmon Management Plan.

Acknowledgments

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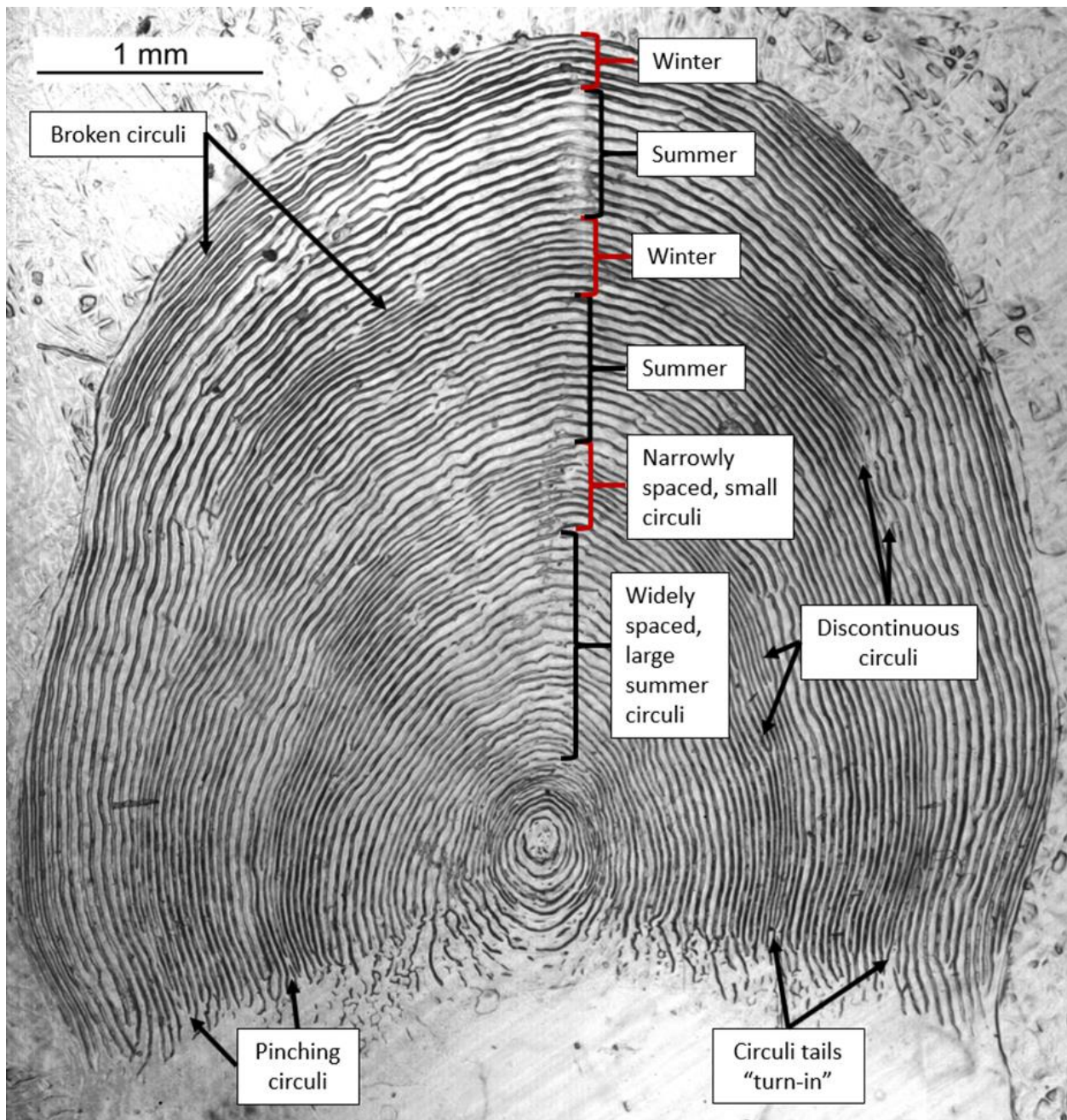
Image of a KRFC scale used to determine the age of the fish. A scale is cut with a fine razor, pressed on a slide, and examined under a microscope. The annuli on the scale increase as salmon grow. The black brackets show a set of rings, or circuli, that accumulate during a summer spent in the ocean when the fish grow more rapidly. The red brackets show rings that accumulate the following winter when they are growing slower. This fish spent three years in the ocean before it matured, and thus was an age-4 fish.
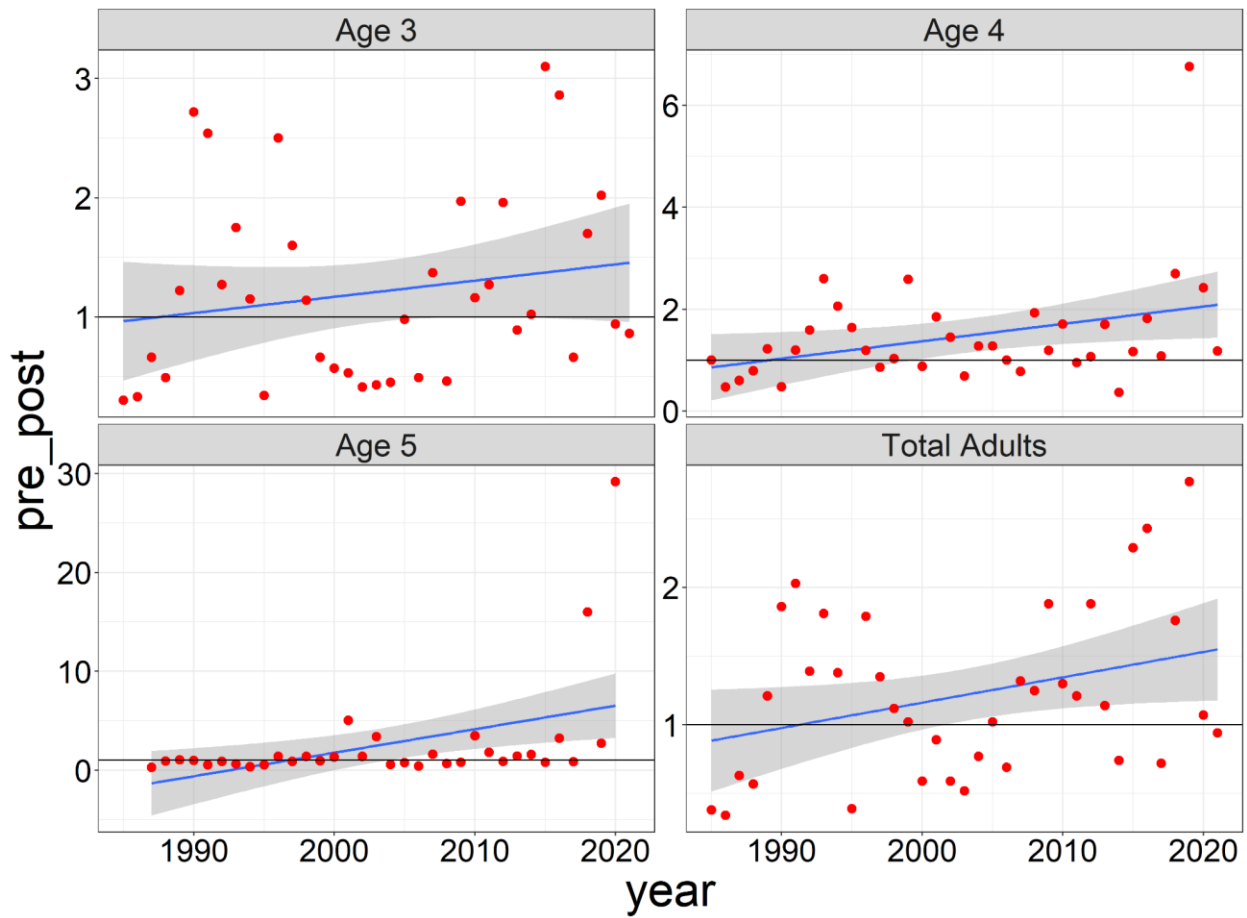
Ratio of preseason forecasts to postseason estimates for age-3 (p = 0.27), age-4 (p = 0.026), and age-5 fish (p = 0.01), and total adults (p = 0.02944), for forecasts years 1985-2021. The blue line is best fit, the grey area is the confidence interval, and the black line is the 1.0 pre/post ratio. A 1.0 pre/post ratio indicates a perfect forecast, <1.0 indicates an underforecast and > 1.0 indicates an overforecast.
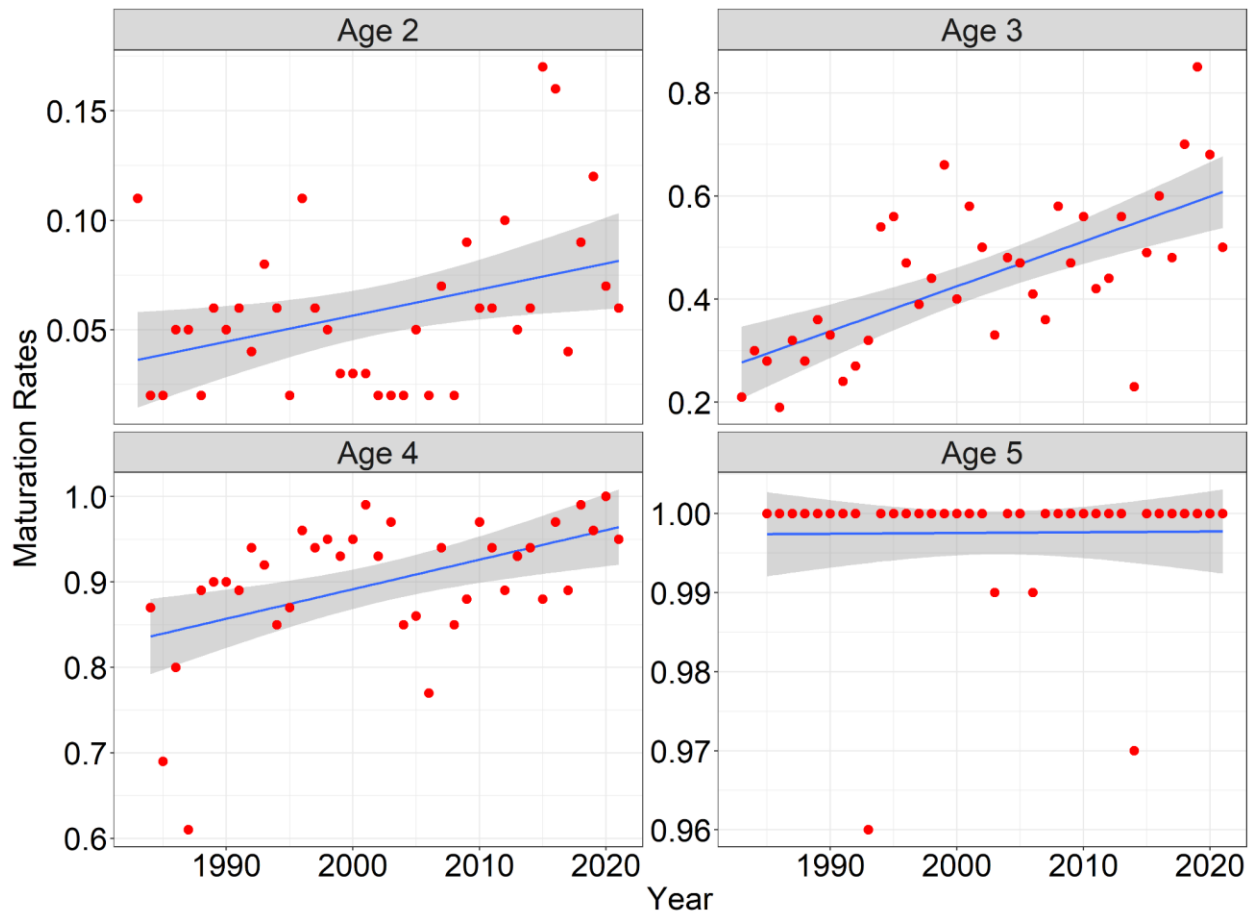
Maturation rates for age-2 (FY1983-2021; p = 0.02344), age-3 (FY1983-2021; p = 9.045e-06), age 4 (FY1984-2021; p = 0.003304), and age-5 fish (FY 1985-2021; p = 0.9421). The blue line is best fit and the grey area is the confidence interval.

The Fit of a Linear Model and a Generalized Additive Model
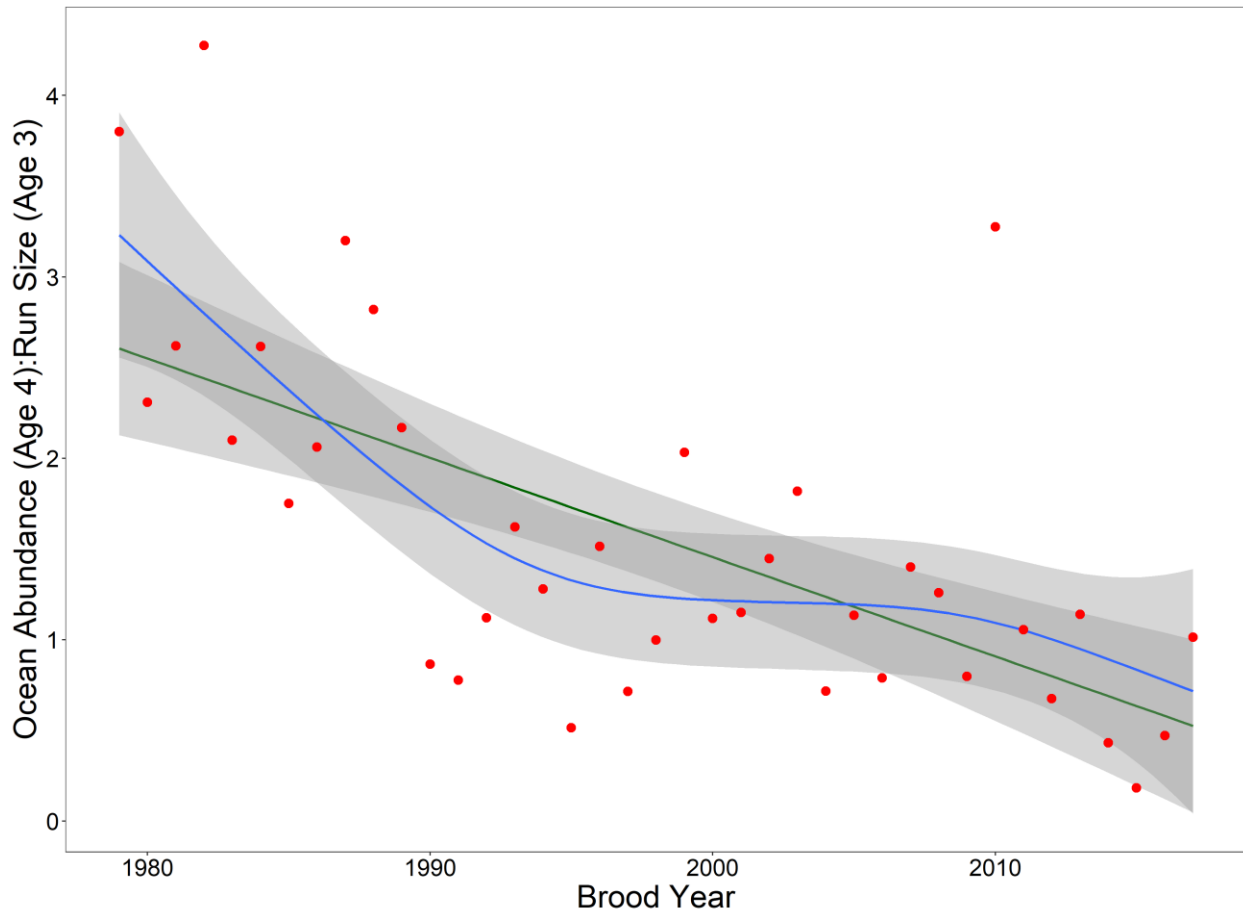
The ratio of age-4 ocean abundance to age-3 run size for brood years 1979-2017, generated from a linear model (dark green best fit line) and a generalized additive model (blue best fit line).

Model 1: Age-3 Forecasts

Run Year	Forecast Year	Brood Years	Slope (RD)	Run Size y-3	Forecast y-4	Postseason Estimate	Pre/post
2003	2004	1990-2000	1.03	94287	97464	105246	0.93
2004	2005	1990-2001	1.04	33105	34433	38079	0.90
2005	2006	1990-2002	1.04	43811	45616	63384	0.72
2006	2007	1990-2003	1.04	18505	19390	33650	0.58
2007	2008	1990-2004	1.05	113685	119376	81411	1.47
2008	2009	1990-2005	1.01	18644	18961	21131	0.90
2009	2010	1990-2006	1.01	78620	79980	62089	1.29
2010	2011	1990-2007	1.00	46129	46453	64570	0.72
2011	2012	1990-2008	1.01	59023	59793	74300	0.80
2012	2013	1990-2009	1.02	243938	248583	194407	1.28
2013	2014	1990-2010	0.95	55152	52598	180669	0.29
2014	2015	1990-2011	0.99	57792	57104	60979	0.94
2015	2016	1990-2012	0.99	36742	36344	24777	1.47
2016	2017	1990-2013	0.99	8619	8508	9821	0.87
2017	2018	1990-2014	0.99	24397	24084	10531	2.29
2018	2019	1990-2015	0.99	85496	84267	15685	5.37
2019	2020	1990-2016	0.96	30166	28920	14964	1.93
2020	2021	1990-2017	0.96	37820	36181	38319	0.94
						Avg.	**1.32**

Model 1: Age-4 Forecasts

Run Year	Forecast Year	Brood Years	Slope (RD)	Run Size y-2	Forecast y-3	Postseason Estimate	Pre/Post
2003	2004	1990-2001	25.80	3845	99205	159446	0.62
2004	2005	1990-2002	25.50	9646	246050	189977	1.30
2005	2006	1990-2003	25.54	2296	58654	90666	0.65
2006	2007	1990-2004	22.41	26935	603694	376940	1.60
2007	2008	1990-2005	22.43	1684	37775	68015	0.56
2008	2009	1990-2006	19.95	25247	503728	240787	2.09
2009	2010	1990-2007	19.79	11914	235861	192750	1.22
2010	2011	1990-2008	19.40	16640	322816	240222	1.34
2011	2012	1990-2009	12.82	84895	1088693	799446	1.36
2012	2013	1990-2010	13.13	21433	281437	438443	0.64
2013	2014	1990-2011	13.16	14356	189011	216493	0.87
2014	2015	1990-2012	12.82	22321	286334	110506	2.59
2015	2016	1990-2013	12.80	6094	78034	32670	2.39
2016	2017	1990-2014	12.81	2787	35704	63236	0.56
2017	2018	1990-2015	12.70	20318	258100	193725	1.33
2018	2019	1990-2016	12.65	10872	137585	82994	1.66
2019	2020	1990-2017	12.66	9951	125980	158696	0.79
2020	2021	1990-2018	12.66	9077	114915	155267	0.74
						Avg.	**1.28**

Age 3

Age 4
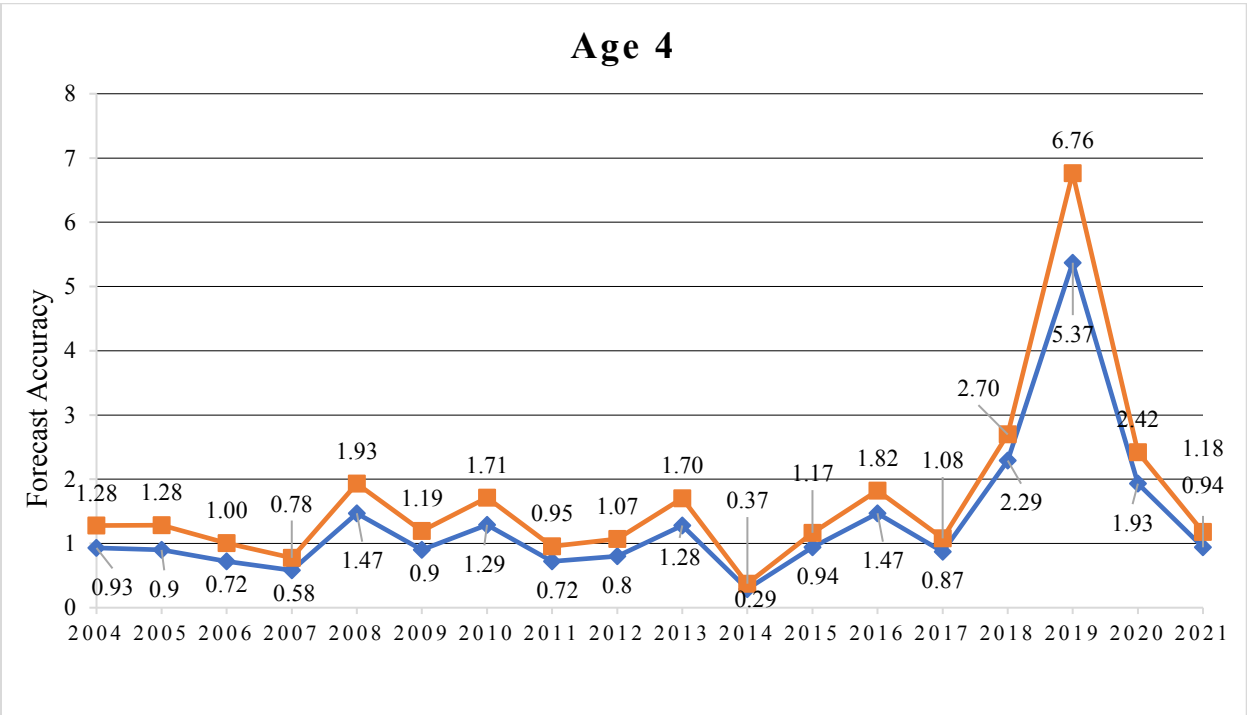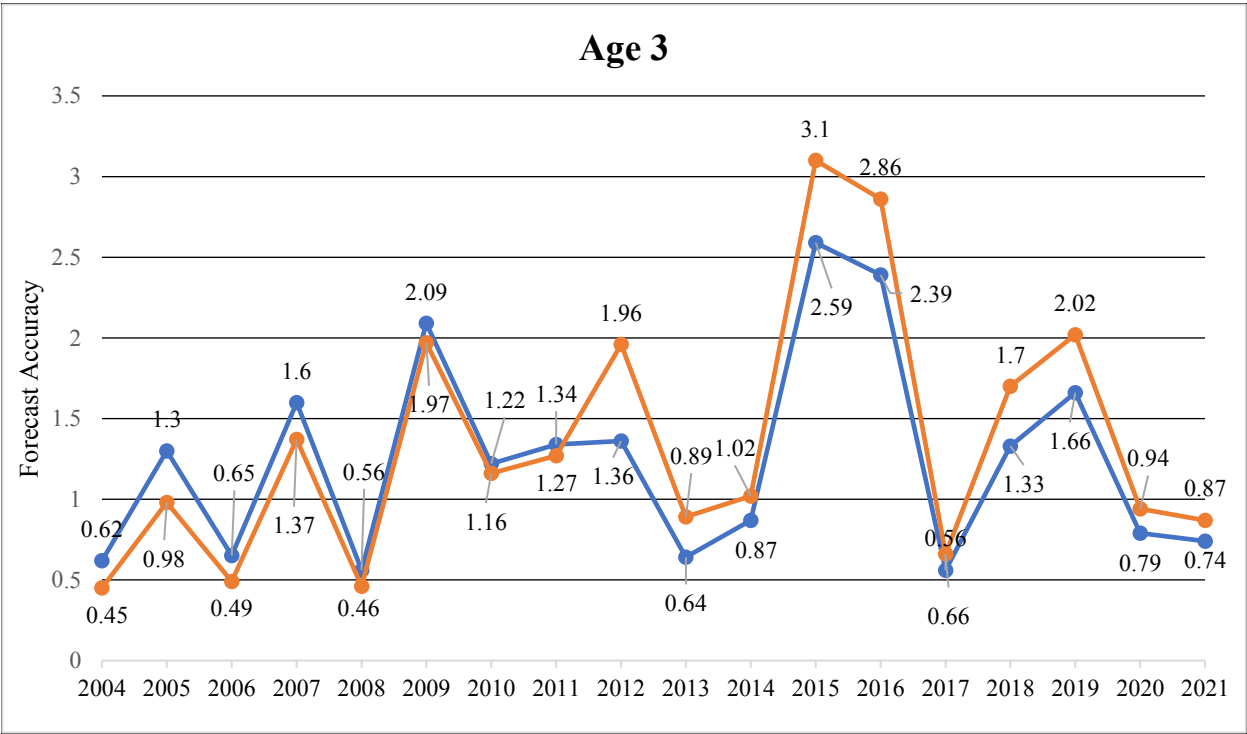
Forecasting accuracy by forecast year (2004-2021) for ages 3 and 4 fish. Original pre/post ratios are shown in orange and Model 1 pre/post ratios are shown in blue. Pre/posts ratios > 1.0 represent overforecasts and < 1.0 represent under forecasts.

APPENDIX F
**10-Year Moving Average**
Model 2: Age-3 Forecasts

Run Year	Forecast Year	Brood Years	Slope (RD)	Run Size (Age 2)	Forecasts (Age 3)	Postseason Estimate	Pre/ post
1992	1993	1979-1988	17.74	13693	242914	168473	1.44
1993	1994	1980-1989	17.56	7598	133421	119915	1.11
1994	1995	1981-1990	19.28	14371	277073	787309	0.35
1995	1996	1982-1991	19.22	22774	437716	192272	2.28
1996	1997	1983-1992	19.89	9532	189591	140153	1.35
1997	1998	1984-1993	19.73	7993	157702	154799	1.02
1998	1999	1985-1994	21.58	4639	100110	129066	0.78
1999	2000	1986-1995	17.88	19248	344154	617097	0.56
2000	2001	1987-1996	19.22	10246	196928	356128	0.55
2001	2002	1988-1997	22.30	11343	252949	513604	0.49
2002	2003	1989-1998	23.18	9226	213859	401112	0.53
2003	2004	1990-1999	24.81	3845	95394	159446	0.60
2004	2005	1991-2000	27.20	9646	262371	189977	1.38
2005	2006	1992-2001	27.74	2296	63691	90666	0.70
2006	2007	1993-2002	23.49	26935	632703	376940	1.68
2007	2008	1994-2003	31.55	1684	53130	68015	0.78
2008	2009	1995-2004	24.61	25247	621329	240787	2.58
2009	2010	1996-2005	24.85	11914	296063	192750	1.54
2010	2011	1997-2006	20.32	16640	338125	240222	1.41
2011	2012	1998-2007	17.77	84895	1508584	799446	1.89
2012	2013	1999-2008	16.49	21433	353430	438443	0.81
2013	2014	2000-2009	10.54	14356	151312	216493	0.70
2014	2015	2001-2010	10.72	22321	239281	110506	2.17
2015	2016	2002-2011	10.77	6094	65632	32670	2.01
2016	2017	2003-2012	10.40	2787	28985	63236	0.46
2017	2018	2004-2013	10.37	20318	210698	193725	1.09
2018	2019	2005-2014	10.01	10872	108829	82994	1.31
2019	2020	2006-2015	10.07	9951	100207	158696	0.63
2020	2021	2007-2016	10.07	9077	91405	155267	0.59
						Avg.	**1.13**

Recreated slopes, preseason forecasts, and pre/post ratios generated for Age-3 fish from Model 2.

Model 2: Age 4 Forecasts

| Forecast Year	Brood Years	Slope (RD)	Run-Size (Age 3)	Forecasts (Age 4)	Postseason Estimates	Pre/post
1993	1979-1988	2.19	6936	15252	15037	1.01
1994	1980-1989	2.17	48301	104861	41736	2.51
1995	1981-1990	2.10	37017	78032	28726	2.72
1996	1982-1991	2.06	201896	417723	226282	1.85
1997	1983-1992	1.62	38766	62917	62820	1.00
1998	1984-1993	1.43	34973	50186	44733	1.12
1999	1985-1994	1.27	59244	75477	30456	2.48
2000	1986-1995	1.13	29171	33051	44176	0.75
2001	1987-1996	1.09	187088	204487	133801	1.53
2002	1988-1997	0.93	99097	92894	98927	0.94
2003	1989-1998	0.94	94576	89062	192180	0.46
2004	1990-1999	1.03	94287	97493	105246	0.93
2005	1991-2000	1.04	33105	34562	38079	0.91
2006	1992-2001	1.04	43811	45914	63384	0.72
2007	1993-2002	1.01	18505	18838	33650	0.56
2008	1994-2003	1.00	113685	114708	81411	1.41
2009	1995-2004	0.95	18644	17893	21131	0.85
2010	1996-2005	0.98	78620	77048	62089	1.24
2011	1997-2006	0.96	46129	44325	64570	0.69
2012	1998-2007	1.14	59023	67404	74300	0.91
2013	1999-2008	1.18	243938	288335	194407	1.48
2014	2000-2009	0.86	55152	47795	180669	0.26
2015	2001-2010	0.92	57792	53325	60979	0.87
2016	2002-2011	0.92	36742	33979	24777	1.37
2017	2003-2012	0.91	8619	7847	9821	0.80
2018	2004-2013	0.90	24397	22133	10531	2.10
2019	2005-2014	0.93	85496	79896	15685	5.09
2020	2006-2015	0.87	30166	26263	14964	1.76
2021	2007-2016	0.87	37820	32987	38319	0.86

Recreated slopes, preseason forecasts, and pre/post ratios generated for Age-4 fish from Model 2.

Age 3
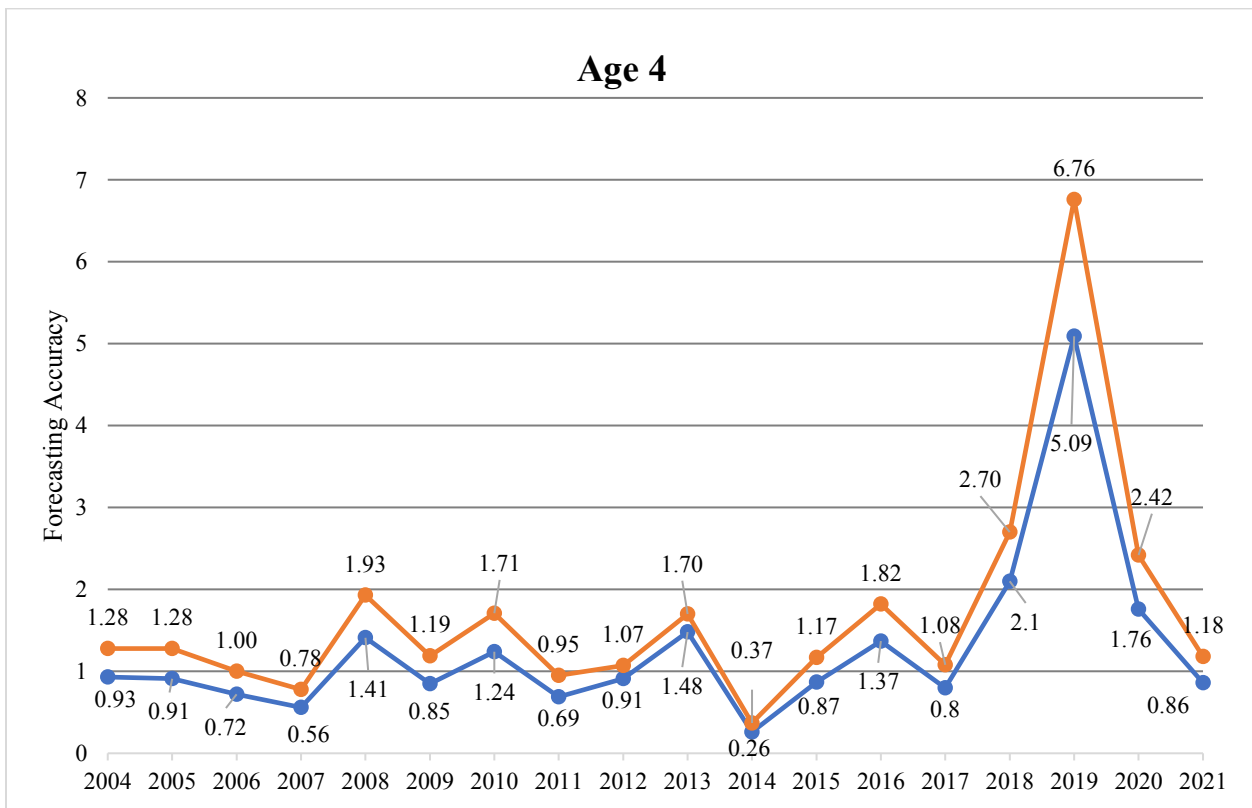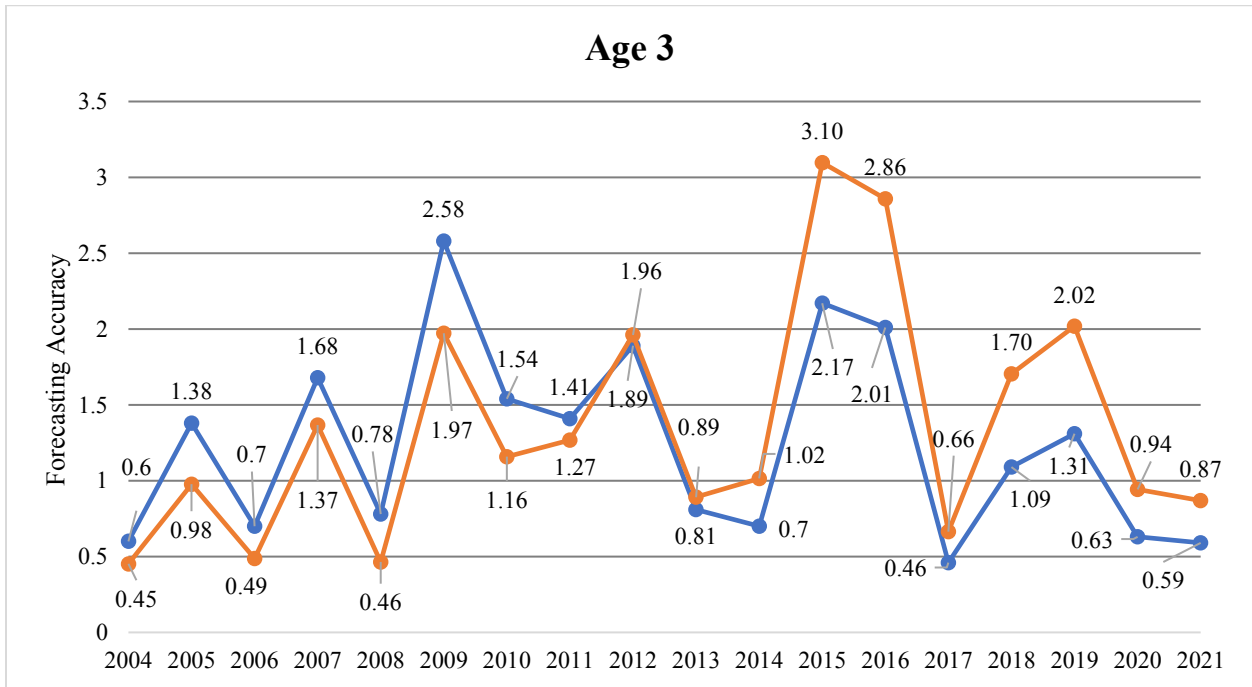
Age 4

Comparison of Model 2 (blue) to existing (orange) accuracy of forecasting age-4 ocean abundance, using pre/post ratios for forecast years 2004 to 2021.

Pre/posts ratios > 1.0 represent overforecasts and < 1.0 represent under forecasts.

Age 3

Age 4
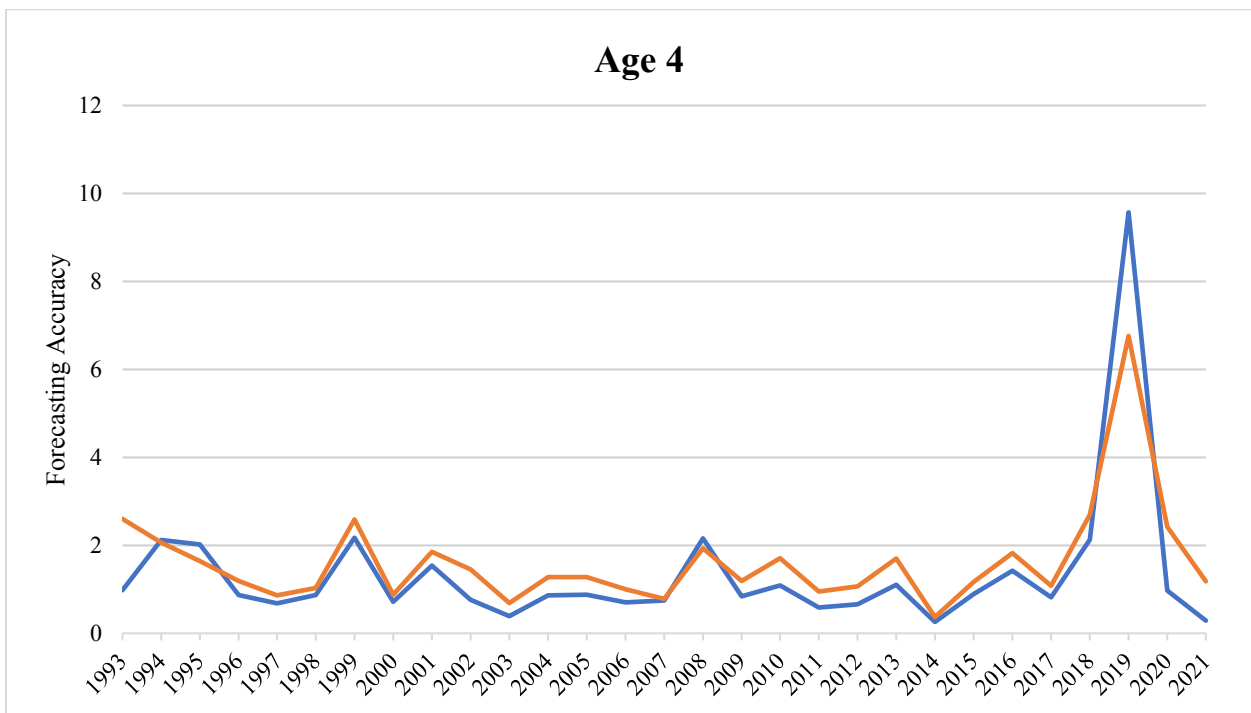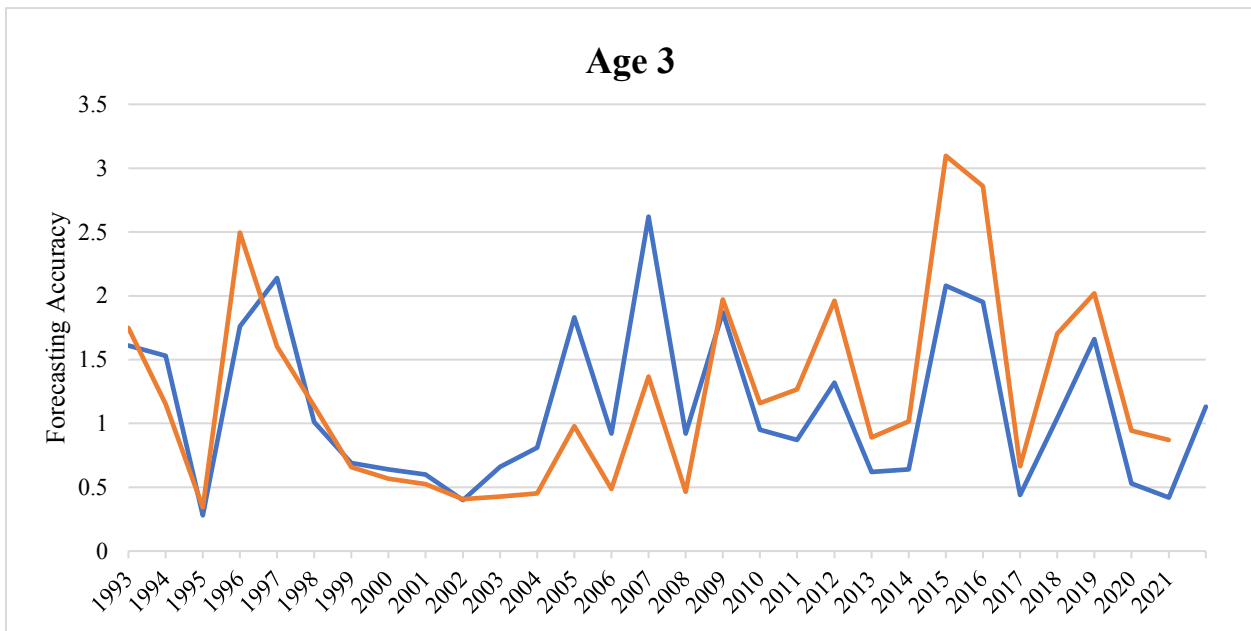
Comparison of Model 3 (blue) to existing (orange) accuracy of forecasting ages 3 and 4 ocean abundance, using pre/post ratios for forecast years 2004 to 2021.

Pre/posts ratios > 1.0 represent overforecasts and < 1.0 represent under forecasts.

APPENDIX H
Changes in Error

Model 1

Age 3

- MRE decreased from 82,218 to 49,628 fish (t = 1.1464; p = 0.2675).
- MAE decreased from 112,479 to 94,914 fish (t = 0.60308; p = 0.5544).
- RMSE decreased from 206,365 to 127,054, a 38% reduction.

Age 4

- MRE decreased from 19,460 to 225 fish (t = -4.3346; p = 0.0004502).
- MAE decreased from 33,215 to 23,963 fish (t = 1.661; p = 0.115).
- RMSE decreased from 52,616 to 39,067, a 26% reduction.

Model 2

Age 3

- MRE decreased from 16,679 to 13,013 fish (t = 0.22145, p = 0.8274).
- MAE decreased from 141,214 to 139,355 fish (t = -0.6957, p = 0.496).
- RMSE decreased from 218,876 to 212,933, a 2.7% reduction.

Age 4

- MRE decreases from -21,135 to -11,097 fish (t = -6.4001; p = 6.589e-06)
- MAE decreases from 34,774 to 34686 fish (t = 1.7331; p = 0.1012)
- RMSE decreased from 1,008,444 to 1,306,692, a 30% reduction.

A t-test on solely FY2012-2021 generated the following results:

- Pre/post decrease of 0.44 (t = 4.3824, p = 0.001765)
- MRE decrease of 58,004 fish (t = 5.64, df = 9, p = 0.0003176)
- MAE decrease of 16,193 fish (t = 0.7712, p = 0.4604)