







Coupled changes in biomass and distribution drive trends in availability of fish stocks to US West Coast ports

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

Keywords: fishery, social–ecological, species distribution, vulnerability

Introduction

Marine species respond to environmental variability at nested spatial and temporal scales. As well as being influenced by long-term trends such as ocean warming (Poloczanska *et al.*, 2013), species are also sensitive to decadal scale climate cycles (e.g. El Niño Southern Oscillation; Lehodey *et al.*, 1997; Atlantic

Multidecadal Oscillation; Nye *et al.*, 2014; Faillettaz *et al.*, 2019; and Pacific Decadal Oscillation; Chavez *et al.*, 2003) and short-term warming events (Cavole *et al.*, 2016; Day *et al.*, 2018; Sanford *et al.*, 2019). This multiscale variability can lead to large fluctuations in the abundance of a species in a given location over time, and directional changes in species distributions can be

counter to predictions based on long-term warming trends alone (Hilbish *et al.*, 2010). As a result, the relative availability of target stocks to fishers within local fishing grounds can be highly dynamic and difficult to predict.

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

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

Methods

Species and port selection

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

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

Ports were selected if they landed at least 30000 Mt of the target species over the time series, and where these species were

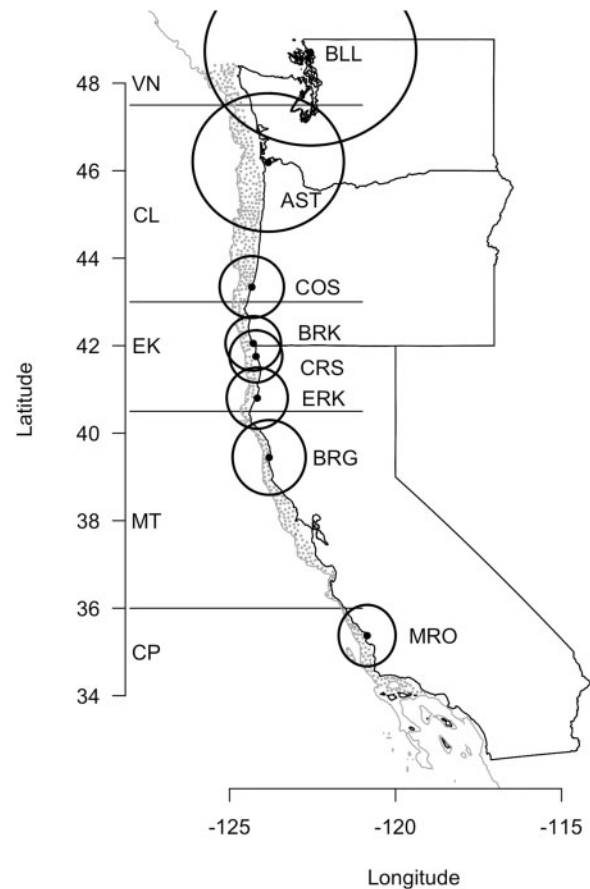


Figure 1. Spatial locations for which biomass density was estimated in this study (gray dots) relative to INPFC subareas (VN, CL, EK, MT, and CP) and focal ports [Bellingham Bay, WA (BLL); Astoria, OR (AST); Coos Bay, OR (COS); Brookings, OR (BRK); Crescent City, CA (CRS); Eureka, CA (ERK); Fort Bragg, CA (BRG); and Morro Bay, CA (MRO)]. The number of spatial locations within each subarea is related to the width of the continental shelf. Contour line represents the 500-m depth contour. The radii of the black circles centred on each port represent the 75th quantile of the distance travelled from port to harvest any of the five species, weighted by catch, as measured by trawl logbooks 1981–2015.

landed in all years for which landings data were available (1981–2017). The focal ports spanned >1000 km of the US west coast: Bellingham Bay, WA; Astoria, OR; Coos Bay, OR; Brookings, OR; Crescent City, CA; Eureka, CA; Fort Bragg, CA; and Morro Bay, CA, ordered from north to south (Figure 1). Landings of each species (Mt) in each of these ports were derived from the Pacific Fisheries Information Network (PacFIN) comprehensive fish tickets database for 1981–2017. We summed landings from fish tickets in each port for species reported with multiple species codes (e.g. combining catch of actual petrale sole with codes for nominal petrale sole; see link for details on how nominal species are defined by PacFIN <https://pacfin.psmfc.org/faqs/what-is-a-nominal-nom-fish-species/>). Commercial trawl logbook data were used to assess the port-specific spatial extent of fishing activity. The ports varied in the relative importance of the focal species to overall catch (median values for the proportion of catch ranged from 0.13 to 0.80) and in the distance travelled to harvest these species (Figure 1 and Supplementary Figure S1).

Stock biomass and spatial distribution

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

- (i) stock assessment estimates of spawning biomass (Mt) $B(t)$ (see the Stock biomass section for details); and
- (ii) Spatio-temporal estimates of biomass density (kg km^{-2}) $d(s, t)$ at each location, where each location s has an area (km^2) $a(s)$ within the sampling domain (see the Stock spatial distribution section for details).

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

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

Estimates of relative biomass at each location s were calculated by multiplying the biomass density $d(s, t)$ (kg km^{-2}) with the area $a(s)$ (km^2) associated with each location and dividing by the sum of this quantity across all spatial locations n . Biomass (Mt) associated with each location $b(s, t)$ was computed by multiplying the relative biomass in each location by the spawning biomass $B(t)$. This estimate corrects spatial distribution estimates derived from a spatio-temporal model by accounting for vulnerability estimates derived from a stock assessment model. This approach predicts that spawning biomass is spatially distributed in proportion to survey catch rates; it implicitly assumes that survey selectivity is (approximately) proportional to functional maturity. This assumption will be violated, e.g. if the survey catches both mature and immature individuals, which would result in predictions of spawning biomass that are influenced by the spatial distribution of immature individuals. Violation of this assumption will result in biased predictions of spatial variation in spawning biomass. Further research could relax this assumption by developing a spatio-temporal model for each size/age and modifying Equation (1) to predict distribution for each category individually, and we suggest that future applications follow this approach.

Stock biomass

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

Stock spatial distribution

We developed estimates of biomass density $d(s, t)$ for each species within the spatial sampling domain of the NMFS shelf-slope surveys and year t from 1977 to 2017. Sampling locations of the survey in each year were limited to those at depths sampled consistently over the entire period (0–500 m). We focus on estimates from 1980 forward to allow further analysis of the relationship between landings and availability, as landings data are available beginning in 1981. We applied a spatio-temporal model to survey-sampled biomass data b_i occurring at location s_i and time t_i , where survey samples of biomass are specified as following a conventional delta model. The delta model includes a logit-linked linear predictor for encounter probability p_i for observation i , and a log-linked linear predictor for expected catch rate r_i , given that the species is encountered. Each linear predictor then includes an intercept for each year and a spatio-temporal term that follows a first-order autoregressive process among years and a Matérn spatial correlation function across space. Density is then predicted as the product of predicted encounter probability and positive catch rate at each location, $d(s, t) = p(s, t)r(s, t)$. The model is estimated for each species individually using the Vector Autoregressive Spatio-Temporal package in R (Thorson, 2019; see Supplementary Appendix S1 for more details). The centre of gravity (COG) for each species was determined as the mean latitude for all locations s weighted by biomass density $d(s, t)$. Species-specific differences in the variance of the COG were evaluated using an analysis of variance (ANOVA) test on the mean absolute deviation from the median (Boos and Brownie, 2004) with Tukey's honest significance test *post hoc* comparisons. Correlations between the COG and spawning biomass $B(t)$ were assessed with a linear model. All analyses were conducted in R (R Core Team, 2019).

Latitudinal variation in stock availability

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

Stock availability to ports

Availability to specific ports was calculated as the sum of biomass $b(s, t)$ of all locations within the fishing grounds utilized by the port to harvest any of the five species. Harvest locations and catch were analysed from commercial trawl logbook data 1981–2015 collected by California, Oregon, and Washington (MAH, pers. comm.). Fishing grounds were defined as a circle centred on the port with a radius equal to the 75th quantile of the distance travelled between harvest location and port of landing for trawl vessels targeting any of the five species, weighted by the catch of those species, pooling all years.

Landings relative to availability

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

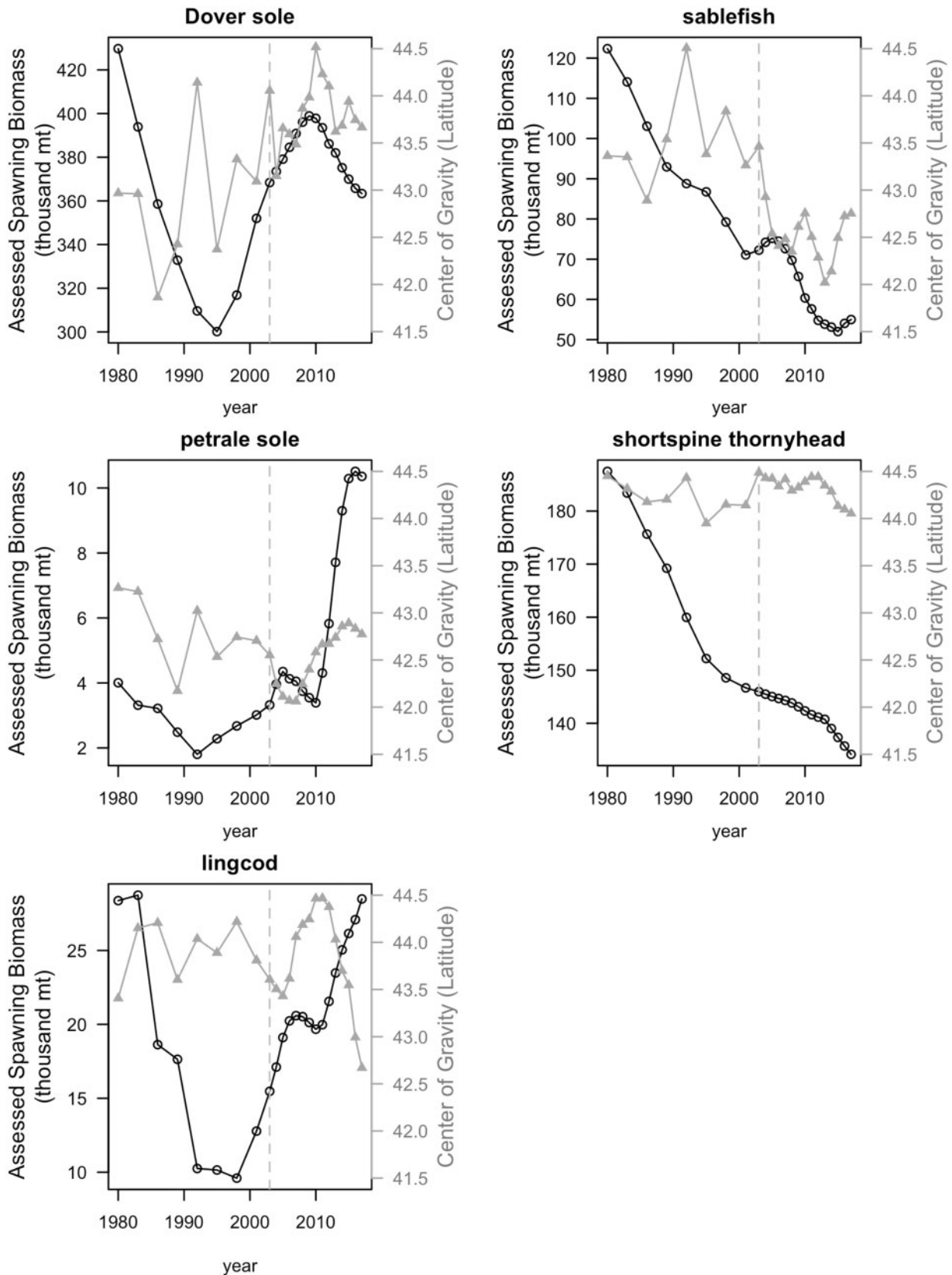


Figure 2. (Left, y-axis) Time series of spawning biomass (1000 Mt) from stock assessments 1980–2013 for five groundfish species on the US west coast. (Right, y-axis) Time series of centre of gravity (in degrees latitude) estimated using the Vector Autoregressive Spatio-Temporal model (Thorson, 2019). Grey dashed lines indicate year 2003, when the NMFS trawl survey transitioned from triennial to annual.

Results

Fluctuations in stock biomass and distribution

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

Latitudinal variation in stock availability

Simultaneous changes in overall stock biomass combined with large fluctuations in spatial distribution led to differences in the relative availability of each species along the coast (Figures 3 and 4). For example, the decline in sablefish biomass over time did not occur simultaneously or at the same magnitude across all INPFC subareas. In the southern subareas of CP and MT, biomass declined sharply in 1992 as the stock shifted northward and biomass was concentrated within the northern subarea CL. Thereafter, biomass in the southern areas increased as the stock distribution moved south, with biomass values in the most southerly subarea of CP exceeding that in CL for the first time in 2005–

2008. Meanwhile, biomass in the northern subarea of CL dropped precipitously since the peak in 1992 due to the combined effect of declines in total biomass and a southern shift in that biomass. In contrast, following its low point in 1992, the middle subarea of EK experienced almost no change in biomass.

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

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

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

Stock availability to ports

Trawl vessels in each focal community differed widely in the distance travelled between port and harvest location (Figure 5). The most northerly ports routinely travelled >150 km while the fishing communities in southern Oregon and California typically

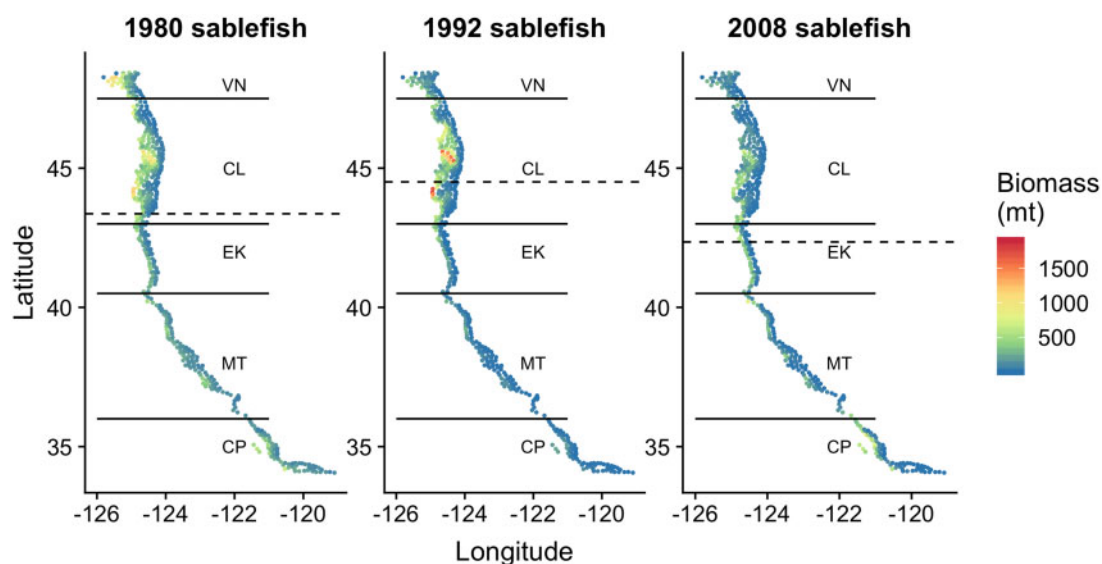


Figure 3. Sablefish biomass in each spatial location [Mt, Equation (1)] relative to each of the INPFC subareas, displayed for years in which the centre of gravity represented by the dashed line was intermediate (1980), north (1992), and south (2008) in the time series from Figure 2. Note the relatively high biomass in the CP subarea in 1980 and 2008, but not in 1992.

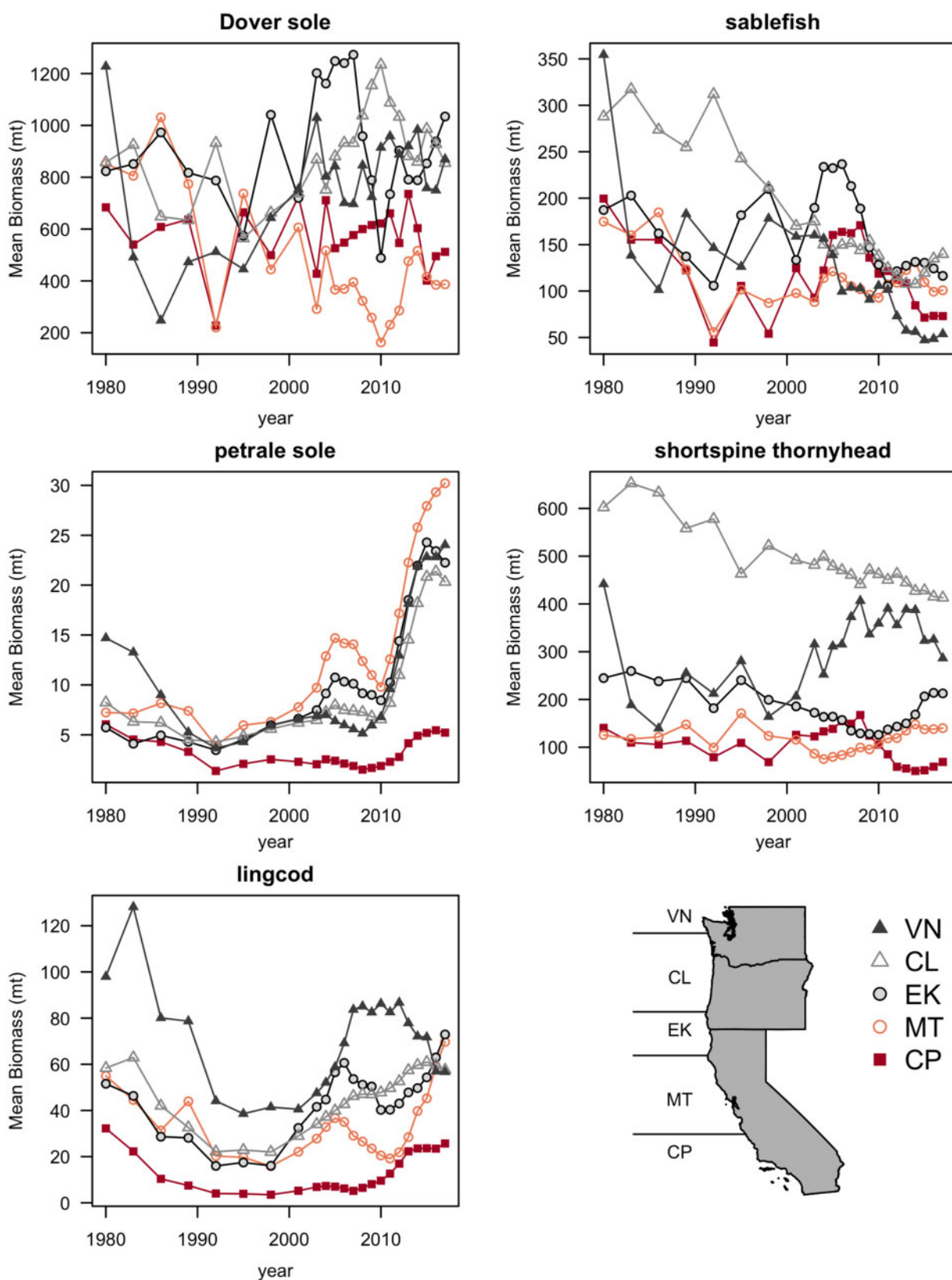


Figure 4. Average biomass for all spatial locations within each INPFC subarea (Mt). Symbols for each INPFC subarea and their relative location along the coastline are shown in the legend in the bottom right.

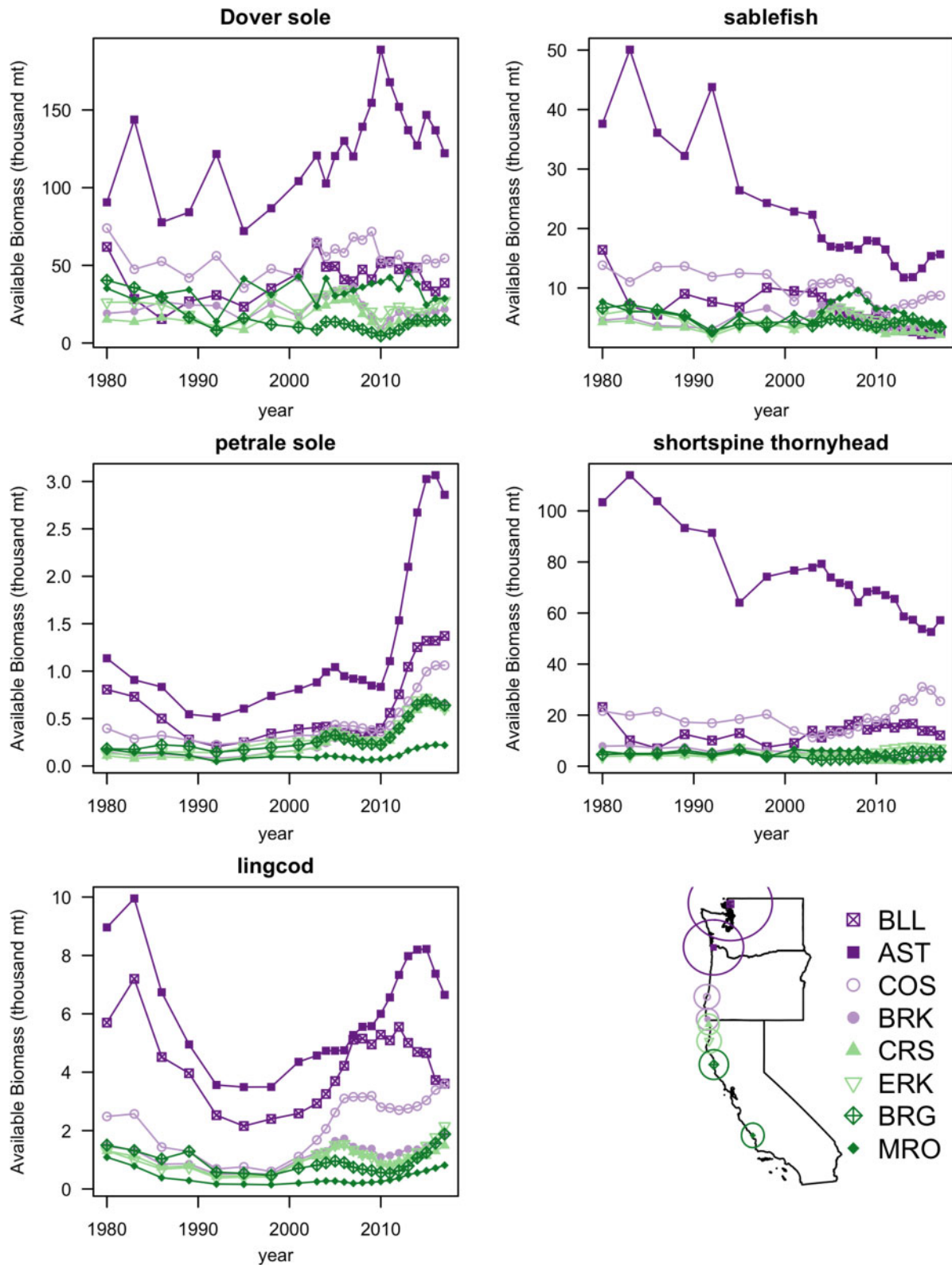


Figure 5. Sum of biomass (1000 Mt) within the radius travelled by vessels originating in each port to harvest any of the five species. The radius is defined by the 75th quantile of the distance between port and harvest location, weighted by catch for vessels originating from each port 1981–2015. Symbols for each port and their relative location along the coastline are shown in the legend on the bottom right. BLL = Bellingham Bay, WA; AST = Astoria, OR; COS = Coos Bay, OR; BRK = Brookings, OR; CRS = Crescent City, CA; ERK = Eureka, CA; BRG = Fort Bragg, CA; MRO = Morro Bay, CA.

travelled 75 km or less (Supplementary Figure S1). For most of the species, biomass was more available to northerly ports due to the combination of greater distance travelled by these ports and greater areal extent of bottom habitat <500 m in depth within the radius of distance travelled (Figure 5). Calculating port-specific stock availability based on the area utilized by fishers substantially altered inferences regarding biomass distribution along the coast. For example, while the INPFC subarea in which Astoria was located was ranked fourth in petrale sole biomass in 2017, the port of Astoria had more than two times the available biomass of all other ports when accounting for fishing area. Likewise, while the southern movement of sablefish during the 2000s led to southerly INPFC subareas having higher mean biomass, the sablefish biomass available to vessels originating from Astoria was consistently the highest across the entire time series.

Relationship between landings and availability

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

Discussion

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

Variation in the areal extent of fish habitat adjacent to port combined with differences in the distances travelled from port indicated that some fishing communities experienced port-specific stock availability that was decoupled from sub-regional (e.g. INPFC) trends in mean biomass. For example, a latitudinal increase in continental shelf area combined with greater distance travelled between port and harvest location buffered the northern port of Astoria from sub-regional changes in biomass. More mobile fishers are thought to have lower vulnerability to environmental changes (Young *et al.*, 2019). Our study suggests even lower vulnerability to changes in biomass when this greater mobility is coupled with greater access to habitat. Furthermore, the exposure to changes in species distribution can vary greatly even for communities with similar distance travelled from port due to the specific trends in biomass within their fishing grounds. These

results are in line with recent work projecting distinct vulnerability of adjacent ports to future changes in species biomass when those ports target different fishing grounds (Rogers *et al.*, 2019). As such, port-specific indices of availability may be increasingly important as an indicator for management and can complement other port-based indices of vulnerability to climate change. The availability indices developed here were included in the 2019 California Current Ecosystem Status Report (Harvey *et al.*, 2019) and have been incorporated in the most recent stock assessment for sablefish (Haltuch *et al.*, in review). Such indicators may be a useful addition to Integrated Ecosystem Assessments that are currently being developed for each of the large marine ecosystems within the United States and are directly relevant to the recently established Climate and Communities Initiative of the Pacific Fisheries Management Council (PFMC, 2019). As data streams become more available in near-real time, such availability indices could be made available to fishers to enable targeting decisions in a way that may facilitate greater resilience to changing species distributions.

In our study, higher stock availability was not consistently associated with higher catch per ticket. This suggests that factors in addition to availability were important drivers of landings. Technological, economic, and management factors can limit both the willingness and capacity for fishers to respond to shifting the availability of target species, thus affecting the coupling between landings and availability. A high degree of reliance on a particular species may result in a mismatch between landings and availability. While all focal ports had a combined total of at least 30000 Mt of total landings of the five species over the time series, they varied in the relative importance of these species over the time series (Supplementary Figure S1). Ports that rely more on a particular species, or the species complex as a whole, may be more likely to target those species, to the extent possible using a relatively unselective trawl gear. Individual transferable quotas, like that implemented in this fishery in 2011, can serve to incentivize targeting. Trawl fishers operating under an individual fishing quota (IFQ) for groundfish in British Columbia were able to adjust the species mixture in their catches by avoiding areas with high abundance of species with lower total allowable catches (Branch and Hilborn, 2008). Recent analyses of West Coast trawlers suggest that fishers used spatial avoidance of areas with high abundance of overfished species but also employed other targeting practices since the implementation of IFQs, including shifting activity from day to night, shortening the duration of trawl tows, and forming cooperatives that shared information about where overfished species were concentrated (Miller and Deacon, 2017). This resulted in a marked decline in the proportion of the catch represented by overfished species. If the same strategies could be used to increase the targeting of desired species, this may contribute to some of the mismatches observed between landings and stock availability.

High market value may incentivize further targeting of a species, such that its landings are not proportional to its availability in the environment. This may be a factor in the observed inverse relationship between catch and availability of sablefish, which garners a high price per pound in the market. Similarly, the higher landings of shortspine thornyhead in the California ports despite its lower availability may have been driven by the dramatic increase in the price per pound for this species in California that was not observed in Oregon or Washington. Management actions on other species in a catch portfolio may

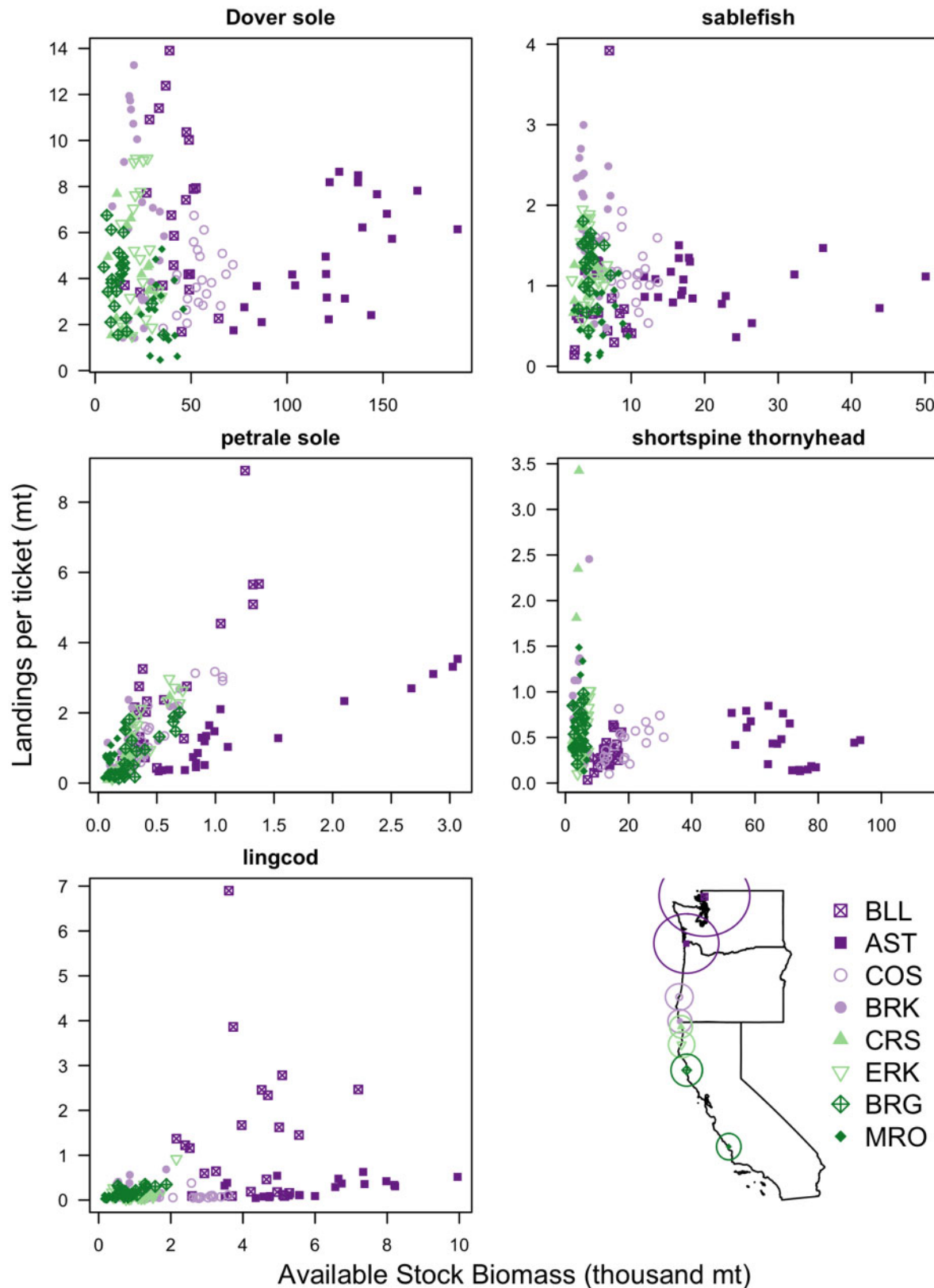


Figure 6. The relationship between port-specific availability and catch per unit effort, measured as total landings per fish ticket in the PacFIN database. Symbols for each port and their relative location along the coastline are shown in the legend on the bottom right. BLL = Bellingham Bay, WA; AST = Astoria, OR; COS = Coos Bay, OR; BRK = Brookings, OR; CRS = Crescent City, CA; ERK = Eureka, CA; BRG = Fort Bragg, CA; MRO = and Morro Bay, CA.

also have knock-on effects. Many species of rockfish were declared overfished in the late 1990s (Starr *et al.*, 2016). The resulting stringent catch limits for rockfish may have driven increased harvesting of the remaining high value species.

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

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

External factors such as management actions and broader economic trends can interact with local context (e.g. infrastructure, livelihood alternatives, governance structures) to create substantial geographic differences in responses (Lyons *et al.*, 2016; Maina *et al.*, 2016). Here, local governance structures may have also played a role in constraining the relationship between availability and landings. Fisheries patterns may be largely influenced by the regulatory changes that have occurred over this time frame. Large-scale closed areas extending along the entire west coast were established in 2002 to facilitate recovery of overfished rockfish species. Furthermore, a catch-share programme that requires full catch accounting was implemented in 2011 in the groundfish fishery. As a result, vessels are largely landing most of what they catch, which could alter the relationship between landings and availability for these communities. These additional regulatory factors may be important drivers of the ways that fishers are responding to changes in availability within their fishing grounds.

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

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

Conclusion

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

Supplementary data

Supplementary material is available at the ICESJMS online version of the manuscript.

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