Quantifying regional patterns of collapse in British Columbia Central Coast chum salmon (*Oncorhynchus keta*) populations since 1960

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Abstract

In recent decades, chum salmon (*Oncorhynchus keta*) on the Central and North Coasts of British Columbia have experienced increasing variability and declining abundance. Chum are targeted by mixed-stock commercial fisheries despite declining trends and limited stock assessment to clarify conservation and fishery tradeoffs. We analyzed trends in chum salmon run sizes to 25 watersheds in the Central Coast region, to support co-governance of fisheries under newly ratified *Fisheries Resources Reconciliation Agreement*. Central Coast chum have declined by ~90% since 1960, and only three populations did not undergo an evident decline. Bella Coola enhanced chum had an increasing trend but have experienced 29-fold variation in run sizes since 2005. Recently, Bella Coola enhanced chum comprised over 50% of Central Coast chum abundance and the contribution of this stock to overall abundance has more than tripled (from 13.8%) since enhancement began. Given concerns about the long-term health of chum salmon stocks and the social–ecological systems they support, commercial fisheries were closed on the Central Coast in 2021. If current trends continue, fishery opportunities may remain limited.

Key words: chum salmon, climate change, sustainable fisheries, Indigenous knowledge, social–ecological systems

Résumé

Au cours des dernières décennies, les saumons kétas (*Oncorhynchus keta*) le long de la côte centrale et nord de la Colombie-Britannique ont présenté une variabilité croissante et une abondance en baisse. Les saumons kétas sont visés par des pêches commerciales de stocks mélangés, en dépit de tendances à la baisse et de peu d'évaluations des stocks permettant de préciser les compromis entre la conservation et la pêche. Nous analysons les tendances de la taille des migrations de saumons kétas vers 25 bassins versants dans la région de la côte centrale pour appuyer la cogouvernance des pêches en vertu *d'Ententes de réconciliation sur les ressources halieutiques* ratifiées récemment. Les saumons kétas de la côte centrale ont connu un déclin d'environ 90 % depuis 1960, seulement trois populations n'ayant pas connu de déclin évident. Les saumons kétas de la rivière Bella Coola, dont l'abondance est enrichie par des lâchers issus d'une écloserie, montraient une tendance à la hausse, mais ont connu de grandes variations de la taille de leurs migrations (jusqu'à 29 fois plus importantes certaines années que d'autres) depuis 2005. Récemment, les saumons kétas enrichis de la rivière Bella Coola constituaient plus de 50 % de l'abondance des saumons kétas de la côte centrale, et la contribution de ce stock à l'abondance globale a plus que triplé (d'une proportion initiale de 13,8 %) depuis le début de l'enrichissement. Au vu des inquiétudes concernant la santé à long terme des stocks de saumons kétas et des systèmes socioécologiques qu'ils soutiennent, les pêches commerciales ont été fermées le long de la côte centrale en 2021. Si les tendances actuelles se maintiennent, les possibilités de pêche pourraient demeurer limitées. [Traduit par la Rédaction]

Mots-clés : saumon kéta, changement climatique, pêches durables, connaissances autochtones, systèmes socioécologiques

Introduction

Wild salmon (*Oncorhynchus* spp.) are a culturally iconic, as well as economically and ecologically significant group of species across their North Pacific range. Through their annual spawning migrations, salmon link the watersheds from California to Japan to the productivity of the North Pacific Ocean, fueling ecosystems, economies, and nourishing human communities. However, in recent decades the impacts of accelerating anthropogenic and climatic changes in freshwater and marine ecosystems have contributed to increased

volatility and ongoing declines for wild salmon in most areas of British Columbia (Malick and Cox 2016; Litzow et al. 2020; Price et al. 2021). A century and a half of freshwater habitat loss and degradation coupled with recent low marine survival are considered key drivers of declining population productivity and are associated with the collapse of many populations (Grant et al. 2019; Walsh et al. 2020a; Wilson et al. 2022). In recent years, a series of marine heatwaves has reduced food-web productivity in the North Pacific (Cheung and Frölicher 2020; Suryan et al. 2021), increased metabolic demands on ectotherms like salmon (e.g., Beauchamp et al. 2007), and exacerbated competition between wild- and hatchery-origin salmon for limited food resources at sea (Ruggerone and Irvine 2018; Connors et al. 2020). Over the last decade, numerous studies have documented declining trends in wild salmon productivity around the Northeast Pacific Rim (Peterman and Dorner 2012; Malick and Cox 2016; Dorner et al. 2018), and this recent period of climate warming has also corresponded to increased intensity of both drought and flooding in fresh water, likely further eroding wild salmon productivity (Ward et al. 2015; Ohlberger et al. 2018a; Chegwidden et al. 2020).

In many cases, these climate-induced declines in survival and productivity for wild salmon have outpaced the ability of current fisheries management frameworks to assess stock status and implement adaptive regulations. On the Pacific coast of Canada, Fisheries and Oceans Canada (DFO) manages commercial and recreational fisheries for wild salmon, and management plans for these fisheries are codified in an annual Integrated Fisheries Management Plans (IFMPs), released each spring before the fishing season. DFO has recently begun formalizing the process for co-developing annual fishery management plans with First Nations, with additional input from stakeholders and members of the public. In recent decades, salmon fisheries have collapsed throughout British Columbia (Walters et al. 2019) with record low commercial catches in 2019 and 2020 (DFO 2020). Numerous factors have contributed to these declines, reducing survival of salmon during their freshwater and marine life stages, and eroding per-capita productivity in many populations (Peterman and Dorner 2012; Malick et al. 2017; Dorner et al. 2018; Wilson et al. 2022). Without compensatory responses in freshwater productivity, lower survival requires reduced harvest to sustain these populations. However, management of many salmon fisheries in British Columbia is informed by limited data on escapement and the stock composition of harvested salmon (e.g., Brown et al. 2020; Atlas et al. 2021a; DFO 2022). Such is the case for the North and Central Coasts of British Columbia, a region that is home to hundreds of locally adapted salmon populations. Currently, only three Central Coast salmon populations—none of them being chum salmon (*Oncorhynchus keta*)—have biologically-based management goals, such as biological escapement goals or limit reference points. Resources for population monitoring and assessment have been extremely limited, undermining the ability of fishery managers to assess stock status and manage exploitation rates (ERs) in response to varying productivity and survival.

In recent years, as populations of salmon around the Central Coast have declined in abundance, the four Central Coast First Nations (CCFN)—Nuxalk, Heiltsuk, Wuikinuxv, and Kitasoo Xai'xais—have repeatedly articulated their concerns over the impacts of ongoing commercial and recreational fisheries and the perceived lack of response among federal managers to the declining status of chum and other species that are intercepted in mixed-stock fisheries in their territories (Connors et al. 2016, 2019; Atlas et al. 2021a; Steel et al. 2021a). This declining trend in productivity, particularly for chum, pink, and sockeye salmon has been well documented by other researchers (e.g., Peterman and Dorner 2012; Malick and Cox 2016; Connors et al. 2018); however, these analyses have rarely focused specifically on populations prioritized by CCFN for their importance to food, social, and ceremonial (FSC) fisheries and often analyze trends among aggregates of stocks rather than evaluating abundance trends for specific watersheds. Importantly, these analyses predate the most recent years of salmon returns to the Central Coast region when the impacts of the marine heatwave and associated collapse of ecosystem productivity and salmon survival have been felt acutely (Steel et al. 2021a). Fisheries within each of the Pacific Fisheries Management Areas (PFMAs) on the Central Coast are managed separately. For example, since 1985, Snootli Hatchery has produced chum salmon in the Bella Coola River to support commercial harvest opportunity. During most of the past decade, commercial seine and gillnet fisheries in PFMA 8 have operated with weekly openings for these enhanced chum salmon during July and August, while PFMA 7 has not had a directed chum fishery since 2016, and fisheries have been similarly limited in PFMA 6 during that period due to low chum returns. There has not been a commercial harvest of chum in PFMA 9 since 1995 (Table S1); however, chum salmon from all Central Coast PFMAs are likely caught as bycatch in other regional fisheries, including Alaska where impacts on BC stocks are unquantified.

The newly ratified Fisheries Resources Reconciliation Agreement (FRRA) between the Canadian Federal Government and eight Nations in the North and Central Coast has created a formal process for First Nations and DFO to share co-management authority (Coastal First Nations 2019), and major commercial closures have been introduced under the Pacific Salmon Strategy Initiative (PSSI) along with fleet reductions through licensed buy-back programs (DFO 2021a). The FRRA establishes a framework for collaborative assessment and management between DFO and eight First Nations on the North and Central Coast of British Columbia. This framework is designed to include local and traditional knowledge in management decision making, but much of Canadian fishery policy (e.g., Sustainable Fishery Framework) hinges on quantitative stock assessment, which is often lacking in the Central Coast region. Yet, local knowledge from CCFN members has indicated accelerating declines among regional chum populations (e.g., Walsh et al. 2020a; Steel et al. 2021a), and these concerns provided motivation for our work to quantify changes in chum salmon abundance that have been observed in recent years. This paper was therefore motivated by Indigenous knowledge and the need, given current fishery management frameworks, to support this knowledge with quantitative analysis.

Here, we focus on a quantitative analysis of data-limited chum salmon stocks of the North and Central Coast to support FRRA implementation and to inform strategies for recovery under the PSSI. To support co-governance, precautionary management, and data-informed recovery actions for chum salmon fisheries, we quantified trends in chum total run sizes (used interchangeably with *return* or *abundance* throughout) from 25 well-monitored spawning populations spanning the territories of the CCFN in PFMAs 6–9. We parameterized and evaluated a series of time series models implemented in MARSS (Holmes et al. 2012), to quantify the magnitude of changes in total chum abundance in recent decades and understand how these patterns of change are distributed across the Central Coast region. These data sets spanned the period from 1960 to 2020, capturing major regime shifts and climate changes in the North Pacific (Beamish et al. 1999; Di Lorenzo and Mantua 2016; Litzow et al. 2020), a period of intensive forestry impacts in some Central Coast watersheds, and the implementation of large-scale chum salmon hatchery production in the Bella Coola River in the mid-1980s.

Methods

Spawner escapement data

We compiled time series of chum salmon escapement for 25 populations from PFMAs 6–9 on British Columbia's Central Coast from a combination of sources starting with a comprehensive data set compiled by English et al. (2018). We updated these data with more recent DFO spawner escapement estimates for each population as reported in the annual postseason review document. These populations were selected because of their relatively continuous monitoring—at least 50 annual counts since 1960 (Fig. 1). All populations that met these criteria and fell within the territories of the CCFN were included in our analysis. Spawner escapement ($e_{i,t}$) and total run size ($y_{i,t}$) data used in this analysis are presented in the Supplementary materials (Table S1).

Harvest data

Total fishery catches are well monitored by DFO through a fishery logbook program; however, uncertainty in population-specific catches has previously hindered estimates of ERs for individual stocks. English et al. (2018) used historical catch data to reconstruct annual ERs for individual conservation units (CUs) on the Central Coast, and estimated CU-specific ERs for run years up to 2017. Except for PFMA 8, there have been no directed fisheries targeting Central Coast chum since 2017. In years without directed fisheries, we assumed that the harvest rate was 0.05 to account for potential interceptions in FSC fisheries and bycatch of chum in other fisheries (Marine Planning Partnership 2015; Steel et al. 2021b). For PFMA 8, estimates of annual ERs using the English et al. (2018) methods were not available after 2017; however, data on the total catch of chum salmon and the estimated total run size to PFMA 8 were available in the annual postseason review (PSR) document (DFO 2020). To generate comparable ER estimates for the years 2018–2020 when directed fisheries targeted chum in PFMA 8, we fit

a linear regression relating the harvest rate reported in the PSR and the harvest rate estimated for the two Area 8 CUs from 1960 to 2017 (Bella Coola/Dean and Spiller/Fitz Hugh/Burke). Preliminary analyses favored a linear relationship between the two harvest rates and suggested that most the variation in the Bella Coola/Dean ERs reported by English et al. (2018) would be explained by the ER values calculated from the PSR ($R^2 = 0.92$). Variability in harvest rates for Spiller/Fitz Hugh/Burke were also correlated with the harvest rates estimated by English et al. (2018), although less of the variability was explained by the harvest rate reported in the PSR ($R^2 = 0.41$). We used the intercept and coefficient values from this linear regression to estimate the 2018–2020 harvest rates in the two CUs in PFMA 8 (Appendix A; Table S2). Annual total run size for each population ($y_{i,t}$) was then computed as $y_{i,t} = e_{i,t}/(1 - ER_t)$, where the ER_t is the yearly harvest rate estimated for a specific PFMA. These data were natural-log transformed for time-series modeling to meet the assumption of normally distributed residuals.

Model fitting and selection

Data on escapement and harvest rates were combined to estimate total run size (total pre-fishery abundance) for each of the 25 populations of chum salmon. Both harvest and escapement data estimates are reported by fishery managers without uncertainty. Escapement estimates were generated from visual counts, either over flights or on foot, and these methods include non-trivial error associated with uncertainty in counts and the subsequent expansions that were applied to estimate total run size. Similarly, harvest rates were not routinely estimated for chum salmon in PFMAs 6–9 and going from total catch, which was relatively well documented, to population-level ER, estimates involved several assumptions and key uncertainties. Taken together, these uncertainties may obscure the true trend in run size if data are assumed to be free of observer error.

To account for observation error, we implemented a set of time-series analyses using a state-space modeling approach implemented in the package "MARSS" in R version 4.1.1 (Holmes et al. 2012; R Core Team 2020). State-space models decompose error into two distinct components, observation error and process error, representing the true underlying variation in chum salmon run size. We used a dynamic factor analysis (DFA), a special case of a MARSS model, to estimate a number of hidden trends m—true underlying trends in the data set of interest once observation error has been accounted for—and the corresponding relationship (i.e., factor loadings) that each population i has with each trend m. DFA has recently been used in several studies evaluating salmon productivity and abundance trends (e.g., Freshwater et al. 2018; Dorner et al. 2018; Ohlberger et al. 2018b). Specifically, our DFA MARSS model took the following form:

$$(1) \quad x_{m,t} = x_{m,t-1} + u_m + w_{m,t}, \quad \text{where } w_{m,t} \sim \text{MVN}(0, \mathbf{Q})$$

$$(2) \quad y_{i,t} = Z_{i,m}x_{m,t} + a_i + v_{i,t}, \quad \text{where } v_{i,t} \sim \text{MVN}(0, \mathbf{R})$$

where eq. 1 describes the process state, an unobserved quantity; in this case, the total run sizes for chum salmon $x_{m,t}$ at

Fig. 1. Map of Central Coast region — Pacific Fisheries Management Areas (PFMAs) 6–9 — with the 25 chum populations included in the time-series analysis as well as biogeoclimatic zones in each of the watersheds. Basemaps and layers were plotted in R using the mapping package bcmaps (Teucher et al. 2021). Projection: NAD83/BC Albers. [Colour online.]
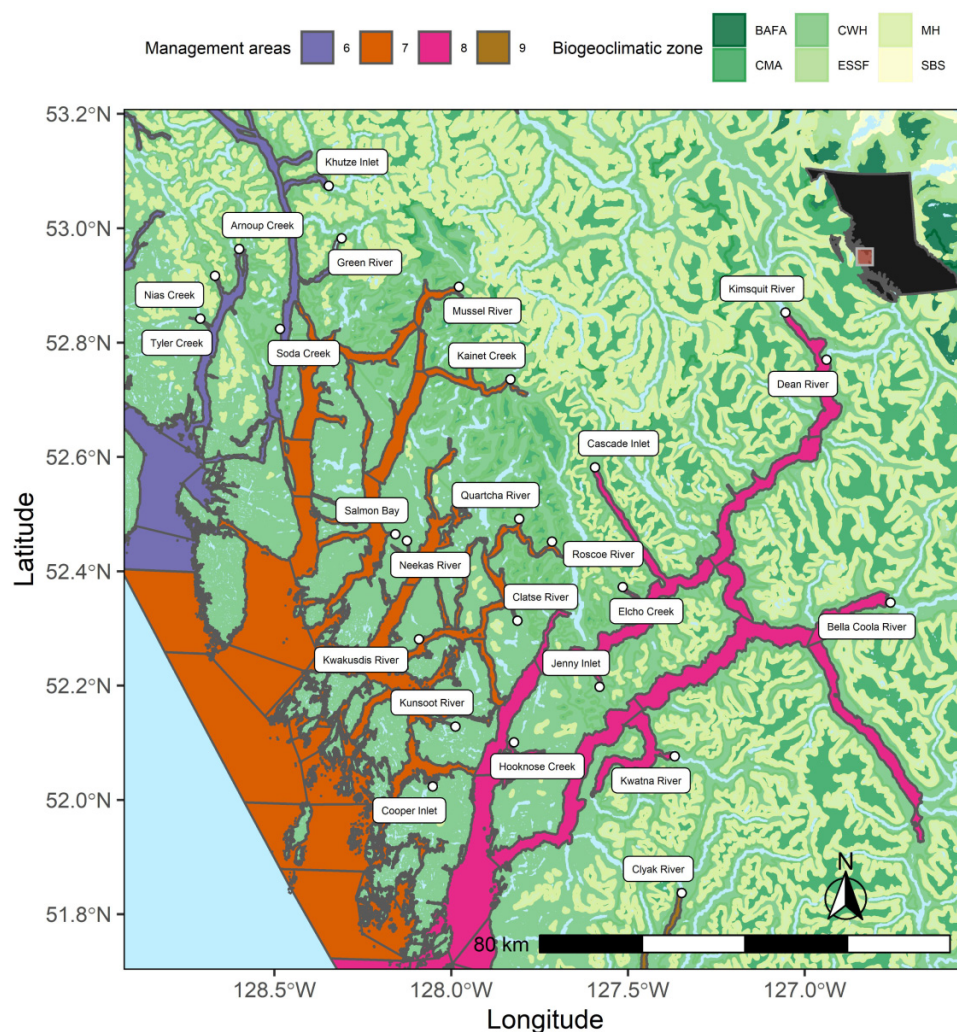
year t under the hidden process state m. Typical in MARSS models, the process state follows an autoregressive form by relating $x_{m,t}$ to $x_{m,t-1}$. Equation 2 describes the observation state, with $y_{i,t}$ the observed chum run size for population i at time t. Each $x_{m,t}$ thus reflects a realization of the hidden process state at time t with a slope parameter u_m controlling the overall hidden trend for state m, the matrix $Z_{i,m}$ represents the factor loadings for each of the hidden process m on the observed population run sizes for the ith population or population grouping, and the vector a_i represents population-specific offsets. Both the process and the observation errors $w_{m,t}$ and $v_{i,t}$, respectively, are drawn from multivariate normal distributions with a mean of zero and variance–covariance matrices **Q** (an $m \times m$ matrix, where m is the number of trends) and **R** (an $n \times n$ matrix, where n is the number of populations), with the diagonals representing the variance and off-diagonals representing the covariance among process (or observation) errors. Because of challenges with parameter identifiability, we estimated a covariance matrix only on for the variance–covariance matrix **Q** to quantify

patterns of synchrony among the hidden state process ($w_{m,t}$). We assumed that observation errors ($v_{i,t}$) were independent and unequal for each population (i.e., no covariance among the observation errors).

We evaluated both the numbers of hidden trends (m in eqs. 1 and 2) and spatial groupings of populations among trends by comparing 10 candidate models defining different groupings of populations in the **Z** matrix, allowing individual time series to either group onto shared trends, or to have their own trend. We then evaluated the level of statistical support for each of these models using Akaike information criterion (AIC; Burnham and Anderson 2002) (Table 1). This model selection procedure allowed us to evaluate the degree of support for different geographic configurations of shared trends among populations, and whether the inclusion of process-error correlations improved model fit. Our two null models included a single trend for all 25 populations (*mod1*) and 25 independent trends (*mod25i*). We then compared models of intermediate spatial complexity by grouping population trends at the level of the CU (*modCU6i*) or the PFMA (*modA4i*). Given

Table 1. Results from AIC model selection to determine most parsimonious groupings and model structure for time-series models of Central BC Coast chum run size trends.

Rank	Model	No. of trends	Groups	Process errors	Log-likelihood	AIC	δAIC
1	modA6c	6	PFMAs + Bella Coola + Kimsquit and Dean	Correlated	−1772.8	3699.7	0.0
2	modA5c	5	PFMAs + Bella Coola	Correlated	−1782.4	3704.9	5.2
3	modA6c.ii	6	PFMAs + Bella Coola + Kimsquit, Dean, and Kwatna	Correlated	−1777.8	3709.6	9.9
4	modA4c	4	PFMAs	Correlated	−1796.7	3721.5	21.8
5	modA6c.i	6	PFMAs + Bella Coola + Kwatna, Kimsquit, and Dean	Correlated	−1786.6	3727.3	27.6
6	mod25c	25	Populations have independent trends	Correlated	−1475.1	3750.2	50.5
7	modA4i	4	PFMAs	Independent	−1832.9	3781.9	82.2
8	mod1	1	NA	Equal	−1855.8	3815.5	115.8
9	modCU6i	6	Conservation Units	Independent	−1875.9	3875.7	176.0
10	mod25i	25	Populations have independent trends	Independent	−1918.4	4036.7	337.0

that aggregating populations by PFMA received greater AIC support, we then evaluated a suite of models that included correlations among process errors based on the PFMA groupings (*modA4c*). To accommodate potential differences in the run size trend of enhanced Bella Coola chum, we also developed a candidate model that included a separate trend for enhanced Bella Coola summer-run (*modA5c*). Chum returning to Kimsquit, Dean, and Kwatna rivers also share marine migration routes with enhanced Bella Coola chum, creating potential for both straying from abundant enhanced chum, ecological interactions between these enhanced and wild stocks, and potentially higher harvest impacts on these stocks by fishers targeting enhanced chum. We therefore evaluated a series of different trend groupings for these stocks to determine support for modeling their trends separately from Bella Coola enhanced chum, and other chum populations in PFMA 8. Among these models, we evaluated support for a separate trend in Kimsquit and Dean chum (*modA6c*) and evidence for grouping the unenhanced Kwatna population with either the Bella Coola enhanced (*modA6c.i*) or Kimsquit and Dean (*modA6c.ii*). We fit a final model which included trends for each of the 25 populations and estimated correlations between these population-specific process errors (*mod25c*).

Trend interpretation

To evaluate trends in Central Coast chum populations, we calculated metrics of changes in population size across three different time horizons. First, we estimated a slope parameter u_m representative of the overall trend for each population or group of populations and calculated the percent annual change in abundance using the equation $e^{u_m} - 1$. We then estimated the total % change in abundance from 1960 to 2020 given this annual rate of change. Second, we estimated the hidden state (x_t) (run sizes) and estimated the average state for three time periods: (*i*) long term from 1960 to 2020, (*ii*) in the most recent generation (5 years), and (*iii*) in the last three generations (15 years). We then quantified the number of years in the last 5 and 15 years that run size fell below the long-term average state (x_t) and in the last 5 and 15 years as a percentage of the long-term average state. We evaluated these trend metrics both for the model which received the highest level of support from AIC model selection (*modA6c*) and for a

model which included all 25 geographically distinct spawning populations in our data set (*mod25c*) to provide insight into watershed-level trends in chum total run size. In the results below, we present insights drawn from each of these metrics of demographic change.

Results

Overall, our analysis of chum salmon total run sizes to the Central Coast region from 1960 to 2020 revealed a high degree of correlation among chum salmon population trends, and evidence that geographically proximate stocks share common trends. Model selection showed strong support for grouping population trends by PFMA, and for including separate trends in PFMA 8 for enhanced Bella Coola chum and for Kimsquit and Dean chum (Table 1). Models that included process-error correlation between groups or populations always received higher support than those with independent trends for each population, and consequently we chose to interpret trend estimates from these models. Parameter estimates for the top model (*modA6c*) and a model with unique but correlated trends for each of the 25 populations (*mod25c*) are presented in the Supplementary materials (Tables S3 and S4)

Our "best-fit" model, according to AIC model selection, revealed strong evidence for a dramatic and accelerating decline among Central Coast chum salmon stocks with an average decline of 91% from 1960 to 2020 across all models, estimated as the magnitude of change in the total run size state (x_t). Mean estimates of the full time-series trend in abundance for each of the six population groups in our AIC-selected model were negative (mean estimates for $u_m < 0$); however, these trends exhibited some uncertainty (i.e., 95% confidence intervals for all u_m overlapped zero) owing to both process variation in salmon returns and high observer error. Nonetheless, these hidden long-term trends (u_m) provide important insight into the relative magnitude of decline among these population groups. For example, mean estimates of u_m were strongly negative for both PFMA 9 (−0.0703, 95% CI: −0.224 to 0.083) and PFMA 6 (−0.0533, 95% CI: −0.200 to 0.094), and were less negative for both Bella Coola enhanced summer chum (−0.019, 95% CI: −0.259 to 0.220) and PFMA 8

Table 2. Estimated long-term run sizes and recent trends in run size for six regionally important chum population groups, values are derived from the mode receiving the highest level of AIC support (modA6c).

Population group	1960–2019 mean	5-year mean	5 years below	5 years	15-year mean	15 years below	15 years	u-trend
PFMA 7	29 365	8 464	5	28.8%	17 110	12	58.3%	−0.038 (SD 0.075)
Bella Coola sum.	124 157	189 853	1	152.9%	118 308	8	95.3%	−0.019 (SD 0.122)
Kimsquit and Dean	82 968	61 389	3	74.0%	52 586	12	63.4%	−0.041 (SD 0.119)
PFMA 8	14 846	14 498	3	97.7%	13 036	9	87.8%	−0.022 (SD 0.087)
PFMA 9	5 222	674	5	12.9%	1 298	15	24.9%	−0.070 (SD 0.078)
PFMA 6	4 510	1 095	5	24.3%	1 914	15	42.4%	−0.053 (SD 0.067)

(−0.022, 95% CI: −0.192 to 0.148) (Table 2). These six trends correspond to annual declines in chum run size of −6.8% per year for PFMA 9 (95% CI: −20.0% to 8.6%) and −3.7% per year for PFMA 7 (95% CI: −15.5% to 9.7%), translating to an overall decline of 98.5% and 91.5%, respectively, over the past 60 years. Bella Coola enhanced chum showed the least severe decline, with an estimated long-term change in run sizes (u_m) of −1.9% per year (95% CI: −22.8% to 24.6%), representing a 68.4% decline overall from 1960 to 2020 (Table 2; Fig. 2; Table S3).

Our analysis also revealed accelerating chum declines in recent years for most PFMAs. Chum population trends in PFMAs 6, 7, and 9 all fell below their long-term average run sizes in each of the last 5 years. PFMA 9 experienced the most dramatic recent decline—for example, run sizes in PFMA 9 were below long-term average returns in each of the last 15 years with the most recent 5-year run sizes were 87% lower than long-term averages. PFMAs 6 and 7 experienced similar declines, with estimated 5-year reductions in run size of 76% and 71% relative to their respective long-term averages and were below their long-term average run size in 15 and 12 of the most recent years, respectively. Declines in chum salmon returns to the Kimsquit and Dean rivers were comparatively moderate but still consequential, with 5-year average run sizes of 74%, and a 15-year average return of 63% of their long-term average. Among the unenhanced stocks on the Central Coast, only the group of populations in PFMA 8 (Elcho, Cascade, Kwatna, Hooknose, Jenny Bay) had a 5-year average return within 5% of their long-term average (98% average) and experienced improved run sizes over the last 15 years (15-year mean = 87.8% of long-term average) (Fig. 2; Table 2). Overall, chum salmon on the Central Coast of BC appear to have naturally cyclical population dynamics, but with most populations experiencing an accelerating collapse in abundance in recent decades (Figs. 2 and 4).

Since 1985, when large-scale chum salmon hatchery enhancement began, the average return of summer chum to the Bella Coola River increased by 243% relative to the pre-enhancement period. Overall, the total run has averaged 163 750 chum salmon since 1985, compared to 67 140 before enhancement. This period of enhancement has also been associated with a high degree of variability in returns, with summer run chum salmon run sizes to Bella Coola varying 29-fold in the last 15 years, ranging from a maximum estimated return of 339 420 fish in 2018 to 11 750 fish in 2010 (Fig. 2). This single stock also comprises an increasingly large

share of the overall chum salmon production on the Central Coast. Prior to hatchery programs, Bella Coola summer chum accounted for an average of 13.8% of total chum returns to the Central Coast. Since enhancement efforts began in 1985, the average contribution of Bella Coola summer chum run has increased to 30.3% of total regional run. This shift in regional salmon production has been amplified in recent years by the collapse of chum populations in PFMA 7, PFMA 6, and Kimsquit; and in the last 5 years, Bella Coola has accounted for 50.5% of the total chum run returning to the 25 populations in our analysis (Fig. 3).

For models which included all 25 chum spawning populations, median estimated slope parameters (u_m) indicated declining trends in abundance for all populations; however, the overall magnitude of decline varied widely across populations (Fig. 4; Table 3). For example, estimated trends for chum populations in the Elcho (mean $u_t = -0.003$, 95% CI: −0.187 to 0.181) and Hooknose ($u_t = -0.002$, 95% CI: −0.147 to 0.142) indicated relatively modest rates of decline (~0.2% per year) for these populations, while chum in the Clyak River ($u_t = -0.070$, 95% CI: −0.309 to 0.168), Kunsoot ($u_t = -0.071$, 95% CI: −0.396 to 0.254), and Green ($u_t = -0.072$, 95% CI: −0.297 to 0.153) experienced much more severe declines between 1960 and 2020 (~6.9% per year). However, given the large interannual variability and uncertainty in chum run sizes, these long-term trend estimates are highly uncertain and typically overlap zero (Tables 3 and S4).

For most chum populations we assessed, run sizes have undergone steep declines over the last 15 years, and especially in the last 5 years. Across these populations of chum, run sizes were below their 1960–2020 average in most recent years; 19 populations were below average in each of the last 5 years, and 3 others were below average in at least 3 of 5 years (Kimsquit, Elcho, Jenny Bay). Only chum salmon returning to the enhanced Bella Coola summer run and to the Cascade River were above average in more than 3 of the last 5 years, although notably both stocks experienced near-record low returns in 2020 (Figs. 4 and 5). Among the 19 stocks that have fallen below their average returns in each of the last 5 years, the average run size has been only 25.8% of their 1960–2020 run sizes. Among unenhanced stocks on the Central Coast, only Elcho (109%) and Cascade (201%) have 5-year average run sizes larger than their long-term average (Table 3; Fig. 5). Run sizes in the last 15 years tell a similar story. Excluding the enhanced summer run to the Bella Coola River, Central Coast chum populations have experienced below average returns of

Fig. 2. Estimated trends for six population groupings of Central Coast chum salmon. Solid lines are the estimated run size (state) colour-coded by PFMA, and gray shaded areas are the 95% confidence intervals for the state variable. Population run size trends have been standardized by the long-term mean run size, and horizontal dashed lines are at 1, indicative of the long-term mean abundance. [Colour online.]
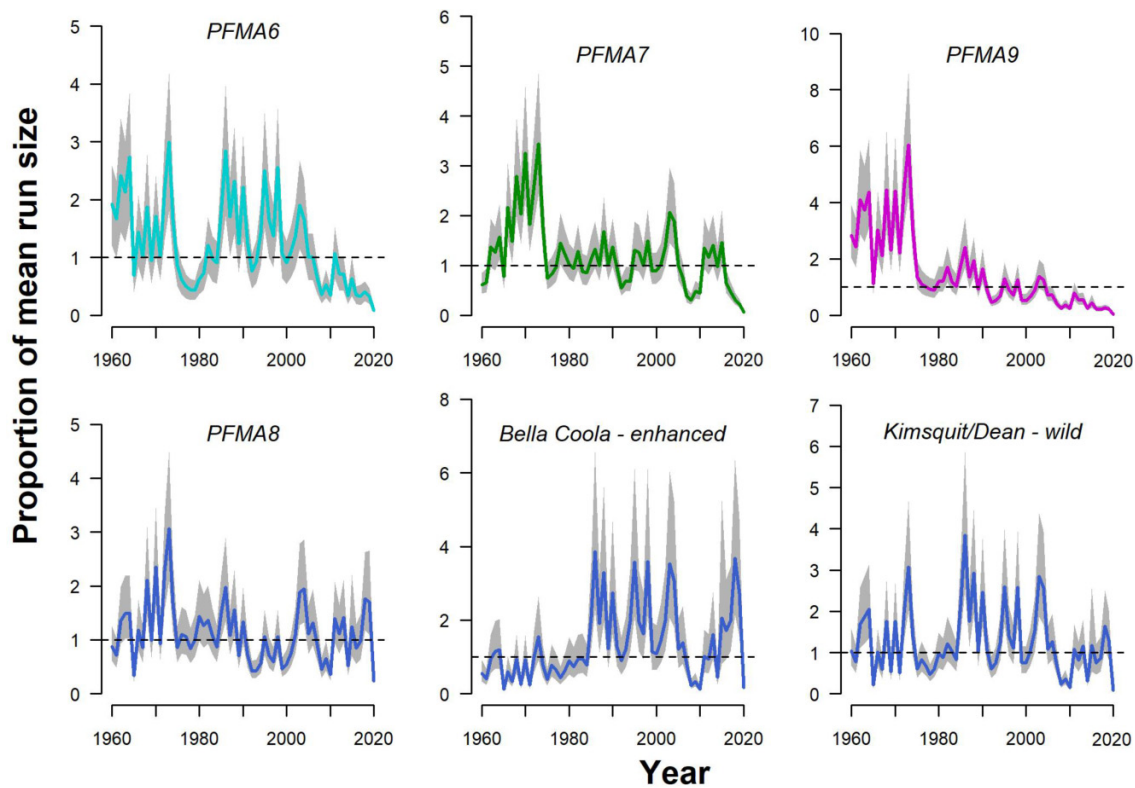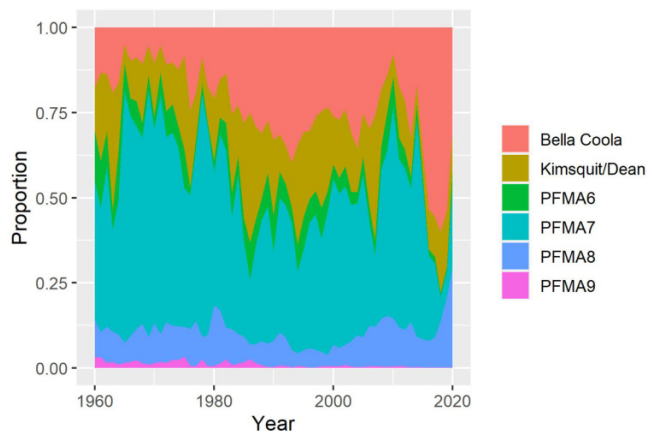

Fig. 3. Proportional contribution of each of the six chum population groups to returns on the Central Coast from 1960 to 2021.

12.65 of the last 15 years. Four populations—Clyak, Arnoup, Soda, and Tyler—have experienced below average returns in each of the last 15 years, and an additional 10 populations have experienced below average returns in at least 13 of the last 15 years. Overall, since 2005 the average return of chum salmon to Central Coast rivers has been 42.4% below their long-term average run size (Table 3; Fig. 5).

Estimated correlations between group- and population-level process states suggested strong regional covariation in chum salmon through time. Correlations between the six regional trends were related to geographic proximity and population-to-population correlations generally indicated groupings within PFMAs (Fig. 6). Among the six trend groups, estimated correlations ranged from moderately correlated (PFMA 6 to Kimsquit/Dean = 0.226) to highly correlated (PFMAs 8 to 7 = 0.849) (Fig. 6; Table S3). Within PFMA 8, Bella Coola enhanced chum were moderately correlated with Kimsquit and Dean stocks (0.335) and were more highly correlated with PFMA 8 stocks in the Spiller-Fitz Hugh-Burke CU (0.518) and PFMA 7 (0.492) (Table S3). Populations also tended to be correlated with their PFMA; for example, populations in PFMA 8 tended to be highly correlated (mean = 0.516), except for Hooknose Creek which had a negative mean correlation with other PFMA 8 stocks (−0.016) (Fig. 6; Table S3). The average correlation coefficient across the 25 populations was 0.32; however, correlations ranged from weakly negative (−0.152; Nias Creek in PFMA 6 to Kwakusdis Creek in PFMA 7) to strongly positive (∼1.0; Kunsoot Creek and Clatse Creek both in PFMA 7) (Fig. 6; Table S4). Populations also varied strongly in their average correlations, and some—Bella Coola enhanced (0.463), Kimsquit (0.455), Jenny Bay (0.474), Kwatna (0.476), and Khutze (0.499)—had high average correlation coefficients, while others had much lower average correlations indicative of a higher degree of asynchrony in trends.

Fig. 4. Estimated trends in total run size for 25 chum salmon populations on the Central Coast of British Columbia. Dots represent observed escapements from visual count surveys and are colour-coded by PFMA. Black lines are the estimated state (total run size), and gray shaded areas are the 95% confidence intervals for the state variable. Abundance trends have been standardized by the long-term mean run size, and the red dashed lines are the mean. [Colour online.]
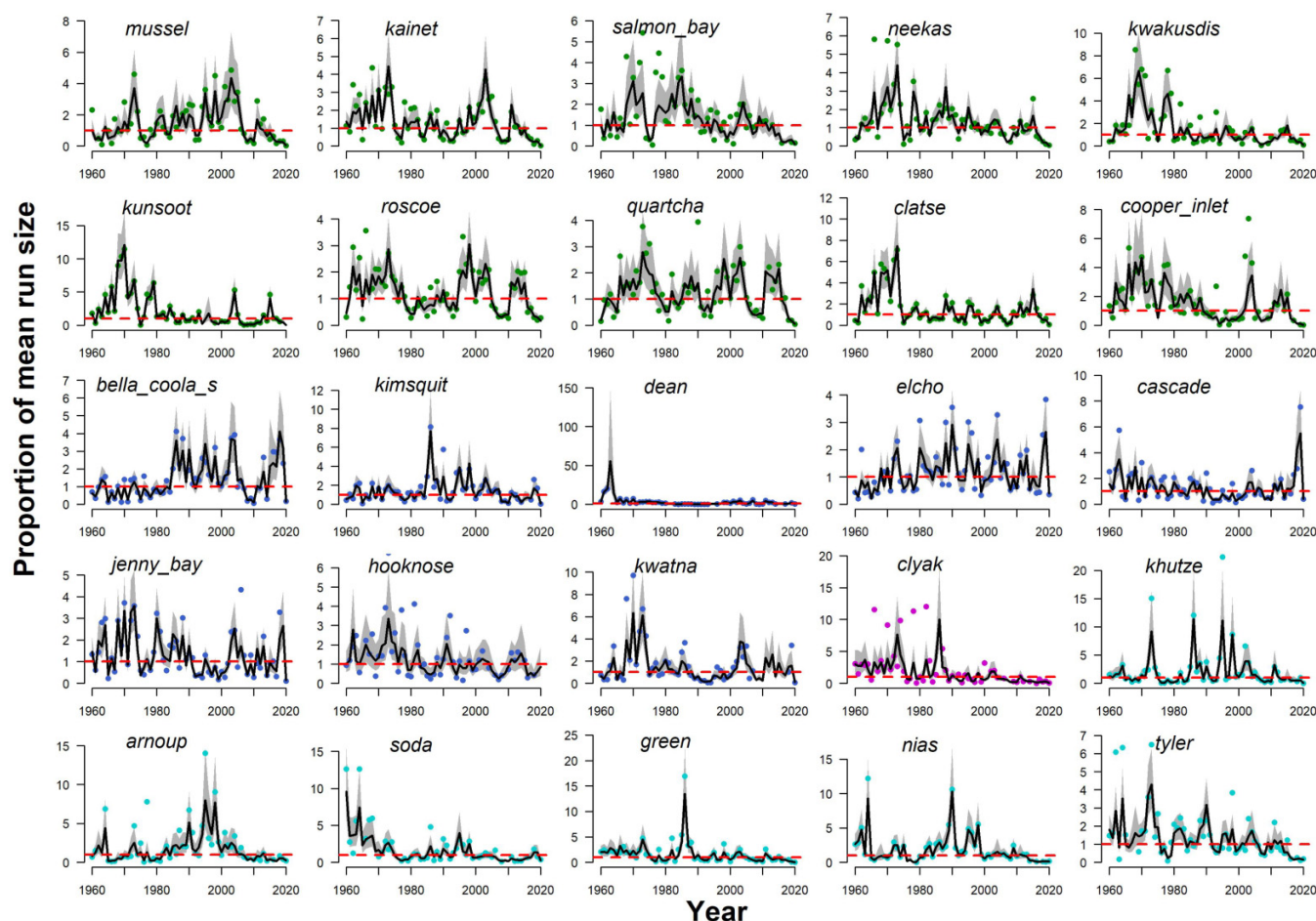
Notably, five out of the six populations with the highest average correlation coefficients were in PFMA 8 in watersheds nearest to the Bella Coola River.

Discussion

Our findings reveal major declines in the abundance of chum salmon returning to the Central Coast of British Columbia since 1960, with an average decline of >90% by 2020 across 25 populations with reliable long-term spawner escapement data over the last six decades. Chum salmon run sizes declined across all areas, but the rate, magnitude, and social–ecological impacts of chum salmon collapse were unevenly distributed along the Central Coast. For example, chum runs declined by an estimated 98.5% and 95.9% among the populations we assessed in PFMAs 9 and 6, respectively. Conversely, run sizes to the Bella Coola River (−31.6%) and PFMA 8 (−26.8%) fared comparatively better, with all populations (except Hooknose Creek) experiencing above average run sizes in at least two of the last 5 years. Nevertheless, despite some regional variation in the magnitude of population decline, chum salmon populations have undergone severe declines across the Central Coast over the last 60 years, culminating in the closure of targeted commercial fisheries in 2021.

These findings match other recent analyses of chum, pink, and sockeye populations on the BC Coast indicating a declining trend in abundance and productivity (Peterman and Dorner 2012; Malick and Cox 2016; Connors et al. 2018). Similar declines have recently been observed for Chinook and coho salmon from California to Alaska (Dorner et al. 2018; Ohlberger et al. 2018b; DFO 2022). Our analysis is unique in that we also evaluated individual populations rather than regional stock-aggregate trends, and quantified trends in abundance in the aftermath of a major climate perturbation in the Northeastern Pacific triggering an apparent ecological regime shift impacting salmon survival and abundance (Di Lorenzo and Mantua 2016; Litzow et al. 2020; Suryan et al. 2021). These events culminated in near-record low returns to many watersheds in 2020 and contributed to our analysis painting a more pessimistic and up-to-date assessment of stock status than previous analyses (e.g., Connors et al. 2018). Evidence of relatively high correlations in run sizes among regional chum populations is consistent with previous research

Table 3. Estimated long-term run sizes and recent trends in run size relative to the long-term average for all 25 populations of chum salmon analyzed independently (mod25c).

Population	PFMA	Mean	5-year mean	5 years below	5 years	15-year mean	15 years below	15 years	u-trend
Mussel	7	33 583	6 437	5	19.2%	16 408	13	48.9%	−0.052 (SD 0.096)
Kainet	7	47 600	9 217	5	19.4%	24 277	14	51.0%	−0.063 (SD 0.096)
Salmon Bay	7	5 802	1 039	5	17.9%	3 084	14	53.2%	−0.038 (SD 0.081)
Neekas	7	47 266	12 710	5	26.9%	23 864	13	50.5%	−0.049 (SD 0.093)
Kwakusdis	7	11 266	3 318	5	29.5%	4 627	14	41.1%	−0.022 (SD 0.094)
Kunsoot	7	7 601	2 205	5	29.0%	2 592	14	34.1%	−0.071 (SD 0.166)
Roscoe	7	35 588	12 147	5	34.1%	23 178	11	65.1%	−0.017 (SD 0.070)
Quartcha	7	6 580	2 320	5	35.3%	5 001	10	76.0%	−0.020 (SD 0.077)
Clatse	7	10 869	4 389	5	40.4%	7 175	12	66.0%	−0.040 (SD 0.125)
Cooper Inlet	7	9 888	1 333	5	13.5%	5 324	12	53.8%	−0.060 (SD 0.097)
Bella Coola s	8	126 948	219 358	1	172.8%	130 165	8	102.5%	−0.025 (SD 0.128)
Kimsquit	8	90 941	58 110	4	63.9%	51 515	12	56.6%	−0.036 (SD 0.133)
Dean	8	6 343	1 558	5	24.6%	2 646	13	41.7%	−0.045 (SD 0.141)
Elcho	8	15 136	16 499	3	109.0%	14 774	10	97.6%	−0.003 (SD 0.094)
Cascade	8	12 218	24 674	2	201.9%	14 469	9	118.4%	−0.023 (SD 0.112)
Jenny Bay	8	5 422	5 184	3	95.6%	4 503	10	83.1%	−0.040 (SD 0.126)
Hooknose	8	2 549	1 253	5	49.2%	1 719	12	67.4%	−0.002 (SD 0.074)
Kwatna	8	10 839	7 414	3	68.4%	8 626	8	79.6%	−0.034 (SD 0.120)
Clyak	9	5 910	619	5	10.5%	1 226	15	20.7%	−0.070 (SD 0.122)
Khutze	6	6 811	1 544	5	22.7%	2 802	14	41.1%	−0.059 (SD 0.159)
Arnoup	6	2 820	606	5	21.5%	961	15	34.1%	−0.019 (SD 0.121)
Soda	6	1 485	823	5	55.4%	503	15	33.9%	−0.060 (SD 0.092)
Green	6	9 083	1 738	5	19.1%	3 308	14	36.4%	−0.072 (SD 0.115)
Nias	6	8 193	560	5	6.8%	3 096	14	37.8%	−0.049 (SD 0.134)
Tyler	6	4 922	729	5	14.8%	2 383	15	48.4%	−0.042 (SD 0.086)

focused on chum and pink salmon (Malick and Cox 2016), and emerging evidence has revealed increasing synchrony in recruitment variation for multiple species of salmon suggesting ocean-scale drivers of survival may be an increasingly dominant force shaping salmon population trends (Kilduff et al. 2015; Hertz et al. 2018)

The mechanisms underlying the collapse of chum salmon are difficult to identify, particularly given the dearth of monitoring focused on freshwater conditions and egg-to-fry survival. Most monitoring programs on the Central Coast focus on adult enumeration. Little attention has been given to the freshwater conditions that spawners and juveniles experience and there are currently no downstream trapping programs that enumerate juvenile chum salmon (Atlas et al. 2021a). Thus, numerous factors may have contributed to collapse in chum salmon populations that we report, but current monitoring and assessment frameworks provide limited insight on the role of hypothesized marine and freshwater drivers shaping these declines (Wilson et al. 2022).

Despite these data gaps, several potential environmental drivers of declining chum productivity have been observed in recent years, with evidence stemming from both scientific and local knowledge. Previous research has demonstrated correlations between chum productivity and climate conditions in the North Pacific, including the sign and strength of the North Pacific Gyre Oscillation, El Niño Southern Oscillation, and the Pacific Decadal Oscillation, although the nature of these correlative relationships may change through time (Kilduff et al. 2015; Malick et al. 2017; Litzow et al. 2020). Since 2014, the North Pacific has experienced a period of anomalously warm temperatures leading to cascading changes in pelagic and nearshore food webs (Frölicher and Laufkötter 2018). This marine heatwave (called the "Blob") led to persistent changes in marine conditions for salmon since 2014 (Di Lorenzo and Mantua 2016; Suryan et al. 2021), with low abundances and poor body conditions of subadult chum salmon sampled along the high seas (Somov et al. 2019; Deeg et al. 2022). These changing marine conditions affecting chum have also corresponded with a period of high overall salmon abundance in the North Pacific, with increasing evidence that interspecific competition for food may be interacting with climate-driven changes to depress growth and survival (Connors et al. 2020; Ruggerone et al. 2021). These poor conditions for growth and survival likely contributed to the lower smolt-to-adult survival that has been reported for chum (among other Pacific salmon) from Southeast Alaska to California (Mantua 2015; Grant et al. 2019).

The effects from these recent climate perturbations have spanned marine and freshwater ecosystems. In the last decade, watersheds along the Central Coast experienced unusually intense drought conditions in some summer and early fall seasons, as well as larger than normal flood events

Fig. 5. Comparison of short-term (5-year) and longer-term (15-year) proportional changes in chum salmon run size relative to their 1960–2020 average return for 25 populations of chum salmon on the Central Coast. Populations are colour-coded by their PFMA. [Colour online.]
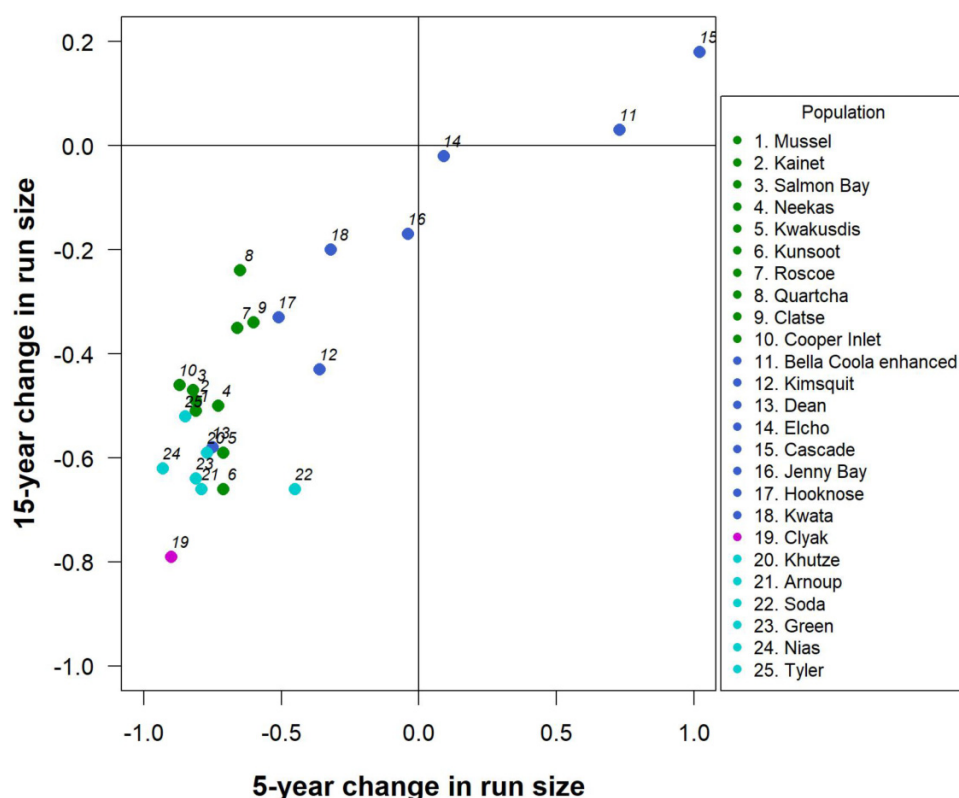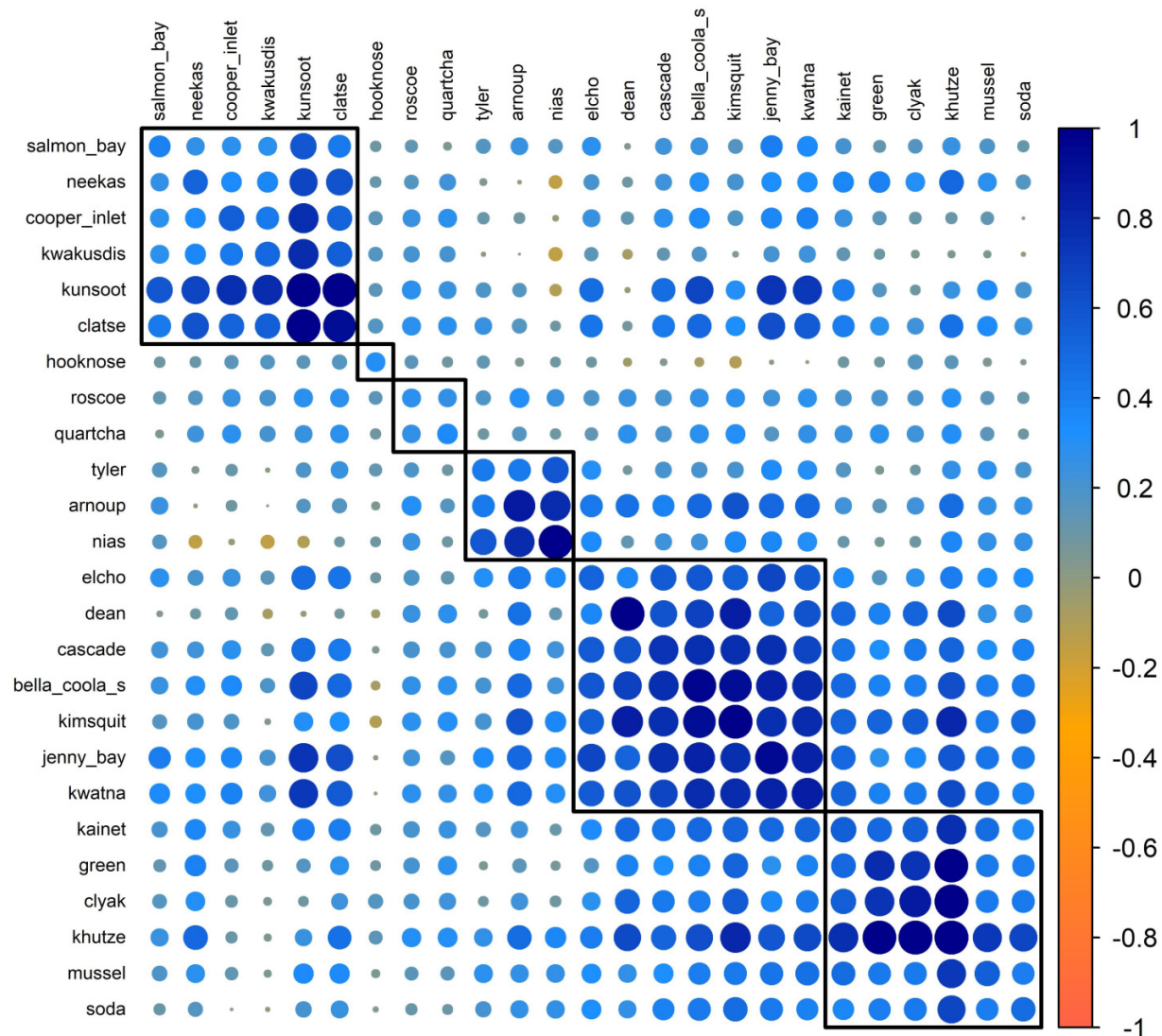
in the late-fall and early winter. Major bed-mobilizing floods have likely contributed to lower-than-average egg-to-fry survival for many populations in the last decade. Prolonged droughts during the fall of 2016, 2018, and 2019 may have contributed to reduced spawner success for many chum populations returning to smaller coastal watersheds by limiting access to spawning areas or increasing pre-spawn mortality (Carlson and Quinn 2007; Westley 2020; Atlas et al. 2021b). In those years, many chum salmon were reportedly stranded in the lower reaches and estuaries of spawning creeks around the Central Coast region and likely had low spawning success (M. Reid, personal communication). The loss of headwater glaciers in the last 10 years in some watersheds, like the Mussel River, have also led to dramatic downstream consequences on temperature and flow regimes. Without glacial melt to cool late-summer flows, temperatures in early September (the traditional spawning window for these chum salmon populations) increased from 11–12 to 18–20 °C (R. Nelson, personal communication)—at or above critical thermal tolerance thresholds for migrating salmon (e.g., Atlas et al. 2021b). Increased temperatures during this critical spawning window have created a potential mismatch between local adaptations in spawn timing and the conditions that adult spawners encounter today. All told, recent climate disturbances have likely impacted chum salmon across most of their life cycle, and there is a need for improved coordination and monitoring to support preseason fishery planning and inseason management in the face of increasingly variable climate conditions.

While hatchery production has buffered the Bella Coola summer chum population from variable freshwater conditions, several concerns remain for the long-term health of both the Bella Coola summer chum stock, specifically, and Central Coast chum more generally. Despite large-scale enhancement and static production goal of 7 million fry, Bella Coola chum salmon run sizes have still fluctuated 29-fold in the last decade. Furthermore, other regional hatcheries experienced declines in recent adult returns and, in some years, missed their egg-take goals because of low numbers of returning spawners (I. Douglas, personal communication). Enhanced populations may have lower resilience to climate variability and change (e.g., Satterthwaite and Carlson 2015; Price et al. 2021) since large-scale hatchery production can limit the diversity or expression of otherwise plastic life-history traits, driving artificial selection on age at maturity, spawn timing, and other traits that allow enable adaptation to cope with adverse climate changes (e.g., McConnell et al. 2018; Tillotson et al. 2019).

As enhanced Bella Coola chum become an increasingly large share of overall regional chum returns, fisheries targeting enhanced population may pose elevated risks to the persistence of wild populations via high rates of bycatch (Connors et al. 2019; Moore et al. 2021), and large numbers of strays can alter or homogenize genetic and life-history

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Fig. 6. Clustered process-error correlations (**Q** matrix off diagonals) among Central Coast chum salmon populations. [Colour online.]

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diversity in adjacent watersheds. For example, in Southeast Alaska where similar large-scale enhancement efforts support fisheries, as many as 50% of spawning adults in unenhanced populations were found to be hatchery origin and these individuals have lower fitness and reproductive success in the wild (McConnell et al. 2018). Data is currently unavailable to evaluate the contribution of hatchery strays to wild chum spawning populations on the Central Coast. However, Bella Coola hatchery managers recently began otolith thermal marking all chum salmon reared in their facility. Spawning ground surveys in the Bella Coola and adjacent watersheds in 2023 when the first cohort of marked fish will begin to return can provide crucial insights into the degree of straying by hatchery chum and their influence on production and natural selection in other regional chum populations.

These stark changes in the overall distribution and abundance of chum salmon have eroded the social–ecological values provisioned by chum salmon, harming food security and livelihood opportunities for Indigenous and local communities (DFO 2021a; Steel et al. 2021a). Chum salmon are also an integral part of aquatic and riparian ecosystems, and numerous predators, scavengers, and plants depend on and benefit from their abundance (Darimont et al. 2010; Hocking and Reynolds 2011; Walsh et al. 2020b). While the Central Coast region supported high catches of chum salmon throughout most of 20th century, fisheries have been restricted since 2017 to a handful of 1-day openings in PFMA 8 per year where fishers target enhanced Bella Coola chum salmon (DFO 2020). This fishery is conducted in Fitz Hugh Sound, Fisher Channel, and in areas around King Island and North Bentinck Arm. Catch composition has not been routinely monitored in these fisheries. However, given the depressed status of many Central Coast salmon populations (Connors et al. 2018), stock assessment biologists and members of the CCFN have repeatedly raised concerns about unsustainable harvest impacts on nontarget species and stocks (Connors et al. 2019; Walsh et al. 2020a; Steel et al. 2021a). Furthermore, in the absence of cooperative marking

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or genetic sampling program, the harvest of Central Coast chum in commercial fisheries outside of British Columbia is unquantified and may be considerable in some years (Witherell et al. 2002; Northern Boundary Technical Committee 2020).

In the face of unprecedented climate changes and declining wild salmon populations throughout British Columbia, First Nations People and coastal communities are bearing the brunt of collapsing social–ecological systems (Steel et al. 2021a; Reid et al. 2022). First Nations People have observed and documented these declines firsthand, but often their local and traditional knowledge has not been valued at management tables. Sometimes there is simply a need to quantify the pattern that is being described by people on the ground to help fish managers and policy makers understand the magnitude of changes that are being described by local and Indigenous knowledge holders. While salmon populations are naturally variable, the causes for these dramatic recent declines are likely anthropogenic. Chum salmon were formerly among the most important species for Indigenous harvesters on the Central Coast (White 2011; Steel et al. 2021a). In just a few human generations, chum salmon run sizes on the Central Coast, one of British Columbia's most ecologically intact regions, declined by more than 90% alongside similar declines observed in other species with equally negative consequences for food security, salmon biodiversity, and ecosystem health (e.g., McKinnell et al. 2001; Connors et al. 2019). In 2021, DFO took the unprecedented step of closing all directed commercial fisheries targeting salmon returning to the Central Coast (DFO 2021a). These announced closures coincided with the announcement of a >$650 million Federal investment in salmon recovery called the PSSI. This funding is intended to support investments in salmon conservation as well as rebuilding and restructuring commercial fisheries to meet the challenges posed by climate change and declining salmon stocks.

This short-term closure of commercial fishing on the Central Coast will likely benefit wild chum and other species that have been harvested as bycatch in the PFMA 8 gillnet fishery, but reduced harvest does not guarantee recovery, and populations in PFMAs 6, 7, and 9 have continued to decline despite the closure of directed fisheries. Regardless, the closure of PFMA 8 commercial fisheries is an opportunity to advance more ecologically sound, forward-looking approaches to salmon management. For example, reduced hatchery chum production in the Bella Coola may benefit wild chum and other species of salmon which compete with enhanced chum salmon for limited resources in the nearshore environment (e.g., Connors et al. 2016). Recent analysis by researchers with DFO found that a 50% reduction in the number of hatchery-born coho released into the Salish Sea did not change the average number of coho surviving to their first winter, and adult coho run sizes increased following reductions in hatchery production (Beamish and Neville 2021). Like the Salish Sea, much of the Central Coast is characterized by inland marine waterways, including a complex network of fjords and islands where juvenile salmon forage and grow en route to the North Pacific. Growth and survival during this first spring and summer can be limited by competition with other juvenile salmonids and is a key determinant of subsequent adult recruitment (Beamish et al. 2004; Connors et al. 2020). Fishery restructuring is also an opportunity to rescale fishing effort and shift to gear types more appropriate to the available catch and conservation risks. First Nations and Federal co-managers are defining new approaches for monitoring and managing fisheries under emerging FRRA, creating opportunities for new management, harvesting, and governance regimes to emerge.

As Canada and other colonial societies seek to redress the harms of past policies and resource management regimes on Indigenous People, working in partnership with Indigenous and local communities to sustain healthy wild salmon populations must be front and center. Colonization and the consolidation of management authority within centralized management agencies disrupted thousands of years of continuous place-based Indigenous resource stewardship, thereby undermining the sovereignty and self-determination of Indigenous Peoples and contributing to the present crisis of collapsing salmon populations throughout British Columbia (Artelle et al. 2021; Atlas et al. 2021c; Reid et al. 2022). The staggering decline of chum salmon we document here serves as a stark reminder of the dangers of inaction: we risk losing food security and economic opportunities for coastal and Indigenous Peoples around the Pacific Rim and the collapse of social–ecological systems that have evolved over more than 10 000 years of continuous human occupation and resource stewardship. Recovery of salmon social–ecological systems therefore hinges not only on precautionary management implemented through existing management processes and governance regimes, but upon a wholesale reimaging of how and where fisheries are conducted, and how Indigenous knowledge and sovereignty are respected in management decisions.

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WIA contributed to the analysis, writing, and data collation. KLW supported analysis, assisted with data visualization and writing. CKW contributed to scoping, convening, and writing. JEM supported project scoping, data interpretation, and writing. CNS contributed to scoping and writing of the manuscript. MR likewise contributed to scoping and writing of the manuscript. MRS contributed to the writing of the manuscript.

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Appendix A

We fit simple linear regressions to quantify the relationship between exploitation rates (ERs) estimated by English et al. (2018) and the ERs reported in the DFO Post Season Review (PSR). The two values differ because the ERs presented in the PSR are calculated using commercial harvest data from Area 8 escapement data for only a subset of major stocks, and the number of stocks visited annually in Area 8 is not constant.

Fig. A1. Relationship between the exploitation rate (ER) estimated for the Bella Coola Dean conservation unit (CU) in the DFO post season review, and the ER estimated by English et al. (2018). [Colour online.]
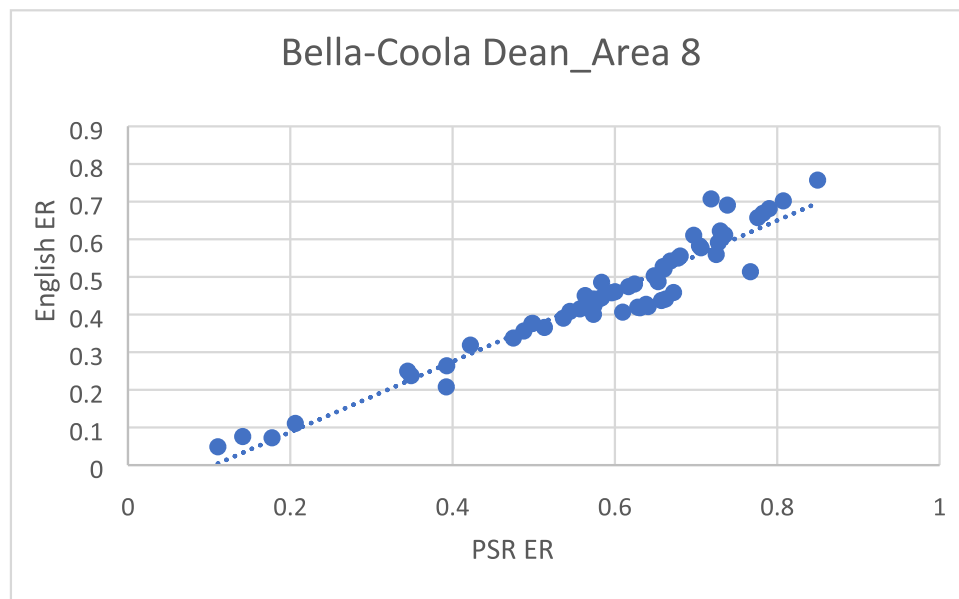

Fig. A2. Relationship between the exploitation rate (ER) estimated for the Spiller/Fitz Hugh/Dean conservation unit (CU) in the DFO post season review, and the ER estimated by English et al. (2018). [Colour online.]