

1 **Title:** Coupled changes in biomass and distribution drive trends in availability of fish stocks to
2 US west coast ports

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22 **Running Head:** Changing fish availability

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24

25 **Abstract**

26 Fishing communities are increasingly required to adapt to environmentally-driven changes in the
27 availability of fish stocks. Here we examined trends in the distribution and biomass of five
28 commercial target species (dover sole, thornyheads, sablefish, lingcod, and petrale sole) on the
29 US west coast, to determine how their availability to fishing ports changed over 40 years. We
30 show that the timing and magnitude of stock declines and recoveries are not experienced
31 uniformly along the coast when they coincide with shifts in species distributions. For example,
32 overall stock availability of sablefish was more stable in southern latitudes where a 40% regional
33 decline in biomass was counterbalanced by a southward shift in distribution of >200 km since
34 2003. Greater vessel mobility and larger areal extent of fish habitat along the continental shelf
35 buffered northerly ports from latitudinal changes in stock availability. Landings were not
36 consistently related to stock availability, suggesting social, economic, and regulatory factors
37 likely constrain or facilitate the capacity for fishers to adapt to changes in fish availability.
38 Coupled social-ecological analyses such as the one presented here are important for defining
39 community vulnerability to current and future changes in the availability of important marine
40 species.

41

42 **1. Introduction**

43 Marine species respond to environmental variability at nested spatial and temporal scales.
44 As well as being influenced by long-term trends such as ocean warming (Poloczanska *et al.*,
45 2013), species are also sensitive to decadal scale climate cycles (e.g. El Niño Southern
46 Oscillation (Lehodey *et al.*, 1997), Atlantic Multidecadal Oscillation (Nye *et al.*, 2014; Faillettaz
47 *et al.*, 2019), and Pacific Decadal Oscillation (Chavez *et al.*, 2003)) and short-term warming
48 events (Cavole *et al.*, 2016; Day *et al.*, 2018; Sanford *et al.*, 2019). This multiscale variability
49 can lead to large fluctuations in the abundance of a species in a given location over time, and
50 directional changes in species distributions can be counter to predictions based on long-term
51 warming trends alone (Hilbish *et al.*, 2010). As a result, the relative availability of target stocks
52 to fishers within local fishing grounds can be highly dynamic and difficult to predict.

53 Coincident changes in biomass and species distributions can lead to heterogeneous
54 effects on different fishing communities (Barange *et al.*, 2018). The vulnerability of communities
55 to shifts in available fish biomass can be broken down into three components: (a) exposure to the
56 bio-physical effects of environmental change, (b) dependence on spatially and temporally
57 shifting resources, and (c) adaptive capacity to offset negative impacts (Himes-Cornell and
58 Kasperski, 2015). As species distributions shift, ports can experience differential losses and gains
59 in landings of target species. Likewise, ports and fishers within a region can vary widely in the
60 number of species targeted (Kasperski and Holland, 2013), the diversity of fisheries in which
61 they participate (Fuller *et al.*, 2017), and the degree to which they are dependent on a particular
62 resource (Colburn *et al.*, 2016). These factors can exacerbate or mitigate the impacts of
63 distribution shifts on fisher livelihoods (Rogers *et al.*, 2019).

64 In this study, we use a coupled social-ecological approach to evaluate the vulnerability of
65 trawl fishing communities in the California Current to shifts in available biomass of target
66 species from 1980-2017. The California Current has experienced both warm and cool phases
67 over this time period (Fiedler and Mantua, 2017), including an extreme warming event during
68 2013-2017 that manifested as a large “blob” of warm water in the North Pacific (Cavole *et al.*,
69 2016). The spatial distributions of important fishery species has varied widely over this period,
70 and species have shown large differences in the direction, magnitude, and timing of spatial shifts
71 (Thorson *et al.*, 2016). We examine how distribution shifts coupled with changes in stock
72 biomass led to distinct trajectories of fish availability along the coast for five commercially
73 important groundfish species. Further, we develop an index of port-specific stock availability
74 that integrates latitudinal availability with patterns of fishing mobility. Finally, we examine the
75 relationship between port-specific availability and fisheries catch, and discuss how factors other
76 than availability may constrain or facilitate adaptation by fishing communities.

77

78 **2. Methods**

79 *2.1 Species and Port Selection*

80 Our analysis focused on groundfish caught by Northwest Fisheries Science Center
81 (NWFSC, NOAA) fisheries-independent surveys using bottom trawl sampling between 1980-
82 2017. We analyzed the distribution, stock biomass, and landings of five species that make up a
83 large component of fisheries landings for vessels using bottom trawl gear along the west coast of
84 the United States: dover sole (*Microstomus pacificus*), shortspine thornyhead (*Sebastolobus*
85 *alascanus*), sablefish (*Anoplopoma fimbria*), petrale sole (*Eopsetta jordani*), and lingcod
86 (*Ophiodon elongatus*).

87 To evaluate latitudinal trends in fish availability, the coast was subdivided into five
88 management subareas (Vancouver (VN), Columbia (CL), Eureka (EK), Monterey (MT), and
89 Conception (CP)) defined by latitude by the International North Pacific Fisheries Commission
90 (INPFC) (Figure 1). INPFC was established in 1952 and dissolved in 1993, but the areas defined
91 by the INPFC are still commonly used in fisheries management.

92 Ports were selected if they landed at least 30,000 metric tons of the target species over the time
93 series, and where these species were landed in all years for which landings data was available
94 (1981-2017). The focal ports spanned more than 1000 km of the US west coast: Bellingham Bay,
95 Washington (BLL, WA), Astoria, Oregon (AST, OR), Coos Bay, Oregon (COS, OR),
96 Brookings, Oregon (BRK, OR), Crescent City, California (CRS, CA), Eureka, California (ERK,
97 CA), Fort Bragg, California (BRG, CA), and Morro Bay, California (MRO, CA), ordered from
98 north to south (Figure 1). Landings of each species (mt) in each of these ports were derived from
99 the Pacific Fisheries Information Network (PacFIN) comprehensive fish tickets database for
100 1981-2017. We summed landings from fish tickets in each port for species reported with
101 multiple species codes (e.g. combining catch of actual petrale sole (PTRL) with codes for
102 nominal petrale sole (PTR1). See link for details on how nominal species are defined by
103 PACFIN <https://pacfin.psmfc.org/faqs/what-is-a-nominal-nom-fish-species/>). Commercial trawl
104 logbook data was used to assess port-specific spatial extent of fishing activity. The ports varied
105 in the relative importance of the focal species to overall catch (median values for the proportion
106 of catch ranged from 0.13 to 0.80), and in the distance traveled to harvest these species (Figure 1,
107 Figure S1).

109 2.2 Stock Biomass and Spatial Distribution

110 We sought to estimate biomass $b(s, t)$ for each species at 500 locations s within the spatial
111 sampling domain of the National Marine Fisheries Service (NMFS) shelf-slope surveys, for each
112 year t from 1980-2017. To do so, we combined two sources of information (see later sections for
113 details):

- 114 1. Stock assessment estimates of spawning biomass (mt) $B(t)$ (see 2.2.1 for details).
- 115 2. Spatio-temporal estimates of biomass-density (kg km^{-2}) $d(s, t)$ at each location, where
116 each location s has an area (km^2) $a(s)$ within the sampling domain (see 2.2.2 for details).

117
118 These two sources of information predict biomass $b(s, t)$ at each location using the following
119 equation:

$$120 \quad b(s, t) = B(t) \frac{a(s)d(s, t)}{\sum_{s=1}^n a(s)d(s, t)} \quad (1)$$

121 Estimates of relative biomass at each location s were calculated by multiplying the biomass
122 density $d(s, t)$ (kg km^{-2}) with the area $a(s)$ (km^2) associated with each location and dividing by
123 the sum of this quantity across all spatial locations n . Biomass (mt) associated with each location
124 $b(s, t)$ was computed by multiplying the relative biomass in each location by the spawning
125 biomass $B(t)$. This estimate corrects spatial distribution estimates derived from a spatio-
126 temporal model by accounting for vulnerability estimates derived from a stock assessment
127 model. This approach predicts that spawning biomass is spatially distributed in proportion to
128 survey catch rates; it implicitly assumes that survey selectivity is (approximately) proportional to
129 functional maturity. This assumption will be violated, e.g., if the survey catches both mature and
130 immature individuals, which would result in predictions of spawning biomass that are

131 influenced by the spatial distribution of immature individuals. Violation of this assumption will
132 result in biased predictions of spatial variation in spawning biomass. Further research could relax
133 this assumption by developing a spatio-temporal model for each size/age and modifying Eq. 1 to
134 predict distribution for each category individually, and we suggest that future applications follow
135 this approach.

136 137 2.2.1 Stock Biomass

138 Modeled estimates of stock-level spawning biomass ($B(t)$, mt) were extracted from the
139 most recent stock assessment for each species: petrale sole (Stawitz *et al.*, 2016), sablefish
140 (Johnson *et al.*, 2016), shortspine thornyhead (Taylor and Stephens, 2014), lingcod (Haltuch *et*
141 *al.*, 2017), and dover sole (A. Hicks, *personal communication*). Projected spawning biomass was
142 used for years post-dating the data included in the stock assessment (2015-2017 for petrale sole,
143 2015-2017 for sablefish, and 2014-2017 for shortspine thornyhead). Lingcod biomass was
144 estimated by summing the estimated spawning biomass for the northern and southern stocks.
145 These spawning biomass estimates are developed based on a variety of data sources and account
146 for age- and length-based selectivity and catchability within available survey data. We used
147 spawning biomass as a reasonable proxy for biomass available to fisheries, in the absence of
148 more specific information.

149 150 2.2.2 Stock Spatial Distribution

151 We developed estimates of biomass density $d(s, t)$ for each species within the spatial
152 sampling domain of the NMFS shelf-slope surveys and year t from 1977-2017. Sampling
153 locations of the survey in each year were limited to those at depths sampled consistently over the
154 entire period (0-500m). We focus on estimates from 1980 forward to allow further analysis of the
155 relationship between landings and availability, as landings data are available beginning in 1981.
156 We applied a spatio-temporal model to survey-sampled biomass data b_i occurring at location s_i
157 and time t_i , where survey samples of biomass are specified as following a conventional delta
158 model. The delta-model includes a logit-linked linear predictor for encounter probability p_i for
159 observation i , and a log-linked linear predictor for expected catch rate r_i given that the species is
160 encountered. Each linear predictor then includes an intercept for each year, and a spatio-
161 temporal term that follows a first-order autoregressive process among years and a Matérn spatial
162 correlation function across space. Density is then predicted as the product of predicted encounter
163 probability and positive catch rate at each location, $d(s, t) = p(s, t)r(s, t)$. The model is
164 estimated for each species individually using the Vector Autoregressive Spatio-Temporal
165 package in R (Thorson, 2019); see Appendix 1 for more details. The center of gravity (COG) for
166 each species was determined as the mean latitude for all locations s weighted by biomass density
167 $d(s, t)$. Species-specific differences in the variance of the COG were evaluated using a ANOVA
168 test on the mean absolute deviation from the median (Boos and Brownie, 2004) with Tukey HSD
169 post-hoc comparisons. Correlations between the COG and spawning biomass $B(t)$ were assessed
170 with a linear model. All analyses were conducted in R (R Core Team, 2019).

171 2.3 Latitudinal variation in stock availability

172 We examined how fluctuations in stock biomass and distribution combined to influence
173 the relative availability of species by latitude along the coast. Mean biomass for each INPFC
174 subarea was calculated as the average biomass $b(s, t)$ across all locations in the subarea.

175

176 2.4 Stock availability to ports

177 Availability to specific ports was calculated as the sum of biomass $b(s, t)$ of all locations
178 within the fishing grounds utilized by the port to harvest any of the 5 species. Harvest locations
179 and catch were analyzed from commercial trawl logbook data 1981-2015 collected by California,
180 Oregon, and Washington (M. Haltuch *personal communication*). Fishing grounds were defined
181 as a circle centered on the port with a radius equal to the 75th quantile of the distance traveled
182 between harvest location and port of landing for trawl vessels targeting any of the five species,
183 weighted by the catch of those species, pooling all years.

184

185 2.5 Landings relative to availability

186 Yearly landings of each species, the number of fish tickets, and the number of trawl
187 vessels in each port were tabulated from PacFIN fish tickets 1981-2017. We qualitatively
188 examined the relationship between port-specific availability and average landings (mt) per fish
189 ticket. Only those years in which a minimum of three vessels landed in the port were reported.

190

191 3. Results

192 3.1 Fluctuations in stock biomass and distribution

193 The five species demonstrated one of two patterns in spawning stock biomass through
194 time (Figure 2): continuous declines (sablefish and shortspine thornyhead), or decline followed
195 by a period of recovery (Dover sole, lingcod and petrale sole). At the same time, the stocks
196 demonstrated widely different patterns in the variance of the centers of gravity (COG) of their
197 spatial distributions (ANOVA $F=5.19$, $p<0.001$). In particular, the variance in the COG for dover
198 sole and sablefish was significantly larger than that for shortspine thornyhead. The center of the
199 shortspine thornyhead distribution remained within a half degree of latitude over the time series.
200 Conversely, the center of the distributions for dover sole and sablefish exhibited fluctuations of
201 more than 2 degrees latitude (>200 km) over the whole time series, and more than 1.5 degrees
202 latitude (>150 km) since the start of the annual survey in 2003. The fluctuations in distribution for
203 petrale sole and lingcod were more moderate, but large changes were evident in the most recent
204 years, particularly for lingcod. The center of the sablefish distribution varied significantly with
205 spawning biomass ($t=3.803$, $p=0.001$), located further north during the early period with high
206 spawning biomass, while the other species had no consistent relationships between center of
207 gravity and spawning biomass.

208

209 3.2 Latitudinal variation in stock availability

210 Simultaneous changes in overall stock biomass combined with large fluctuations in
211 spatial distribution led to differences in the relative availability of each species along the coast
212 (Figure 3 and Figure 4). For example, the decline in sablefish biomass over time did not occur
213 simultaneously or at the same magnitude across all INPFC subareas. In the southern subareas of
214 Conception (CP) and Monterey (MT), biomass declined sharply in 1992 as the stock shifted
215 northward, and biomass was concentrated within the northern subarea Columbia (CL).
216 Thereafter, biomass in the southern areas increased as the stock distribution moved south, with
217 biomass values in the most southerly subarea of Conception exceeding that in Columbia for the
218 first time in 2005-2008. Meanwhile, biomass in the northern subarea of Columbia dropped
219 precipitously since the peak in 1992 due to the combined effect of declines in total biomass and a

220 southern shift in that biomass. In contrast, following its low point in 1992, the middle subarea of
221 Eureka (EK) experienced almost no change in biomass.

222 The high biomass of Dover sole combined with substantial fluctuations in its distribution
223 led to large changes in the available biomass within each subarea. The principally northern
224 movement of the stock since the mid-1990s combined with its increase in stock size during that
225 period led to a doubling of biomass available in the two northern subareas of Vancouver (VN)
226 and Columbia. At the same time, biomass in the southern subareas remained steady (CP) or
227 declined (MT) (Figure 4).

228 Likewise, the small increase in petrale sole overall biomass in 2000-2005, coincident
229 with a southern shift in its distribution, led to differential trajectories of recovery as a function of
230 latitude. The middle (EK) and southern (MT) subareas experienced the largest increases, while
231 those in the north remained steady (CL) or declined (VN). On the other hand, as stock biomass
232 more than doubled in size after 2009, the distribution returned towards its historical center
233 (Figure 2). As a result, biomass increased more moderately in the most southerly subarea, while
234 increasing by ~300-400% in all other subareas (Figure 4).

235 Shortspine thornyhead had relatively stable biomass and distribution (Figure 2). As such,
236 latitudinal variation in available biomass along the coast was more stable over time (Figure 4).
237 Lingcod demonstrated large changes in overall biomass over the time series, and this dominated
238 trends in available biomass along the coast, with most subareas showing qualitatively similar
239 patterns (Figure 3).

240

241 3.3 Stock availability to ports

242 Trawl vessels in each focal community differed widely in the distance traveled between
243 port and harvest location (Figure 5). The most northerly ports routinely traveled more than
244 150km while the fishing communities in southern Oregon and California typically traveled 75km
245 or less (Figure S1). For most of the species, biomass was more available to northerly ports due to
246 the combination of greater distance traveled by these ports and greater areal extent of bottom
247 habitat <500m in depth within the radius of distance traveled (Figure 5). Calculating port-
248 specific stock availability based on the area utilized by fishers substantially altered inferences
249 regarding biomass distribution along the coast. For example, while the INPFC subarea in which
250 Astoria was located was ranked 4th in petrale sole biomass in 2017, the port of Astoria had more
251 than two times the available biomass of all other ports when accounting for fishing area.
252 Likewise, while the southern movement of sablefish during the 2000s led to southerly INPFC
253 subareas having higher mean biomass, the sablefish biomass available to vessels originating
254 from Astoria was consistently the highest across the entire time series.

255

256 3.4 Relationship between landings and availability

257 The relationship between landings (mt) per fish ticket and available biomass was not
258 consistent across ports or species (Figure 6). The highest levels of catch per fish ticket for
259 sablefish and shortspine thornyhead were achieved at lower values of availability. For shortspine
260 thornyhead, this was driven by higher landings for California ports relative to that in Oregon and
261 Washington, potentially driven by a quadrupling in price per pound for the species in California
262 but not in the other two states (Figure S2). In contrast, catch per fish ticket for petrale sole
263 showed an increasing trend with increasing availability. Dover sole and lingcod did not show
264 clear trends in catch as a function of availability.

265

266 **4. Discussion**

267 Fisheries resources are changing in both their productivity and distribution, yet it is
268 unclear how these synergistic changes affect the communities that rely on them. Our study
269 makes advances relevant to this field in two ways. First, by coupling changes in biomass and
270 species distributions, we uncovered heterogeneous patterns of fish stock availability at different
271 latitudes along the US west coast. This demonstrates that trends in local stock availability at a
272 subregional scale may be amplified or dampened relative to trends at the stock-wide scale.
273 Second, we integrated information on distances traveled by fishers with our estimates of
274 availability along the coast to generate port-specific indices of availability. This analysis
275 provides the first estimate of port-specific exposure to the combined effects of historical changes
276 in fish biomass and distributional shifts.

277 Variation in the areal extent of fish habitat adjacent to port combined with differences in
278 the distances traveled from port indicated that some fishing communities experienced port-
279 specific stock availability that was decoupled from sub-regional (e.g., INPFC) trends in mean
280 biomass. For example, a latitudinal increase in continental shelf area combined with greater
281 distance traveled between port and harvest location buffered the northern port of Astoria from
282 sub-regional changes in biomass. More mobile fishers are thought to have lower vulnerability to
283 environmental changes (Young *et al.*, 2019). Our study suggests even lower vulnerability to
284 changes in biomass when this greater mobility is coupled with greater access to habitat. Further,
285 the exposure to changes in species distribution can vary greatly even for communities with
286 similar distance traveled from port due to the specific trends in biomass within their fishing
287 grounds. These results are in line with recent work projecting distinct vulnerability of adjacent
288 ports to future changes in species biomass when those ports target different fishing grounds
289 (Rogers *et al.*, 2019). As such, port-specific indices of availability may be increasingly important
290 as an indicator for management, and can complement other port-based indices of vulnerability to
291 climate change. The availability indices developed here were included in the 2019 California
292 Current Ecosystem Status Report (Harvey *et al.*, 2019) and have been incorporated in the most
293 recent stock assessment for sablefish (Haltuch *et al.* In Review). Such indicators may be a useful
294 addition to Integrated Ecosystem Assessments that are currently being developed for each of the
295 large marine ecosystems within the United States, and are directly relevant to the recently
296 established Climate and Communities Initiative of the Pacific Fisheries Management Council
297 (PFMC, 2019). As data streams become more available in near-real time, such availability
298 indices could be made available to fishers to enable targeting decisions in a way that may
299 facilitate greater resilience to changing species distributions.

300 In our study, higher stock availability was not consistently associated with higher catch
301 per ticket. This suggests that factors in addition to availability were important drivers of
302 landings. Technological, economic, and management factors can limit both the willingness and
303 capacity for fishers to respond to shifting availability of target species, thus affecting the
304 coupling between landings and availability. A high degree of reliance on a particular species may
305 result in a mismatch between landings and availability. While all focal ports had a combined
306 total of at least 30,000 metric tons of total landings of the five species over the time series, they
307 varied in the relative importance of these species over the time series (Fig. S1). Ports that rely
308 more on a particular species, or the species complex as a whole, may be more likely to target
309 those species, to the extent possible using a relatively unselective trawl gear. Individual
310 transferable quotas, like that implemented in this fishery in 2011, can serve to incentivize
311 targeting. Trawl fishers operating under an IFQ for groundfish in British Columbia were able to

312 adjust the species mixture in their catches by avoiding areas with high abundance of species with
313 lower total allowable catches (Branch and Hilborn 2008). Recent analyses of West Coast
314 trawlers suggest fishers used spatial avoidance of areas with high abundance of overfished
315 species but also employed other targeting practices since the implementation of IFQs, including
316 shifting activity from day to night, shortening the duration of trawl tows, and forming
317 cooperatives that shared information about where overfished species were concentrated (Miller
318 and Deacon 2017). This resulted in a marked decline in the proportion of the catch represented
319 by overfished species. If the same strategies could be used to increase targeting of desired
320 species, this may contribute to some of the mismatches observed between landings and stock
321 availability.

322 High market value may incentivize further targeting of a species, such that its landings
323 are not proportional to its availability in the environment. This may be a factor in the observed
324 inverse relationship between catch and availability of sablefish, which garners a high price per
325 pound in the market. Similarly the higher landings of shortspine thornyhead in the California
326 ports despite its lower availability may have been driven by the dramatic increase in the price per
327 pound for this species in California that was not observed in Oregon or Washington.
328 Management actions on other species in a catch portfolio may also have knock-on effects. Many
329 species of rockfish were declared overfished in the late 1990s (Starr *et al.*, 2016). The resulting
330 stringent catch limits for rockfish may have driven increased harvesting of the remaining high
331 value species.

332 Market forces may also dictate the willingness of fishers to change their catch
333 composition as new species become available. Species that become available to a region as a
334 result of shifting distributions may be poor substitutes for traditional target species due to large
335 price differences that affect fishery profitability (Sumaila *et al.*, 2011), geographic restrictions on
336 processing capacity (Gibson, 2017), or limits on the availability of permits (Murray *et al.*, 2010).
337 For example, processing capacity for sablefish in the south is limited (M. Haltuch *personal*
338 *communication*), and may constrain the ability of fishers in that region from taking advantage of
339 increased sablefish availability. Changes in market value of a given species can also offset
340 climate-driven costs of shifting distributions and declining productivity (Seung and Ianelli,
341 2016). Such market constraints and incentives can alter the potential for fishers to adapt to
342 changes in species composition in fishing grounds.

343 In addition, the multispecies nature of trawl fisheries may further constrain the
344 relationship between landings and availability. For example, landings for a single species may be
345 limited by quota for other species caught with the same gear (i.e., choke species), such that
346 landings level off at higher stock availability. At a stock-wide level, thornyhead and dover sole
347 landings are limited by quotas of sablefish with which they co-occur (Taylor and Stephens,
348 2014), which may serve to decouple catch per unit effort and availability at a port level.

349 External factors such as management actions and broader economic trends can interact
350 with local context (e.g., infrastructure, livelihood alternatives, governance structures) to create
351 substantial geographic differences in responses (Lyons *et al.*, 2016; Maina *et al.*, 2016). Here,
352 local governance structures may have also played a role in constraining the relationship between
353 availability and landings. Fisheries patterns may be largely influenced by the regulatory changes
354 that have occurred over this time frame. Large-scale closed areas extending along the entire west
355 coast were established in 2002 to facilitate recovery of overfished rockfish species. Further, a
356 catch-share program that requires full catch accounting was implemented in 2011 in the
357 groundfish fishery. As a result, vessels are largely landing most of what they catch, which could

358 alter the relationship between landings and availability for these communities. These additional
359 regulatory factors may be important drivers of the ways that fishers are responding to changes in
360 availability within their fishing grounds.

361 Communities vary in the degree to which they can use their resources (natural, physical,
362 financial, human and social capital) to respond to shifts in available biomass, and in the time
363 scale over which they can withstand change (Miller *et al.*, 2018). In the short-term, communities
364 may be able to survive anomalous periods by making small adjustments in location of fishing
365 effort or target catch composition, but long-term solutions may be necessary to adapt to novel
366 conditions that may emerge due to climate change or other influences (Smit and Wandel, 2006;
367 Barange *et al.*, 2018; Hobday *et al.*, 2018; Miller *et al.*, 2018). The changes in availability seen
368 here are likely driven by relative short-term environmental fluctuations, making it potentially
369 more difficult for fishers to respond if such responses require a build up of capital.

370 Even if fishers were able to perfectly and immediately respond to changing fish
371 availability, in most cases management is not designed to respond to shifting species
372 distributions (Pinsky and Mantua, 2014). Further, shifting distributions present policy challenges
373 for how to equitably balance quota allocation among fishers who may have traditionally had
374 access to a species relative to those who wish to gain access to a new species within their fishing
375 grounds. Allocations of quota among management jurisdictions based on historical landings
376 allow fishers that historically targeted a species to follow the fish, but make it more difficult for
377 fishers to take advantage of emerging fisheries within their traditional fishing grounds. Static
378 spatial restrictions on allowed gears or limited vessel mobility can further constrain the ability of
379 fishers to follow fish into new fishing grounds (Pinsky and Fogarty, 2012; Young *et al.*, 2019).
380 Taking advantage of newly available species within fishing grounds in other management
381 regions may be more difficult whenever new species are managed by different management
382 entities and require different permits. On the Atlantic Coast of the US, for example, many of the
383 groundfish species that are exhibiting large changes in availability are managed by separate
384 fisheries management bodies (e.g., the New England Fisheries Management Council and Mid-
385 Atlantic Fisheries Management Council) and require separate permits. The situation becomes
386 even more complicated when species are moving over international borders. Indeed, shifting
387 species distributions due to climate change are projected to lead to more than 50 new
388 transboundary stocks, which may cause future international conflicts (Pinsky *et al.*, 2018).
389 Projections of where we expect fish to go in the short and medium term will be useful in
390 identifying where species are likely to cross management jurisdictions, enabling more proactive
391 rather than reactive management responses to shifting distributions.

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393

394 **5. Conclusion**

395 Our results provide insight into how changes in species distribution and productivity
396 differentially impact fishing communities along a coastline. These results are important in
397 anticipating the spatially heterogeneous impacts of climate-driven changes in fisheries resources.
398 Our port-centric approach could be coupled with projections of future changes in available
399 biomass at global (Cheung *et al.*, 2010) and regional scales (Morley *et al.*, 2018) to derive a
400 metric of aggregate risk across the suite of species exploited in a port. In this way, indices of
401 current and future vulnerability of fishing communities can be integrated into management
402 efforts that are preparing for species on the move.

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549 Figure Legends

550 Figure 1. Spatial locations for which biomass-density was estimated in this study (black dots)
551 relative to INPFC subareas (Vancouver (VN), Columbia (CL), Eureka (EK), Monterey (MT),
552 and Conception (CP)) and focal ports (Bellingham Bay, WA (BLL), Astoria, OR (AST), Coos
553 Bay, OR (COS), Brookings, OR, (BRK), Crescent City, CA (CRS), Eureka, CA (ERK), Fort
554 Bragg, CA (BRG), and Morro Bay (MRO). The number of spatial locations within each subarea
555 is related to the width of the continental shelf. The radii of the circles centered on each port
556 represent the 75th quantile of the distance traveled from port to harvest any of the five species,
557 weighted by catch, as measured by trawl logbooks 1981-2015.

558
559 Figure 2. (left y-axis) Time series of spawning biomass (thousand mt) from stock assessments
560 1980-2013 for five groundfish species on the US west coast. (right y-axis) Time series of center
561 of gravity (COG, in degrees latitude) estimated using the Vector Autoregressive Spatio-
562 Temporal model (VAST) (Thorson, 2019). Grey dashed lines indicate the year 2003, when the
563 NMFS trawl survey transitioned from triennial to annual.

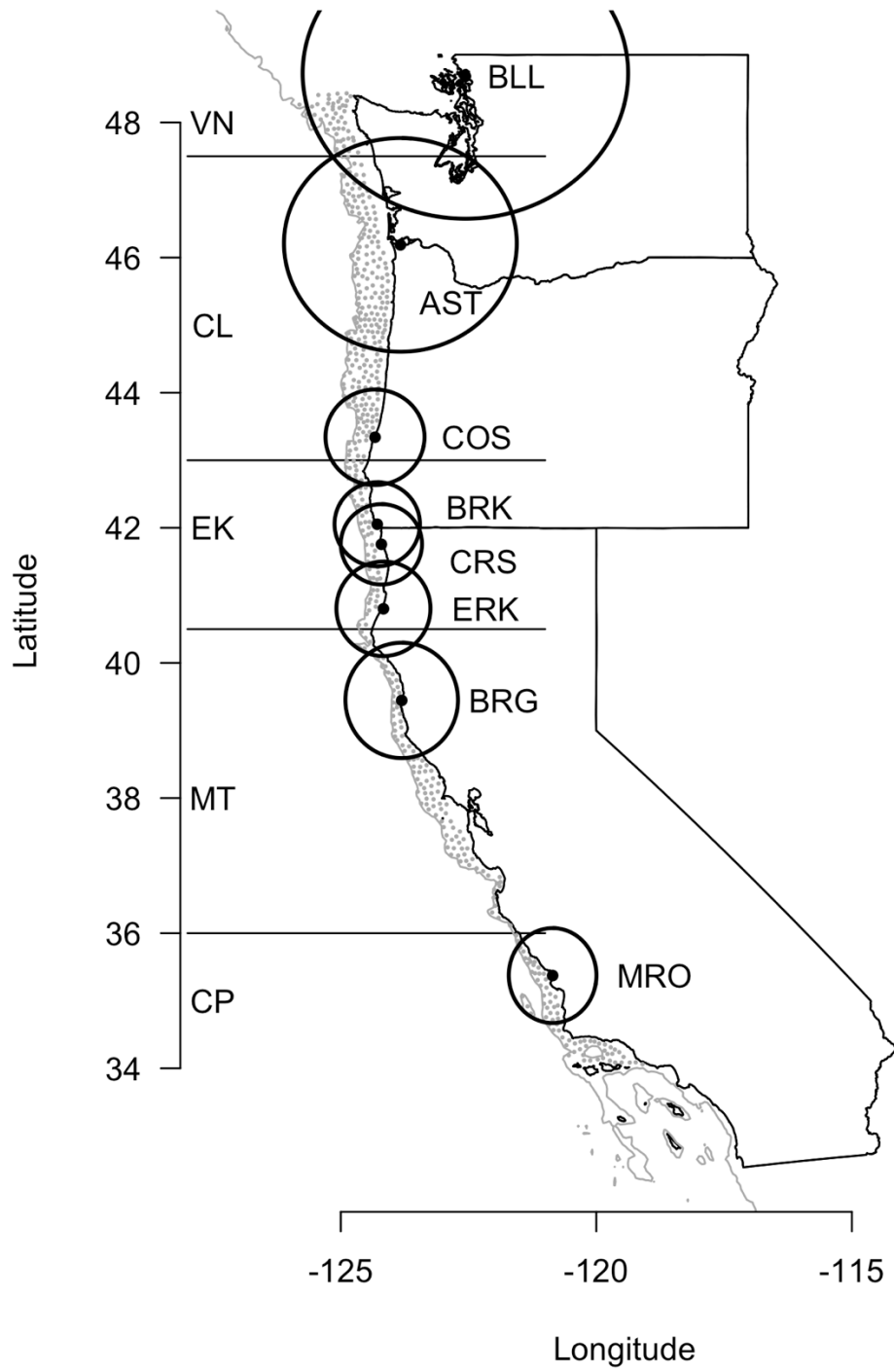
564
565 Figure 3. Sablefish biomass in each spatial location (mt, Eq. 1) relative to each of the INPFC
566 subareas, displayed for years in which the center of gravity represented by the dashed line was
567 intermediate (1980), north (1992), and south (2008) in the time series from Figure 2. Note the
568 relatively high biomass in the Conception subarea in 1980 and 2008, but not 1992.

569
570 Figure 4. Average biomass for all spatial locations within each INPFC subarea (mt). Symbols
571 and colors for each INPFC subarea and their relative location along the coastline is shown in the
572 legend in the bottom right.

573
574 Figure 5. Sum of biomass (thousand mt) within the radius traveled by vessels originating in each
575 port to harvest any of the 5 species. The radius is defined by the 75th quantile of the distance
576 between port and harvest location, weighted by catch for vessels originating from each port
577 1981-2015. Symbols and colors for each port and their relative location along the coastline are
578 shown in the legend on the bottom right.

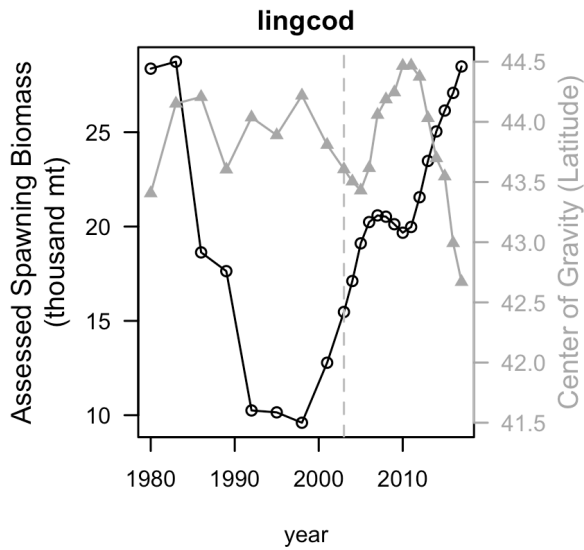
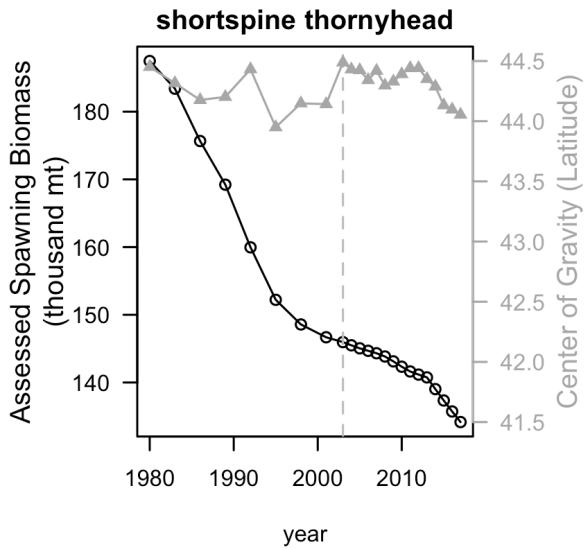
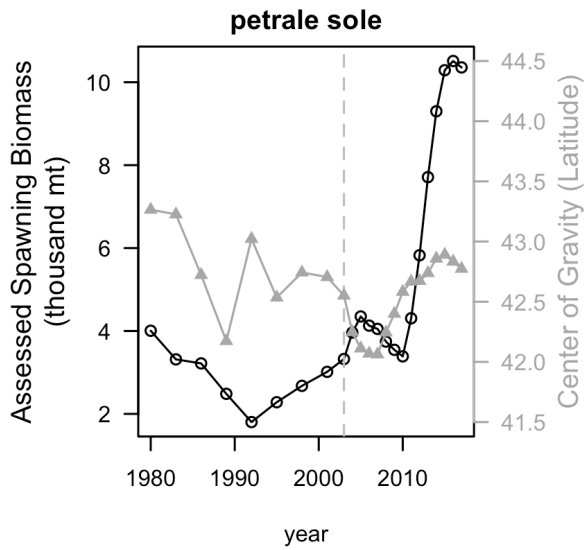
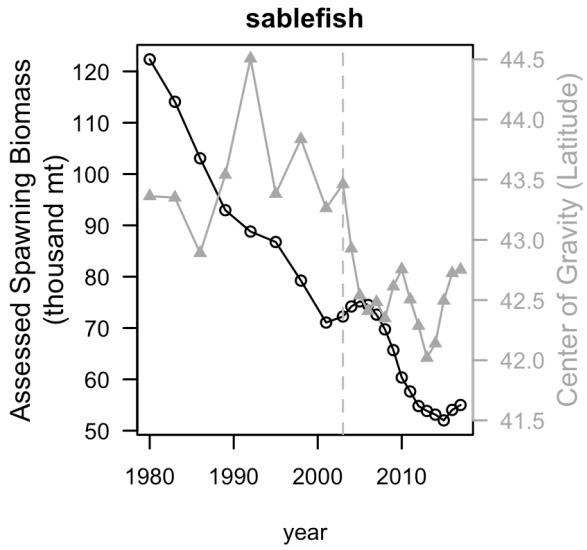
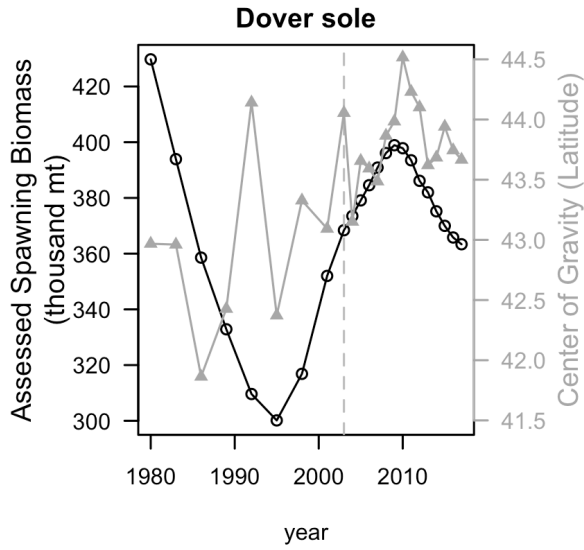
579
580 Figure 6. The relationship between port-specific availability and catch per unit effort, measured
581 as total landings per fish ticket in the PacFIN database. Symbols and colors for each port and
582 their relative location along the coastline are shown in the legend on the bottom right.

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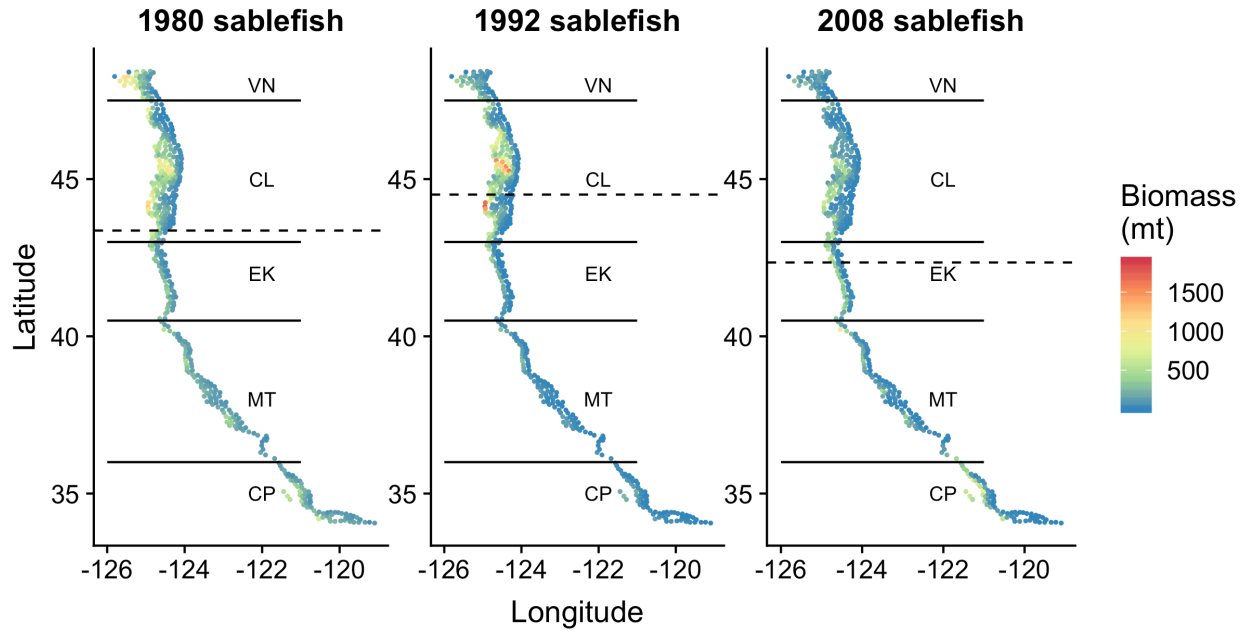
Figure 1.



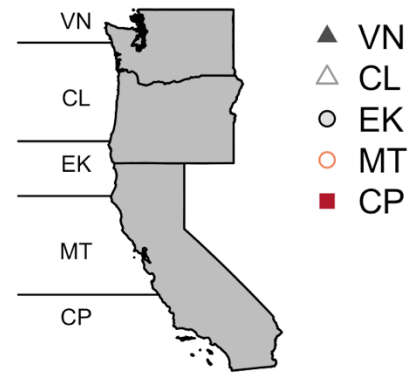
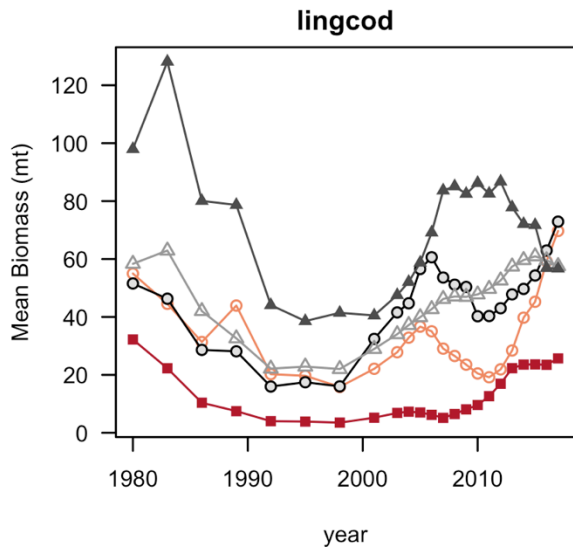
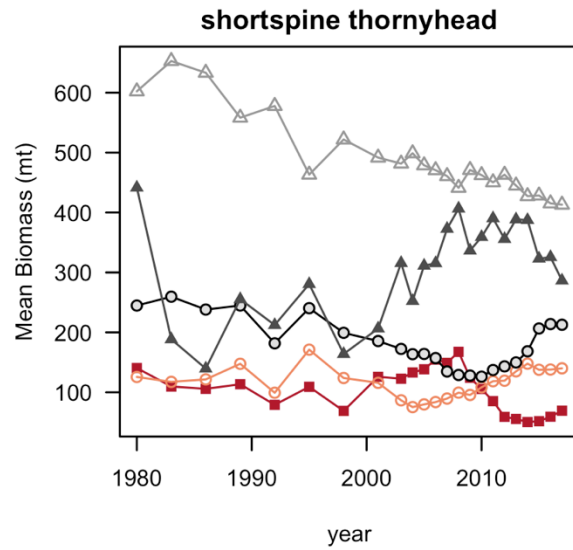
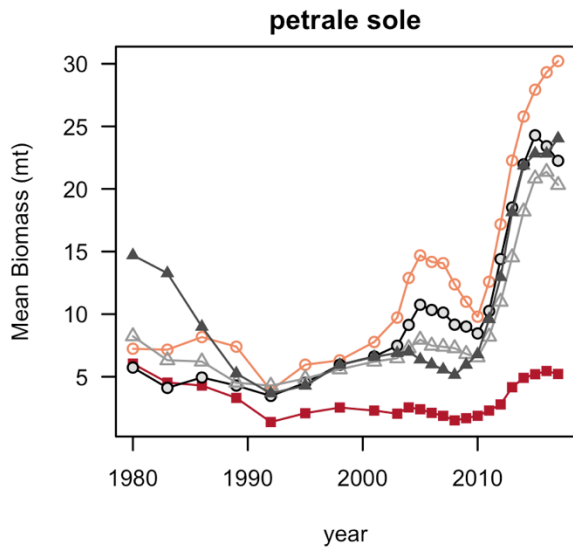
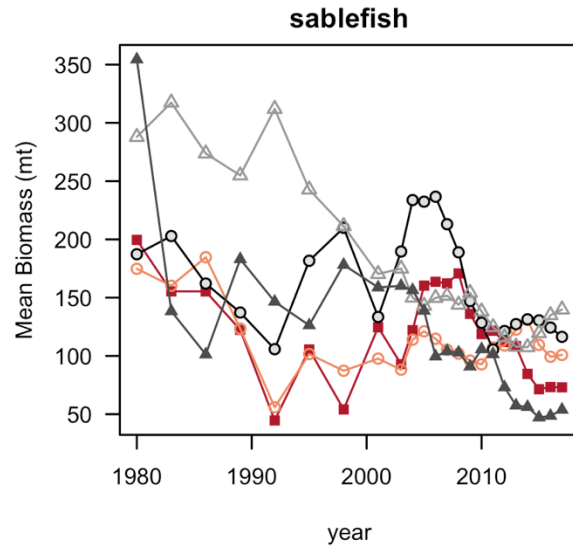
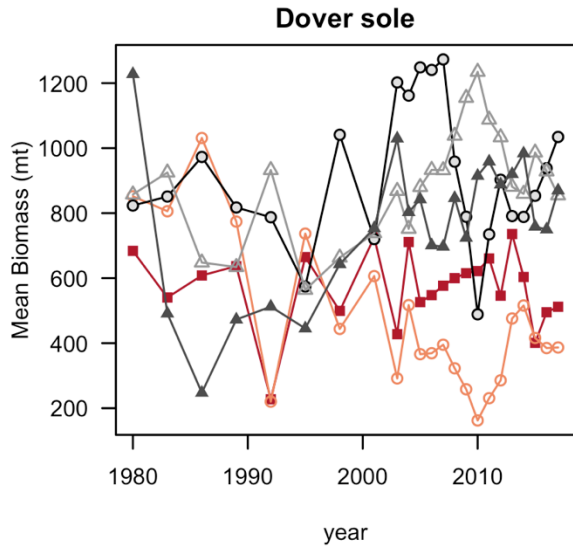
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Figure 2.

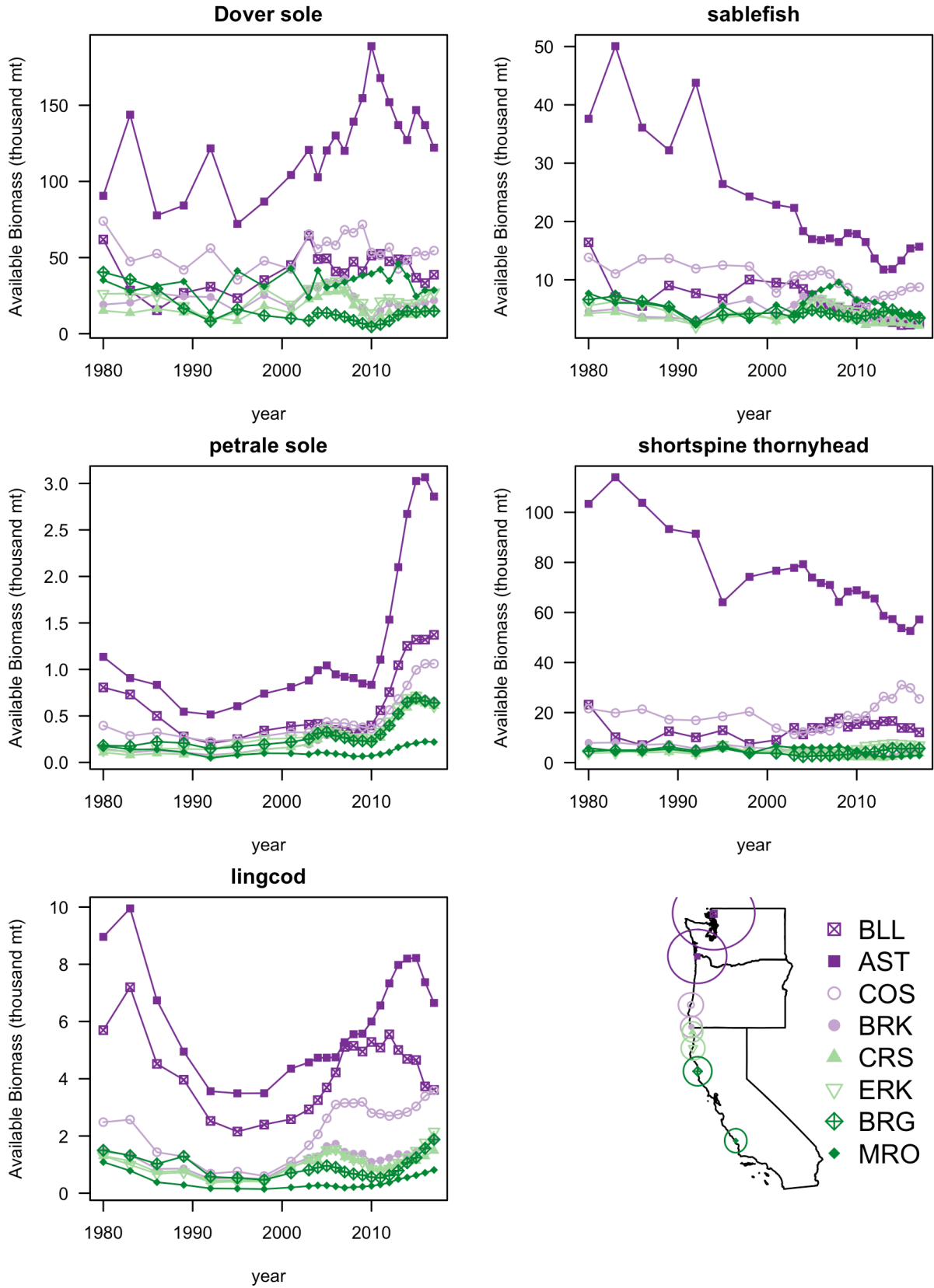
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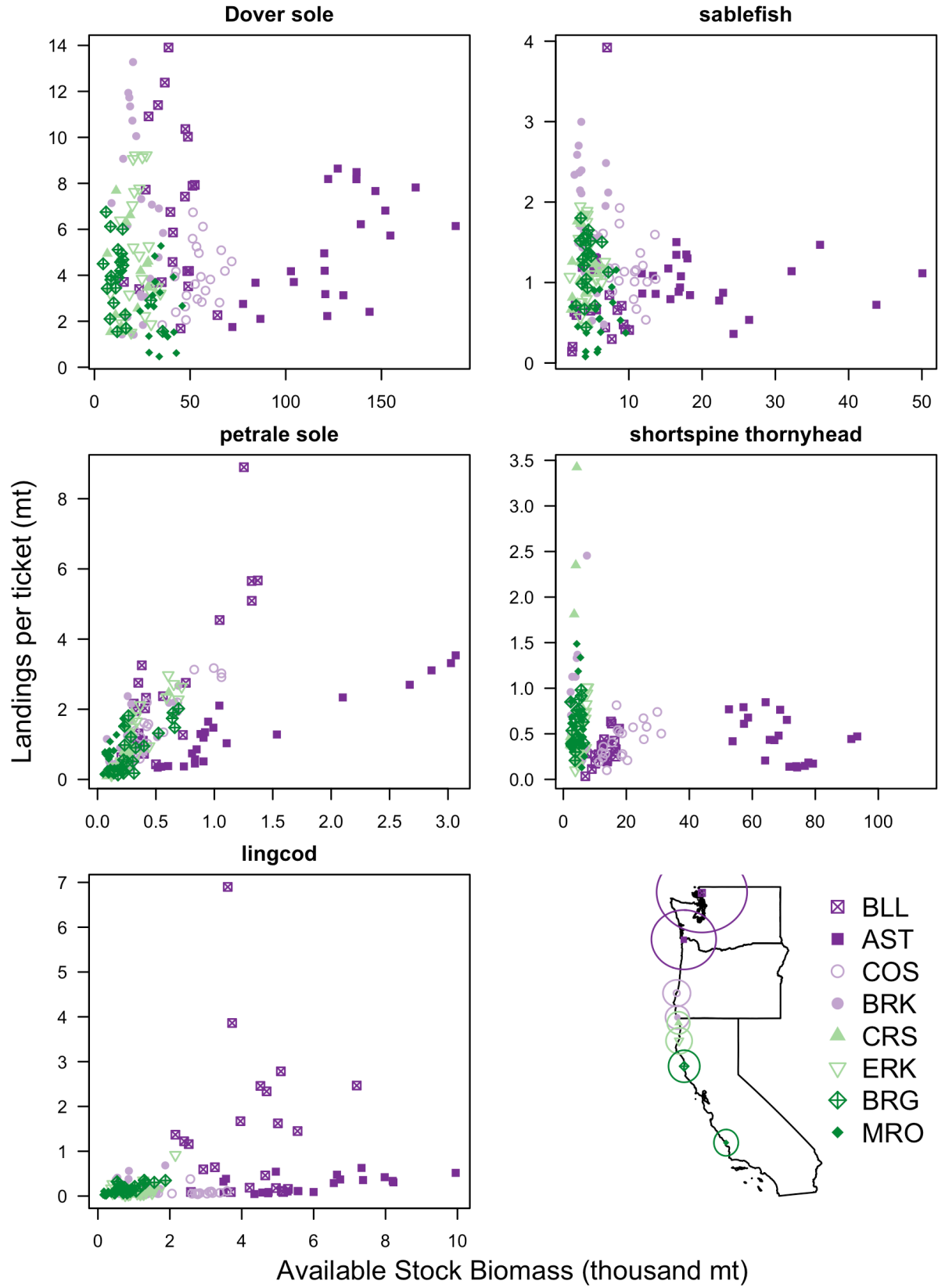


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595 Figure 4.



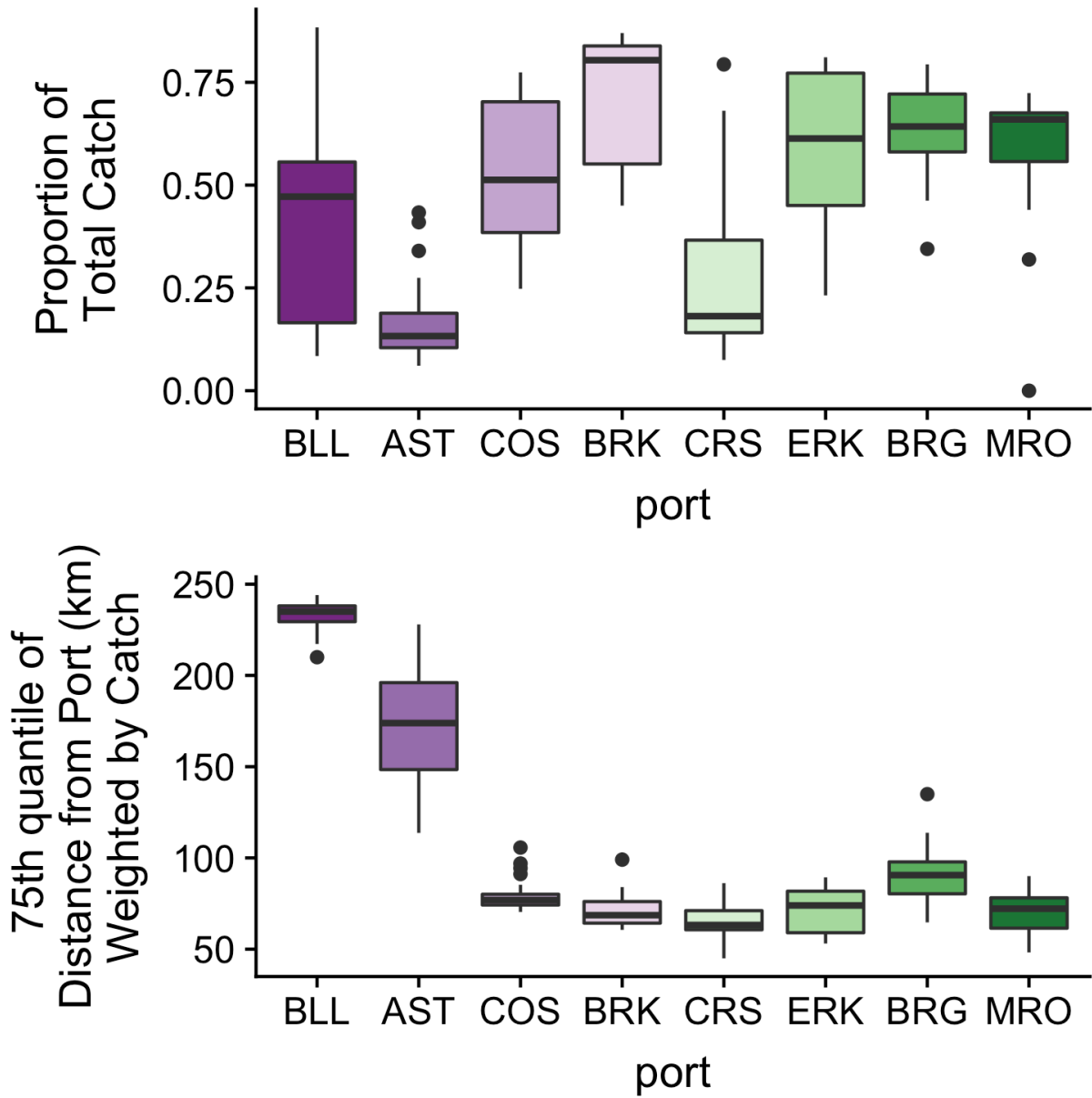
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Figure 5.



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Figure 6.



600
 601 Figure S1. (top) Proportion of total catch in each port represented by any of the 5 species.
 602 (bottom) 75th quantile of distance from port (km) weighted by combined total of catch of any of
 603 the 5 species

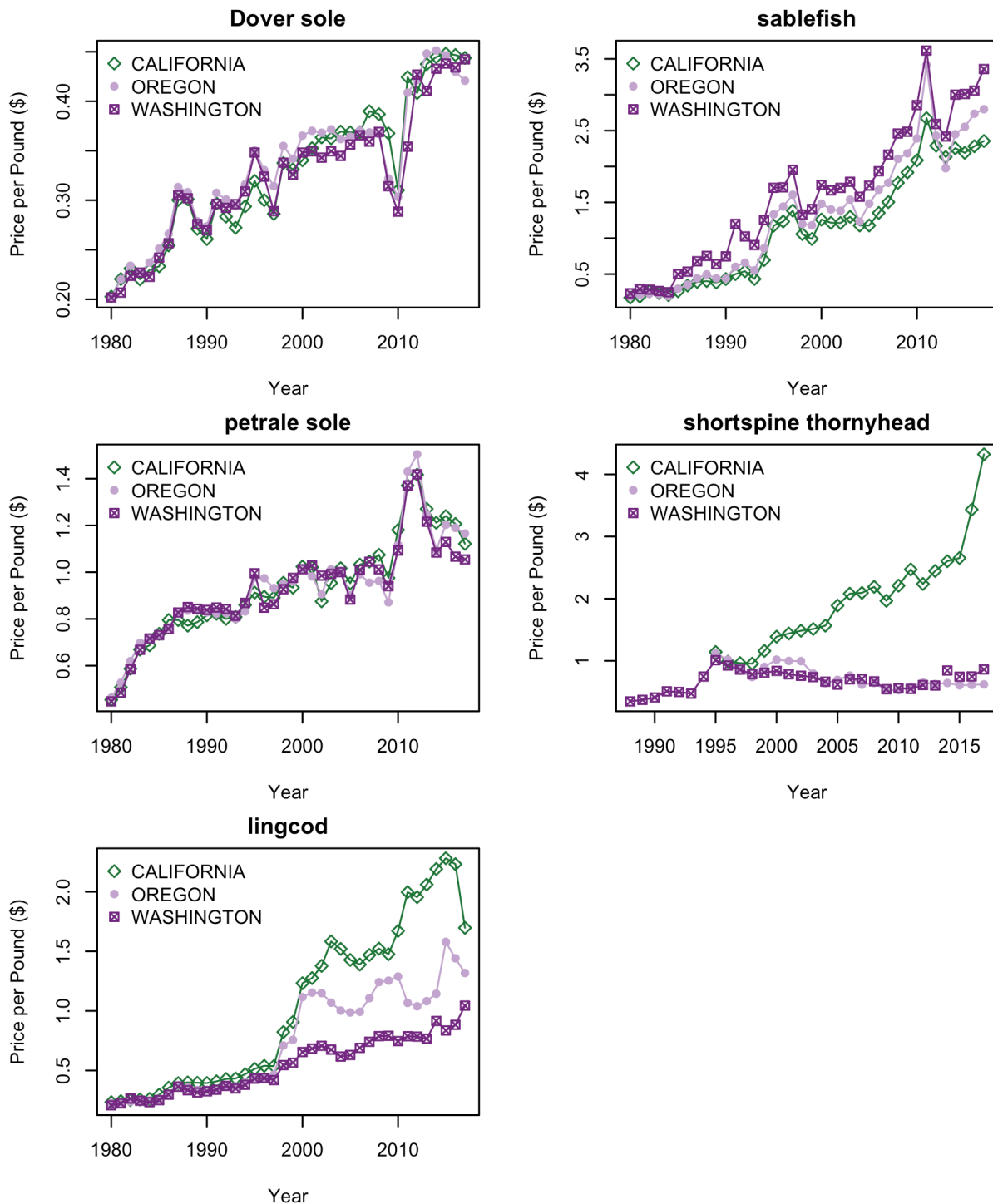


Figure S2. Price per pound for each species in each state based on NOAA Commercial Catch Statistics (<https://www.st.nmfs.noaa.gov/commercial-fisheries/>).