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NOTE

Multidecadal Trends in Body Size of Puget Sound Chinook Salmon: Analysis of Data from the Tengu Derby, a Culturally Unique Fishery

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Abstract

In Pacific salmon *Oncorhynchus* spp., downward trends in size and abundance have been reported for species and stocks for over 40 years, but the patterns are inconsistent among regions and species. Interpretation of these trends is complicated by many possible contributing factors, including short time series, data comprising a mix of stocks, and varying gear types. Here, we present data on the mass of individual Chinook Salmon *Oncorhynchus tshawytscha* caught in the winter from 1946 to 2019 in central Puget Sound, Washington, by participants in what may be the longest running Pacific salmon derby in North America, the Tengu Derby. In this annual recreational fishing competition, established by Japanese Americans immediately after release from internment camps at the end of World War II, participants follow strict gear, area, and methods regulations and catch almost exclusively salmonids originating from and remaining in Puget Sound. Records revealed an overall decline in fish mass over the decades, with a high degree of variability throughout the time series. Specifically, resident Chinook Salmon exhibited several shifts, including a decrease in size from a high in the 1950s to a low around 1980, followed by an increase to another high around 1990 and then a decline over the most recent 30 years. These size trends of residents differed from those of Puget Sound Chinook Salmon as a whole. We infer that the resident fish experienced ecological conditions affecting their growth that were distinct from those of fish feeding along the Pacific Ocean in the same periods. These distinct trends in size of Chinook Salmon from common origins indicate that the different migration patterns of fish within stocks must be considered in the analysis and interpretation of body size trends and also in patterns of survival.

Long-term trends in size and age at maturity of fishes have been the subject of interest for many decades as they may reflect natural changes in environmental conditions (Cox and Hinch 1997; Rogers et al. 2011), density dependence (Millner and Whiting 1996; Pyper and Peterman 1999), fishery management (Richards and Rago 1999), fishery-induced evolution (Swain et al. 2007; Sharpe and

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Hendry 2009), and other processes or combinations of processes (Edeline et al. 2007). For example, scientists have investigated long-term trends (typically declines) in body size and age at maturity in Atlantic Salmon *Salmo salar* (Gardner 1976; Summers 1995) using data from commercial fisheries (Shearer 1990) and recreational fisheries recorded by governmental bodies (Bal et al. 2017), angling clubs (Bielak and Power 1986), privately held fisheries (Quinn et al. 2006), or newspapers (Valiente et al. 2011).

As with Atlantic Salmon, there is also a long history of interest in trends in the body size of Pacific salmon *Oncorhynchus* spp., with reports of decreases in many species, regions, and periods of record (Ricker 1981, 1995; Bigler et al. 1996; Lewis et al. 2015; Oke et al. 2020). As outlined by Ricker (1980) and echoed in subsequent reviews of size trends, many factors can cause genuine or apparent changes over decades, especially in Chinook Salmon *O. tshawytscha* owing to its diverse life history and migration patterns. Catch data may include shifting proportions of immature and maturing fish of multiple ages, hence different sizes, or fishing may occur at different times of the year, affecting the average size of fish still growing at sea. Smolts produced in hatcheries are often larger than wild smolts, and smolt size affects the duration of marine residence (Scheuerell 2005; Tattam et al. 2015). Hatchery production of Chinook Salmon and Coho Salmon *O. kisutch* increased very gradually from about 1900 to 1950 but then accelerated upward in the Pacific Northwest region, with later increases in British Columbia and Alaska (Mahnken et al. 1998). Salmonid growth is also affected by oceanographic conditions, competition, and the quantity and quality of prey (Helle et al. 2007; Wells et al. 2008; Siegel et al. 2017; Claiborne et al. 2021), all of which have changed over the past decades, and growth rate at sea affects age at maturity (Parker and Larkin 1959; Siegel et al. 2017). Fisheries themselves can be size selective (Todd and Larkin 1971), shifting the overall size distribution or that inferred from a particular fishery (Kendall and Quinn 2011). These and other factors affecting the size of salmonids are not mutually exclusive, making it difficult to explain the many declines (and some increases) in size and age (see Quinn 2018 for a discussion and review of these factors).

Many data sets examined for patterns of body size in Pacific salmon come from commercial fisheries targeting the most numerous species: Sockeye Salmon *O. nerka*, Chum Salmon *O. keta*, and Pink Salmon *O. gorbuscha*. However, Chinook Salmon and Coho Salmon are also commonly caught by anglers in coastal marine waters and rivers. Recreational fisheries can complicate analysis of size trends because they may differ in places and times of the year from commercial fisheries, and the lack of centralized processing means that data on size may not be recorded. However, when used with appropriate caution, recreational fisheries can also be a source of data to complement data from commercial fisheries and recoveries at spawning grounds and hatcheries. For example, Fagen (1988) examined data from recreational fishing derbies for Chinook Salmon in southeastern Alaska from the 1940s to 1980s and reported significant declines in the largest fish in two of the four derbies. Interpretation of these data was complicated by the factors noted by Ricker (1980), especially because southeastern Alaska is a feeding area for wild and hatchery Chinook Salmon originating from a range of locations (Healey and Groot 1987; Weitkamp 2009, 2012). Indeed, Ricker (1980) concluded that analysis of size trend data and causes is especially complicated for Chinook Salmon. They vary greatly in age at maturity and size at age within and among populations (Roni and Quinn 1995) and in marine distribution patterns and timing of entry into fresh water for spawning (Quinn 2018; Riddell et al. 2018) and are fished over a protracted period of the year using a variety of commercial and recreational gear types. Here we consider yet another issue: possible size differences resulting from differential migration within populations.

Recent analysis of trends in survival, abundance, and body size of Chinook Salmon in Puget Sound, Washington, based on commercial purse seine fishery data revealed a decline in average body mass from 1970 through 2015 (Losee et al. 2019). However, these Chinook Salmon would have differed in feeding locations at sea. Specifically, some might have migrated to the coastal ocean, whereas others remained in Puget Sound as so-called “residents.” Such resident Chinook Salmon and Coho Salmon are smaller than those that migrate to the coast (Jensen 1948; Milne 1950; Pressey 1953), complicating interpretation of catch data if the proportion of residents is not constant or if their trends differ from those of conspecifics feeding along the coast. Here we present data on the size of resident Chinook Salmon (see details below on this migratory variant) caught in the winter in central Puget Sound in a culturally unique recreational fishery with consistent methods held annually since 1946. Trends in these data, specific to resident Chinook Salmon originating in Puget Sound, were examined and compared with those of the species caught in Puget Sound as a whole using non-size-selective commercial purse seines (Losee et al. 2019). Our first goal was to use the data to determine the long-term trends in the body size of resident Chinook Salmon, and we then determined whether these trends differed from those of Puget Sound Chinook Salmon as a whole (including residents and Chinook Salmon caught in Puget Sound that had fed along the coast). In so doing, we highlight the value of recreational fisheries data in general for examining life history trends and the value of this unique fishery.

METHODS

Resident Chinook Salmon.— It has long been known that Chinook Salmon and Coho Salmon occur throughout the year in Puget Sound and other inland marine waters (Jordan and Evermann 1896), though many other salmonids enter these waters as smolts and then migrate to the coastal ocean, feed there, and pass through the inland marine waters on their homeward migration (Pressey 1953; Haw et al. 1967). The resident Chinook Salmon are fully anadromous but exhibit differential migration (Quinn 2021), remaining in the general vicinity of their natal rivers for much of their period of marine life (Chamberlin et al. 2011; Chamberlin and Quinn 2014; Arostegui et al. 2017; Kagley et al. 2017). In the winter and spring, these resident Chinook Salmon are subject to capture before they mature and spawn the following fall, or thereafter. Analysis of coded wire tag (CWT) data indicated that Chinook Salmon caught in Marine Area 10 (central Puget Sound, including the location where the derby occurs that produced the data examined here) were almost exclusively from Puget Sound. Specifically, 90.2% of CWTs recovered from Chinook Salmon from October through April (the resident period) in central Puget Sound between 1973 and 2018 originated from Puget Sound (Washington Department of Fish and Wildlife [WDFW] data, average of annual values). Consistent with this analysis, Shelton et al. (2019) examined CWT data from the West Coast of North America and concluded, “Virtually all fish estimated to be present in the Salish Sea (Puget Sound, Strait of Georgia) originated there, indicating few Chinook Salmon from the outer coast migrate into the Salish Sea.” Consequently, it is appropriate to consider the fish caught in the winter as having originated from Puget Sound rivers and hatcheries.

The Tengu Derby.— The history and origins of the derby that provided the data for our analyses are described on a monument plaque at the current weigh-in station in West Seattle:

> The Tengu Club of Seattle, formed in the 1930s by Japanese Americans, held its first Tengu Blackmouth Salmon Fun Derby in 1946. Arguably the longest continually running salmon derby in North America, it continues to be held each winter in Elliott Bay. Club members, returning from wartime internment camps, were denied entry into local salmon derbies so they organized the first Tengu Derby in December of 1946. More than 170 people, including about a dozen non-Japanese, fished in the first four Sundays-long competitions. The technique of ‘mooching’[1] was invented in Elliott Bay by these fishers, who perfected a way to entice salmon by working bait in an up-and-down motion while drifting. This method proved to be so effective that non-Japanese would “mooch” herring from them. The Tengu Club recognized the historical significance of mooching and adheres to this ‘purist’ way of salmon fishing to this day. The name ‘Tengu’ is from Japanese folklore that describes mythical creatures that were mischievous braggarts. Their long noses are symbolic of exaggerating the truth, which is typical of fish stories.

In the decades that followed, participants in the Tengu Derby continued to use the same technique (e.g., no artificial lures and no trolling with downriggers) in precisely the same small, well-defined area east of a line between Alki Point and Fourmile Rock (Figure 1). Each year, the club’s board of directors determines the specific dates, but fishing typically occurs on Sundays in late October, November, and December. Dates and other details are posted annually, and registration provides a record of the number of participants. Fish are brought to a central weighing station rather than being self-reported, and thus the data on fish mass (recorded in pounds but converted to kilograms) can be taken as accurate.

Data and statistical models.— Each year, the mass of each fish was determined in the Tengu Derby but permanent records were only retained for the top five fish. These data were the focus of our analysis, but the numbers of Chinook Salmon over 4.5 kg (10 lb) and over 2.3 kg (5 lb) were also recorded and we present these graphically for comparison. The total number of Chinook Salmon caught was also recorded each year, but changes in regulations over the decades complicate analyses of the count data. Specifically, fish were retained and counted in early decades that would have been released and uncounted in subsequent years because they were below the size limit (currently 56 cm [22 in]). For the present analysis we used the average mass of the top five fish from 1946 to 2017, omitting 2 years (2010 and 2013) when fewer than five Chinook Salmon were recorded and 2015 when fishing was closed. In 2018 and 2019, fewer than five Chinook Salmon were caught so the averages were not included. The trends were compared with annual mean body mass of Chinook Salmon caught in Puget Sound commercial purse seine fisheries (chosen because of their lack of size-selectivity) from 1970 to 2014 (Losee et al. 2019) and updated through 2019 (WDFW, unpublished data). Consistent with Losee et al. (2019), we divided the total number landed in Washington State and Treaty Indian Tribal commercial catches by the total landed weight annually. The data files for this study have been archived at Zenodo (Quinn et al. 2022).

We modeled the sizes of fish caught in the Tengu Derby and WDFW surveys using univariate and multivariate state–space models (Auger-Méthé et al. 2021). These models consist of two parts: (1) a state model that describes the changes in the true but unknown size of fish, and (2) an observation model that relates the observed time series of

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[1] This word refers to the practice of getting something without paying, as in sponging or cadging.

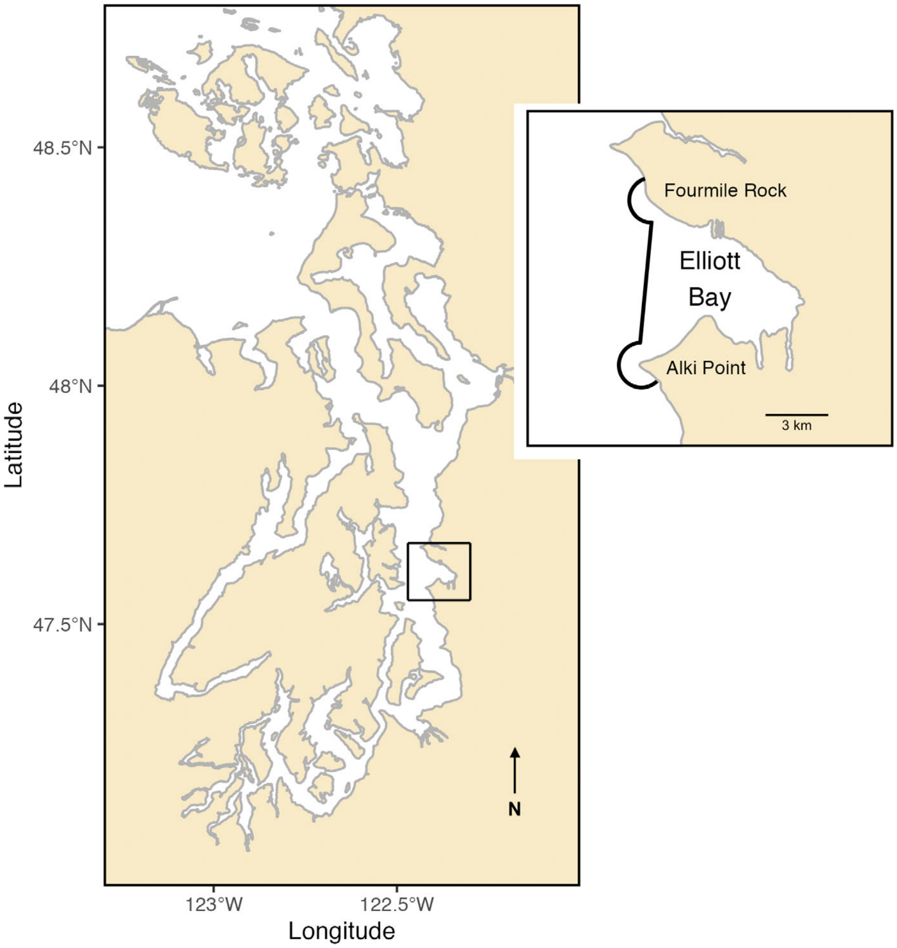

FIGURE 1. Map of Puget Sound, Washington, with an insert showing the location of the Tengu Blackmouth Derby.

fish sizes to the true state. Each of the component models varied subtly, depending on the underlying hypothesis about how the two sources of data were related. Here we wanted to evaluate (1) if there was any evidence for a systematic change in fish size over time and (2) whether changes in the size of Chinook Salmon caught in the derby over time were like that of fish caught in commercial purse seines. For objective (1), we fit models to the two different time periods mentioned above; models in objective (2) were based solely upon the later period (1970–2014).

Beginning with the state model, we modeled changes in fish size using a random walk, for which the change in size over time was assumed to be either biased or unbiased, indicating whether the changes in fish size over time were random or generally trending upward or downward. Specifically, the model takes the form

$$x_{i,t} = x_{i,t-1} + u_i + w_{i,t}, \tag{1}$$

where $x_{i,t}$ is the natural logarithm of fish size from source i in year t, u_i is the bias term for source i, and $w_{i,t}$ is a residual process error for source i in year t, such that $w_{i,t} \sim \mathrm{N}(0, q)$. Setting $u_i = 0$ gives an unbiased random walk.

The observation model treats the measured masses of adult Chinook Salmon each year as samples from the distribution of true sizes in the population. Specifically, the model is

$$y_{j,t} = x_{i,t} + a_j + v_{j,t}, \tag{2}$$

where $y_{j,t}$ is the natural logarithm of observed fish mass (kg) from source j in year t, a_j is an offset term for source j, and $v_{j,t}$ is a residual sampling error for source j in year t, such that $v_{j,t} \sim \mathrm{N}(0, r)$.

When $i = j = 1$, both the state and observation models are univariate and the subscript i in equations (1) and (2) can be ignored as we did when examining the entire time series from the Tengu Derby. When $i = j = 2$, the Tengu and WDFW data are assumed to be samples from their own unique populations. For this case, we write equations 1) and (2) in matrix notation, where T and W indicate Tengu Derby and WDFW, respectively, and

$$\begin{bmatrix} x_T \\ x_W \end{bmatrix}_t = \begin{bmatrix} x_T \\ x_W \end{bmatrix}_{t-1} + \begin{bmatrix} u_T \\ u_W \end{bmatrix} + \begin{bmatrix} w_T \\ w_W \end{bmatrix}_t \tag{3}$$

$$\begin{bmatrix} y_T \\ y_W \end{bmatrix}_t = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_T \\ x_W \end{bmatrix}_t + \begin{bmatrix} a_T \\ a_W \end{bmatrix} + \begin{bmatrix} v_T \\ v_W \end{bmatrix}_t. \tag{4}$$

As with equation (1), setting the vector $[u_T \, u_W]^\top = 0$ yields an unbiased random walk.

When each set of observed masses is assumed to be a sample from the same population, $i = 1$, $j = 2$, and

$$x_t = x_{t-1} + u + w_t \tag{5}$$

$$\begin{bmatrix} y_T \\ y_W \end{bmatrix}_t = \begin{bmatrix} 1 \\ 1 \end{bmatrix} x_t + \begin{bmatrix} a_T \\ a_W \end{bmatrix} + \begin{bmatrix} v_T \\ v_W \end{bmatrix}_t. \tag{6}$$

Setting $u = 0$ in equation (5) results in an unbiased random walk.

In equations (3), (4), and (6), the error vectors are distributed as a multivariate normal. In all those cases, we assumed that the errors were independent but not identically distributed, such that the covariance matrices had a different variance term in each of the elements of the diagonal and zeros in the off-diagonals.

We compared the data support for each of the six state–space models using the corrected form of Akaike information criterion (AIC$_c$) (Table 1). All models were fit using version 3.11.3 of the MARSS package (Holmes et al. 2020) for the R statistical software (R Core Team 2020). All the data and code necessary to reproduce our results can be found online at https://github.com/mdscheuerell/tengu.

RESULTS

The Tengu Derby data indicated that body size was initially high in the late 1940s and 1950s, declined to a low in about 1980, rose to another peak about as high as the first peak around 1990, and then declined steadily to a current size below the earlier low. These patterns were evident in our primary metric, the average mass of the five largest Chinook Salmon (Figure 2), and also in the maximum size each year and the numbers caught exceeding 2.3 and 4.5 kg (5 and 10 lb) (Figure 3), with peaks occurring in the middle of the time series in the early 1990s. Consistent with these large shifts in fish mass over time, we found no support for a model that included a consistent bias in size over the entire time period; the AIC$_c$ for the biased random walk was ~0.6 units higher than that for the unbiased random walk (Table 1).

TABLE 1. Differences in AIC$_c$ (ΔAIC$_c$) values between univariate models fit to the full time period and multivariate models fit to the late period only. Bias indicates whether a bias term was included in the random walk model. The columns labeled "States" and "Observations" indicate the number of underlying states and time series of observations, respectively.

Time period	Bias	States (i)	Observations (j)	ΔAIC$_c$
Full	Yes	1	1	0.0
	No	1	1	0.6
Late	Yes	2	2	0.0
	No	2	2	1.2
	Yes	1	2	34.6
	No	1	2	35.3

During the period from 1970 to 2014, the mean fish mass of fish from commercial fisheries appeared to generally decrease, but we found no data support for a decreasing bias in the mass of fish caught in purse seines or the Tengu Derby as both models with bias terms had AIC$_c$ values about one unit greater than their corresponding models without bias terms (Table 1). Furthermore, temporal patterns in fish mass from the Tengu Derby did not generally match those from the purse seine fishery, despite some similarities from the late 1980s to the late 1990s (Figure 4); models with two unique states had AIC$_c$ values that were about 35 units less than the models with only one shared state.

DISCUSSION

The data from the Tengu Derby showed a decline in average mass of the five largest fish (also evident in the maximum mass and the numbers caught per angler over 2.3 and 4.5 kg [5 and 10 lb] each year) from the first

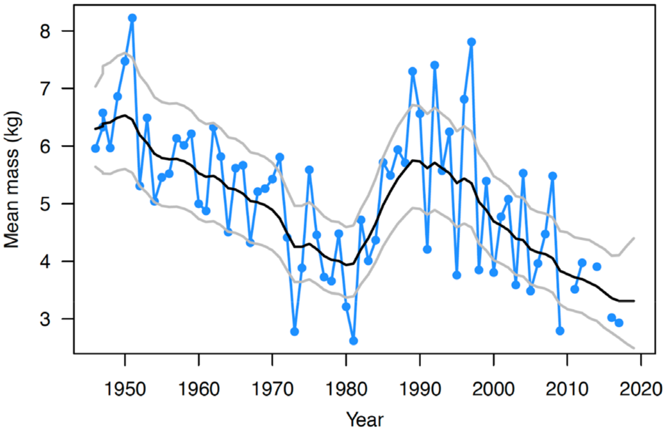

FIGURE 2. Time series of the mean mass of the five largest Chinook Salmon caught in the Tengu Derby (connected blue dots), with the model-fitted values (black line) and approximate 95% confidence intervals (gray line). Missing points reflect years when less than five fish were caught.

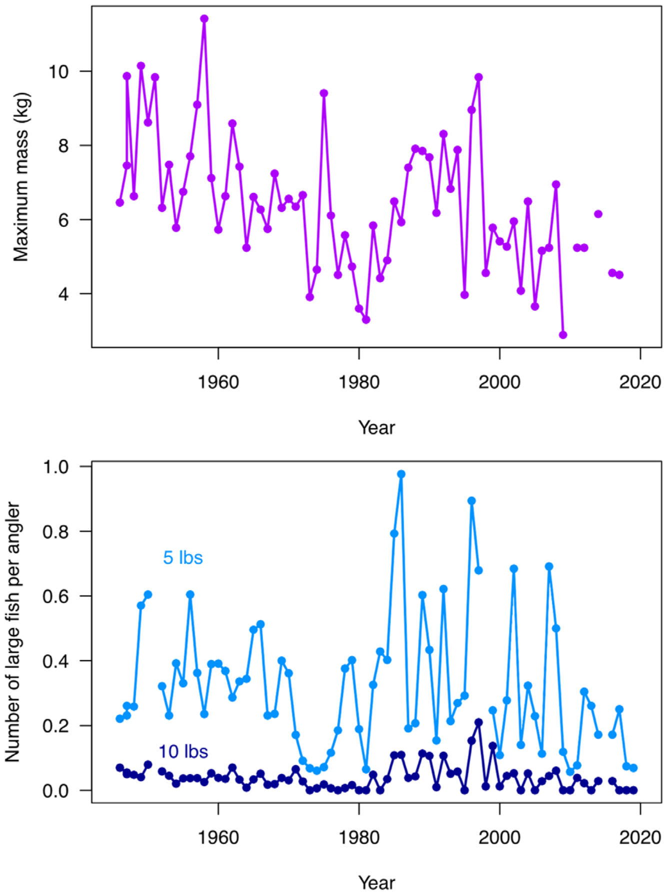

FIGURE 3. Time series of the mass of the single largest Chinook Salmon caught in the Tengu Derby each year (top panel), and the number of fish ≥2.3 kg (5 lb; light blue) and ≥4.5 kg (10 lb; dark blue) divided by the number of participating anglers each year (bottom panel).

records in the mid to late 1940s to a low about 1980. This initial decline mirrored that reported by Ricker (1981) for several regions along the British Columbia coast. Subsequent investigations in British Columbia reported an increase in Chinook Salmon average mass from that low period to a high around 1990–2000 (Bigler et al. 1996), followed by another decline (Jeffrey et al. 2017). These patterns approximated those seen in the Tengu Derby data, but they may not reflect common underlying causes. Importantly, we found a lack of alignment between the Puget Sound data from commercial purse seine fisheries targeting migratory adults and those from the derby (though the Tengu Derby data, over a longer period, indicated an early peak in size prior to the WDFW data). Interestingly, data from four regions of Alaska showed downward trends in mean mass of Chinook Salmon from about 1970 to 2000 (Helle et al. 2007) and thus are more similar to the Puget Sound purse seine fishery data than the data from British Columbia reported by Jeffrey et al. (2017).

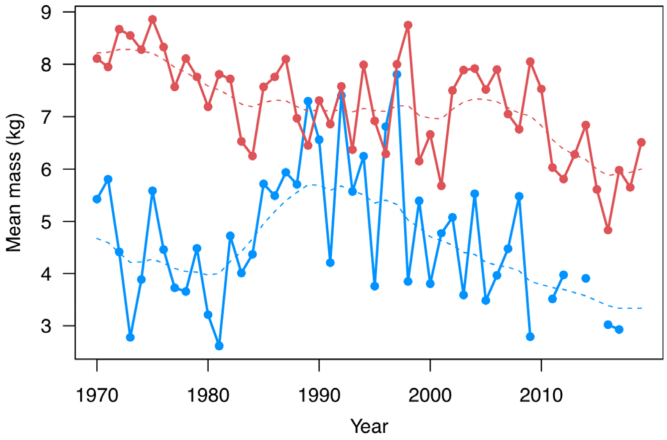

FIGURE 4. Time series of observed Chinook Salmon mass from purse seine fisheries (red) from 1970 to 2014 and the Tengu Derby (blue), including fits from the multivariate random walk model for both time series (dashed lines). Note the shorter period of record compared with Figure 2.

Changes in average size may result from differences in growth rate and shifts in the population's age composition (Bigler et al. 1996; Lewis et al. 2015; Ohlberger et al. 2018). Indeed, declines in overall size recently reported for Alaskan Chinook, Coho, Chum, and Sockeye salmon were attributed primarily to reductions in age at maturity rather than size at age (Oke et al. 2020). The specific causal mechanisms and factors controlling these changes in age and size remain uncertain, in part because (1) growth and age at maturity are complex interrelated traits, (2) the data typically include varying proportions of populations that differ in size and age, and (3) there are many environmental influences (Ricker 1980; Oke et al. 2020). As with other salmonid species, the number of years Chinook Salmon spend at sea is typically inversely related to smolt size (Scheuerell 2005; Tattam et al. 2015; Quinn 2018) and initial growth rate (Siegel et al. 2017). Salmonids produced in hatcheries are commonly larger at release than wild conspecifics and thus younger at maturity (Norris et al. 2000). The proportion of hatchery-origin Chinook Salmon caught in Puget Sound has increased considerably over the past decades, from <40% in 1968 and 1969 to an average of 64% in the 1970s, 74% in the 1980s, 79% in the 1990s, 82% in the 2000s, and 87% from 2010 to 2015 (Losee et al. 2019), complicating interpretation of size trends.

Puget Sound and the entire Salish Sea have undergone many changes over the past decades in physical and ecological attributes (Quinn and Losee, in press), and we did not try to ascribe the observed changes in Chinook Salmon mass to specific causes. However, data such as these on the resident component, over such a long period, are unique and especially valuable. Salish Sea resident Chinook Salmon and Coho Salmon are smaller than those feeding along the Pacific Ocean coast (Milne 1950; Pressey 1953; Rohde et al. 2014); thus, changes in the proportions of residents and migrants could strongly affect mean body size, depending on where and when the sampling took place. Indeed, the proportion of Chinook Salmon remaining as residents in Puget Sound has decreased over the period covered by the Tengu Derby data (Quinn and Losee, in press). The lack of correspondence between the Tengu Derby and purse seining data presented here spanning more than four decades, and the decreasing resident component in the populations, illustrates yet another important complexity in the analysis of temporal trends in salmonid body size. That is, the differential migration patterns observed in several species, especially Chinook Salmon and Coho Salmon (Quinn 2021; Quinn and Losee, in press), can cause differences in vulnerability to fisheries of contingents that migrate to different areas (Sharma and Quinn 2012). If those migratory contingents also differ in size, then the resulting data can be biased, depending on where and when the fish were sampled.

Finally, it is increasingly clear that declines in abundance of Atlantic Salmon and Pacific salmon are strongly influenced by survival rates (Olmos et al. 2019; Welch et al. 2021). However, as exemplified by Atlantic Salmon from the Bay of Fundy, Canada, considerable variation in survival rates can occur among spatially proximate populations (Pardo et al. 2021). The proportions of populations adopting resident or migratory behavior patterns seem to affect survival (Lacroix 2013) and growth rates (Hubley et al. 2008) for these populations. Thus, our results highlight the need to better understand where different genetic groups of salmonids go over their lives at sea.

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