1 Using hierarchical models to estimate stock-specific and seasonal variation in ocean
2 distribution, survivorship, and aggregate abundance of fall run Chinook salmon.
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28 Supplement S2: Detailed methods
29 Supplement S3: Smolt outmigrant data description

30   **Abstract**

31   Ocean fisheries often target and catch aggregations comprised of multiple populations or

32   groups of a given species. Chinook salmon originating from rivers throughout the west

33   coast of North America support mixed-stock ocean fisheries and other ecosystem

34   components, notably as prey for marine mammals. We construct the first coastwide state-

35   space model for fall Chinook salmon tagged fish released from California to British

36   Columbia between 1977 and 1990 to estimate of seasonal ocean distribution along the

37   west coast of North America. We incorporate recoveries from multiple ocean fisheries

38   and allow for regional variation in fisheries vulnerability and maturation. We show that

39   Chinook salmon ocean distribution depends strongly on region of origin and varies

40   seasonally while survival showed regionally varying temporal patterns. Simulations

41   incorporating juvenile production data provide proportional stock composition in

42   different ocean regions and the first coastwide projections of Chinook salmon aggregate

43   abundance. Our model provides an extendable framework that can be applied to

44   understand drivers of Chinook salmon biology (e.g. climate effects on ocean distribution)

45   and management effects (e.g. consequences of juvenile production changes).

Introduction

Migratory species present unique challenges for conservationists and managers. A diversity of taxa from insects through mammals occupy and migrate across vast areas of the Earth's surface (Martin et al. 2007; Block et al. 2011), and the movements of many marine fish, marine mammal, and sea turtle species pose challenges for sustainable management as multiple regulatory bodies must collaborate on fishing and management.

Population structure, where individuals in a given area consist of multiple, distinct groups, may further complicate marine management. Particular populations, sub-populations, or life-history types within a single population often co-occur (e.g. Schindler et al. 2010; Teel et al. 2015; Satterthwaite and Carlson 2015), but the contribution of each group to the aggregate abundance in migratory species may vary spatially and temporally and therefore the importance of a given component in one region often differs from the same component in another. Portfolio theory (Markowitz 1952; Koellner and Schmitz 2006) has shown that population complexes with a diverse set of contributing groups will result in reduced variation in aggregate abundance (Hilborn et al. 2003; Schindler et al. 2010, 2015). Most applications of portfolio theory to natural systems have emphasized the temporal attributes of aggregate abundance, showing how increased diversity among components (Moore et al. 2010; Thorson et al. 2014; Satterthwaite and Carlson 2015) or life-history diversity (Hilborn et al. 2003; Schindler et al. 2010; Greene et al. 2010) lead to resilience and stability in aggregate.

For migratory species, it is important to recognize that the portfolio framework is relevant in a spatial as well as temporal context (Griffiths et al. 2014). Movement may create a shifting mosaic in which the distribution of both the aggregate abundance and the

69   individual contributors to abundance shift in space and time. Furthermore, while fisheries

70   are often focused on maintaining robust aggregate abundances over the long term,

71   conservation decisions are often focused on avoiding low abundance for component

72   populations or sub-populations. Management actions to protect or conserve these less

73   productive stocks is generally referred to as 'weak stock' management. Thus, conflict

74   between managing aggregate abundance and the protection of a particular population

75   may arise and strategies for spatial and temporal management must consider this conflict.

76   Chinook salmon (*Oncorhynchus tshawytscha*) are a highly migratory species

77   native to the Pacific coast of North America. In the eastern Pacific, Chinook salmon

78   occur along the continental shelf and into the open ocean, ranging from central California

79   to Alaska (Healey 1991), where they support extensive and economically valuable

80   fisheries (PFMC 2016a; PSC 2016). Chinook salmon also serve important roles in the

81   ecosystem, as prey for both marine predators such as sharks, pinnipeds, and killer whales

82   (Ford 2012; Chasco et al. 2017) and terrestrial predators including birds and bears (Good

83   et al. 2007; Schindler et al. 2013). Chinook salmon inhabiting any given coastal area are

84   comprised of fish from multiple stocks (Healey 1991; Norris et al. 2000; Weitkamp

85   2010). Understanding the spatial and temporal dynamics of Chinook salmon throughout

86   their range is critical, as some populations of the northeast Pacific are depleted, and listed

87   under the US Endangered Species Act (ESA) or Canadian Species At Risk Act (SARA).

88   While Chinook salmon are one of the iconic species of the northeast Pacific and

89   subject to large-scale fisheries and extensive research (Ruckelshaus et al. 2003), their

90   marine spatial distribution and migration patterns are poorly understood. Some stock-

91   specific distributions for juvenile Chinook salmon are available from research surveys

92   (Trudel et al. 2009; Tucker et al. 2011; Burke et al. 2013) while others have provided

93   stock-specific estimates of ocean distribution using coded-wire tags (CWT; Norris et al.

94   2000; Nandor et al. 2010; Weitkamp 2010) or genetic stock identification (Winans et al.

95   2001; Bellinger et al. 2015; Satterthwaite et al. 2015). The vast majority of these tagging

96   and sampling programs are a result of decades of intensive marking and tagging of

97   hatchery raised fish (Nandor et al. 2010; Weitkamp 2010; Satterthwaite et al. 2013).

98   Fisheries management models such as those developed and used annually by the Pacific

99   Salmon Commission's Chinook Technical Committee (CTC; e.g., CTC 2015) use

100   information from CWT recoveries in many fisheries along the coast in concert with

101   spawning escapement to provide information about the abundance and status of Chinook

102   salmon stocks from Oregon to Alaska. The CTC's work provides vital fisheries

103   management advice annually, but it does not include information on Chinook salmon

104   stocks from California and does not provide direct estimates of spatial distribution.

105   In the most comprehensive peer-reviewed coastwide study to date, Weitkamp

106   (2010) examined tag recoveries for 93 Chinook salmon stocks in ocean fisheries from

107   California to the Bering Sea to produce the only comprehensive description of inferred

108   stock-specific spatial distributions. While Weitkamp (2010) was groundbreaking in its

109   breadth and scope, it did not account for fishing effort nor changes in seasonal

110   distribution, meaning that estimated distributions may be biased by uneven fishing and

111   fisheries sampling effort in space and time. Because of differences in stock-specific

112   tagging rates, numbers of tag recoveries could not be compared among stocks to infer

113   relative densities. More targeted studies have inferred season-specific local densities from

114   catch per unit effort (CPUE), typically involving fewer stocks, a smaller spatial range,

115   and only considering one gear type at a time (Norris et al. 2000; Sharma et al. 2013;

116   Satterthwaite et al. 2013, 2015). Although Newman (1998) developed a state-space

117   framework for integrating spatial data on tag recoveries into a demographic model

118   including mortality and movement, there are limited applications of this approach to

119   empirical datasets aside from a coho salmon (*Oncorhynchus kisutch*) stock in

120   Washington (Newman 2000).

121   Here we explore the spatio-temporal dynamics of fall-run Chinook salmon

122   occurring along the Pacific coast of North America using an integrated modeling

123   approach. We use tag release and recovery data from ocean harvest along with data on

124   commercial and recreational fishing effort to estimate a spatio-temporal model for fall

125   Chinook salmon. By modeling all stocks simultaneously, our model shares information

126   among stocks in a biologically reasonable way and leverages the fact that fish derived

127   from different rivers swim in the same areas of the coastal ocean to improve estimates of

128   shared processes. We provide estimates of seasonal ocean distribution and abundance for

129   Chinook salmon populations representing the full geographic extent of North American

130   fall Chinook salmon. To our knowledge, this is the first coastwide analysis of seasonal

131   patterns in density that simultaneously accounts for multiple axes of biological variation

132   among Chinook stocks (differences in maturation, variation in ocean distribution, and

133   spatio-temporal variation in early ocean survival), variation in detection probabilities due

134   to fisheries effort and gear type vulnerabilities, and both measurement and process error.

135   After estimating our biological model, we combine estimates of Chinook salmon ocean

136   distribution with regional estimates of juvenile Chinook salmon production to generate

137   estimates of the cumulative abundance and distribution of fall Chinook salmon

138   abundance along the entire west coast of North America on a seasonal basis. This

139   unifying statistical framework improves our understanding of Chinook salmon biology

140   and provides a methodology from which it is possible to explore changing ocean

141   distributions, spatio-temporal variation in mortality, and interactions with other species

142   and fisheries.

143

144   **METHODS**

145   *Study Species*

146   Chinook salmon (*Oncorhynchus tshawytscha*) are the largest of the northeast

147   Pacific salmon and native populations spawn in rivers along the northern Pacific Ocean

148   from northern Japan to Siberia along the Asian coast and central California to Alaska

149   along the North American coast (Healey 1991; Quinn 2005). Although considerable life-

150   history diversity exists both across and within watersheds, populations are typically

151   classified based on the season when adults return to their natal rivers to spawn (run

152   timing, generally designated as fall, winter, spring, and summer runs). Adult run timing

153   may be a good predictor of additional aspects of life-history including the timing of major

154   events in the freshwater phase of the lifecycle (Healey 1991). The life history variation in

155   run-timing for adults also translates into differences in when juveniles of each run type

156   migrate to the ocean. For example, fall run Chinook salmon juveniles typically emigrate

157   to sea during their first year of life while spring run fish typically spend an extra year in

158   freshwater before emigrating. There can be considerable variation within runs, and

159   variability in run timing appears to have evolved independently many times (Waples et

160   al. 2004; Moran et al. 2012). Adults typically spend 2-4 years at sea with northern

161   populations more often maturing at older ages (Myers et al. 1998; Quinn 2005).

162   Considerable loss and degradation of freshwater habitat, along with a desire to

163   supplement harvest, has led to the establishment of numerous hatchery programs

164   coastwide (Naish et al. 2007). Hatchery production now substantially exceeds natural

165   production in many regions (Table S3.1). Many hatchery fish (and a small number of

166   wild fish) are tagged with CWT (Johnson 1990) which contain a numeric identifier

167   unique to each batch of fish, providing information on stock-of-origin, time of release,

168   and other details about a hatchery release group or wild fish collection event.

169

170   *Data*

171   Although there are multiple Chinook salmon run types on the west coast of North

172   America, fall Chinook salmon are the most dominant and data rich (both in terms of

173   population size and tagging programs). Thus, we restricted our analysis to developing

174   models of fall Chinook salmon ocean distribution, with the idea that these general

175   methods are extendable and applicable to other life-history types and species. We used

176   three sources of data to estimate ocean abundance and distribution. First, we extracted

177   information on CWT releases from the Regional Mark Information System (RMIS;

178   http://www.rmis.org/rmis_login.php?action=Login&system=cwt). We extracted

179   information from tagged releases from 43 major hatcheries spanning central California to

180   Vancouver Island British Columbia and representing fish released between 1978 and

181   1991 (from brood years 1977 to 1990). Fall Chinook salmon are rare in rivers north of

182   British Columbia, where the majority of Chinook salmon runs are spring run. The range

183   of years analyzed was constrained primarily by the availability of fishing effort data (see

184   below) and the high intensity of fishing effort during this period. If the model failed for

185   years with substantial fishing effort, it would likely fail for more recent years which have

186   seen coastwide declines in Chinook salmon fisheries. For central Oregon to Canada, we

187   selected hatcheries based on their previous identification as major hatcheries associated

188   with indicator stocks by the Pacific Salmon Commission (CTC 2015). Major hatcheries

189   from southern Oregon and California were selected based on the indicator stocks used by

190   the Pacific Fishery Management Council (PFMC 2016b). Table S1.1 presents a complete

191   list of hatcheries included in the analysis.

192   For this set of years and hatcheries, we identified 2,196 unique CWT tag codes to

193   include, representing approximately 83 million CWT fish released during the study

194   period (see Table S1.6 for a complete list). This list of tag codes excludes releases where

195   comments indicated major problems with the release (e.g. high disease prevalence). We

196   then aggregated tag codes released by individual hatcheries, brood year, brood stock,

197   release year, and release season. For hatcheries that released fall Chinook salmon at

198   multiple points during the year (i.e., they release both fingerling and yearling Chinook

199   salmon), we categorized tag release into two groups based on season of release. This

200   consolidation resulted in 454 unique hatchery-brood year-release season combinations

201   (see Table S1.1), each of which we refer to as a "release" in subsequent sections.

202   Second, we compiled recovery information for each identified tag code from

203   RMIS. We noted the recovery date, location code, and port at which the fish were

204   sampled. As each tag recovery in the RMIS database has an associated expansion that

205   aims to correct for the proportion of the catch sampled, we used the expanded number

206   reported for each of the tag codes in the RMIS database. Using the expanded number

207   helps account for temporal and spatial variation in the sampling intensity of the fisheries

208   catch. For marine recoveries, we assigned each recovery to the fishing gear type used, to

209   one of 17 coastal regions (Fig. 1), and to one of four seasons (spring: April-May;

210   summer: June-July; fall: August-October; winter: November-March). Ocean recovery

211   areas were derived largely from those used by Weitkamp (2010). The division of seasons

212   was informed by both the biology of fall Chinook salmon (they enter their natal rivers to

213   begin their spawning migration in the fall) and practical considerations (there is much

214   less information about the spatial distribution of fish in the winter due to reduced salmon

215   fishing effort; see Fig. S1.1-S1.4). We only include recovery information from the three

216   fishing gear types for which we have effort information (see below). In total, this

217   included an estimated 527,711 ocean recoveries for the focal release groups. In addition

218   to the ocean recoveries, we use freshwater recoveries (both from river fisheries and

219   escapement to hatcheries and natural spawning areas) reported in RMIS to parameterize

220   some model components (see *Observation Model* below). As illustrative examples, we

221   provide recovery data from the commercial troll fishery for two releases (Fig. 2).

222   Third, we compiled data on commercial and recreational fishing effort from the

223   United States and Canadian government sources. For commercial troll, treaty troll, and

224   recreational fisheries along the outer coast of Washington, Oregon, and California, we

225   used the PFMC 'blue book' (http://www.pcouncil.org/salmon/background/document-

226   library/historical-data-of-ocean-salmon-fisheries/). Recreational effort in Puget Sound,

227   Washington was extracted from published WDFW reports (e.g., WDFW 1979). Alaska

228   troll effort was supplied through a data request to the Alaska Department of Fish and

229   Game (ADFG) and included both power troll and hand troll gear types. We detail how we

230   combine these two effort types in Supplement S2. We acquired Canadian troll effort

231   through a data request to the Canadian Department of Fisheries and Oceans (DFO) for

232   1982-1995. Earlier years of Canadian troll effort were extracted from official Canadian

233   government data reports (British Columbia Catch Statistics, available at

234   http://www.pac.dfo-mpo.gc.ca/stats/comm/ann/index-eng.html). The lack of publically

235   available data describing Canadian commercial troll fishing effort targeting Chinook

236   salmon between 1996 and 2004 limited our analysis to 1979-1995 and to brood years

237   1977-1990. We hope to expand the time-frame in future analyses. Recreational fishing

238   effort data for the study period were also not available from Canada (except for some

239   years in the Strait of Georgia, Fig. S1.4) or from Alaskan waters. We describe how we

240   accounted for these gaps in the model description section below. Complicating matters,

241   each type of effort is reported in different units; recreational effort is reported in units of

242   angler-days in the United States and boat-days in Canada, troll effort is reported in units

243   of boat-days, and treaty troll in units of deliveries (see Supplement S1 and S2 for fishing

244   effort for each gear type)

245   Troll, treaty troll, and recreational fisheries account for >95% of CWT ocean

246   recoveries for our release groups. The remaining recoveries were largely from

247   commercial gillnet and seine fisheries with a few other rare types (e.g. test fisheries).

248   Many gillnet and seine fisheries incidentally catch Chinook salmon, but some are active

249   in fisheries in the mouth of the natal river or near the hatchery ("terminal" fisheries).

250   Since many net fisheries only catch fish from individual sources, they are not a

251   representative sample of multiple stocks within regions, and including them could affect

252   model inferences about ocean distribution of Chinook salmon. Therefore, we did not

253   incorporate data from these sources, but address the implications for these missing

254   fisheries in the methods and discussion.

255

256   **Model**

257   To estimate the seasonal abundance and distribution of fall Chinook salmon, we

258   simultaneously model the abundance and distribution of hatchery fall Chinook salmon

259   released into 10 of the 17 ocean regions (Fig. 1) over 14 years (brood years 1977-1990).

260   Our model tracks the abundance of fish from the spring of age 2 (defined as calendar year

261   minus brood year) to fall of age 6, encompassing 19 seasonal time steps. As conventions

262   for describing the age of Chinook salmon are confusing and vary regionally and by run

263   type, we provide a table outlining fall Chinook salmon age classification used here (Table

264   S1.2). Unfortunately, some model components such as fishing mortality vary and are

265   reported by calendar year and season, not model season, and so have appropriate

266   subscripts to reflect this complexity.

267   To generate estimates of the abundance of fall Chinook salmon from distinct

268   regions, we need to quantify at least six core processes: 1) the number fish entering the

269   ocean from natal rivers; 2) the natural mortality of juvenile fish; 3) the natural mortality

270   of adult fish; 4) fishing mortality by age and region; 5) the spatial distribution of fish in

271   the ocean; and 6) the age-specific loss of fish from the ocean due to maturation (salmon

272   leaving the ocean and returning to their natal streams to spawn). We use a state-space

273   framework which separates the biological processes (fish moving, dying from natural

274   causes or fisheries, etc.) from what we observe about these fish populations (generally

275 fisheries catches). This allows us to explicitly account for and make inferences about

276 populations in locations and areas which may have no observations or missing data.

277   Using parameter estimates from the model and estimates of the number of

278 juvenile fall Chinook salmon, we make projections of the number of Chinook salmon in

279 each ocean region for fish originating from different regions and by age class (see

280 *Projected ocean distribution of fall Chinook salmon*). Due to the complexity of the model

281 we outline the process and observation models briefly in the main text and highlight

282 model components that are novel to this work. We present a comprehensive model

283 description in online Supplement S2. We provide a full list of parameters and subscripts

284 used in model description in Table S2.1.

285

286 *Process Model*

287   We track the number and distribution of each Chinook salmon release for the

288 entirety of its life-cycle. Each release is associated with a particular natal region, brood

289 and release year. Because we use hatchery releases, the initial number of fish in each

290 release group is treated as known without error. We estimate an independent juvenile

291 mortality rate – spanning the period from date of release to season 1 of the model – for

292 each release and denote it ϕ_i for release *i*. During the 19 seasonal time steps of the model

293 (subscript *a;* Table S1.2), we model the total abundance of each release coastwide as an

294 unobserved, latent variable, $N_{i,a}$. In each season, fish are subjected to age-specific natural

295 mortality rate, M_a, and are captured in commercial and recreational fisheries at fishing

296 mortality rates, F_- (subscripts suppressed, see below) that are determined by the fishing

297 effort in a particular region and the age- and gear-specific vulnerability. Both natural and

13

298   fishing mortality are modeled as density-independent processes and modeled as occurring

299   simultaneously. An important assumption of the model is that fish of the same age in the

300   same spatial region and season are considered to be equivalently vulnerable to ocean

301   fisheries occurring in that spatial box and season. We incorporate information on

302   retention size limits for each year, season, and spatial region (see Table S1.5).

303   Additionally, we include a process variability term to incorporate additional, unmodeled

304   aspects of fisheries and the environment.

305   The distribution of Chinook salmon among the 17 ocean regions varies among

306   seasons and is estimated within our population dynamic model. We let $\theta_{r,l,s}$ be the

307   proportion of fish from natal region r, present in ocean region l, at the beginning of

308   season s, and estimate $\theta_{r,l,s}$ within the model. For a given natal region and season, across

309   all locations the proportions must sum to 1. We assume that fish from the same natal

310   region, but potentially different rivers or hatcheries, have identical ocean distributions in

311   a given season and that ocean distributions within a season are the same across Chinook

312   salmon ages. Weitkamp (2010) suggested that ocean distribution may vary with ocean

313   age (ocean age = recovery year – release year) with very young fish (ocean age = 1)

314   found closer to their natal river mouth than older fish (ocean ages 2 to 5), but with the

315   older age classes being broadly similar in distance from their natal river (their Tables 5,

316   6). As our model starts well into ocean age 1 (using Weitkamp's (2010) age accounting;

317   see Table S1.2) and focuses on modeling older fish – those that are susceptible to ocean

318   fisheries – this model assumption matches available information. Although results from

319   Satterthwaite et al. (2013) indicates modest differences in age-specific distributions of

320   older fish from a single stock, the statistical significance of these differences was not

321   assessed. Therefore, modifications that allow for age-dependence in ocean distribution

322   should be an important consideration in future work, but are unlikely to fundamentally

323   change our conclusions.

324   In the fall, adult Chinook salmon leave the ocean to return to the freshwater

325   spawning grounds. We model spawning as the proportion of fish leaving the ocean in the

326   middle of the fall season. We define a small number of ocean regions near the river

327   mouth from which fish can enter their river to spawn (see Table S1.3). This ensures that

328   fish cannot instantaneously jump thousands of kilometers into their natal river, but does

329   acknowledge that fish from several ocean regions may contribute spawning fish. This

330   assumption differs substantially from other Chinook salmon models which do not

331   explicitly consider spatial distributions (e.g. CTC 2015). We model the proportion of

332   mature fish leaving the ocean as a logistic function of age in years. Again, we

333   acknowledge alternate formulations for leaving the ocean to spawn may be appropriate.

334

335   *Observation Model*

336   There are few direct, fisheries independent surveys of Chinook salmon in the

337   ocean, but Chinook salmon were caught coastwide across a range of fisheries (but see

338   surveys of very young Chinook salmon; Trudel et al. 2011; Burke et al. 2013). We use

339   spatially explicit recovery data from three fisheries gear types in our analysis

340   (commercial troll, recreational hook and line, and commercial treaty troll) to calculate the

341   expected catch of fish from release i, gear g, ocean region l, season s, and calendar year c

342   as a function of the number of age a Chinook salmon present and fishing mortality in

343   each region. For winter, spring, and summer seasons (seasons without fish escaping to

344   freshwater), the catch follows the Baranov catch equation (Baranov 1918; Beverton and

345   Holt 1957)

$$\mu_{i,a,l,g} = \frac{F_{a,s,c,l,g}}{(M_a + \sum_g F_{a,s,c,l,g})} N_{i,a}\theta_{r,l,s}\left\{1 - \exp\left[-\left(M_a + \sum_g F_{a,s,c,l,g}\right)\right]\right\} \quad (1)$$

346   For the fall season, let $N_{i,a,l,S}$ be the number of Chinook salmon present in the

347   ocean after spawning fish enter the river midway through the season. Then catch for the

348   entire fall season is

$$\mu_{i,a,l,g} = \frac{F_{a,s,c,l,g}}{(M_a + \sum_g F_{a,s,c,l,g})} N_{i,a}\theta_{r,l,s}\left\{1 - \exp\left[-0.5\left(M_a + \sum_g F_{a,s,c,l,g}\right)\right]\right\}$$

$$+ \frac{F_{a,s,c,l,g}}{(M_a + \sum_g F_{a,s,c,l,g})} N_{i,a,l,S}\left\{1 - \exp\left[-0.5\left(M_a + \sum_g F_{a,s,c,l,g}\right)\right]\right\}$$

349   (2)

350   We use two likelihoods to connect the estimated catch ($\mu_{i,a,l,g}$) to the observed

351   catch. First, for all year-season-location-gear combinations for which we have either

352   documented fishing effort and catches (all troll fisheries and recreational fisheries in the

353   California, Oregon, Washington, and part of British Columbia) or only observed catches

354   (recreational fisheries in most of Canada and Alaska), we model the probability of

355   observing greater than zero Chinook salmon as a Bernoulli random variable,

356        $G_{i,l,g,a} \sim Bernoulli(logit^{-1}[logit(W_{l,s,c,g}\pi_0) + \pi_1\log(\mu_{i,a,l,g})])$ (3)

357   where G takes on a value of 1 if the observed catch, C, is positive, and a value of 0

358   otherwise. Here, $W_{l,s,c,g}$ is the fraction of the catch sampled as extracted from the RMIS

359   database (see Table S1.5). The parameters π_0 and π_1 serve to transform the catch to the

360   logit scale and acknowledge that some stocks may be present and caught in fisheries even

361   if the sampling of the catch does not observe them. As sampling effort for CWT has

362 varied both spatially and through time, we calculated the observed sampling fraction

363 from the RMIS database for each tag recovery and aggregated them by season, spatial

364 region, and gear type. We calculated the median value for the sampling fraction among

365 all reported catches in each region and season and set $W_{l,s,c,l}$ to be the median sampling

366 fraction. We estimate a single offset, π_0, which is a proportion bounded between 0 and 1

367 to account for potential non-independence among individual sampled fish in the catch.

368 Finally, we estimate a slope, π_1, to scale how observation probability increases with

369 increases expected catch.

370 　　　　The second component of the likelihood consists of linking the observed catches

371 to the estimated catches if greater than zero Chinook salmon were observed.

372 $$C_{i,l,g,a} \sim LogNormal(\log(\mu_{i,a,l,g}), \exp(\sigma_0 + \sigma_1 log(\mu_{i,a,l,g}))$$

373 $$\text{if} \quad C_{i,l,g,a} > 0 \qquad (4)$$

374 Here observation error term for the dispersion between observed and predicted catch has

375 two parameters (σ_0, σ_1) and allows the observation error to vary with larger values of

376 predicted catch.

377 　　　　As expressed in eq. 3 and 4, our models explicitly acknowledge that our

378 observations of fisheries catches of particular release groups are uncertain (i.e. there is

379 observation error). This contrasts with some models used in salmon management (e.g.

380 CTC 2015) and cohort reconstruction approaches used by other authors (e.g. Coronado

381 and Hilborn 1998; Kilduff et al. 2014) that assume error free observation of catches.

382 　　　　In addition to recoveries from fisheries, we need to account for the Chinook

383 salmon that leave the ocean and return to their natal river or hatchery and complete their

384 life-cycle. Ideally, we would have a likelihood component corresponding to the observed

385 fish in rivers and hatcheries for each release group. Unfortunately, preliminary

17

386 examination of the RMIS database revealed notable deficiencies in the freshwater

387 recovery data; we identified some individual tag groups from throughout the study region

388 with many ocean recoveries but zero or near zero freshwater recoveries. Such

389 discrepancies have been noted by other authors (e.g. Baker and Morhardt 2001).

390 Furthermore, we compared freshwater recoveries reported in RMIS with recoveries used

391 in several stock assessments. For example, we were unable to reproduce the results

392 reported for Iron Gate and Trinity River hatcheries in Hankin and Logan (2010), which

393 we know included significant quality control and additions to the data beyond the raw

394 RMIS data. We could not identify which RMIS freshwater recovery data were reliable

395 and which were not and so we elected to incorporate only information about the relative

396 occurrence of different age Chinook salmon in freshwater recoveries, not the actual

397 expanded numbers of total observed freshwater recoveries. We detail these approaches in

398 the online supplement and provide the mean estimated proportion returning at each age

399 for each region in Table S1.4. This aspect of our model is important because by not using

400 information about in river recoveries we rely on catches in ocean fisheries to estimate

401 both spatial distributions and the various parameters that scale overall abundance (e.g.

402 juvenile survivorship and gear specific catchability). As a result, our estimates of

403 parameters that the scale total abundance of Chinook salmon – including most

404 prominently juvenile survival and catchabilities – are difficult to estimate and likely mis-

405 estimated by an unknown factor. However, this factor will apply to all modeled releases

406 and thus does not change the relative order of survivorships among releases. We note that

407 virtually all other estimates of survivorship for salmon based on cohort reconstructions

408   face this problem as well (Coronado and Hilborn 1998; Kilduff et al. 2014, 2015; CTC

409   2015).

410   Finally, we added two constraints to penalize biologically unreasonable life-

411   histories within the model and help account for our imprecision in freshwater recovery

412   data (see Supplement S2 for details). First, we constrained the model so that on average,

413   between age 1 and 6 greater than 99% of individuals are assumed to leave the ocean by

414   the final model time step. They must either die from natural causes or fisheries or leaving

415   the ocean for freshwater. This ensures the model avoids parameter spaces where there are

416   a large number of old fish present in the ocean (age 7+) and which accords with Chinook

417   biology. Second, we constrained the model so that the total number of fish from a single

418   cohort surviving from release to make a spawning migration to freshwater average (all

419   ages summed) averaged nearly 2%. For both constraints, we allow for substantial

420   variation among releases so individual releases may differ substantively from these

421   average rates (Supplement S2).

422

423   *Estimation*

424   We implemented the above state-space model in STAN (Gelman et al. 2015,

425   Carpenter et al. 2016) as implemented in the R statistical language (R Core Team 2016,

426   Stan Development Team 2016). STAN uses a Hamiltonian Monte Carlo (HMC) sampling

427   (Neal 2011; Hoffman and Gelman 2014; see Monnahan et al. 2016 for a description

428   targeted at ecologists). Table S2.1 provides a description of all parameters and prior

429   distributions. STAN estimates the joint posterior distribution of parameters and latent

430   states. For all results reported here we used five chains using a warmup period of 300

431   iterations and 2000 monitoring iterations. We used model diagnostics such as checks for

432   divergent transitions, comparisons among chains (Gelman-Rubin statistics), and posterior

433   predictive checks.

434

435   *Analysis of juvenile survival estimates*

436   After estimation of the juvenile mortality rate for each of the 454 release groups,

437   we constructed a linear mixed model to understand drivers juvenile variation. We used

438    $\log(\phi_i)$ as the response variable and explained variation in survivorship using number of

439   months between release and model start (*n_month*) as a continuous fixed effect and year,

440   origin region, and *n_month* nested within origin region as random effects. This model

441   allows fish from different origin regions and fish that spend more time at liberty in the

442   river and ocean to have different juvenile survivorships. Past analyses comparing early

443   mortality among releases have often ignored such attributes (Coronado and Hilborn 1998;

444   Kilduff et al. 2014, 2015).

445

446   *Projected ocean distribution of fall Chinook salmon*

447   The above model provides estimates of many parameters that are important for

448   determining the abundance and distribution of Chinook salmon. However, since hatchery

449   releases of Chinook salmon are not tagged with CWT at constant rates, and hatchery-

450   versus natural-origin fish make up substantially different proportions of different stocks,

451   CWT data alone cannot be used to generate estimates of Chinook salmon abundance in

452   the ocean. We use model estimates in conjunction with estimates of out-migrating

453   juvenile Chinook salmon leaving rivers and hatcheries to provide predicted fall Chinook

454   salmon abundances in space and time. We outline an approach to simulating Chinook

455   salmon using model estimates and show how both the proportional contribution of

456   individual stocks and aggregate abundance change under two illustrative scenarios.

457   Generating predicted fall Chinook salmon distributions require specifying three

458   model components. First, we need estimates of the number of juvenile fall Chinook

459   salmon produced by each origin region (including both hatchery and wild). Second, we

460   need to specify the fishing mortality occurring in space and time. Finally, we need to

461   determine scenarios for juvenile mortality.

462   For the first scenario, we compiled available information on juvenile fall Chinook

463   salmon production from hatchery and wild sources for each origin. We present

464   approximate estimates of juvenile production in Table S3.1 and detail the methods and

465   data sources used for each area estimate in Supplement S3. For fishing mortality, we

466   used the median mortality for each area and season estimated across the observed time-

467   series (1979-1995). For juvenile mortality, we used a simple assumption: all juvenile fish

468   experience the same mortality regardless of their origin. Together these assumptions are

469   designed to reflect the distribution of fall Chinook salmon in the ocean under typical

470   ocean conditions, not the distribution and abundance in a particular year. We refer to this

471   as the "base" scenario.

472   For the second scenario, we used the same value of fishing mortality (median) and

473   juvenile mortality (mean, spatially invariant) as the base scenario. But for Chinook

474   salmon production, we reduced hatchery production in Puget Sound (PUSO) by half from

475   37 to 18.5 million. We then compare the abundance and distribution of Chinook salmon

476   in the ocean under the base and "PUSO hatchery" scenarios to illustrate the consequences

477 of changing aspects of hatchery production for ocean abundance and distribution. Other

478 assumptions and simulations could be used to generate distributions and abundance under

479 other scenarios but we provide a relatively simple, hypothetical scenario here as an

480 example of the possibilities of this approach.

481 For both scenarios, we use Monte Carlo methods to sample from the posterior

482 estimates of estimated parameters and simulate abundance and distribution through time.

483 As we have fixed juvenile survival, fishing mortality, and the number of juveniles arising

484 from each region, variation only reflects uncertainty in the spatial distribution and in the

485 parameters associated with spawning. Thus the simulations underestimate the overall

486 uncertainty in abundance and distribution. We also use the average process error for each

487 origin region (Fig. S1.7), which further underestimates uncertainty.

488

489 **Results**

490 Despite the large amount of data and many latent states and parameters, the model

491 converged and produced reasonable biological estimates for parameters. The effective

492 sample size for all parameters was greater than 1,000 and maximum $\hat{R}$ (a measure of

493 model convergence) was less than 1.01. We focus on two model components in the main

494 text before turning to two simple scenarios to understand the attributes of Chinook

495 salmon ocean aggregations using simulations. We present posterior estimates of model

496 parameters in the online supplement along with figures of other major model

497 components.

498

499 *Spatial distribution of Chinook salmon by origin and season*

500   We detected strong differences in seasonal ocean distribution among different

501   origin regions for fall Chinook salmon (Fig. 3). A common pattern across stocks was that

502   fish were generally distributed near their origin region. For example, fish originating

503   between California and southern Oregon (SFB, NCA, SOR) remained in United States

504   waters south of the British Columbia border (regions WAC and south) and were observed

505   rarely in Canadian and Alaskan waters in our dataset. Fish from the most northern region,

506   SWVI, were almost never present south of their origin, and were estimated to be almost

507   exclusively in Alaska and Canada. Fish from the Columbia River basin (COL, MCOL,

508   and UPCOL) showed the broadest spatial distribution with significant proportions present

509   in areas from California to Alaska. Virutally all fish estimated to be present in the Salish

510   Sea (PUSO, SGEO) originated there, indicating few Chinook salmon from the outer coast

511   migrate into the Salish Sea.

512   There was a signature of seasonal distributions in fish from nearly all regions.

513   Fish from a given ocean region tended to be more northerly distributed in summer than in

514   winter-spring, and due to spawning migrations Chinook salmon tend to be located near

515   their region of origin during the fall. Ocean distributions also tend to be spatially less

516   concentrated in the winter-spring. In part, this may reflect the uneven length of the

517   seasons in our model as winter-spring spans seven months (November – May) while

518   summer spans only two (June – July).

519

520   *Variation in early mortality*

521   Estimates of mortality for each of the 454 release groups, showed wide variation

522   in mortality rates among releases (range of posterior medians for ϕ_i: 1.39 to 3.29; across

523 release mean = 2.02) corresponding to a range of survivorship of 0.037 to more than

524 0.248 for the period between release and the start of the model in April of brood year + 2.

525 As this range includes releases from all origin regions and years, and thus includes

526 releases with vastly different lengths of time between release and the start of the model

527 (from 1 to 13 months), such large variation is not unexpected. We further summarized

528 model estimates of early mortality in two ways.

529   The linear mixed effect model showed a large effect of *n_month* on $\log(\phi_i)$ with

530 longer time periods associated with increase mortality (slope estimate for *n_month*:

531 0.002(0.002); mean(SE)), indicating that on average, an increase of one month resulted

532 in an increase of 0.002 in $\log(\phi_i)$. There was strong among region variation in the

533 overall mortality intercept (SD among regions = 0.053) and variation among years (SD =

534 0.033). This result coincides with intuition – fish that spend more time in the river and

535 ocean should have greater mortality– but this result does highlight that many past

536 analyses comparing early mortality among releases have ignored such attributes

537 (Coronado and Hilborn 1998; Kilduff et al. 2014, 2015).

538   Second, to make our results comparable to estimates of previous analyses of

539 Chinook salmon early survivorship (Kilduff et al. 2014), we used estimated model

540 parameters to calculate estimated survivorship to the beginning of fall season, age 2. We

541 estimated survivorship for each release in the absence of fishing which accounted for

542 juvenile mortality, natural mortality, and estimated process error, $S_i = \exp(-\phi_i -$

543 $\sum_{a=1}^{a=2}[M_a + \omega_{i,a}])$, where $\omega_{i,a}$ is the estimated process variability. For region

544 combinations that had at least three releases in a given year, we calculated a weighted

545 mean and weighted standard deviation for each region and converted estimated

546   survivorship to z-scores (subtracted the among-year mean, divided by the standard

547   deviation among years; Fig. 4). We use z-scores to emphasize that our results should not

548   be used as estimates of absolute survivorship as we do not include release-specific

549   information about freshwater recoveries or recoveries from marine net fisheries. Due to

550   relatively few releases in SOR, COR, and NOR, we combined these three regions to

551   calculate a single mean for the Oregon coast (denoted "OR"). Survivorship between

552   release and age 2 was highly variable among regions and both within and among years.

553   Interestingly, most regions show substantial temporal variation in survivorship, but years

554   of high and low survivorship are not coincident among regions. Survivorship trends from

555   the Columbia River tended to be fairly coincident (Fig. 4b), as did fish from Oregon and

556   California (Fig. 4c), but similar trends among northern stocks were less obvious (Fig. 4a).

557   Overall there was very high variability within regions in some years (e.g. SFB in 1985)

558   indicating strong differences in survivorship among hatchery releases. As our model does

559   not include abundances of CWT recoveries from freshwater or the small number of

560   recoveries from non-target fisheries, we expect these estimated survivorships biased from

561   their true values. However, the patterns of relative survivorship across time and among

562   regions should be correct.

563

564   *Comparing distributions and cumulative abundance*

565   Given the varied production of Chinook salmon among origin regions (Table

566   S3.1), and the distinct ocean distributions of these fish (Fig. 3), it is not surprising that

567   ocean areas vary substantially in proportional compositions and aggregate abundance of

568   Chinook salmon (Fig. 5). In terms of proportional contribution, seasonal variation is

569   present but not striking. For example, the two southeast Alaska regions (NSEAK and

570   SSEAK) are comprised predominantly of fall Chinook salmon from Canada, Washington,

571   and the Columbia River basin in all seasons, thought the proportion from Columbia basin

572   increases notably from spring to summer. The Salish Sea (regions PUSO and SGEO) are

573   dominated by fish originating in those regions in all seasons, while the Californian ocean

574   regions (MONT, SFB, MEN, and NCA) all have close to or more than 50% of fish

575   present originating from California rivers in all seasons (Fig. 5).

576   While the proportional composition of a given area may be relatively consistent

577   across seasons, the distribution changes for many origin regions simultaneously, resulting

578   in substantial difference among seasons in the cumulative abundance of fall Chinook

579   salmon (Fig. 5). Notably the southern most regions (MONT and SFB) and PUSO have

580   the lowest total abundance in all seasons. In contrast, the northern regions (SSEAK and

581   NSEAK) have relatively low abundance in the spring (Fig. 5a) but the abundance

582   increases markedly during the summer (Fig. 5b) reflecting a northerly shift in

583   distributions of most Chinook salmon stocks (Fig. 3).

584   The cumulative abundance and distribution of fall Chinook salmon also depend

585   strongly on the age range of Chinook salmon considered. For example, the cumulative

586   abundance of fish age 2 and older is substantially different from the distribution of fish

587   age 4 and older (compare Fig. 6e and 6j). Old and large fish are notably more abundant

588   in the northern regions, whereas young and small fish are more available in the southern

589   parts of the range. Note that this change in distribution is not driven by changes in the

590   distribution of fish with age (fish of different ages are modeled as having identical ocean

591   distributions; see *Methods*) but is due instead to strong differences in maturation

592 probability among origin regions. Fish originating from northern areas tend to mature at

593 older ages (Fig. S1.8; Table S1.4). This is readily apparent in comparing the increasing

594 contribution of WAC and SGEO origin fish to total age 4+ fish relative to age 2+ and the

595 concomitant decline of SFB and COL fish (Fig. 6).

596 Finally, comparisons of the base and PUSO hatchery scenarios reveal how

597 changes in management have ramifications beyond the region of origin. We contrast the

598 projected abundance in total abundance between scenarios for age 3+ during the summer

599 (Fig. 7). From a fisheries perspective, most Chinook salmon are vulnerable to both

600 commercial and recreational fisheries by summer age 3 (model season 10; Table S1.2,

601 Fig. S1.6), and we can consider the changes between the two scenarios as affecting the

602 number of fish potentially available to fisheries in a given region. We clearly show that a

603 reduction of hatchery production by half is predicted to change Chinook salmon

604 abundance most dramatically in Puget Sound - a decline in abundance by nearly one-third

605 between base and PUSO hatchery scenarios – but declines of more than 10% are

606 predicted along the Washington coast (WAC) and southern Canadian regions (SGEO,

607 SWVI, NWVI) as well. Changes to PUSO hatchery production are predicted to have a

608 limited effect on the most southerly and northerly regions.

609

610 **Discussion**

611 We present a coast-wide model for fall Chinook salmon that simultaneously

612 models populations originating from California to British Columbia and accounts for

613 biological variation among populations and across time. We explicitly account for the

614 fisheries effort and sampling of fisheries that affect the detection of Chinook salmon

615   populations in the ocean. Together, our model provides a joint estimate of salmon spatial

616   distribution, juvenile mortality, and spatio-temporal estimates of fisheries mortality;

617   processes that are typically estimated and discussed separately (e.g. Weitkamp 2010;

618   Kilduff et al. 2014; CTC 2015). By estimating a joint time-series model that includes

619   populations spanning much of the northeastern Pacific, we are able to move beyond

620   comparisons of CPUE of different Chinook salmon stocks derived from CWT

621   (Satterthwaite et al. 2013; Norris et al. 2000) or Genetic Stock Identification (GSI;

622   Bellinger et al. 2015; Satterthwaite et al. 2015) and translate information from fisheries

623   catch into estimates of spatial distribution and total abundance. Importantly, our work

624   explicitly accounts for missing data – locations and times where no one was fishing and

625   therefore no sampling of Chinook salmon occurred – and thus expands on previous

626   examinations of salmon ocean distribution. Our work is a tool has broad application for

627   understanding patterns of spatio-temporal variation among Chinook salmon and other

628   tagged salmonid populations. Additionally, it is a simulation platform for exploring the

629   consequences of biological variation and management decisions on an important marine

630   resource.

631   We present a step toward understanding the portfolio of Chinook salmon

632   populations contributing to each coastal region in each season. A full exploration of

633   spatial portfolios of Chinook salmon would involve accounting for factors contributing to

634   variation within and covariation among populations and is beyond the scope of this paper.

635   However, basic tenets of portfolio theory do allow us to begin to discuss the implications

636   of the spatial patterns. Broadly, portfolio theory suggest that regions that are more highly

637   reliant on fish originating from one or a few areas would experience more temporal

638 variability than areas with more contributing populations. In the base scenario, three areas

639 had greater than 50% of their abundance derived from a single region in all seasons: two

640 in California (MONT, SFB) and Puget Sound, Washington (PUSO). Additionally, these

641 three areas are also estimated to have the lowest total Chinook salmon abundance.

642 Together these facts suggest these regions with low stock diversity are likely susceptible

643 to periods of especially low abundance. Indeed, the ocean fishery in California and

644 southern Oregon was recently closed for two consecutive years due to poor production of

645 Sacramento River fall Chinook salmon (Lindley et al. 2009; Carlson and Satterthwaite

646 2011), and our simulation of reduced hatchery production highlights the sensitivity of

647 PUSO to changes in local hatchery production (Fig. 7). In contrast, other regions are

648 composed of fish from diverse sources and have a more balanced contribution (e.g. NOR,

649 SWVI, NWVI, NBC, SSEAK, NSEAK) and would be expected to have more stable

650 portfolios over the long-term. Interestingly, these areas largely correspond to locations

651 with important and historically productive Chinook salmon troll fisheries (Southeast

652 Alaska, west coast Vancouver Island, and Oregon coast).

653   From the perspective of predator populations, increased stock diversity (and

654 stability) may translate to increased growth rates. Anecdotally, piscivorous killer whale

655 populations with higher latitude distributions tend to have higher population growth rates

656 (Ward et al. 2013). When considering portfolios, though, it is important to note that this

657 analysis does not include other Chinook salmon life-history types. Spring-run Chinook

658 salmon are the other major life-history type in the northeastern Pacific; other run-types

659 such as winter run Chinook salmon are confined to California rivers and relatively rare

660 (Quinn 2005), though in some locations summer runs are also present. Spring Chinook

661   become more abundant with increasing latitude as all Chinook originating from Alaskan

662   and northern British Columbian rivers are spring-run. Thus, while this analysis presents a

663   reasonable approximation of the Chinook portfolio in California, it dramatically

664   underestimates both the total number of Chinook and life-history diversity present in

665   British Columbia and Alaskan waters in particular. Further work must be done to

666   incorporate the range of life-histories of Chinook salmon into ocean portfolios. Overall,

667   however, portfolio approaches have clear potential for examining the consequences of

668   aggregate patterns of abundance, how they may affect directed fisheries or incidental

669   catch in non-directed fisheries, ecosystem considerations for species dependent upon

670   aggregate abundance such as killer whales or other marine mammal predators, and how

671   portfolio properties vary in response to management or environmental changes.

672   While the outlined model incorporates many important attributes of Chinook

673   biology, it necessarily makes simplifying assumption to accommodate missing or

674   incomplete data and ensure model identifiability. Several major aspects of our estimation

675   model should be the foci of future improvement and research. Most importantly, reliable

676   data pertaining to tag recoveries in the escapement of Chinook to freshwater would

677   greatly improve estimates of both maturation probabilities and ocean survivorship. Such

678   information would have the largest impact on the juvenile survivorship estimates (Fig. 4)

679   and the catchability coefficients ($q;$ see Supplement S2$)$ as they serve to scale the overall

680   abundance of fish available in the ocean for fisheries. However, corralling and verifying

681   such data coast-wide is a major task that is beyond the scope of this project. Other

682   reasonable and important extensions to the model include: *a*) allowing for age-specific or

683   oceanographic driven changes to seasonal distributions; *b*) accounting for population

684   specific growth rate and/or temporal variation in growth which would translate into

685   population difference in vulnerability to fishing gear types; *c*) including the fishing effort

686   data necessary to expand the study time-window to include data from 1996 onward; and

687   *d*) incorporating information from non-mixed stock fisheries such as terminal gillnet and

688   seine fisheries that are not equally likely to capture fish from different origins.

689   Projections of total Chinook salmon abundance could be substantially improved with

690   improved information about the outmigration of juvenile Chinook salmon from rivers

691   coastwide.

692   Much of the interannual dynamics of ocean mortality for Chinook tends to happen

693   very early after migrating downstream, when size and growth play a large role in survival

694   (Beamish et al. 2004; Duffy and Beauchamp 2011). These complex ecological dynamics

695   vary by season and year and require much more data to describe than we could include in

696   this model. Moreover, disentangling juvenile salmon mortality rates in different habitats

697   (rivers, estuaries, coastal ocean) is an ongoing effort. We applied a simple approach -

698   allowing juvenile survival to be independent of adult survival and vary by release – but

699   did not model the full mechanistic processes underlying variation in juvenile mortality.

700   Given the importance of early life-stages on overall population dynamics, connecting this

701   model more closely to early survivorship is likely one of the more crucial aspects to

702   tackle in future work.

703   An important additional consideration for ocean distribution modeling is

704   understanding how to incorporate information from both physical tagging using older

705   technologies (CWT) and information derived from more recently developed and applied

706   genetic stock identification tools (GSI; Satterthwaite et al. 2014; Bellinger et al. 2015). In

707   practice, GSI data provides information about the proportional contribution of fish from

708   different origins in a given area or catch per unit effort information for different stocks.

709   Using GSI data alone without an accompanying analysis of scales or otoliths lacks

710   information about age-structure. As the age-structure will strongly affect the estimated

711   stock composition of any given ocean region, GSI information alone may provide

712   difficult to interpret patterns (Fig. 6). Overall, however, our predictions (Fig. 5-7) should

713   provide predictions for proportional compositions that can be compared directly to GSI

714   studies. Integrating GSI and CWT data in a single integrated framework is an exciting

715   and important area for future work.

716   Beyond data and model complexity, computational limitations do present a

717   challenge for large models like ours. In theory, there is no constraint upon how many

718   releases can be modeled simultaneously, but the 454 releases modeled here require

719   estimation of nearly 8,600 latent states and incorporate over 228,000 observations for the

720   binomial likelihood (the total number of release-location-season-gear type combinations)

721   and over 17,000 observations for the log-normal component. Expanding the number of

722   releases substantially would require substantially improving computational resources or

723   moving away from full Bayesian estimation toward approximations of the posterior

724   distribution such as Laplace approximations (Rue et al. 2009).

725   Overall, we provide a framework to integrate information from multiple fall

726   Chinook salmon stocks to simultaneously estimate parameters from a complex population

727   dynamic model. We emphasize the spatio-temporal attributes of the parameters here –

728   particularly estimates of ocean distribution and regional patterns in juvenile survival –

729   and provide illustrative examples of how these estimates can be used to simulate

730   scenarios and that these scenarios may be useful in a variety of management and

731   ecosystem contexts in the future.

732

733   **Acknowledgements**

741

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957 Figure 1: Map of study area, hatchery locations (black dots), and 17 coastal regions used
958 in the study. Locator map (left) attribution: Esri, DeLorme, GEBCO, NOAA NGDC, and
959 other contributors. Main map attribution: Esri, NOAA NGDC, NOAA GSHHG, and
960 other contributors.
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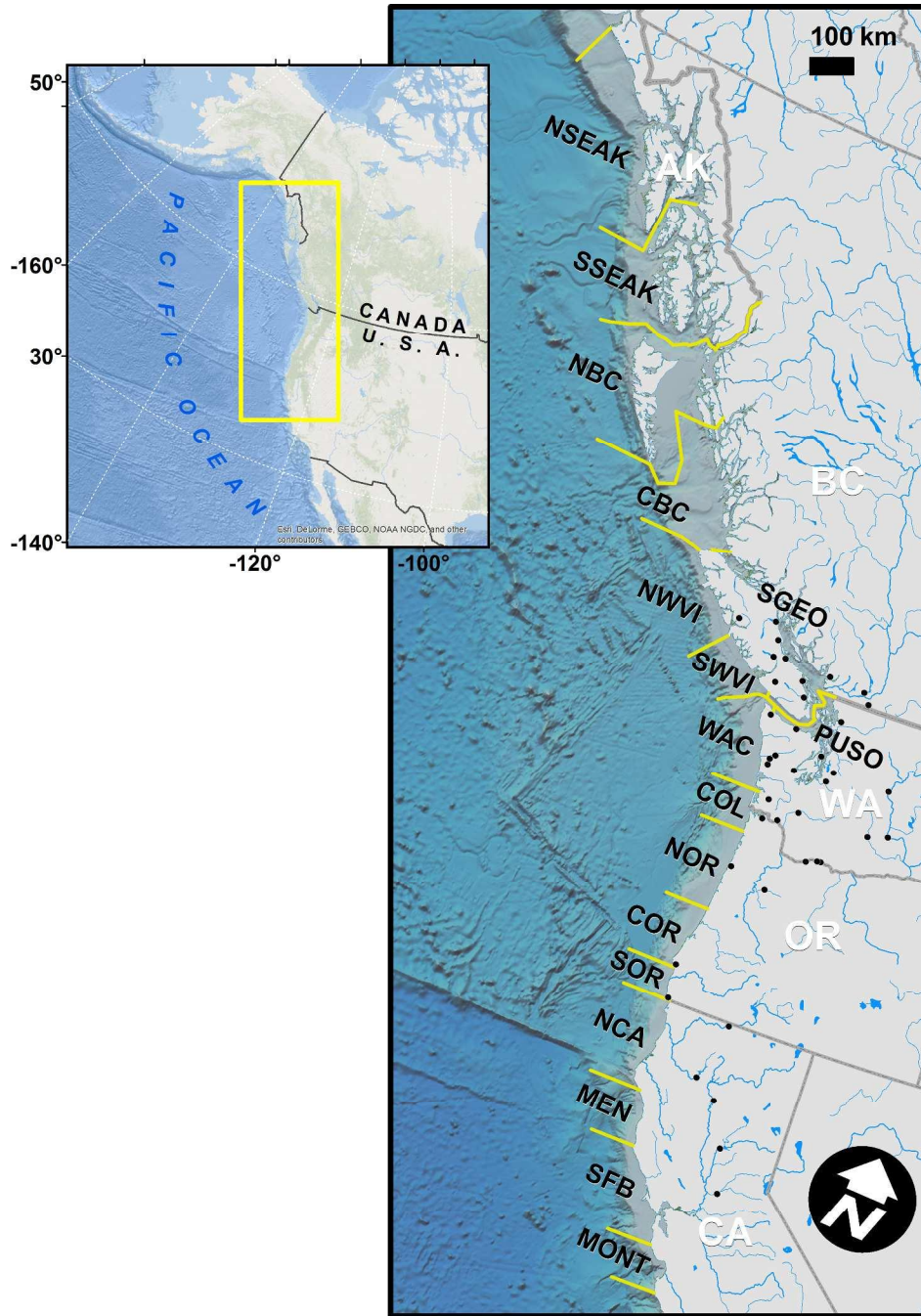
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964   Figure 2: Example raw CPUE data for two releases. *Left panel:* Observed CPUE (fish per
965   boat-day) from commercial troll fisheries for fall Chinook salmon released from Coleman
966   National Fish Hatchery (SFB region) in 1980 (N=393,932 at release). Black indicates
967   region-season combinations with commercial troll fisheries but zero observed catches.
968   Grey indicates no commercial troll fishery occurred region-season combination. *Right*
969   *panel:* Observed CPUE from commercial troll fisheries for fall Chinook released from
970   Lyons Ferry (UPCOL region) released in 1984 (N=234,985 at release). Note that the
971   color ramp differs between panels.

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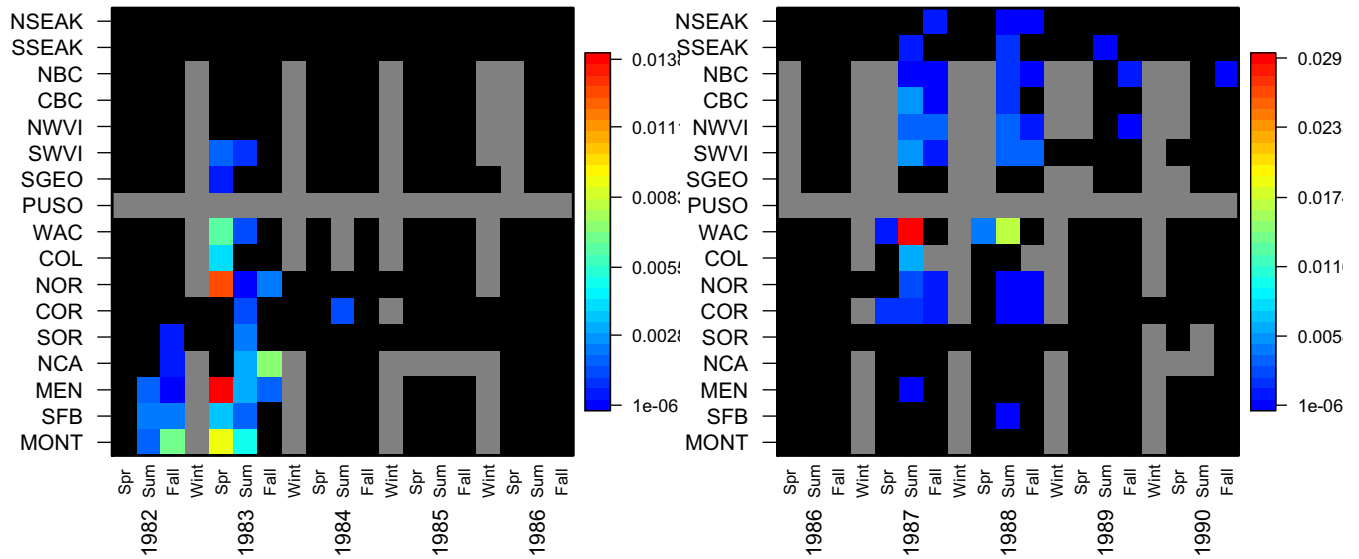
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977 Figure 3: Estimated proportional spatial distribution by season of fall Chinook salmon
978 originating from 11 different regions ($\theta_{l,r,s}$). Each row represents the proportion of fish
979 from a region present in each ocean region (rows sum to one). Posterior means are
980 shown.
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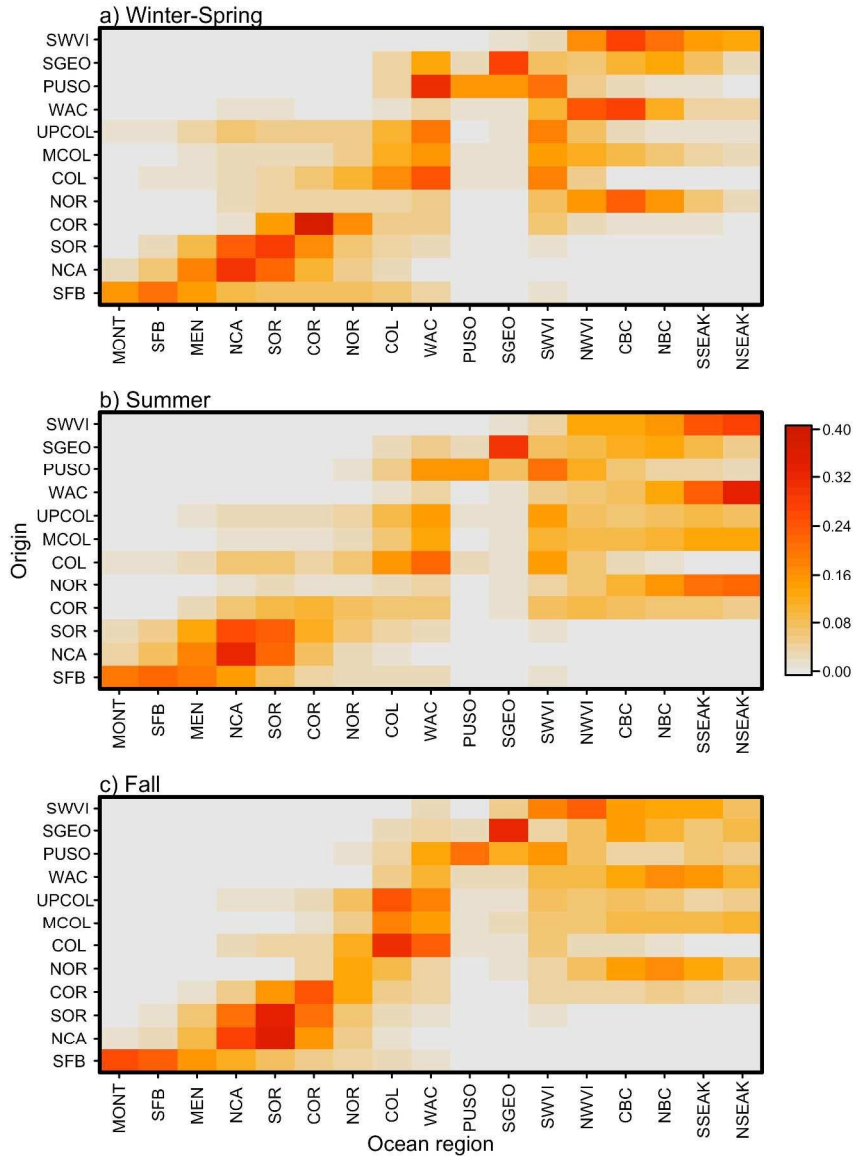
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985 Figure 4: Survivorship trends for juvenile Chinook salmon from release to August 1,
986 brood year +2 for different origin regions between 1978 and 1990. Raw survivorship
987 scores have been converted to z-scores (subtract the among-year mean, divide by the
988 standard deviation) to make trends in survival comparable among regions. Panels show
989 weighted mean for Chinook from northern regions (*a*), the Columbia basin (*b*), and
990 southern regions (*c*; see also Fig. 1). Individual points show mean estimates for
991 individual release groups. Due to low numbers of release groups in Oregon regions
992 (NOR, COR, SOR), we combined Oregon releases into a single "OR" region.
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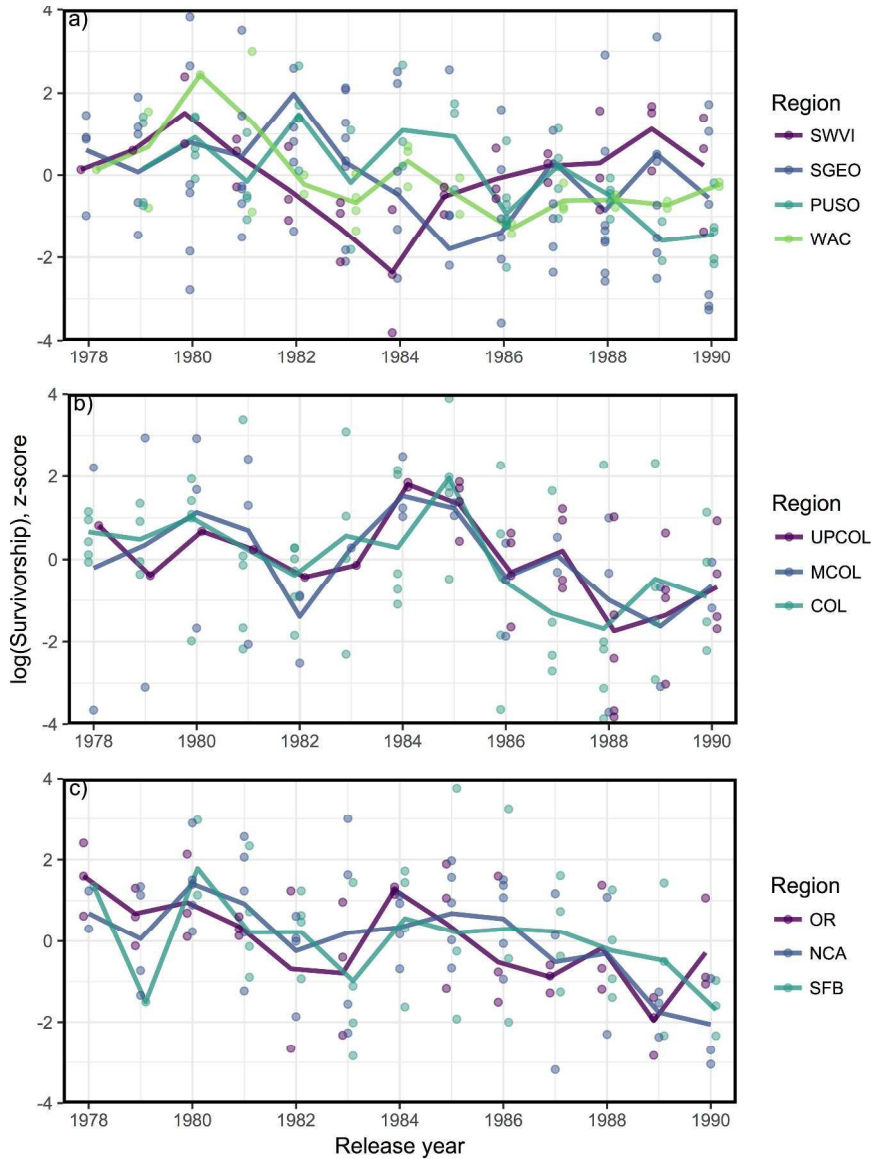
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997 Figure 5: Distribution and abundance of fall Chinook salmon age 3 and older in the
998 ocean. We show proportional contribution of age 3+ fish to each ocean region (left
999 panels) and total abundance (right panels) at the beginning of spring (*a*), summer (*b*), and
1000 fall (*c*) seasons. Results arise from simulations assuming median fishing mortality for
1001 each area and season (see Fig. S1.9) and a single juvenile mortality rate shared across all
1002 regions.

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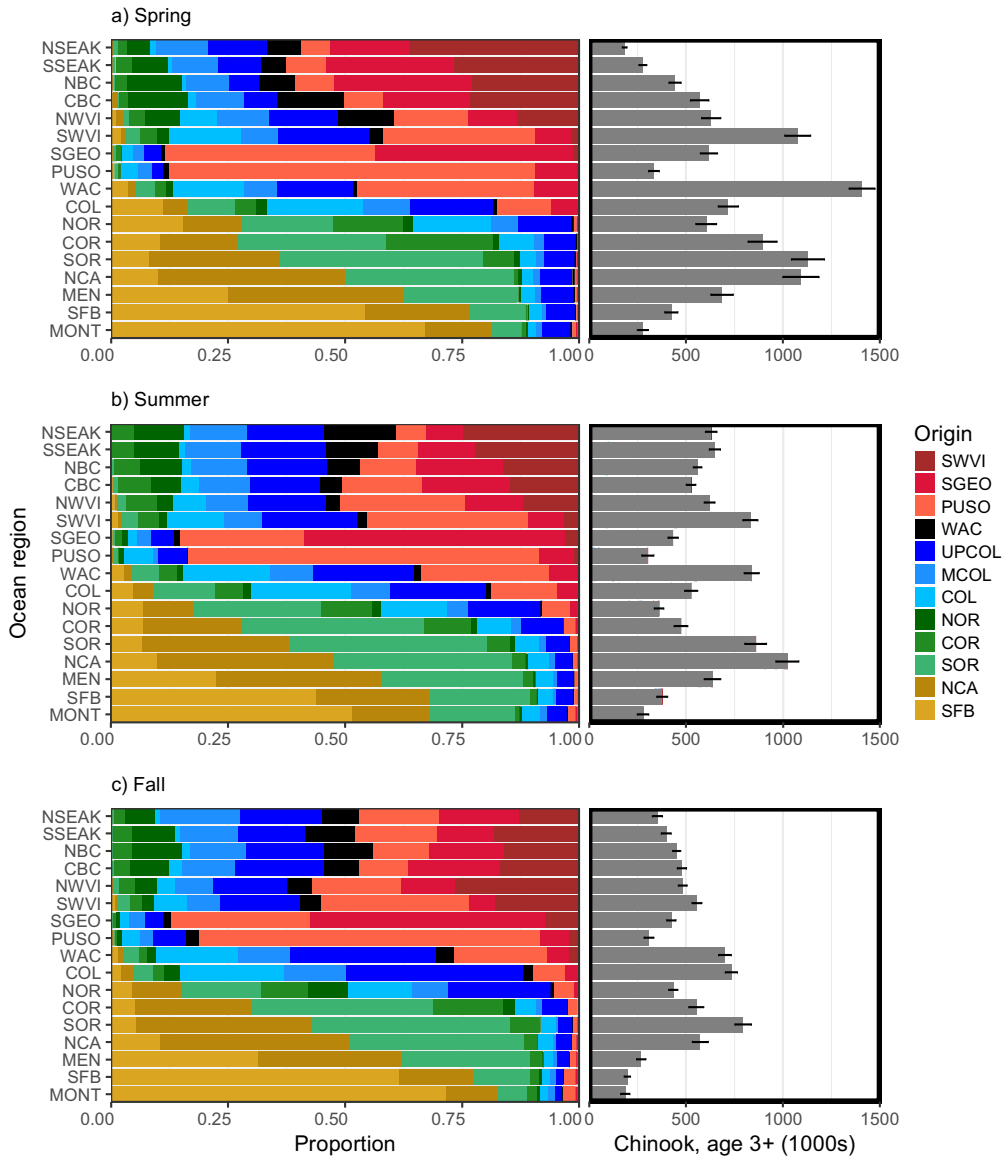
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1008   Figure 6. Summer distribution and abundance of fall Chinook salmon from four
1009   representative regions and two age groups under the base scenario. Areas SFB (*a,f*),
1010   COL(*b,g*), WAC *(c,h)*, SGEO *(d,i)*, and aggregate abundance across all stocks *(e,j)*
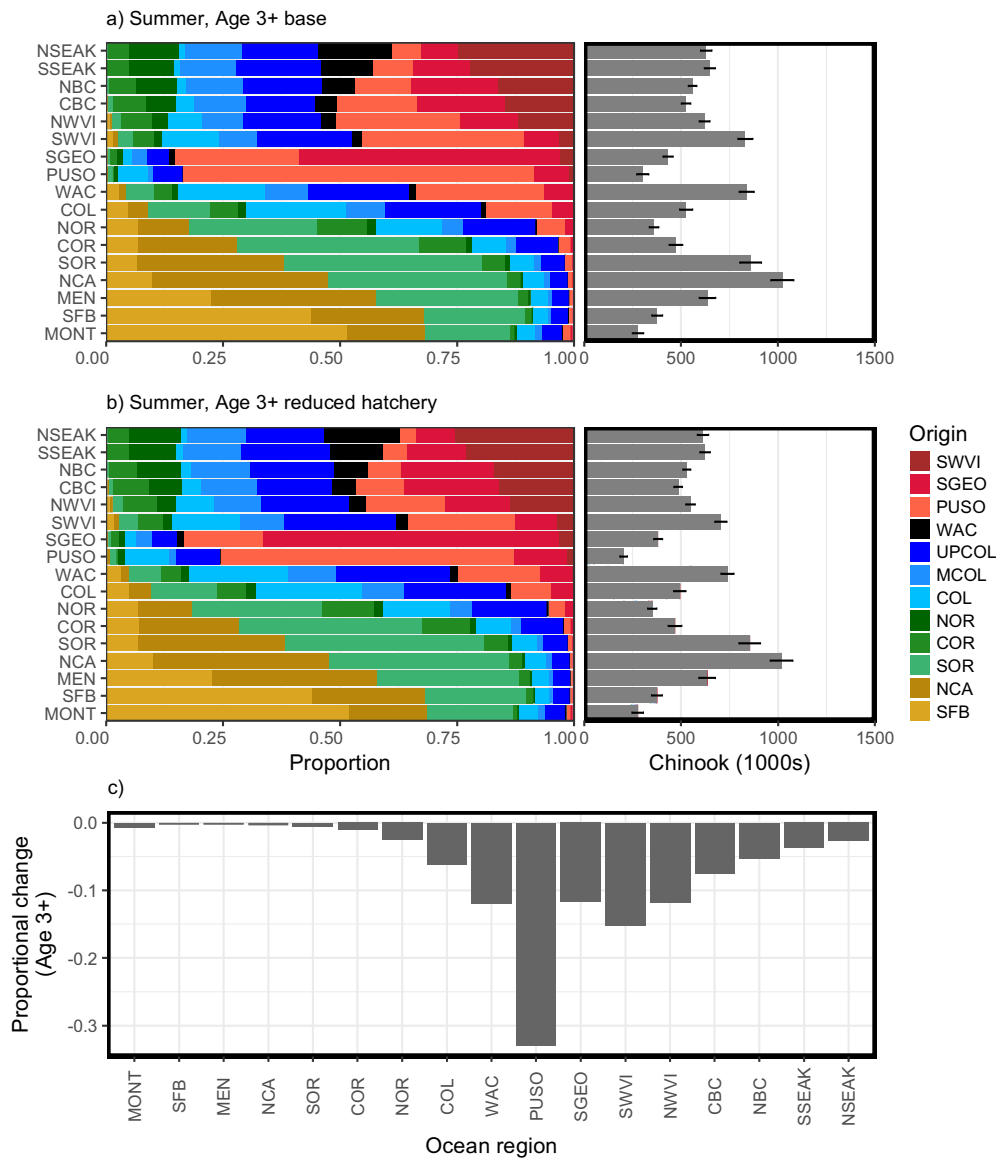1011
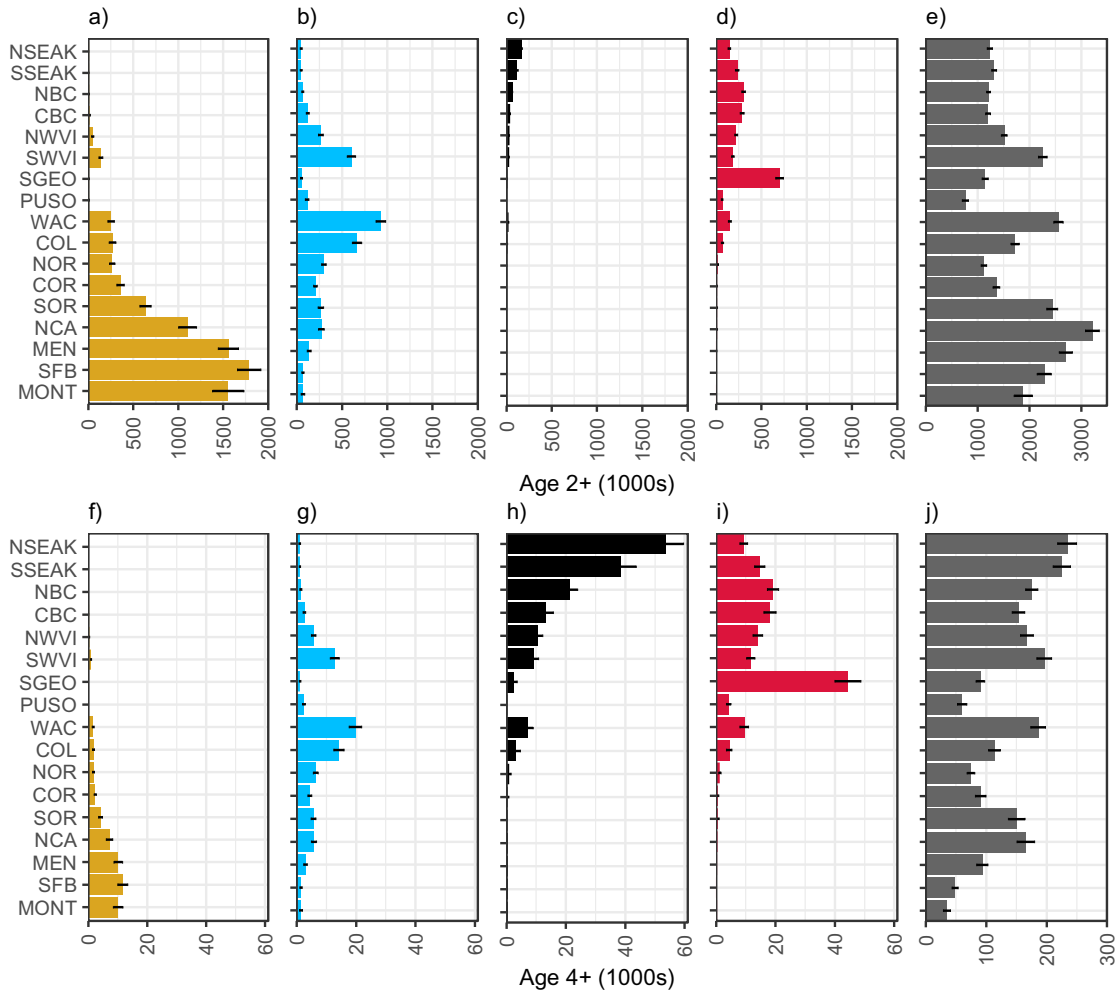
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1014   Figure 7: Comparison of two simulation scenarios. *(a,b)* Proportional contribution of age
1015   3+ fish to each ocean region (left panels) and total abundance (right panels) at the
1016   beginning of summer under the base scenario *(a)* and under reduced hatchery production
1017   from the PUSO region *(b)*. Panel *(c)* shows the proportional change in total abundance
1018   from base to PUSO hatchery scenarios for age 3+ Chinook salmon.
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