



Impact of the 2014-16 marine heatwave on U.S. and Canada West Coast fisheries: surprises and lessons from key case studies

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Abstract:	Marine heatwaves are increasingly affecting marine ecosystems, with cascading impacts on coastal economies, communities, and food systems. Studies of heatwaves provide crucial insights into potential ecosystem shifts under future climate change and put fisheries social-ecological systems through “stress tests” that expose both vulnerabilities and resilience. The 2014-16 Northeast Pacific heatwave was the strongest and longest marine heatwave on record and resulted in profound ecological changes that impacted fisheries management and human livelihoods. Here, we synthesize the impacts of the 2014-16 marine heatwave on U.S. and Canada West Coast fisheries and extract key lessons for preparing global fisheries science, management, and industries for the future. We set the stage with a brief review of the

impacts of the heatwave on marine ecosystems and the first systematic analysis of the economic impacts of these changes on commercial and recreational fisheries. We then examine ten key case studies that provide instructive examples of the complex and surprising challenges that heatwaves pose to fisheries social-ecological systems. These reveal important insights into improving the resilience of monitoring, management, and adaptive capacity to future stressors. Key recommendations include: (1) expanding monitoring to enhance mechanistic understanding, provide early warning signals, and improve predictions of impacts; (2) increasing the flexibility, adaptiveness, and inclusiveness of management where possible, and using simulation testing to help guide management decisions; and (3) enhancing the adaptive capacity of fishing communities by promoting engagement, flexibility, experimentation, and failsafes. These advancements are important as global fisheries prepare for a changing ocean.

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1 Impact of the 2014-16 marine heatwave on U.S. and Canada
2 West Coast fisheries: surprises and lessons from key case
3 studies

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38 Northeast Pacific marine heatwave

39 Abstract

40 Marine heatwaves are increasingly affecting marine ecosystems, with cascading impacts on
41 coastal economies, communities, and food systems. Studies of heatwaves provide crucial
42 insights into potential ecosystem shifts under future climate change and put fisheries social-
43 ecological systems through “stress tests” that expose both vulnerabilities and resilience. The
44 2014-16 Northeast Pacific heatwave was the strongest and longest marine heatwave on record
45 and resulted in profound ecological changes that impacted fisheries management and human
46 livelihoods. Here, we synthesize the impacts of the 2014-16 marine heatwave on U.S. and
47 Canada West Coast fisheries and extract key lessons for preparing global fisheries science,
48 management, and industries for the future. We set the stage with a brief review of the impacts of
49 the heatwave on marine ecosystems and the first systematic analysis of the economic impacts
50 of these changes on commercial and recreational fisheries. We then examine ten key case
51 studies that provide instructive examples of the complex and surprising challenges that
52 heatwaves pose to fisheries social-ecological systems. These reveal important insights into
53 improving the resilience of monitoring, management, and adaptive capacity to future stressors.
54 Key recommendations include: (1) expanding monitoring to enhance mechanistic
55 understanding, provide early warning signals, and improve predictions of impacts; (2) increasing
56 the flexibility, adaptiveness, and inclusiveness of management where possible, and using
57 simulation testing to help guide management decisions; and (3) enhancing the adaptive
58 capacity of fishing communities by promoting engagement, flexibility, experimentation, and
59 failsafes. These advancements are important as global fisheries prepare for a changing ocean.

60
61 **Keywords:** climate change, ocean warming, climate-adaptive management, climate-resilient
62 fisheries, harmful algal blooms, ecological surprises

63 1. Introduction

64 Marine heatwaves have increased in frequency, duration, and intensity over the last
65 century (Oliver et al., 2018) and are expected to become even more common and severe under
66 climate change (Frölicher et al., 2018; Laufkötter et al., 2020). These discrete and extended
67 periods of warm water anomalies (Hobday et al., 2016) can greatly impact marine ecosystems
68 (Smale et al., 2019) with cascading impacts on coastal economies, communities, and food
69 systems (Smith et al., 2021). Learning from past heatwaves is essential to building resilience to
70 both future heatwaves and to directional warming for two key reasons. First, conditions during
71 heatwaves are a harbinger of the future and provide insights on what to expect and how to
72 prepare. Second, heatwaves put management systems and livelihoods through a “stress test”
73 that exposes vulnerabilities and opportunities for increasing resilience.

74

75 As of 2022, the 2014-16 heatwave in the Northeast Pacific was the strongest and
76 longest marine heatwave in recorded history (Laufkötter et al., 2020). It lasted >700 days,
77 spanned >2.5 million km² at its largest extent, and sea surface temperatures were, on average,
78 >2.0°C above the climatological mean (Gentemann et al., 2017). The heatwave occurred in one
79 of the best monitored and managed regions of the world (Gallo et al., 2022; Hilborn et al., 2020;
80 Melnychuk et al., 2021), yet still greatly affected marine ecosystems and economies (Cavole et
81 al., 2016). For example, the heatwave caused (1) the loss of kelp forests and the abalone and
82 urchin fisheries that depend on kelp (Rogers-Bennett & Catton, 2019, p.); (2) an unprecedented
83 harmful algal bloom that resulted in coastwide shellfish fishery closures (McCabe et al., 2016);
84 (3) a spike in humpback whale (*Megaptera novaeangliae*) entanglements resulting from
85 increased overlap of whale foraging grounds with the Dungeness crab (*Metacarcinus magister*)
86 fishery (Santora et al., 2020); and (4) recruitment failures for several fishery species (Laurel &
87 Rogers, 2020; McClatchie et al., 2016). Learning from these impacts can bolster the resilience
88 of monitoring programs, management systems, and fishing communities to the negative impacts
89 of future heatwaves and climate change.

90

91 The heatwave also benefited many species (Cavole et al., 2016), which present their
92 own unique management challenges. For example, an explosion in the abundance of shortbelly
93 rockfish (*Sebastodes jordani*) in Oregon, a non-target bycatch species, required rapid
94 management action to avoid the closure of the Pacific hake (*Merluccius productus*) fishery,
95 which nearly exceeded its bycatch limit within the first two weeks of the season (NMFS, 2020).

96 Similarly, the northward expansion of California market squid (*Doryteuthis opalescens*) (Chasco
97 et al., 2022) required rapid management action to regulate the newly emerging fishery in
98 northern latitudes (ODFW, 2021). In addition, movement of large Pacific bluefin tuna (*Thunnus*
99 *orientalis*) into U.S. waters during the heatwave was a boon for recreational fishing (Runcie et
100 al., 2019). However, it increased fishing mortality on this already overfished stock and
101 highlighted an incomplete understanding in the relationship between local availability and
102 stockwide abundance. Flexible, agile, and informed management is thus crucial to preparing
103 coastal communities for both positive and negative climate impacts.

104

105 Here, we synthesize the impacts of the 2014-16 marine heatwave on fishing
106 communities along the West Coast of the United States and Canada and extract key lessons for
107 preparing fisheries science, management, and industries for future climate change and
108 heatwaves based on this experience. We set the stage with a brief review of the impacts of the
109 heatwave on the ecosystem and the first systematic analysis of the economic impacts of these
110 changes on commercial and recreational fisheries. This analysis examines the change in
111 commercial fisheries revenues and recreational fisheries landings that occurred during and after
112 the heatwave relative to before the heatwave. We then examine ten key case studies that
113 provide instructive examples of the complex, and often surprising, challenges that heatwaves
114 pose to fisheries social-ecological systems. These reveal important insights into improving the
115 resilience of monitoring, management, and adaptive capacity to future stressors.

116 2. The 2014-16 marine heatwave

117 The marine heatwave began in fall 2013 as a large “blob” of anomalously warm water in
118 the Gulf of Alaska (**Figure 1**) (Bond et al., 2015). This warm pool began to spread south in
119 spring 2014 and encompassed the entire California Current ecosystem by late 2014. The pool
120 formed as a result of an unusually persistent ridge of high atmospheric pressure that
121 suppressed zonal winds, limited heat loss from surface waters, and reduced advection of cooler
122 water into the upper ocean (Bond et al., 2015). It persisted as a result of a strong El Niño that
123 began in mid-2015 and caused warm conditions to last until summer 2016 in the California
124 Current (Di Lorenzo & Mantua, 2016; Jacox et al., 2016) and through 2017 in the Gulf of Alaska
125 (Suryan et al., 2021). Throughout this period, anomalously warm conditions only abated in
126 spring in nearshore upwelling zones under favorable wind stress (Gentemann et al., 2017).
127 However, cool, nutrient-rich, subarctic source water was locally available before and during the

128 heatwave (Schroeder et al., 2019). Additionally, the high-pressure conditions that initiated the
129 heatwave weakened typical winter storm and wind patterns (Whitney, 2015). This resulted in
130 persistent stratification of the surface layer, and a reduction in upwelling-favorable alongshore
131 winds. Increased stratification and reduced upwelling limited the vertical mixing of cold, nutrient-
132 rich, deep water into surface waters, leading to reduced nutrient fluxes into the euphotic zone
133 and deepening of the nutricline in 2014-15 (Zaba & Rudnick, 2016).

134

135 These physical changes had profound impacts on plankton communities throughout the
136 California Current ecosystem. In nearshore waters, enhanced stratification reduced nutrient
137 renewal, leading to low phytoplankton abundance (Delgadillo-Hinojosa et al., 2020; Peña et al.,
138 2019; Whitney, 2015). However, in offshore waters, increased stratification increased effective
139 light levels in the surface layer and increased production in an area normally co-limited by iron
140 and light (Peña et al., 2019). These conditions contributed to a harmful algal bloom of
141 unprecedented size, duration, and intensity, leading to widespread fishery closures and
142 contributing to mass mortalities of seabirds and marine mammals (McCabe et al., 2016;
143 McKibben et al., 2017). The bloom, composed of diatoms in the *Pseudo-nitzschia* genus, was
144 induced through a perfect storm of events. First, anomalously warm conditions allowed *Pseudo-*
145 *nitzschia*, which is tolerant to low nutrient levels, to thrive in warm, nutrient-poor, offshore waters
146 north of its typical range. Then, a series of seasonal storms transported the offshore bloom to
147 the coast, where seasonal upwelling injected nutrients that further intensified the bloom
148 (McCabe et al., 2016). As for the zooplankton community, abundance remained high throughout
149 the heatwave, but with dramatic changes in composition. In general, there was a surge in warm-
150 water species from southern and offshore waters, an increase in the abundance of gelatinous
151 zooplankton, and a decrease in the abundance of crustacean holoplankton, particularly krill
152 (Batten et al., 2022; Brodeur et al., 2019; Lilly & Ohman, 2021; McKinstry et al., 2022; Peterson
153 et al., 2017; Thompson et al., 2022). The dominance of lipid-poor warm-water zooplankton
154 relative to lipid-rich cool-water zooplankton likely contributed to lower productivity in higher
155 trophic levels (Peterson et al., 2017).

156

157 The heatwave induced many changes to higher trophic-level species. In general, the
158 ranges of southern warm-water fish and large invertebrates extended northward, and the ranges
159 of offshore warm-water species extended inshore as waters warmed coastwide (Thompson et
160 al., 2022). Interestingly, many cool-water species generally appeared to persist within their
161 historical geographic ranges, likely due to the presence of pockets of cool water (Sanford et al.,

162 2019). The heatwave also induced shifts, both positive and negative, in the productivity of many
163 ecologically and economically important fish species (Cavole et al., 2016). For example, while
164 rockfish (*Sebastodes* spp.) and Northern anchovy (*Engraulis mordax*) recruitment was high during
165 the heatwave, Pacific sardine (*Sardinops sagax*) and salmon recruitment was low (Munsch et
166 al., 2022; Schroeder et al., 2019; Thompson et al., 2022); hypothesized mechanisms are
167 discussed in greater detail in the case studies below. Furthermore, the heatwave reduced the
168 nutrient content of key forage fish species as result of shifts in the availability of their prey
169 (Mantua et al., 2021; von Biela et al., 2019). In some cases, changes in the abundance,
170 composition, and nutrient content of forage fish triggered the mass mortality of marine mammals
171 (NMFS, 2022) and seabirds (Drever et al., 2018; Jones et al., 2018, 2019; Piatt et al., 2020, p.
172 2). In other cases, high recruitment of anchovy and other fishes during the marine heatwave
173 fueled marine mammals and seabird population growth that have persisted to at least 2021
174 (Thompson et al., 2022).

175 3. Socioeconomic impacts of the heatwave on fisheries

176 The socioeconomic impacts of the heatwave on commercial, recreational, and
177 Indigenous fisheries are documented for some high profile fisheries suffering large negative
178 impacts, but have not been systematically quantified for the majority of the coast's fisheries. In
179 the United States, federal fisheries disasters were declared as a result of the heatwave for
180 commercial and Indigenous fisheries targeting Dungeness crab and rock crab (*Cancer* spp.),
181 Pacific sardine, red sea urchin (*Mesocentrotus franciscanus*), and many salmon stocks (Figure
182 2), resulting in over US\$141 million in relief to impacted fishers, processors, and dealers
183 (Bellquist et al., 2021). Among these disaster declarations, the largest appropriation (US\$56.3
184 million) was to the Gulf of Alaska pink salmon (*Oncorhynchus gorbuscha*) industry following low
185 salmon returns attributed to poor oceanographic conditions (Pritzker, 2017a). The second
186 largest appropriation (US\$25.8 million) was to the California Dungeness crab industry following
187 extended fishery closures due to harmful algal blooms (Pritzker, 2017b). Amongst recreational
188 fisheries, negative economic impacts are best documented for razor clams (*Siliqua patula*)
189 (Ekstrom et al., 2020; Moore et al., 2019; Ritzman et al., 2018), which support large tourist
190 economies in Oregon and Washington (Dyson & Huppert, 2010). The 2015 harmful algal bloom
191 caused widespread closures in both states causing an estimated loss of US\$22 million in
192 tourism revenues (Mapes, 2015). In addition to causing increased financial hardship, these

193 events contributed to increased emotional stress and reduced sociocultural well-being (Moore et
194 al., 2020, p. 96).

195

196 To provide the first systematic overview of the potential economic impacts of the
197 heatwave on the commercial fisheries of the U.S. and Canada West Coast, we compared
198 revenues during (2014-2016) and after the heatwave (2017-2019) with revenues before the
199 heatwave (2011-2013) using commercial landings data (see supplemental information). To
200 account for inflation, we adjusted all revenues to 2020 U.S. dollars. This analysis is limited in
201 that it cannot attribute causality, it does not account for lags in heatwave impacts, and it
202 assumes that profits are proportional to revenues, but it still provides useful insights into the
203 identity and rank order of potential heatwave “winners” and “losers”. We found that fleetwide
204 revenues fell during the heatwave in California and Alaska, were stable in Oregon and
205 Washington, and increased in British Columbia. The largest decreases occurred in California
206 (**Figure 3A**), largely due to exceptionally high revenue losses in California’s Dungeness crab,
207 Pacific sardine, and market squid fisheries (**Figure 3B**). Whereas a small dip in revenues
208 rebounded to pre-heatwave levels in Oregon and Washington, revenues remained low in both
209 Alaska and California throughout the three years following the heatwave (**Figure 3A**). British
210 Columbia experienced higher revenues after the heatwave than in either the periods before or
211 during the heatwave, largely driven by increase in revenues from coastal pelagic species. All
212 four U.S. states saw revenue losses in coastal pelagic fisheries and significant revenue
213 increases in shrimp fisheries during the heatwave. Only California saw increases in revenues in
214 fisheries for highly migratory species during the heatwave, and only Oregon saw increases in
215 revenues from bivalve fisheries (**Figure 3B**). Among management groups with reduced
216 revenues during the heatwave, recovery to pre-heatwave revenues only occurred in Oregon and
217 Washington’s Dungeness crab fisheries and British Columbia’s salmon fisheries. Species-
218 specific results show an array of winners and losers, illustrating the complex heterogeneity of
219 heatwave impacts (**Figure 4**).

220

221 We performed a similar analysis on recreational fisheries landings using estimates of the
222 number of fish retained across all fishing modes (e.g., charter boats, private boats, jetties, piers,
223 beaches, etc.) (see supplemental information). Recreational fisheries are significantly larger in
224 California than in British Columbia or the other U.S. states (**Figure 5**). Overall, recreational
225 landings in California declined during and after the heatwave, though this may be part of a
226 longer-term trend (**Figure 5A**). Declines during the heatwave were driven by large declines in

227 coastal pelagic species (e.g., sardine, anchovy), flatfish, and other miscellaneous species and
228 were only slightly offset by large increases in tuna, roundfish (e.g., sablefish, hake, cod),
229 surfperch, and rockfish (**Figure 5B**). Overall, recreational landings in Oregon, Washington, and
230 Alaska have been relatively constant through time and even increased during the heatwave
231 (**Figure 5A**). In these states, increased landings were apparent in every species group except
232 sharks and rays and the “other fish” category (**Figure 5B**). As with commercial fisheries
233 revenues, species-specific results show a diversity of complex impacts (**Figure 6**).
234

235 Indigenous fisheries in the Pacific Northwest are especially vulnerable to climate change
236 (Koehn et al., 2022) and it is likely that they were disproportionately impacted by the heatwave.
237 Although limited availability of Indigenous landings and revenue data in public databases
238 precludes impact analyses like those described above, U.S. federal fishery disaster declarations
239 provide some indication of the socioeconomic impacts of the heatwave on Native American
240 fisheries (note: First Nation fisheries are not considered here because Canada does not have
241 an analogous disaster relief program). Tribal fishery disaster declarations, primarily occurring
242 among salmon fisheries, increased significantly beginning in 2017 as the impacts of the
243 heatwave were fully realized (Bellquist et al., 2021). Fifteen individual tribes were identified as
244 being impacted by these disasters, as well as four tribal associations that represent
245 approximately two hundred tribes across the Pacific Northwest and Alaska (Bellquist et al.,
246 2021). Overall, between US\$111-188 million was appropriated to tribal fishing communities as a
247 result of the marine heatwave. However, disaster declarations do not fully capture the complex
248 and profound nature of impacts to Indigenous fisheries, which provide significant sociocultural
249 and subsistence values (Crosman et al., 2019). More cooperative research is necessary to
250 characterize and mitigate the impacts of climate change and heatwaves on Indigenous
251 communities.

252 4. Case studies

253 In this section, we present ten key case studies that provide instructive examples of the
254 complex, and sometimes surprising, challenges that heatwaves pose to fisheries social-
255 ecological systems and reveal important insights into improving the resilience of monitoring,
256 management, and adaptive capacity to future stressors (**Figure 7**). These case studies
257 represent a diversity of management regimes (international, federal, state), sectors
258 (commercial, recreational, Indigenous), and taxonomic groups (finfish, crabs, shrimp, squid,

259 abalone, urchins). Case studies were selected to describe both positive and negative heatwave
260 impacts. The five case studies focused on negative impacts include five fisheries that received
261 U.S. federal disaster relief as a result of the heatwave: Pacific cod (*Gadus macrocephalus*),
262 Chinook salmon (*Oncorhynchus tshawytscha*), Dungeness crab, urchin/abalone, and Pacific
263 sardine. The five case studies focused on positive impacts were selected based on common
264 examples from the literature (California market squid, Pacific bluefin tuna, two rockfish species;
265 see Cavole et al. 2016) and a prominent example from this study's data analysis (shrimp). In
266 each case study, we provide a brief overview of the fishery, the impact of the heatwave on the
267 fishery, the response of industry and management to these impacts, and the revealed
268 opportunities for improving resilience to future heatwaves and climate change.

269 4.1. Pacific cod

270 Pacific cod has long supported a productive commercial fishery in the Gulf of Alaska.
271 However, in 2017, a sudden and severe decline in biomass was detected that could not be
272 explained by harvest alone (Barbeaux et al., 2021). Rather, the stock experienced the double
273 impact of increased adult mortality and sustained low recruitment, both linked to the heatwave.
274 High mortality of adult cod was associated with poor body condition (Barbeaux et al., 2020) as a
275 result of reduced prey availability and increased metabolic demands by predators during the
276 heatwave (Piatt et al., 2020; Rogers et al., 2021; von Biela et al., 2019). Simultaneously, warm
277 thermal conditions at depth likely reduced egg survival and recruitment (Laurel & Rogers, 2020).
278 Heatwave conditions returned in 2019, further depressing recruitment and delaying recovery of
279 the stock. The sharp stock decline in 2017 resulted in severe reductions to catch limits for 2018
280 and 2019. However, the stock continued to decline, and the North Pacific Fisheries
281 Management Council closed the directed federal Pacific cod fishery for 2020 (Barbeaux et al.,
282 2021) (**Figure 8E**). Impacts to fishing communities were significant, and ultimately, a U.S.
283 federal fisheries disaster was declared. By 2022, the stock was increasing, but catch limits were
284 still a small fraction of pre-heatwave levels.

285

286 The management response to the dramatic stock declines reflects the system of
287 ecosystem-based fisheries management in Alaska and highlights lessons for fisheries
288 management under rapidly changing climate conditions. First, precautionary buffers, which
289 reduce catch limits from the maximum allowable, have a precedent for use when ecosystem
290 conditions raise red flags for a stock that are not captured in the stock assessment process
291 (Dorn & Zador, 2020). Such reductions were made in 2018, 2019, and 2020. The continued

incorporation of ecosystem information into the management process can allow managers to respond precautionarily, but requires effective monitoring and research to be most effective (Peterson Williams et al., 2022). Second, a forward-looking perspective is needed: for instance, recruitment projections based on historical observations become less informative as we encounter unprecedented ocean conditions (Litzow et al., 2021). Early warning indicators can enable proactive management in the case of rapid ecosystem or stock shifts (Litzow et al., 2022). Finally, climate-linked stock assessment approaches (e.g., Barbeaux et al., 2021) will be important for proactively responding to future heatwaves and other extreme events.

4.2. Chinook salmon

Chinook salmon range from central California to Alaska and support Indigenous, commercial, and recreational fisheries of considerable economic (Richerson et al., 2018), subsistence (Poe et al., 2015), and cultural (Campbell & Butler, 2010) value. Ocean Chinook salmon fisheries south of Cape Falcon, Oregon are primarily regulated using harvest control rules that limit harvests in ways expected to achieve escapement goals based on forecasts of preseason abundance for both the Sacramento and Klamath River Fall Chinook stocks. In general terms, both forecast models are based on the previous year's returns (Peterman, 1982; Winship et al., 2015); they do not explicitly include environmental covariates despite their known importance (Friedman et al., 2019; Wells et al., 2016). The marine heatwave impacted juveniles entering the ocean in 2014-16 from both these stocks, with cohorts predominantly returning as adults in 2016-18 in the Sacramento and 2017-2019 in the Klamath River. Both stocks' models forecasted low preseason abundance, but both also nonetheless overestimated actual return size (**Figure 8D**). In the Klamath River, the 2016 run size was the lowest since 1983 and the 2017 run size was the third-lowest (1992 was lower). In the Sacramento River, 2016 escapement was below average and 2017 escapement was the second-lowest since 1983. As a result of low escapements, both stocks were declared overfished in 2018. Following both restricted fishing opportunity (based on low preseason abundance forecasts) and low abundance of harvestable fish, harvests and incomes were greatly reduced and several federal fishery disasters were declared, impacting all fishery sectors, including both commercial harvesters and the Klamath Basin tribes. These disasters were attributed to the marine heatwave and simultaneous extreme drought conditions that resulted in warmer river temperatures and anomalously low water levels, particularly on the Klamath River (PFMC, 2019a, 2019b). While catch limits were adjusted downwards in response to low preseason abundance forecasts, they were not reduced as much as they would have been if the impacts of

325 the heatwave (and other factors) had been perfectly forecast. Thus, optimistic model forecasts
326 and/or insufficiently precautionary control rules may have contributed to overharvest and the
327 eventual overfished designation. This suggests that improved forecasts and control rules could
328 ameliorate overharvest risk; however, even with perfect foresight, poor environmental conditions
329 still lead to loss in commercial revenues, recreational fishing opportunities, and cultural and
330 subsistence benefits in Indigenous fisheries (O'Rourke, 2018; PFMC, 2018, 2019b). This
331 highlights the importance of restoring freshwater habitats to buffer against poor ocean
332 conditions and increasing community resilience through additional policy actions that, for
333 example, promote the ability to switch to alternative fisheries or reform disaster relief to be more
334 accurate, timely, and equitable.

335 4.3. Kelp, urchin, abalone

336 In 2015, a perfect storm of stressors tipped some bull kelp (*Nereocystis luetkeana*)
337 forests into unproductive urchin barrens in northern California, ultimately causing the collapse of
338 the recreational abalone and commercial urchin fisheries, as both species are kelp herbivores
339 (Rogers-Bennett & Catton, 2019). This began in the summer of 2013 when Sea Star Wasting
340 syndrome caused a massive die-off of sunflower sea stars (*Pycnopodia helianthoides*), an
341 important predator of urchins in kelp forest ecosystems (Harvell et al., 2019). Then, in 2014,
342 warm waters and nutrient limitation throughout the summer growing season likely suppressed
343 kelp growth and spore production, reducing productivity (Rogers-Bennett & Catton, 2019). As a
344 result of reduced productivity and increased urchin grazing pressure following a sea star
345 predation release, bull kelp forests were reduced by >90% along the northern California coast
346 (McPherson et al., 2021; Rogers-Bennett & Catton, 2019). In 2015, the loss of kelp forage
347 resulted in the collapse of the commercial red sea urchin fishery. While the abundance of red
348 sea urchins, which are marketed for their roe, remained high, starvation due to lack of kelp led
349 to poor gonad production and unmarketable urchins. This collapse was declared a federal
350 fisheries disaster and \$3.3 million in disaster relief was distributed to impacted fishers,
351 processors, and dealers (Bellquist et al., 2021). In 2017, the mass mortality of red abalone
352 (*Haliotis rufescens*) due to starvation (kelp is the primary food resource for abalone) led to the
353 closure of the recreational abalone fishery in California and Oregon (**Figure 8C**), which
354 previously supported an estimated 35,000 participants and the infusion of \$24-44 million
355 annually into local economies (Reid et al., 2016). The fishery remains closed at the time of
356 writing (Oct 2022). Active recovery facilitated by reductions in urchin grazing pressure and
357 enhancements to kelp growth could increase the resilience of kelp forests and the fisheries they

358 support to climate change (Hamilton et al., 2022; Hohman, 2019). The first could involve
359 encouraging new fisheries for purple sea urchin (*Strongylocentrotus purpuratus*), which are less
360 attractive than red urchins because they are smaller, have smaller gonads (the product that is
361 marketed), and require more effort to harvest and process (Parker & Ebert, 2003). The latter
362 might involve area-based protection or active restoration through seeding (Arroyo-Esquivel et
363 al., 2022). Restoration is expensive and may require developing innovative strategies for
364 financing the restoration of these vital ecosystems (Eger et al., 2020).

365 4.4. Dungeness crab

366 The Dungeness crab fishery is the U.S. West Coast's most lucrative commercial fishery
367 and is the central source of income for a large proportion of fishers coastwide (Fuller et al.,
368 2017). Historically, this fishery has been managed profitably and sustainably by limiting harvest
369 to large male crabs during a November-August season (Richerson et al., 2020). However, the
370 heatwave significantly disrupted this fishery through two indirect pathways. First, the 2015-16
371 harmful algal bloom triggered widespread fishery closures due to unsafe levels of biotoxins in
372 crabs (**Figure 8A**). Closures were especially harmful in California, extending from the traditional
373 November start of the season into mid-April (McCabe et al., 2016). As a result, the 2015-16
374 season was declared a federal fisheries disaster and \$25.8 million in disaster relief was
375 allocated to impacted fishers, processors, and dealers, though not until over three years later
376 (C. Bonham, personal communication, July 19, 2018). When indirect losses from other fisheries
377 were included, the delay was associated with over \$43 million in lost income (Holland &
378 Leonard, 2020). Second, the delayed opening of the fishery and the heatwave-induced
379 nearshore compression of coastal upwelling increased the overlap between fishing and the
380 foraging grounds of returning humpback whales, causing a dramatic spike in entanglements of
381 whales in crab pot lines, especially in California (Santora et al., 2020). This precipitated a
382 lawsuit by the Center for Biological Diversity alleging that California's management of the
383 Dungeness crab fishery threatened endangered species and was non-compliant with the
384 Endangered Species Act (CA-DOJ 2017). These events prompted an overhaul of California's
385 entanglement risk management program (CDFW 2020), which has implemented early closures
386 in the last four fishing seasons (2018-19 to 2021-22) to reduce entanglement risk, but at
387 significant cost to fishers (Seary et al., 2022). Increasing the resilience of the Dungeness crab
388 fishery could be advanced by: (1) expanding the spatial-temporal scale of biotoxin monitoring to
389 enable surgical closures that protect public health with the least impacts on fishers (Free,
390 Moore, et al., 2022); (2) developing entanglement prevention strategies that are proven to be

391 effective, robust or adaptable to changing conditions, and co-developed with stakeholders
392 (Samhouri et al., 2021); (3) reforming the federal fisheries disaster program to enable fast,
393 accurate, and equitable relief (Bellquist et al., 2021); and (4) easing access to alternative
394 fisheries as a means of diversifying fishing opportunities (Oken et al., 2021) and potentially
395 escaping the “gilded trap” presented by the lucrative, yet volatile, Dungeness crab fishery
396 (Fisher et al., 2021).

397 4.5. Pacific sardine and northern anchovy

398 Pacific sardine and northern anchovy have historically been two of the most abundant
399 and ecologically important forage fish species in the California Current. Populations of both
400 species are characterized by highly variable “boom-and-bust” cycles, even in the absence of
401 fishing (McClatchie et al., 2018). For many decades, this variability was believed to relate to
402 basin-scale oceanographic regimes (e.g., as characterized by the Pacific Decadal Oscillation),
403 with warm conditions favoring sardine and cool conditions favoring anchovy (Chavez et al.,
404 2003). Several hypotheses were proposed to explain this apparent relationship. While some
405 studies suggest that anchovy larvae are more tolerant of cold water than sardine larvae (Lasker,
406 1964; Lluch-Belda et al., 1991), others suggest that stronger upwelling during warm periods
407 may favor the small planktonic prey preferred by adult sardine (Rykaczewski & Checkley, 2008).
408 However, the paradigm of warm conditions favoring sardine has been upended over the past
409 two decades. Although it was predominantly cool from 1999-2013, anchovies were abundant
410 during warm conditions from 2004-06 and remained scarce during the other cool years
411 (Sydeman et al., 2020). Moreover, the heatwave was expected to help recover the declining
412 sardine population and curb growth in the increasing anchovy population; instead, sardine
413 abundance continued to decline throughout the heatwave (Nielsen et al., 2021), contributing to
414 the closure of the directed fishery in 2015 (**Figure 8B**), and anchovy abundance rose to near
415 record highs (Thompson et al., 2022). Although the environmental mechanisms driving
416 fluctuations in sardine and anchovy abundance remain poorly resolved, (Swalethorp et al.,
417 2022) found that changes in larval anchovy diet explained a significant proportion of spawning
418 stock biomass two years later. Shifting anchovy and sardine dynamics illustrate the risks of
419 relying on historical statistical correlations to guide management decisions, as climate change
420 increasingly results in no-analog conditions in ecosystems such as the California Current.
421 Although anchovy do not support substantial fisheries, their high biomass inshore likely
422 contributed to increased entanglements of humpback whales with crab fishing gear (Santora et
423 al., 2020), but also appears to have led to a trend of more and healthier sea lion pups since

424 2016 in the California Channel Islands (Weber et al., 2021) and successful nesting of resident
425 seabirds on Southeast Farallon Island (Fennie et al. in review). While the heatwave did not
426 trigger the initial decline in sardine biomass, the lack of recovery of this species continued to
427 cause loss of revenue for direct commercial fisheries, and for the live-bait fishery supporting
428 recreational fishers (PFMC, 2020, p.). Successfully managing these species under future
429 climate conditions will require a better understanding of the links between complex
430 environmental changes (beyond temperature alone), foraging ecology, and productivity of the
431 stock, and/or using management strategies that are robust to these dynamics (Siple et al.,
432 2019).

433 4.6. Shortbelly rockfish

434 Shortbelly rockfish are an important prey species for seabirds and marine mammals in
435 the California Current, and a non-target bycatch species in the commercial rockfish and Pacific
436 hake trawl fisheries. In 2018, the explosion of shortbelly rockfish abundance following high
437 recruitment during the marine heatwave nearly caused the closure of the hake fishery. In 2001,
438 the Pacific Fisheries Management Council (PFMC) established a catch limit for shortbelly
439 rockfish based on the belief that a commercial fishery would develop (Field et al., 2007).
440 Although a directed fishery did not emerge, catch limits remain in place. Historically, shortbelly
441 bycatch in the hake fishery has not approached the catch limit, but this changed radically as a
442 result of the heatwave. Within the first two weeks of the 2018 fishing season, the commercial
443 hake fishery off Oregon encountered several shortbelly bycatch hotspots and came very close
444 to exceeding the annual catch limit (**Figure 9A**). Without management intervention, the high
445 catch of shortbelly rockfish threatened to shut down the hake fishery at the very beginning of its
446 season. To make a rapid but informed decision, the PFMC examined recruitment estimates
447 from NOAA's Rockfish Recruitment and Ecosystem Assessment Survey (Sakuma et al., 2015).
448 They found that recruitment increased for most rockfish species during the heatwave and that
449 shortbelly recruitment jumped an order of magnitude above other rockfish winners. This was
450 likely due to the predominance of subarctic source water in upper depths (100-400 m) over the
451 outer shelf-slope where many rockfish spawn; that water is generally cooler, fresher, and more
452 oxygenated than other source waters and is correlated with high rockfish recruitment
453 (Schroeder et al., 2019). As the fastest-lived rockfish (i.e., fast growth, early age at maturity,
454 high mortality; Love et al., 2002), shortbelly rockfish were probably particularly poised to benefit
455 from these favorable conditions (Field et al., 2007; Pearson et al., 1991). As a result of these
456 massive recruitment events, shortbelly abundance was likely higher than it had been in

457 decades. After considering this best available science and statements from advisory bodies and
458 the public, the PFMC decided to raise the catch limit for the 2018 season, saving the hake
459 fishery from early closure. This case study highlights the importance of fishery-independent
460 monitoring of all life stages for detecting and explaining ecological surprises as well as the
461 importance of nimble and flexible management that is responsive to such surprises.

462 **4.7. California market squid**

463 The heatwave triggered significant range expansions and geographical shifts in the
464 productivity of California market squid, which have persisted beyond the heatwave years and
465 resulted in emerging fisheries in sudden need of management. Historically, the range of market
466 squid has been concentrated in California, where it supports one the state's largest and most
467 valuable fisheries (Free, Vargas Poulsen, et al., 2022). In the past, strong El Niño conditions
468 have supported temporary (i.e., weeks long) extensions of market squid range as far north as
469 the Gulf of Alaska. However, the 2014-16 marine heatwave resulted in an especially
470 pronounced northward shift that has persisted for a longer duration than ever recorded (Burford
471 et al., 2022; Chasco et al., 2022; M. Navarro, 2020). From 2016-2020, California's landings fell
472 by more than 50% relative to the previous 5 years, while Oregon's landings increased by orders
473 of magnitude (**Figure 9B**). During the same time period, squid observations increased
474 throughout the Gulf of Alaska, with squid spawning as far as Kodiak Island (M. O. Navarro et al.,
475 2018) and adults seen as far as the Shumagin (East Aleutian) Islands (Eiler, 2021). The
476 development of a significant squid fishery in Oregon has led to several proposed fishery
477 regulations, particularly in response to concerns over conflicts with other fishing gears (e.g.,
478 Dungeness crab pots), bycatch (e.g., Dungeness crab and salmon), and impacts on benthic
479 habitats (ODFW, 2021). Similarly, a proposal for a new market squid fishery in Alaska was
480 submitted in 2017 (Peeler, 2018), but was not passed due to concerns over bycatch of Chinook
481 salmon, which are declining in abundance. Similar proposals are likely to resurface as warming
482 waters decrease the productivity of traditional target species (Cheung & Frölicher, 2020) and
483 increase the availability of market squid as a profitable alternative. This case study illustrates
484 how managers will need to prepare for rapidly emerging fisheries that introduce novel conflicts
485 between fisheries and between economic and conservation goals. While improved monitoring
486 and forecasting may help, decisions will still need to be made on short notice and with limited
487 data, especially for species with fast life histories like squid.

488 4.8. Shrimp species

489 In our systematic analysis of fisheries revenues, West Coast commercial shrimp
490 fisheries showed one of the strongest and most consistent increases in revenues during the
491 marine heatwave (**Figure 3**), but have received little attention in the scientific literature.
492 Revenues of Pacific pink shrimp (*Pandalus jordani*), the 5th most important U.S. West Coast
493 fishery species in terms of revenues over the last decade and by far the most significant shrimp
494 species (PSMFC, 2021), experienced an enormous spike in revenues in both Oregon and
495 Washington in 2015 (**Figure 9C**). Similarly, ridgeback prawn (*Sicyonia ingentis*) experienced a
496 profound spike in revenues in California, the only state in which it is fished (**Figure 9C**). Spot
497 prawn (*Pandalus platyceros*) revenues increased throughout the heatwave, continuing growth
498 observed since 2003 (**Figure 9C**). These increases were unexpected as Pacific shrimp are
499 generally thought to experience low recruitment in warm years and to have low landings
500 following El Niño events (Groth et al., 2017; Groth & Hannah, 2018). Furthermore, jellies, which
501 clog the bycatch reduction devices required in shrimp trawl nets, were highly abundant during
502 the heatwave, requiring shrimpers to develop innovative methods for maintaining adequate flow
503 through nets (Groth et al., 2017). Ultimately, the 2015 revenue spike can be explained by record
504 high prices, which are determined by global markets, with an assist from a strong cohort of 2-
505 year-old shrimp from the 2013 year class (Groth et al., 2022). Although the Oregon Department
506 of Fish and Wildlife (ODFW) identified revisiting the relationship between shrimp recruitment
507 and environmental conditions as a top research priority (Groth et al., 2017), it also highlighted
508 that continued monitoring and improved stock assessment are, perhaps, more important to
509 near-term fisheries outcomes. Thus, this case study highlights that: (1) global markets and
510 lagged population dynamics can potentially mitigate (or, in other situations, exacerbate)
511 heatwave impacts; (2) innovation by fishermen can overcome some negative climate change
512 impacts; and (3) addressing climate change impacts may not be the highest priority if there are
513 more pressing concerns (i.e., improving stock assessments).

514 4.9. Pacific bluefin tuna

515 Pacific bluefin tuna, targeted by recreational fisheries in both U.S. and Mexican waters,
516 and by commercial fisheries primarily in Mexican waters, appeared to increase in availability
517 and size during the heatwave (Heberer & Lee, 2019; Runcie et al., 2019). While total
518 recreational bluefin landings from Commercial Passenger Fishing Vessels (CPFVs or party-
519 boats) increased prior to the heatwave (i.e., in 2011), increases in other availability metrics

520 coincided with heatwave years. For example, the proportion of annual CPFV landings showed a
521 clear and sustained shift to U.S. waters beginning in 2014 (**Figure 9D**). Prior to 2014, the U.S.
522 accounted for an average of 23% of annual CPFV bluefin landings, but from 2014-2021, the
523 U.S. accounted for an average of 75% of annual landings. While this shift could partially be
524 explained by regulatory shifts, such as when Mexico began enforcing restrictions against U.S.
525 recreational vessels in 2012, the shift occurred later and offshore fishing by U.S. vessels was
526 still allowed with a 'Forma Migratoria Multiple' (FMM) tourist permit. Additionally, before the
527 heatwave, the majority of bluefin were landed in warm summer months and were less than 2
528 years old (ISC, 2020). Since 2014, warm waters extended availability throughout the year and
529 more large bluefin (many 4-6 year-olds) were landed (James et al., 2021). This increase in
530 age/size is also supported by time series analyses of recreational "trophy" sizes of bluefin tuna
531 (Bellquist et al., 2016), which we recently updated (**Figure S1**) to include the heatwave and
532 post-heatwave periods. Furthermore, the heatwave drove shifts in bluefin diets that may have
533 affected availability (Portner et al., 2022). In 2015-2016, bluefin tuna diets abruptly switched to
534 being dominated by pelagic red crabs (*Pleuroncodes planipes*), coincident with the anomalous
535 northwards advection of this southern crustacean (Cimino et al., 2021). In 2016, bluefin
536 increased their consumption of anomalously abundant anchovies (Thompson et al., 2022). This
537 switch towards more epipelagic prey may have increased the aggregation of bluefin near the
538 surface, where they are more vulnerable to fishing. Increased availability and size drove interest
539 in recreational trips targeting bluefin and provided substantial economic benefits to the for-hire
540 fleet. This was especially valuable given low numbers of albacore (*T. alalunga*), the traditional
541 target of many of these vessels, over the previous 10 years. Benefits for commercial vessels
542 were limited given low quotas for this overfished stock (ISC, 2020); in fact, increased availability
543 introduced management challenges. In 2017, the U.S. exceeded its catch limit by more than 50
544 metric tons due to high local availability, increased purse seine effort, and a several day lag in
545 catch reporting, resulting in the August closure of the fishery (Laughlin, 2018). Mexico's purse
546 seine fishery also reached its harvest limits early, by July in 2014 and 2015. This illustrates how
547 the locally increased abundance of species subject to strict harvest control rules can challenge
548 fisheries management. Increasing the resilience of this highly migratory species will require
549 improved understanding of bluefin ecology, distribution, and migratory movements to help
550 managers better anticipate and respond to challenges posed by future change.

551 4.10. Bocaccio rockfish

552 In British Columbia, Canada, bocaccio rockfish (*Sebastodes paucispinis*) occur at depths of
553 60–300 m along most of the coast and are regularly caught by the commercial trawl fleet (Starr
554 & Haigh, 2022). The stock experienced a prolonged decline in spawning biomass from the
555 1930s that was arrested only somewhat by a series of moderate recruitment events in the
556 1970s. As a result, the Committee on the Status of Endangered Wildlife in Canada designated
557 the stock as Threatened in 2002 and Endangered in 2013 (COSEWIC, 2013). In response,
558 management reduced allowable catch and introduced trip limits with priority access for First
559 Nations and scientific surveys—the total mortality cap reached a low of 80 metric tons (mt) by
560 2016 (DFO, 2022). The commercial fleet was largely successful in actively avoiding the species
561 and averaged only 69 mt from 2015–2019. However, by the late 2010s, the fleet began
562 experiencing considerable challenges avoiding bocaccio—increasing abundance of the species
563 began limiting the ability for the fleet to avoid bocaccio and thereby target other species (e.g.,
564 Pawson, 2021). A stock assessment conducted in 2019 estimated a massive recruitment event
565 in 2016 at 44 times (30–58 times 90% CI) average recruitment from the previous 85 years and
566 of a magnitude sufficient to rebuild the stock above the limit reference point with 95% probability
567 within four years (DFO, 2020; Starr & Haigh, 2022). This recruitment may have been due to the
568 availability of oxygen-rich water at depth during gestation (Schroeder et al., 2019) associated
569 with the coincident marine heatwave (DFO, 2020; Starr & Haigh, 2022). An update to the
570 assessment in 2021 estimated an even larger 2016 year class (47 vs. 25 million one-year olds
571 in 2017) and a more rapid recovery with the stock in the “healthy zone” ($> 0.8 B_{MSY}$) with high
572 (87%) probability as of 2022 and near 100% probability by 2024 (DFO, 2021). Given this new
573 science advice, management raised the bocaccio total mortality cap to 300 mt in 2020/21, 500
574 mt in 2021/22, and 1800 mt for 2022/23 (DFO, 2022). However, First Nations raised concerns
575 about the rapidity of the TAC increases and about the suitability of MSY-based reference points
576 given the recruitment patterns (CCIRA, 2022). This case study is a success story in terms of
577 rebuilding an endangered fish stock, but highlights institutional challenges to respond rapidly to
578 sudden increases in abundance of “choke species” (i.e., a species with low quotas relative to
579 other species in a multi-species fishery), and raises questions about long term management of
580 stocks dependent on rare, environmentally driven recruitment events.

581 5. Lessons learned

582 5.1. For improving monitoring

583 The resilience of fisheries to heatwaves and climate change can be increased by
584 improving the scale, utility, diversity, accessibility, and funding of monitoring programs. First,
585 strategically enhancing the spatial-temporal scale of monitoring can promote dynamic
586 management that reduces tradeoffs among competing management objectives. For example,
587 increased spatial-temporal monitoring of harmful algal blooms and biotoxin contamination can
588 protect public health while minimizing impacts on fishing opportunities (Free, Moore, et al.,
589 2022). Similarly, data generated from expanded monitoring enables the development of
590 predictive models that can, for example, help to avoid bycatch of protected species under
591 changing environmental conditions (Hazen et al., 2018). Second, targeted monitoring is
592 necessary to understand drivers of the surprising shifts that have occurred during past
593 heatwaves and to use this knowledge to better prepare for future heatwaves. For instance,
594 targeted monitoring is necessary to resolve the relationship between the local availability and
595 stockwide abundance of Pacific bluefin tuna and the reasons for the unexpected reversal in the
596 relationship between warming and sardine and anchovy abundance (Thompson et al., 2022, p.
597 65). Third, developing novel monitoring programs can accelerate the detection and
598 understanding of sudden and/or unexpected shifts in productivity or distributions. By
599 complementing existing fisheries-independent surveys with information derived from fisheries-
600 dependent data, heatwave-driven shifts in abundance and distribution could be detected earlier
601 and more comprehensively (Maureaud et al., 2021). Furthermore, cooperative research with
602 fishers (Gawarkiewicz & Malek Mercer, 2019; Lomonico et al., 2021), citizen science programs
603 (Walker et al., 2020), and emerging technologies such as eDNA (Pikitch, 2018) and
604 autonomous sampling present opportunities to expand coverage while also reducing costs.
605 Fourth, developing tools for rapidly processing, visualizing, and disseminating raw monitoring
606 data can democratize and accelerate the rate at which “unknown unknowns” and other
607 surprises are detected and responded to (Anderson et al., 2020). The standardized summaries
608 of available fisheries-dependent and fisheries-independent data for Canadian Pacific groundfish
609 (Anderson et al., 2019) provide a useful template for such tools. Finally, monitoring
610 enhancements can be achieved without adding costs through technological advancements that
611 make monitoring cheaper (e.g., electronic monitoring, automated sensors, autonomous

612 vehicles, etc.) or through partnerships between public, private, and industry groups that make
613 monitoring more efficient (Lomonico et al., 2021).

614 5.2. For improving management

615 The resilience of fisheries to heatwaves and climate change can also be increased by
616 increasing the inclusivity, flexibility, and adaptiveness of fisheries management and by using
617 simulation testing to compare and choose between alternative management strategies. First,
618 arguably, the most fundamental step towards improving the resilience of fisheries management
619 is to broaden co-management systems that leverage stakeholder knowledge, lower monitoring
620 and management costs, and empower diverse stakeholder voices (Wilson et al., 2018). For
621 example, the inclusion of fishermen in the management of whale entanglement risk in the
622 California Dungeness crab fishery assisted in identifying and implementing management
623 solutions that are likely to be feasible, equitable, and effective (Humberstone et al., 2020).
624 Second, increasing the agility and flexibility of fisheries management institutions and procedures
625 may allow management to respond to surprises quickly and effectively. As illustrated by the
626 shortbelly and bocaccio rockfish case studies, this may require establishing procedures for
627 updating bycatch quotas outside of the usual process in response to unexpectedly high
628 recruitment events. As illustrated by the market squid case study, it may also involve
629 establishing plans for evaluating and managing rapidly-emerging fisheries that introduce novel
630 conflicts between fisheries and between economic and conservation goals. Third, fisheries
631 management must be adaptive and/or robust to the impacts of heatwaves and climate change.
632 This need has been well-described in many reviews (e.g., Holsman et al., 2019; Karp et al.,
633 2019; Pinsky & Mantua, 2014), but key suggestions are to account for shifting productivity by
634 incorporating climate variables into stock assessments (Marshall et al., 2019) and to design
635 harvest control rules (HCRs) that are robust to climate impacts (Free, Mangin, et al., 2022;
636 Wainwright, 2021). For example, Pacific sardine might have benefited from the application of an
637 HCR that was more robust to process uncertainty in the assumed relationship between
638 temperature and productivity in the years leading to the heatwave. Similarly, Chinook salmon
639 might have benefitted from HCR application that was more robust to assessment uncertainty in
640 the pre-season abundance forecast (Satterthwaite & Shelton, in press). Finally, wider use of
641 climate-linked management strategy evaluation (Kaplan et al., 2021) to compare the
642 performance of alternative management strategies under climate change will help to
643 quantitatively inform management decisions. Management strategy evaluation uses closed-loop
644 simulation to compare the performance of alternative management strategies (Punt et al.,

645 2016). Critically, it can evaluate the robustness of performance across various climate change
646 trajectories, assumed relationships between climate change and the fishery, levels of
647 observation and assessment uncertainty, and any other key sources of variability (Haltuch et al.,
648 2019; Jacobsen et al., 2022). Thus, management strategy evaluation represents the gold
649 standard in using quantitative evidence to guide climate-ready fisheries management decisions.

650 5.3. For improving adaptive capacity of fishing communities

651 The resilience of fishing communities to climate change depends on their adaptive
652 capacity, i.e., their ability to anticipate, respond to, cope with, and recover from the effects of a
653 climate stressor. Adaptive capacity can be enhanced by policies that promote inclusivity,
654 flexibility, experimentation, and failsafes, such as disaster relief or insurance. First, as indicated
655 in the section above, the adaptive capacity of fishing communities can be enhanced by
656 strengthening co-management systems that seek to leverage stakeholder knowledge and
657 balance diverse and sometimes diverging perspectives (Wilson et al., 2018). Second, policies
658 that promote livelihood diversification can help to buffer fishing communities against the
659 negative impacts of heatwaves and climate change. For example, easing access to fishing
660 permits can promote target species diversification and buffer revenues against heatwaves,
661 climate change, and other market shocks (Cline et al., 2017; Sethi et al., 2014), though tradeoffs
662 exist between ease of access and the financial viability of permit structures and their
663 effectiveness in controlling fishing effort. Third, the enhancement of state and federal Exempted
664 Fishing Permits programs, which allow experimentation in new fisheries, conservation
665 engineering, health and safety, environmental cleanup, and data collection that would otherwise
666 be prohibited, could accelerate innovation in climate-ready strategies (Bonito et al., 2022). For
667 example, Exempted Fishing Permits with good experimental design could be leveraged to
668 stimulate an expanded purple sea urchin fishery that enhances kelp reforestation, design whale-
669 safe fishing gear or practices that jointly prevent entanglements and fishery closures, or develop
670 new fisheries-dependent data streams that enhance adaptive management. Fourth, enhancing
671 programs that provide economic relief in response to negative environmental impacts can
672 improve the resilience of fishing communities to climate change. This could be achieved by
673 reforming the federal fisheries disasters relief program to be faster, more accurate, and more
674 equitable in its assessment and distribution of disaster relief (Bellquist et al., 2021).
675 Alternatively, this program could be complemented or replaced by novel fisheries insurance
676 programs. If index-based, such programs could provide immediate payouts following an
677 environmental trigger. As with the Caribbean Oceans and Aquaculture Sustainability Facility

678 fisheries insurance, in which policy-holding nations only receive insurance payouts triggered by
679 storms if they invest in best practices in fisheries management, insurance programs may even
680 be designed to incentivize the adoption of climate-resilient management and/or fleet behavior
681 (Sainsbury et al., 2019). Because adaptive capacity depends on social and demographic
682 factors that are heterogeneous across West Coast fishing communities (Koehn et al., 2022), the
683 success of the suggested strategies will be context dependent. For example, easing access to
684 permits will only help communities in locations where new or alternative target species are
685 available (Fisher et al., 2021).

686 6. Conclusions

687 The 2014-16 Northeast Pacific heatwave was the largest marine heatwave on record
688 (Laufkötter et al., 2020) and impacts of the heatwave on the fisheries of the West Coast of the
689 U.S. and Canada provide important insights into improving the resilience of global fisheries to
690 climate change. The heatwave resulted in positive as well as negative ecological impacts, both
691 of which generated challenges for fisheries management. Increasing the resilience of fisheries
692 to future heatwaves and directional climate change will require improvements throughout
693 fisheries social-ecological systems, from monitoring to management to the adaptive capacity of
694 communities. Key improvements include (1) enhancing monitoring to provide early warnings of
695 impacts, gain better mechanistic understanding of impacts, and inform predictive models of
696 impacts; (2) increasing the flexibility, adaptiveness, and inclusiveness of management and using
697 management strategy evaluation to guide strategic management decisions; and (3) enhancing
698 the adaptive capacity of fishing communities by promoting engagement, flexibility,
699 experimentation, and failsafes. These improvements come with increased costs, which can be
700 reduced through technological advancements, partnerships, and incentives that make
701 monitoring and management more efficient (Bradley et al., 2019; Lomônico et al., 2021).
702 Investments in these initiatives will be vital to ensuring that fisheries continue to support
703 livelihoods, food, and nutrition for billions of people around the globe (Costello et al., 2020).

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708 **Data Availability Statement**

709 All data and code associated with this paper is available on GitHub here:

710 https://github.com/cfree14/wc_mhw_case_studies

711 **Conflict of Interest Statement**

712 The authors have no conflicts of interest to declare.

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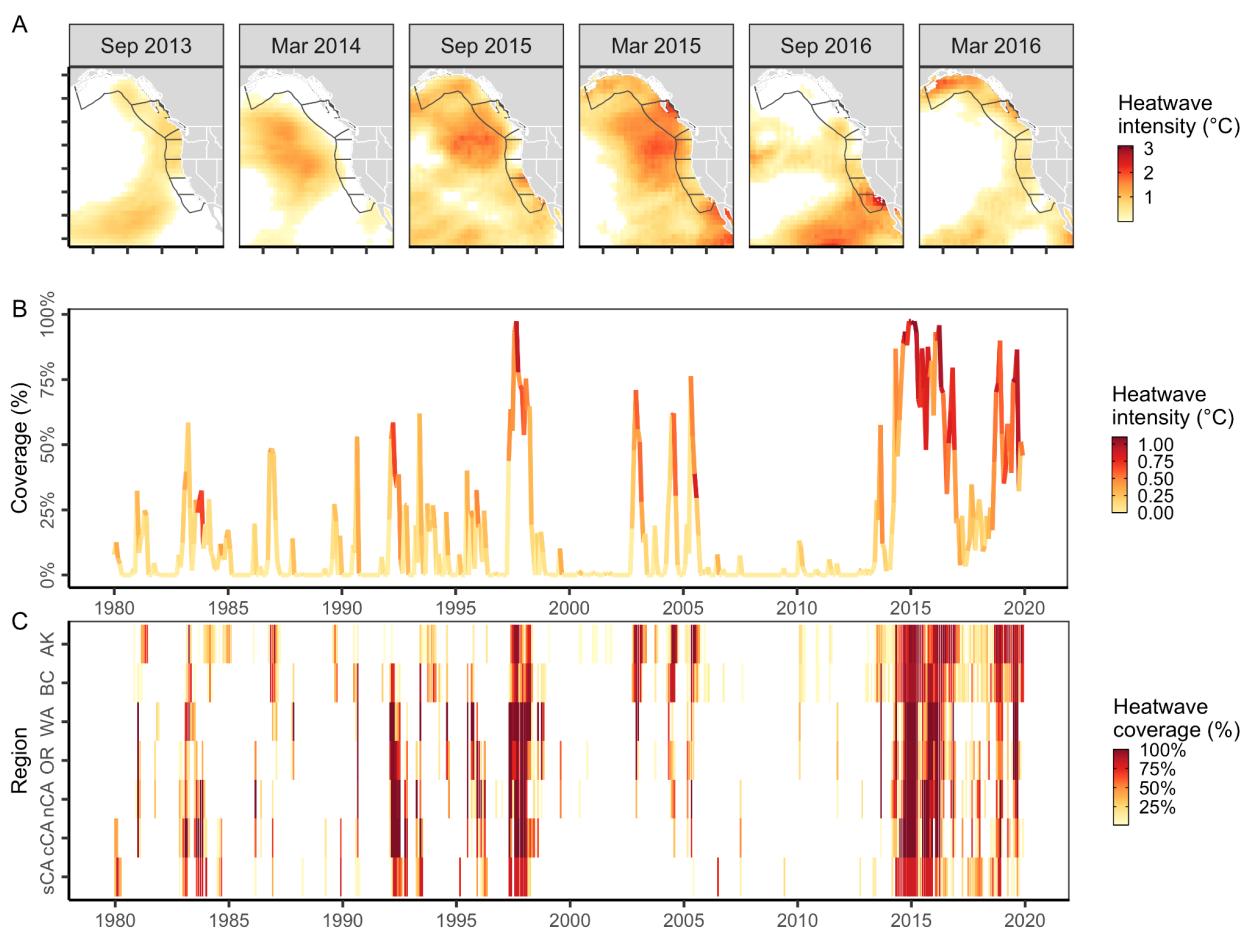
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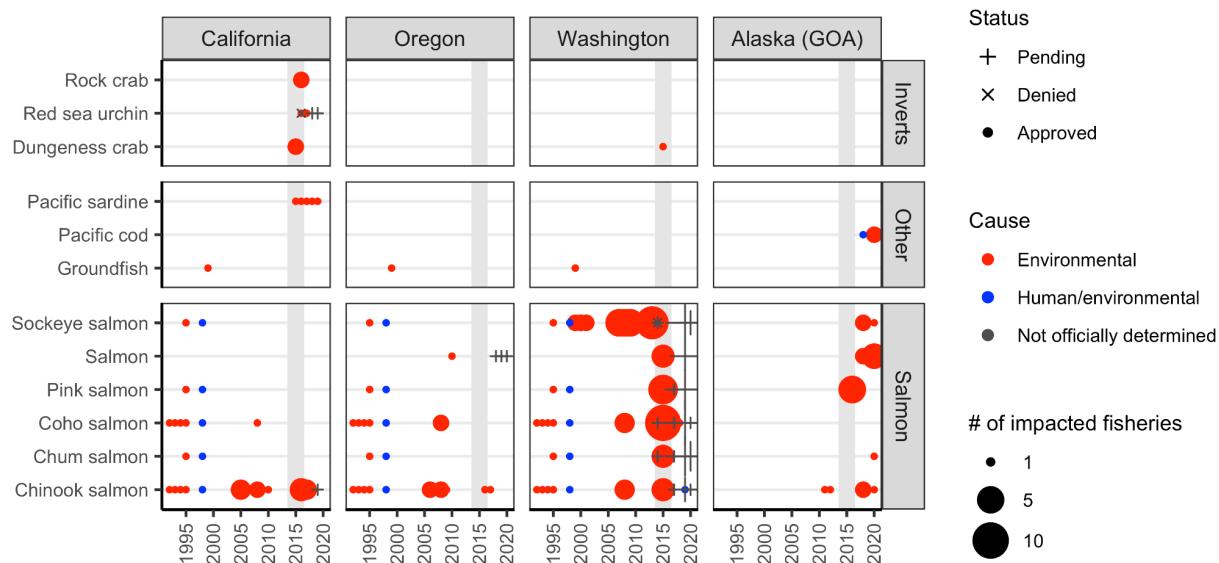
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1305 **Tables & Figures**

1306

1307 **Figure 1.** History of marine heatwaves on the U.S. and Canada West Coast based on analysis
 1308 of the COBE Sea Surface Temperature (SST) dataset (Ishii et al., 2005). In **(A)**, gray lines
 1309 indicate the Exclusive Economic Zones of southern (sCA), central (cCA), and northern
 1310 California (nCA), Oregon (OR), Washington (WA), British Columbia (BC), and the Gulf of Alaska
 1311 (AK). The lower panels show the history of marine heatwaves **(B)** across these seven regions
 1312 and **(C)** within each of the seven regions. Heatwave conditions were identified as temperatures
 1313 above the 90% of the historical climatology (1980-2010) for a given month and raster cell
 1314 (Hobday et al., 2016); thus, heatwave intensity represents the difference between the observed
 1315 temperature and the 90% heatwave threshold. In **(B)**, heatwave intensity is averaged across all
 1316 cells experiencing heatwave conditions.

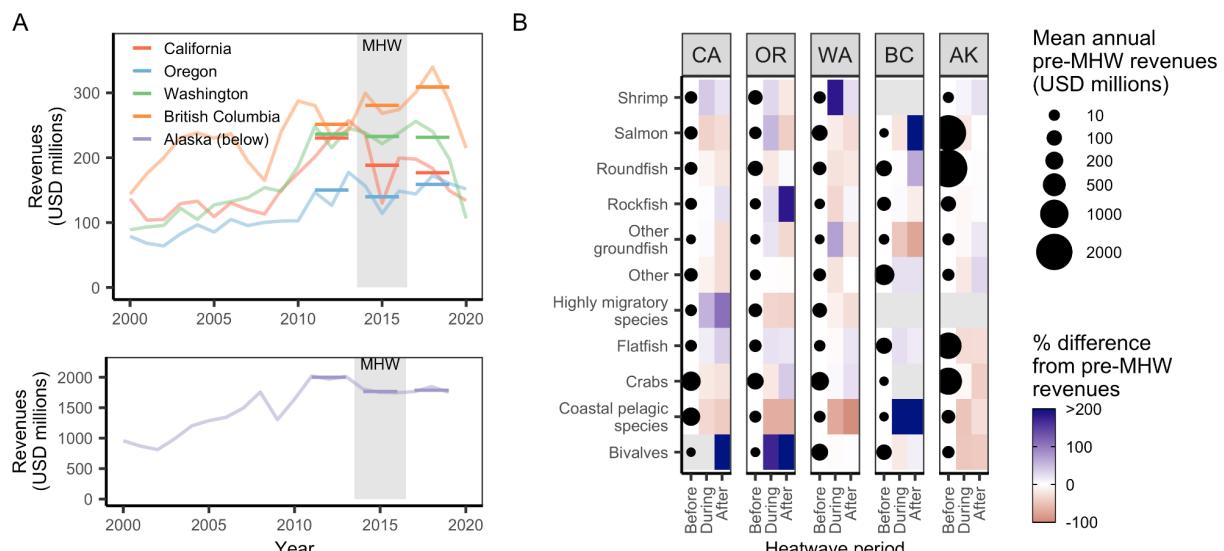


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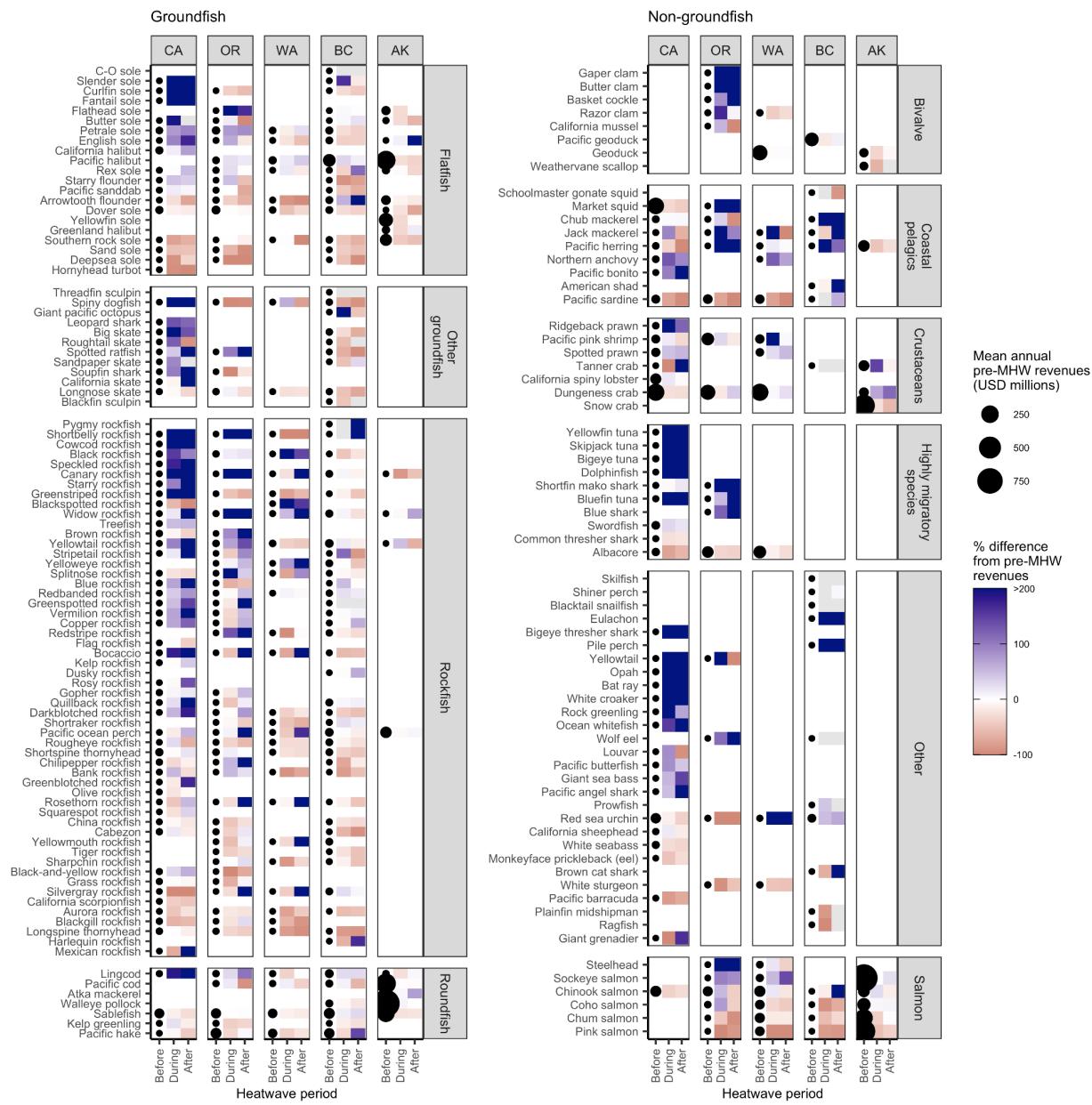
1319 **Figure 2.** History of U.S. federal fisheries disaster declarations on the West Coast from 1989-
 1320 2020 based on the database of Bellquist et al. (2021). Gray shading indicates years of the 2014-
 1321 16 marine heatwave. Disaster declarations for Alaska fisheries occurring outside the Gulf of
 1322 Alaska (GOA) are excluded.

1323



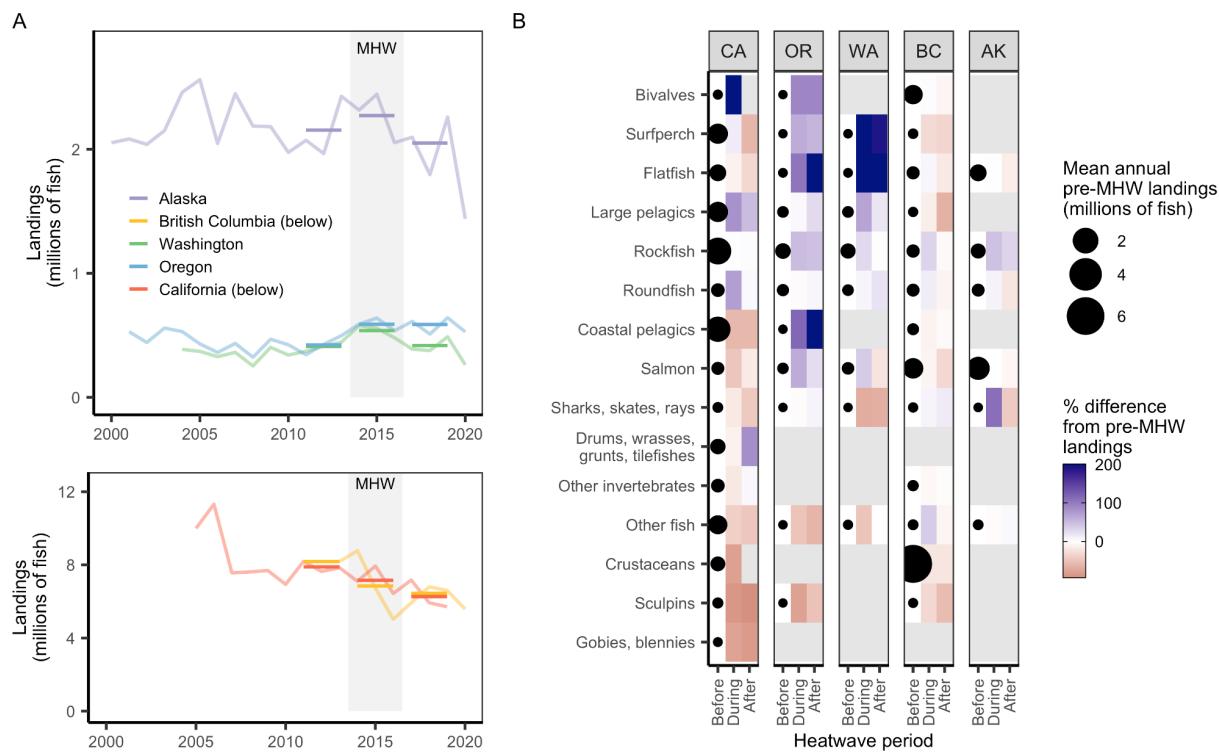
1324

1325 **Figure 3.** Commercial fisheries revenues by **(A)** state and **(B)** state and management group
 1326 before, during, and after the 2014-16 marine heatwave (MHW). In **(A)**, light lines indicate time
 1327 series of total annual revenues and dark lines indicate the mean total annual revenue for years
 1328 before (2011-13), during (2014-16), and after (2017-19) the heatwave. In **(B)**, the size of the
 1329 points plotted in the “before” column indicate mean annual revenues during the years before the
 1330 heatwave and the colors plotted in the “during” and “after” columns indicate the percent change
 1331 in revenues relative to the years before the heatwave. Management groups are vertically
 1332 ordered from greatest losses (bottom) to the greatest gains (top) in revenues during the
 1333 heatwave averaged across states.



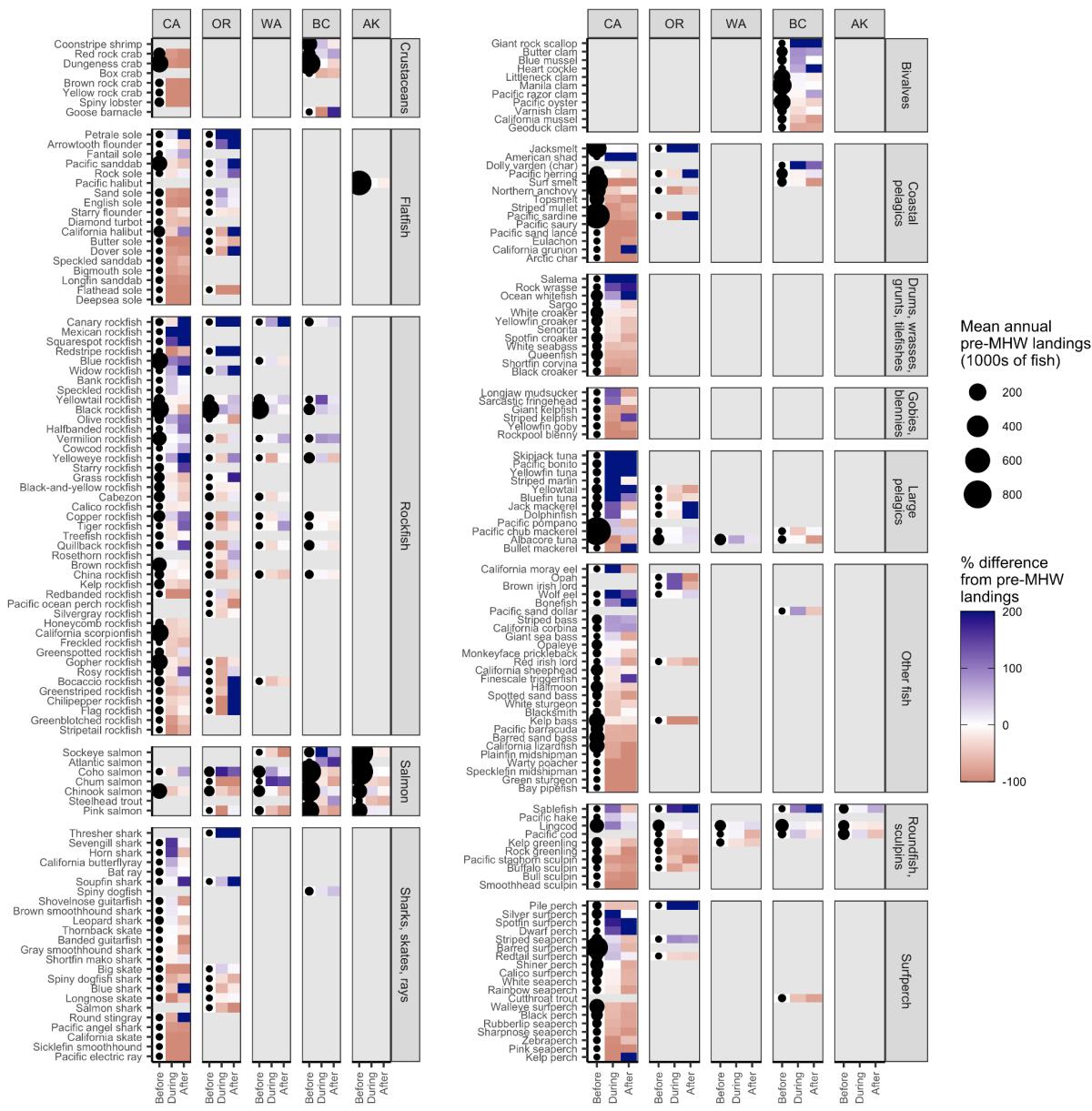
1334

1335 **Figure 4.** Commercial fisheries revenues before the 2014-16 marine heatwave and the percent
 1336 change in revenues during and after the heatwave by state, management group, and species.
 1337 Species (rows) are grouped by management group and are vertically ordered from greatest
 1338 losses (bottom) to the greatest gains (top) in revenues during the heatwave averaged across
 1339 states. The size of the points plotted in the "before" column indicate mean annual revenues
 1340 during the years before the heatwave and the colors plotted in the "during" and "after" columns
 1341 indicate the percent change in revenues relative to the years before the heatwave.



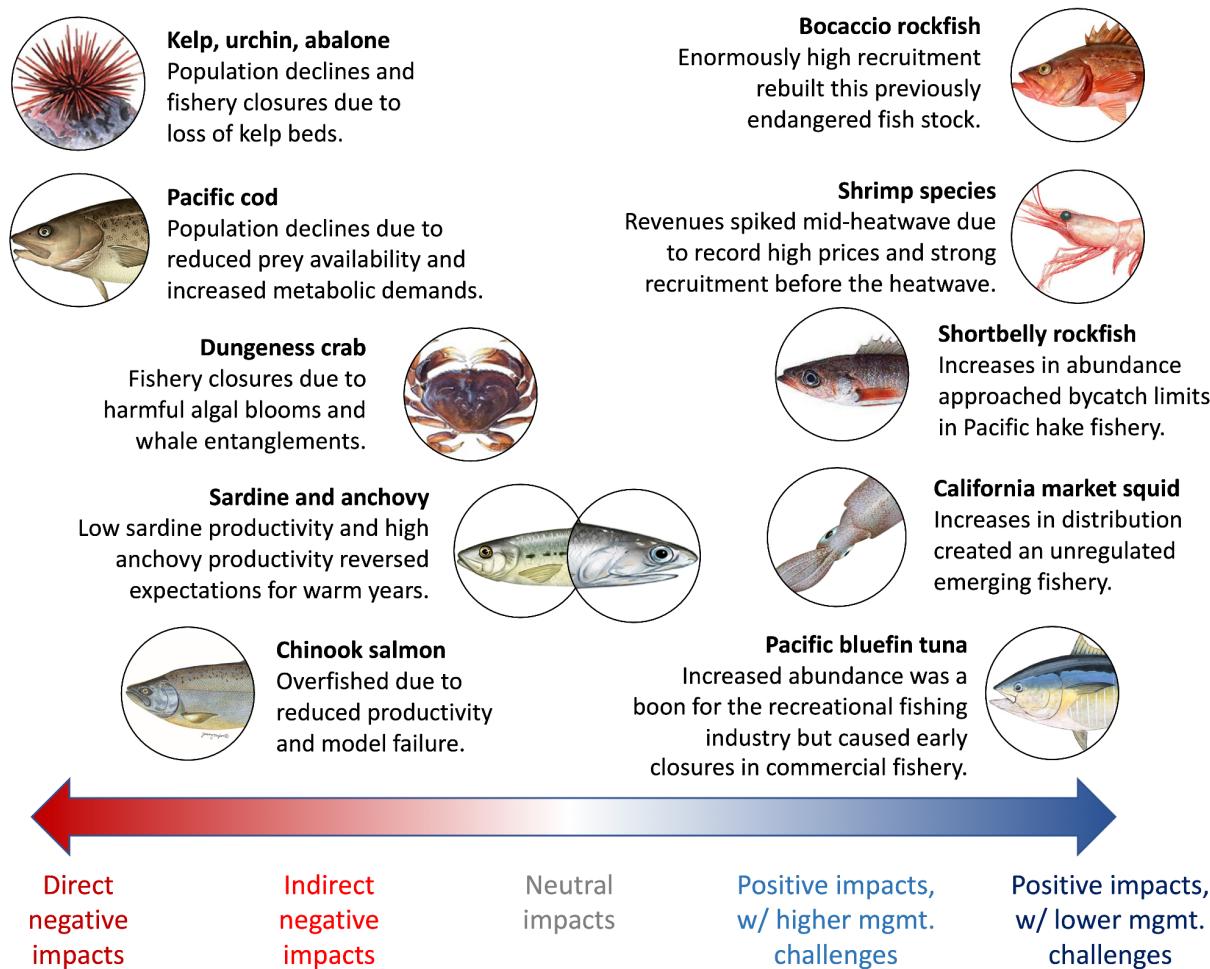
1342

1343 **Figure 5.** Recreational fisheries landings by **(A)** state and **(B)** state and taxonomic group
 1344 before, during, and after the 2014-16 marine heatwave (MHW) based on multiple recreational
 1345 landings databases. In **(A)**, light lines indicate time series of total annual landings and dark lines
 1346 indicate the mean total annual landings for years before (2011-13), during (2014-16), and after
 1347 (2017-19) the heatwave. In **(B)**, the size of the points plotted in the “before” column indicate
 1348 mean annual landings during the years before the heatwave and the colors plotted in the
 1349 “during” and “after” columns indicate the percent change in revenues relative to the years before
 1350 the heatwave. Taxonomic groups are vertically ordered from greatest losses (bottom) to the
 1351 greatest gains (top) in revenues during the heatwave averaged across states.



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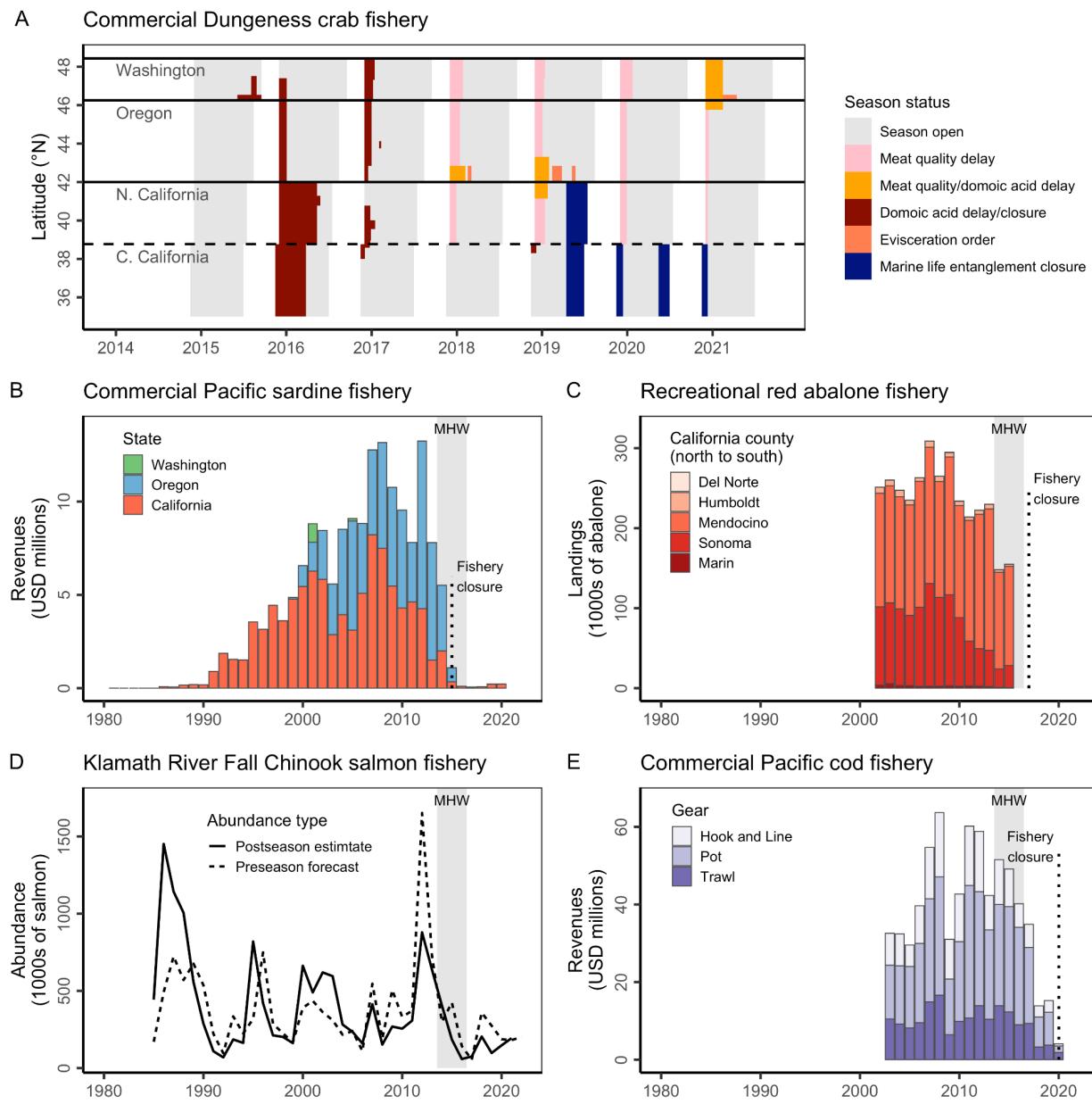
1353 **Figure 6.** Recreational fisheries landings (number of retained individuals) before the 2014-16
 1354 marine heatwave and the percent change in landings during and after the heatwave by state,
 1355 management group, and species based on multiple recreational landings databases. Species
 1356 (rows) are grouped by taxonomic group and are vertically ordered from greatest losses (bottom)
 1357 to the greatest gains (top) in landings during the heatwave averaged across states. The size of
 1358 the points plotted in the “before” column indicate mean annual landings during the years before
 1359 the heatwave and the colors plotted in the “during” and “after” columns indicate the percent
 1360 change in revenues relative to the years before the heatwave.



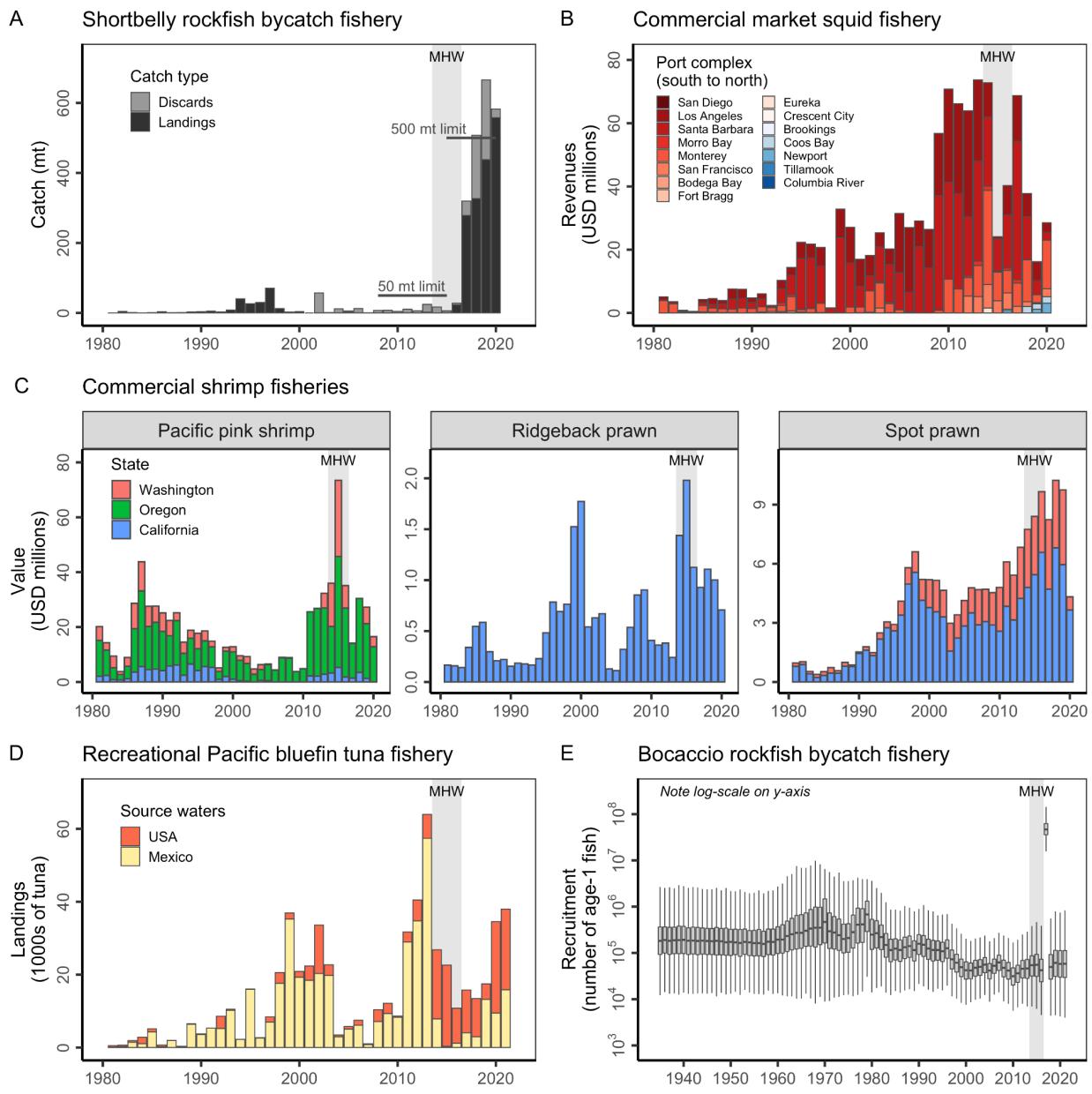
Social-ecological impact of the heatwave

1361

1362 **Figure 7.** Case studies evaluated in this paper. Case studies were selected to illustrate
 1363 instructive examples of West Coast fisheries that experienced either positive ($n=5$) or negative
 1364 ($n=5$) social-ecological impacts during the 2014-16 marine heatwave and to derive insights into
 1365 improving monitoring, management, and adaptive capacity of communities to be more resilient
 1366 to future heatwaves and climate change. Photo credits: NOAA (Pacific bluefin tuna, Pacific
 1367 sardine, Pacific cod, California market squid, northern anchovy), CDFW (Chinook salmon,
 1368 Dungeness crab, Pacific pink shrimp, red sea urchin), and WDFW (shortbelly rockfish).



1369
1370 **Figure 8.** Illustrations of some of the negative ecological and economic impacts of the 2014-16
1371 marine heatwave. Panel **A** shows the history of closures to the commercial Dungeness crab
1372 fishery due to domoic acid contamination, whale entanglement, and meat quality. Panel **B**
1373 shows the collapse of the commercial Pacific sardine fishery and its closure during the
1374 heatwave. Panel **C** shows the collapse and closure of the recreational red abalone fishery
1375 during the heatwave. Panel **D** shows the collapse of the commercial Klamath River Fall Chinook
1376 salmon fishery after the marine heatwave and the contribution of overly optimistic model
1377 forecasts. Panel **E** shows the collapse of the commercial Pacific cod fishery in the Gulf of
1378 Alaska after increased adult mortality and reduced juvenile recruitment during the heatwave.



1379

1380 **Figure 9.** Illustrations of some of the positive ecological impacts of the 2014-16 marine
 1381 heatwave. Panel **A** illustrates the explosion in shortbelly rockfish bycatch following anomalous
 1382 recruitment during the heatwave. Panel **B** illustrates the persistent northward shift of California
 1383 market squid landings initiated during the heatwave. Red colors indicate port complexes in
 1384 California and blue colors indicate port complexes in Oregon. Panel **C** illustrates the spike in
 1385 revenues in the commercial Pacific pink shrimp and ridgeback prawn fisheries during the
 1386 heatwave and the continued growth of the commercial spot prawn fishery through the heatwave.
 1387 Panel **D** illustrates the increased availability of Pacific bluefin tuna in U.S. waters during the
 1388 heatwave. Panel **E** illustrates how the enormous spike in British Columbia bocaccio recruitment
 1389 is projected to lead to the rebuilding of this endangered stock. In the boxplots, the solid line
 1390 indicates the median, the box indicates the interquartile range (IQR; 25th to 75th percentiles),
 1391 the whiskers indicate 1.5 times the IQR. Note the log-scale.

1392 **Supplemental Information**

1393 **Supplemental methods**

1394 This paper compiles several datasets to illustrate impacts of the 2014-16 marine heatwave on
1395 fisheries of the U.S. and Canada West Coast. We describe the compilation of these datasets
1396 below.

1397

1398 **Federal fisheries disaster data**

1399 The federal fisheries disaster data was developed by Bellquist et al. (2021).

1400

1401 **Commercial revenues data**

1402 We used annual statewide fisheries revenue data to evaluate impacts of the heatwave
1403 on commercial fisheries. To create this dataset, we combined data from a few sources. We
1404 used annual revenue data from the PacFIN database for the U.S. West Coast (California,
1405 Oregon, and Washington) and data from the NOAA FOSS database for Alaska. We used data
1406 from the NOAA FOSS database rather than from the AKFIN database (i.e., the equivalent of
1407 PacFIN for Alaska) because the AKFIN database only includes crabs and groundfish
1408 (i.e., it is less comprehensive) and is not species-specific (i.e., it is more generic). The NOAA
1409 FOSS database is more comprehensive and species-specific. While we could have also used
1410 the NOAA FOSS database for the other West Coast states, we preferred to use PacFIN
1411 because it's closer to the raw data (i.e., NOAA FOSS is built using PacFIN data). We used
1412 annual revenue data provided directly by Fisheries and Oceans Canada (DFO) for British
1413 Columbia.

1414

1415 **Recreational landings data**

1416 We used estimates of annual statewide fisheries landings (i.e., number of retained fish)
1417 to evaluate impacts of the heatwave on recreational fisheries. To create this dataset, we
1418 combined data from a few sources. We used estimates of annual landings from the RecFIN
1419 database for the U.S. West Coast (California, Oregon, and Washington) and from the ADFG
1420 website for Alaska. However, the RecFIN data does not include catches of highly migratory
1421 species in California's for-hire (Commercial Passenger Fishing Vessel or CPFV) fleet. Thus, we
1422 used data from the CDFW Landings Reports for these species. We used the ADFG database
1423 for Alaska because the AKFIN database does not include recreational landings estimates.

1424 Although the NOAA FOSS database includes estimates of recreational landings by state, these
1425 estimates have been transformed into biomass (pounds) and are thus less representative of the
1426 original data. Furthermore, they do not include recreational landings estimates for Alaska.

1427

1428 **Case study time series data**

1429 Dungeness crab management history: We obtained the spatial-temporal history of the
1430 Dungeness crab fishery shown in **Figure 8A** from Free et al. (2022).

1431

1432 Pacific sardine revenues data: We obtained time series of commercial Pacific sardine fisheries
1433 revenues from the PacFIN database (PSMFC, 2021), as compiled in the CALFISH database
1434 (Free, Vargas Poulsen, et al., 2022).

1435

1436 Red abalone landings data: We obtained time series of recreational red abalone landings
1437 estimates from a CDFW report (CDFW, 2015). CDFW estimated these values using abalone
1438 “report cards” (i.e. creel survey) and telephone surveys (Kalvass & Geibel, 2006).

1439

1440 GOA Pacific cod revenues data: We obtained time series of commercial Gulf of Alaska (GOA)
1441 Pacific cod fisheries revenues by gear and subarea from the AKFIN database.

1442

1443 Klamath River Fall Chinook escapement forecasts and observations: We obtained time series of
1444 Klamath River Fall Chinook salmon pre-season escapement forecasts and post-season
1445 escapement observations from the 2022 pre-season report (PFMC, 2022).

1446

1447 Shortbelly rockfish bycatch data: We obtained time series of shortbelly rockfish landings and
1448 discard estimates from the Groundfish Expanded Mortality Multiyear (GEMM) (Somers et al.,
1449 2020, 2021).

1450

1451 Market squid revenues data: We obtained time series of commercial market squid fisheries
1452 revenues by port complex from the PacFIN database (PSMFC, 2021), as compiled in the
1453 CALFISH database (Free, Vargas Poulsen, et al., 2022).

1454

1455 Pacific bluefin tuna landings data: We obtained time series of Pacific bluefin tuna landings by
1456 California’s recreational for-hire fleet from the California Marine Logbook System (MLS). The
1457 data query was submitted and processed by a co-author who is a CDFW employee.

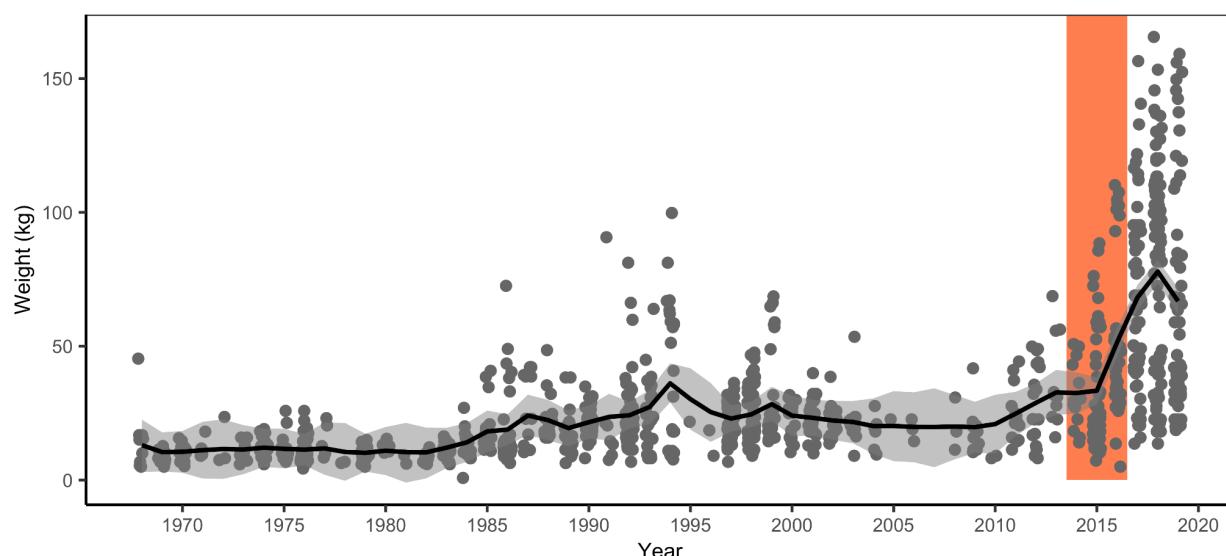
1458

1459 Bocaccio recruitment time series: We obtained time series of Bocaccio rockfish recruitment
1460 estimates from the first author of the most recent bocaccio rockfish stock assessment (DFO,
1461 2021).

For Review Only

1462 Supplemental figures

1463



1464

1465 **Figure S1.** Time series of trophy size Pacific bluefin tuna reported in the “Whoppers of the
1466 Week” section of Western Outdoor News from 1968-2019. The vertical orange rectangle
1467 illustrates the 2014-16 marine heatwave. The black line and shading indicate the median and
1468 95% confidence interval of a state-space model fit to the data. The data and modeling
1469 framework are an extension of that published in Bellquist et al. (2016).