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ARTICLE

Spatial and Temporal Characteristics of California Commercial Fisheries from 2005 to 2019 and Potential Overlap with Offshore Wind Energy Development

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Abstract
As climate change accelerates and fisheries management continues to evolve, California's commercial fisheries are changing. To improve the understanding of recent California fisheries dynamics, we compiled and analyzed commercial landings receipts to characterize temporal and spatial variation in landing and value of key fisheries groups within the exclusive economic zone across the state from 2005 to 2019. We found that California fisheries continue a shift first observed in the 1980s from higher-biomass, lower-value species, such as coastal pelagic species and market squid, toward lower-biomass, higher-value species, such as Dungeness crab *Cancer magister* and groundfish. Over the 15-year time series analyzed, total landings declined by nearly two-thirds but total value remained relatively stable, likely due to a focus on higher value species and rising prices. The northern half of the state has become much more economically valuable, accounting for over 50% of total value across the state in 2019. A case study analysis found groundfish to be the dominant fisheries in the two areas that have been identified as priorities for potential offshore wind development in central and northern California. Our results elucidate the most recent status and trends of California's commercial fisheries, over time, across space, and among different fisheries groups, providing valuable information for informing fisheries management and marine spatial planning.

Fisheries in California are diverse and highly productive, fueled in part by strong seasonal upwelling in the California Current Large Marine Ecosystem (CCLME) (Checkley and Barth 2009; McClatchie 2014). These fisheries have been an important part of the state's economy, supporting local and regional economies and working waterfronts across California for decades (Miller et al. 2017). The National Marine Fisheries Service estimated that commercial fishing in California generated nearly US$200 million in exvessel value in 2018 (NMFS 2021) and that commercial and recreational fishing activity was responsible for nearly $25 billion in economic activity and the creation of 142,000 jobs in 2016 (NMFS 2018). Because of its economic importance, state and federal

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fishery regulators invest significant resources into managing these fisheries to ensure both economic productivity and ecological sustainability (Mamula and Kosaka 2019; Richmond et al. 2019). However, the diverse nature of these fisheries can complicate their management since a great deal of information is needed to support regular stock assessments for a wide range of species, each of which has its own particular biology, ecology, and fishery dynamics that vary both temporally and spatially (Allen et al. 2006). To drive these important assessments as well as manage trade-offs associated with competing interests in marine environments, managers rely on numerous data sources, most notably state fishery landings, which can provide temporally and spatially resolved catch information for a range of different species. In addition to assessing stocks and setting catch regulations, fisheries landings data are used to explore potential conflicts with other ocean sectors such as aquaculture and wind energy, examine the impacts of climatic variation and marine heatwave events, and identify spatial trophic hot spots (White et al. 2012; Santora et al. 2014; Lester et al. 2018; Barbeaux et al. 2020; Suryan et al. 2021).

Fisheries landings data also are used to examine changes in California fisheries through time, revealing substantial shifts in the relative importance of different species and locations (Thomson 2015; Miller et al. 2017). In the first half of the 20th century, California's commercial fisheries were dominated by a few lower trophic level coastal pelagic species, mainly sardines. Fisheries became more diversified in the latter part of the past century, with an increased proportion of the landings represented by groundfish, such as rockfish and flatfish, and invertebrate species, such as urchins, lobster, and Dungeness crab *Cancer magister* (Miller et al. 2017). Along with this diversification was a shift away from higher-biomass, lower-value species and toward lower-biomass, higher-value species (Miller et al. 2017). Additionally, landings data have revealed clear shifts in fisheries linked to large-scale climate oscillations. For example, the large El Niño-Southern Oscillation (ENSO) events in 1982–1983 and 1997–1998, which substantially decreased oceanic and nearshore primary production, precipitated substantial declines in landings of shorter-lived species at lower trophic levels, such as coastal pelagic fishes and squid (Zeidberg et al. 2006). Additionally, multidecadal shifts in oceanic and atmospheric forcing in the Pacific Ocean (e.g., Pacific Decadal Oscillation) impacted the proportional abundance of sardines versus anchovies, as well as other important species like salmon, throughout the CCLME (Mantua et al. 1997; Chavez et al. 2003).

Over the past few decades, fisheries in California and their management have continued to change and evolve, as has the marine ecosystem. It is now clear that anthropogenic activities and climate change are impacting the CCLME. Multiple stressors, including habitat loss and climatic stress (e.g., increased temperatures, deoxygenation, ocean acidification, marine heatwaves [MHW]), have increased (Marshall et al. 2017; Hart et al. 2020), and species ranges have begun to shift with these oceanographic changes (Zacherl et al. 2003; Lonhart et al. 2019; Sanford et al. 2019). Climate models predict that MHW, such as the record 2014–2016 North Pacific marine heatwave (2014 warm "blob" followed by the record 2015–2016 ENSO event) and ENSO events, will increase in frequency and intensity (Power et al. 2013; Cai et al. 2015; Frölicher et al. 2018; Holbrook et al. 2019; Wang et al. 2019), which has the potential to disrupt local marine ecosystems and fisheries (Rogers-Bennett and Catton 2019; Smale et al. 2019). Additionally, this century has seen an increased emphasis on sustainable fisheries management, including legislation that mandates sustainability in federal fisheries (e.g. reauthorization of the Magnuson–Stevens Act), as well as new technical approaches to fishing and fisheries monitoring. For example, stock assessments and population modeling have become more sophisticated (Methot and Wetzel 2013; Punt et al. 2014) and there is an increased recognition of the importance of habitat and spatial planning in the management of fisheries (White et al. 2012; Hazen et al. 2013; Maxwell et al. 2015; Kroodsma et al. 2018; Murray and Hee 2019). There continues to be a culturally and legally mandated emphasis on fishery sustainability, including efforts to move to true ecosystem-based management plans that incorporate risk assessment (Field and Francis 2006; Samhouri et al. 2019). Finally, fishery managers are increasingly planning for the impacts of climate change and ocean acidification (Chavez et al. 2017; Marshall et al. 2017), spatial planning for new uses of ocean space (Yates et al. 2015; Lester et al. 2018), and protection of endangered species (Santora et al. 2020).

As a result of these changes, the dynamics of California fisheries are likely much different now than they were just a few decades ago (e.g., as described from 1931 to 2005 by Miller et al. 2017). Thus, updated information on the status and trends of the state's fisheries is critical for supporting current fisheries management. This study aims to help address this need by describing the recent spatiotemporal dynamics of California fisheries in terms of commercial landings and exvessel value (revenue) across different fisheries groups over the past 15 years (2005–2019). The results presented here are statewide and could be used to support stock assessments, spatial planning, economic impact analyses, climate change mitigation efforts, and other marine management and research efforts requiring current spatial and temporal characteristics of California's commercial fisheries. This work aims to help managers, policymakers, and other stakeholders design and plan for the sustainability and economic vitality of fisheries in

California and the industries that depend on them over the coming decades.

DATA AND METHODS

This study used commercial fisheries landings receipts (fish ticket data) for California commercial marine fisheries, provided by the California Department of Fish and Wildlife (CDFW) through a data sharing agreement, from 2005 to 2019 (CDFW, unpublished data). Fish tickets were submitted to CDFW by commercial fish businesses at port when vessels return from a fishing trip with harvested fish. Each fish ticket recorded the landing weight (hereafter, "landing") and unit price (i.e., price per pound) of the fish species caught, the landing date and port, and a fishing block catch location, as well as unique identification numbers for vessels, fishers, and businesses. Most of the fishing blocks within the exclusive economic zone (EEZ; 200 nm) are defined by a 10′ by 10′ (~10 nm on a side) grid, with a few blocks that range up to 30′ or 40′; these blocks are assigned a three-digit identification (ID) number. Additionally, there are 10 larger fishing blocks that are assigned a four-digit ID number (Figure S1 available in the Supplementary Materials). These larger blocks are effectively latitudinal bins that extend from the coast to the edge of the U.S. EEZ. They are generally used for trawling surveys where vessels do not specify a three-digit block fishing block, but are occasionally used by other fisheries as well (Todd Nearhr, personal communication).

Following Miller et al. (2017), we categorized landed species into nine broad taxonomic/functional groups (Table S1 available in the Supplementary Materials). We excluded the 'Abalone' group since the commercial fishery for abalone in California has been closed since 1997 (Rogers-Bennett et al. 2002). The nine taxonomic groups in Table S1 are representative of California's commercial fisheries, accounting for more than 95% of the total landings in the data.

The exvessel value or revenue of the catch landed (hereafter, "value") was calculated by multiplying the landing in pounds by the unit price in U.S. dollars reported on each fish ticket. Prior to calculating value, we corrected unit prices for inflation by multiplying the original unit price by the consumer price index in 2019 December divided by the consumer price index in the month and year the fish ticket data were submitted (data.bls.gov/timeseries/CUUR0000SA0).

A small fraction of fish ticket records reported implausible unit prices, which led to erroneous value estimates. We adjusted these outliers as follows. We replaced reports of $0/lb unit price (~0.35% of total landings) by the median of all non-$0 unit prices within that fishery's taxonomic group. This adjustment accounts for the presumed economic value of landings with no reported value. We also adjusted price outliers greater than a set upper threshold by replacing these with the median price for the group. We chose an upper threshold of $27/lb since this number exceeds the reasonable exvessel price of any of the landed seafood. It also accounts for <0.0005% of total landings; a sensitivity analysis found that the results were largely unaffected by any upper threshold ≥$25/lb.

In addition to characterizing statewide statistics averaged over the 15-year time series, we explored temporal and spatial variation. We computed annual landings and values for individual fishery groups and their proportional contribution to total landings and values. The four-digit blocks are too large to reveal detailed spatial information, and it is unknown how these data would have been distributed in the three-digit blocks had three-digit blocks been used. Thus, we mapped the annual average of landings and values using catch in three-digit blocks only. Given that not all three-digit blocks are the same size, we calculated the area of each block and divided the annual average by the area of that block for visualization. In the maps, fishing blocks with less than three unique vessel, fisher, and business IDs are not displayed to protect the privacy of vessel operators (e.g., the so-called "rule of three," cf. CDFW). The fish ticket data in these blocks are still included in the calculations in the tables and other figures that are not spatially explicit. We computed Moran's I to objectively quantify spatial clustering of landings across three-digit blocks for each fish group. Moran's I ranges from −1 to 1, with a value of 1 indicating perfect clustering, a value of 0 corresponding to randomness, and a value of −1 signifying perfect dispersion (Cliff and Ord 1981). We also mapped the depth limit of each taxonomic group (Miller et al. 2017; Table S1); to explore the spatial accuracy of block information, we compared catch reported in three-digit blocks inside of the prescribed depth limit with catch reported outside of the depth limits in three-digit blocks, and compared these values to catch reported in the four-digit blocks. Finally, we investigated annual spatial patterns—effectively latitudinal trends—in four-digit blocks for Dungeness Crab and groundfish, the two taxonomic groups with the highest-value reported in four-digit blocks.

To better understand regional trends, we divided ports along the California coast into five regions following Thomson (2015). We calculated the relative importance of landings and value for key fishery groups in each region based on the port of landing reported in fish tickets. The five regions are Northern California (Eureka Area), North Central California (Fort Bragg, Bodega Bay, and San Francisco Area), Central California (Monterey and Morro Bay Area), South Central California (Santa Barbara/Ventura Area), and Southern California (Los Angeles and San Diego Area) (Figure S2).

To assess potential overlap between offshore wind development and commercial fisheries in California, we used fish ticket data to estimate fishing activity in relation to the Humboldt and Morro Bay wind energy areas (WEAs, Figure S3; BOEM 2022). We calculated the relative importance of landings and value for each fishery group in the Humboldt and Morro Bay regions and WEAs by summing data in the following way: (1) all local ports in the respective regions, (2) all blocks that overlapped with the WEAs in the respective regions, and (3) all blocks that overlapped with the WEAs in the respective regions and were also within the biological depth limits of a given fishery group. For the Humboldt Wind Energy Area, the local port complex included Crescent City, Klamath, Arcata Bay, Eureka, Fields Landing, Humboldt Bay, King Salmon, Orick, Shelter Cove, and Trinidad. For the Morro Bay Wind Energy Area, adjacent ports included Avila/Port San Luis, Morro Bay, and San Simeon. Note that this analysis only considers data from the three-digit blocks since data from four-digit blocks have little to no useful spatial information.

RESULTS

Long-Term, Statewide Comparison among Taxonomic Groups

California statewide landings over the 15-year evaluation period (2005–2019) were dominated by market squid and coastal pelagic species (CPS) (Figure 1). However, these two groups were not as valuable as several low-volume, high-value species groups, such as Dungeness crab and groundfish, which had significant economic value despite their smaller landings (Figure 2). The top three species in revenue value for each broad taxonomic group are highlighted in Table S1. For example, in the groundfish group, the top three species were Sablefish *Anoplopoma fimbria* (~39%), rockfish *Sebastes* spp. (~14%), and thornyheads *Sebastolobus* spp. (~14%).

For some taxonomic groups, a large proportion of landings was reported in four-digit blocks, which effectively only provides information on the latitudinal range for landings data in those blocks (Figure 3). For example, approximately 70% of the landings of "other crustacean" was reported in four-digit blocks (however, only about 10% of this group's value was from landings reported in four-digit blocks due to a lower price reported for landings in those blocks versus in three-digit blocks). For Dungeness crab and groundfish, approximately 43% and 53% of their landings were reported in four-digit blocks, representing about 41% and 34% of their respective value.

For the groups with a prescribed depth limit (see Methods), the landings reported in three-digit blocks outside the depth limit was relatively small (Figure 3). While Dungeness crab had the highest number of landing receipts reported from blocks outside their prescribed depth limit, these apparent misreports comprised less than 6% of the total landings and value for this species.

Temporal Variation in Landings and Value

Statewide landings showed a general decline over the 15-year time series; 2019 landings were approximately one-third of those in 2005 (Figure 4; Figure S4). In contrast, overall value remained relatively constant due to the shifting focus toward higher value species. Average price per pound across all fisheries increased over 170% between 2005 and 2019, even when accounting for inflation (Figure 2).

Statewide landings and value also varied considerably among years, though not necessarily in concert with one another (Figure 4). Landings peaked in 2010 and were dominated by squid, while value peaked in 2013, largely

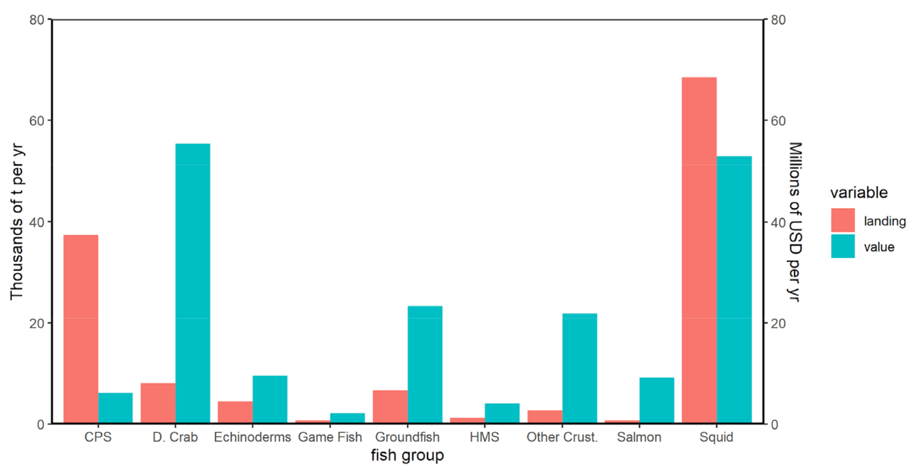

FIGURE 1. Statewide landings (left y-axis) and value (right y-value) averaged over the entire time series for individual taxonomic groups recorded in all blocks.

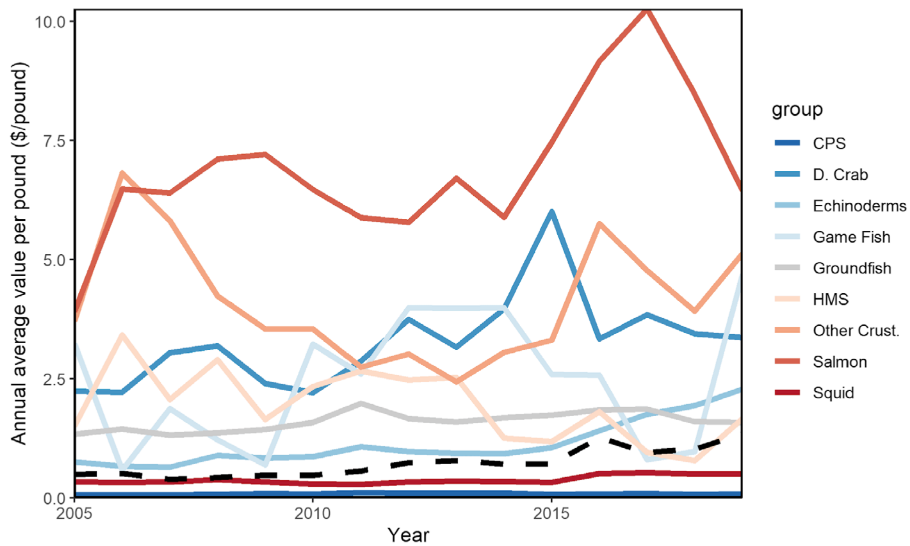

FIGURE 2. Statewide annual average value per pound ($/pound) for each taxonomic group. Dashed line represents the annual average value per pound using all nine taxonomic groups.

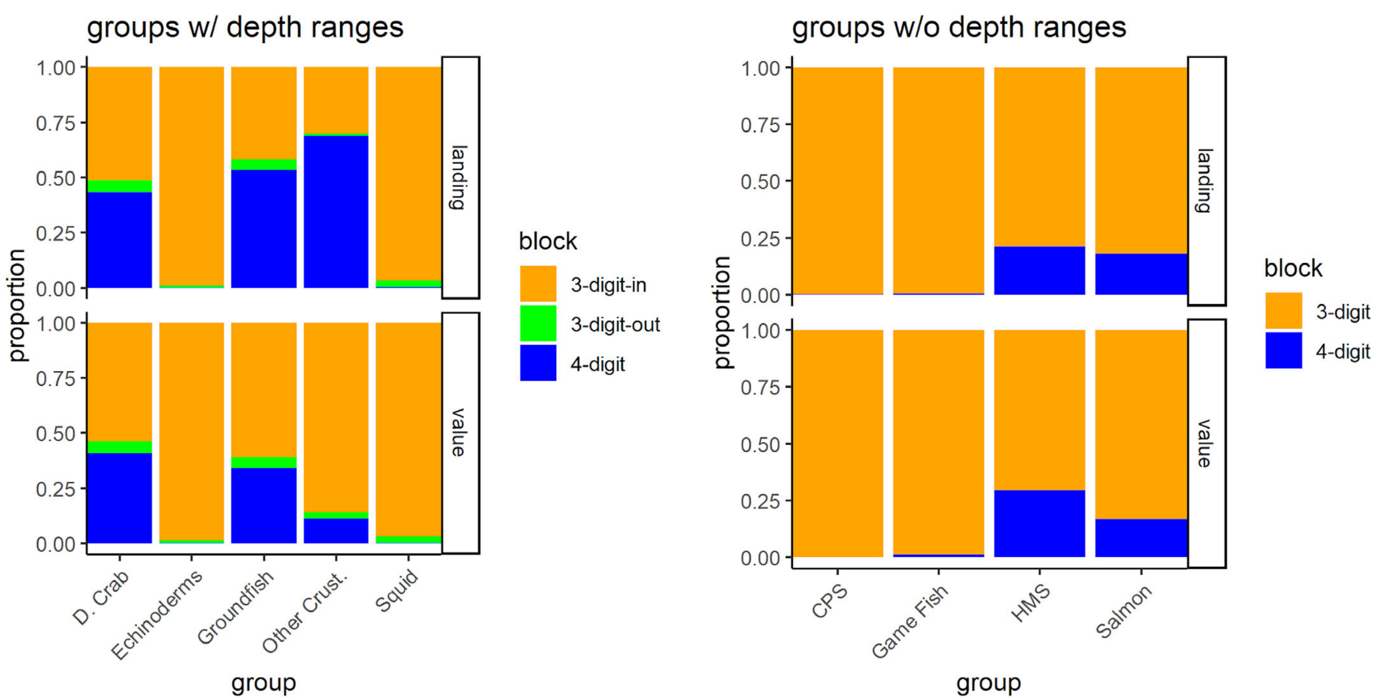

FIGURE 3. Proportion of landings (top) and value (bottom) under different block-depth criteria for each taxonomic group. Left: Groups with depth limits (Table S1). Right: Groups without depth limits (i.e., CPS, game fish, HMS, and salmon).

driven by Dungeness crab and squid. Both total statewide landings and value dropped precipitously in 2015 to around half of what they were in 2014, largely due to lower landings of both Dungeness crab and squid.

The relative importance of each fisheries group varied substantially over time (Figure 5). Coastal pelagic species was the top contributor to overall landings until 2008 but was replaced by squid thereafter. At its peak in 2017, squid accounted for nearly 70% of overall statewide landings. While squid fisheries declined in recent years, high-value fisheries such as Dungeness crab remained relatively stable.

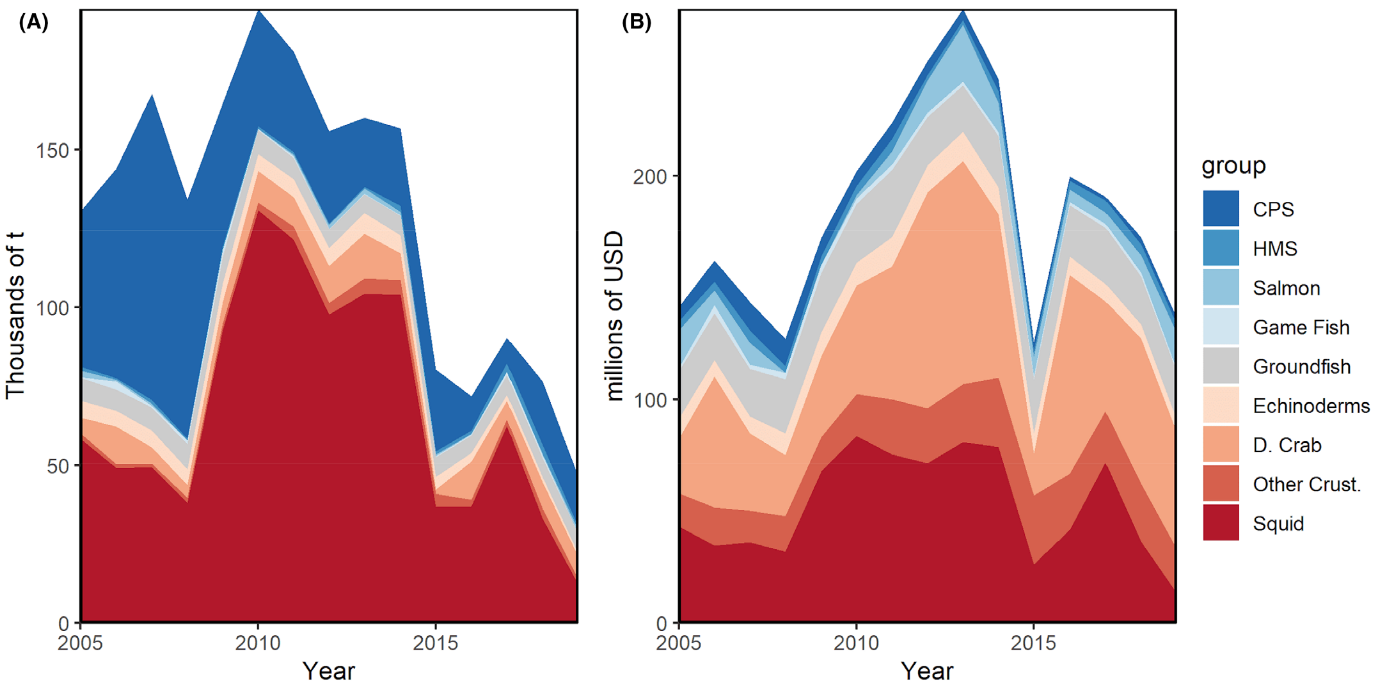

FIGURE 4. Statewide annual time series of **(A)** landings and **(B)** value recorded in all blocks.

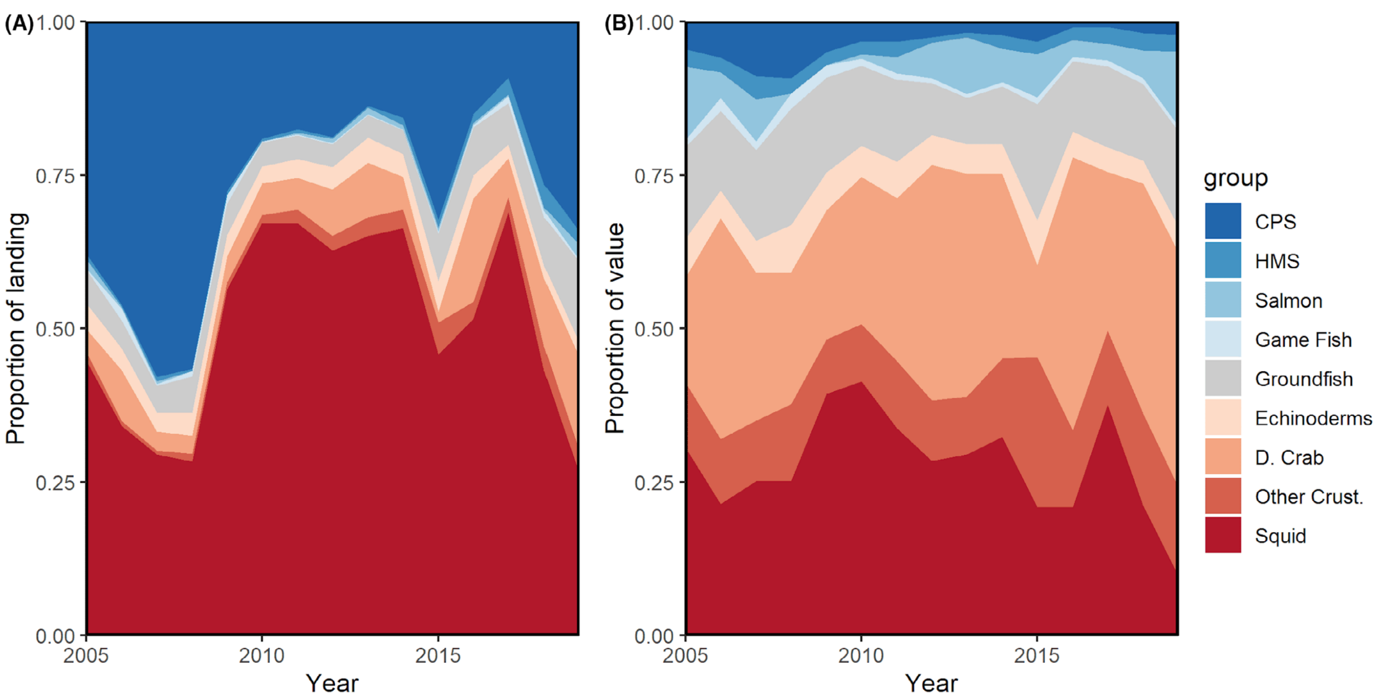

FIGURE 5. Statewide annual times series of proportion of each taxonomic group **(A)** for landings and **(B)** value recorded in all blocks.

Spatial Distribution across Regions

Fisheries landings and values varied substantially from region to region (Figure 6). For much of the time series, Southern California was the dominant region, constituting nearly 50% of the statewide landings until 2013, after which it declined to <25%. Northern California and North Central California contributed the least to statewide landings; however, their combined landings and values

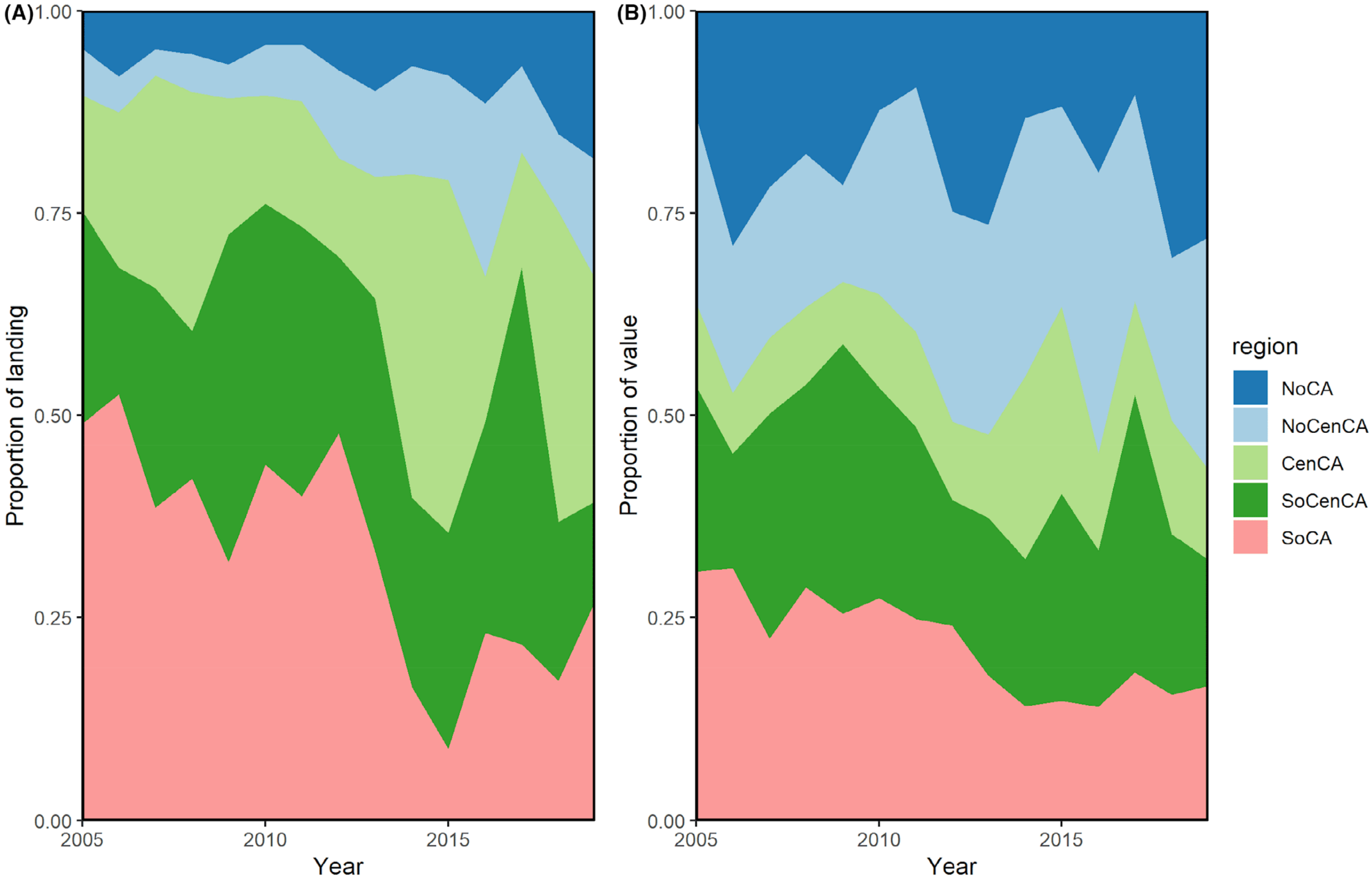

FIGURE 6. Annual proportion of fisheries in each region **(A)** for landings and **(B)** value recorded in all blocks.

gradually increased over the time series. Despite having moderate landings, Central California consistently had the lowest total value among the regions.

Regional fisheries also showed significant variation in landings among the broad taxonomic groups (Figure 7). Fisheries in Northern California were dominated by Dungeness Crab and groundfish, though the landings of other crustacean was substantial in some years (e.g., 2015). Compared to Northern California, North Central California fisheries were more diverse, with significant contributions from Dungeness Crab, groundfish, salmon, echinoderms, and even squid and CPS in some years. Central California was dominated by CPS and squid; the low price per pound for these species contributed to the low total value for this region. Like Central California, Southern California supported mainly CPS and squid fisheries. Southern California had higher value than Central California because of the contribution of high-value other crustacean fisheries, mostly spiny lobster. In South Central California, squid was the most important species, accounting for more than 75% of landings almost every year.

Spatial Distribution across Blocks

Detailed three-digit block landings and values after applying the "rule of three" are shown across the individual taxonomic groups in Figures 8 and 9, respectively. For display purposes, taxonomic groups are divided into finfish groups (groundfish, CPS, salmon, HMS, and game fish) and invertebrate groups (echinoderm, squid, Dungeness Crab, and other crustacean). In general, the spatial patterns of landings and value were similar for most groups.

For finfish groups, groundfish was caught across the entire EEZ. Most groundfish catch was reported within the maximum depth limit (i.e., 1,200-m isobath), though some were reported farther offshore. In comparison, CPS fisheries were concentrated in the Southern California Bight and near Monterey Bay, whereas salmon fisheries were scattered north of 36°N. Game fish were mainly caught in the Southern California Bight. Highly migratory species fisheries were concentrated further south near the U.S.–Mexico border. Invertebrate groups were primarily distributed close to the shore within their respective depth ranges. Both echinoderm and other crustacean fisheries

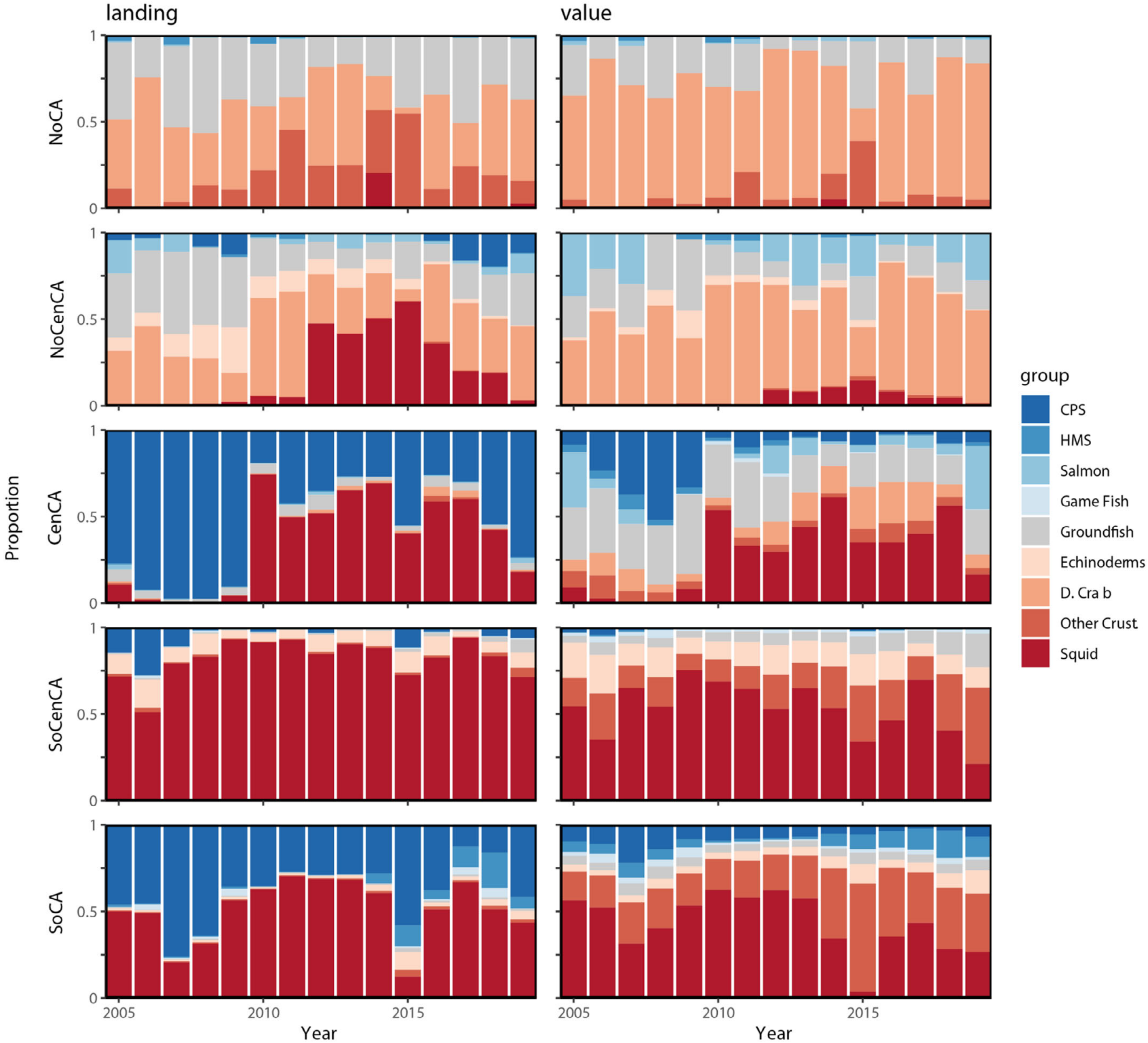

FIGURE 7. Annual proportion of landings (left) and value (right) for each taxonomic group in different regions. The rows from top to bottom represent regions: Northern California (NoCA), North Central California (NoCenCA), Central California (CenCA), South Central California (SoCenCA), and Southern California (SoCA).

were clustered near the Channel Islands in Southern California, squid fisheries were mainly located south of 38°N, and most Dungeness crab were caught north of 36°N. These findings are consistent with those presented by region (Figure 7). Among all taxonomic groups, Dungeness crab had the highest Moran's I, indicating high spatial clustering, whereas groundfish had the smallest Moran's I, suggesting that fishing activity for groundfish is more evenly distributed across the state (Table 1).

Given the significant proportion of values reported in four-digit blocks for Dungeness crab and groundfish, we further characterized Dungeness crab and groundfish fisheries in four-digit blocks, which displayed spatial inconsistency over time (Figure S5). Dungeness crab fisheries in the northern-most four-digit block accounted for over 40% of landings in 2006, 2009, and 2018. In comparison, groundfish fisheries in the second northern-most four-digit block were more important than others, which

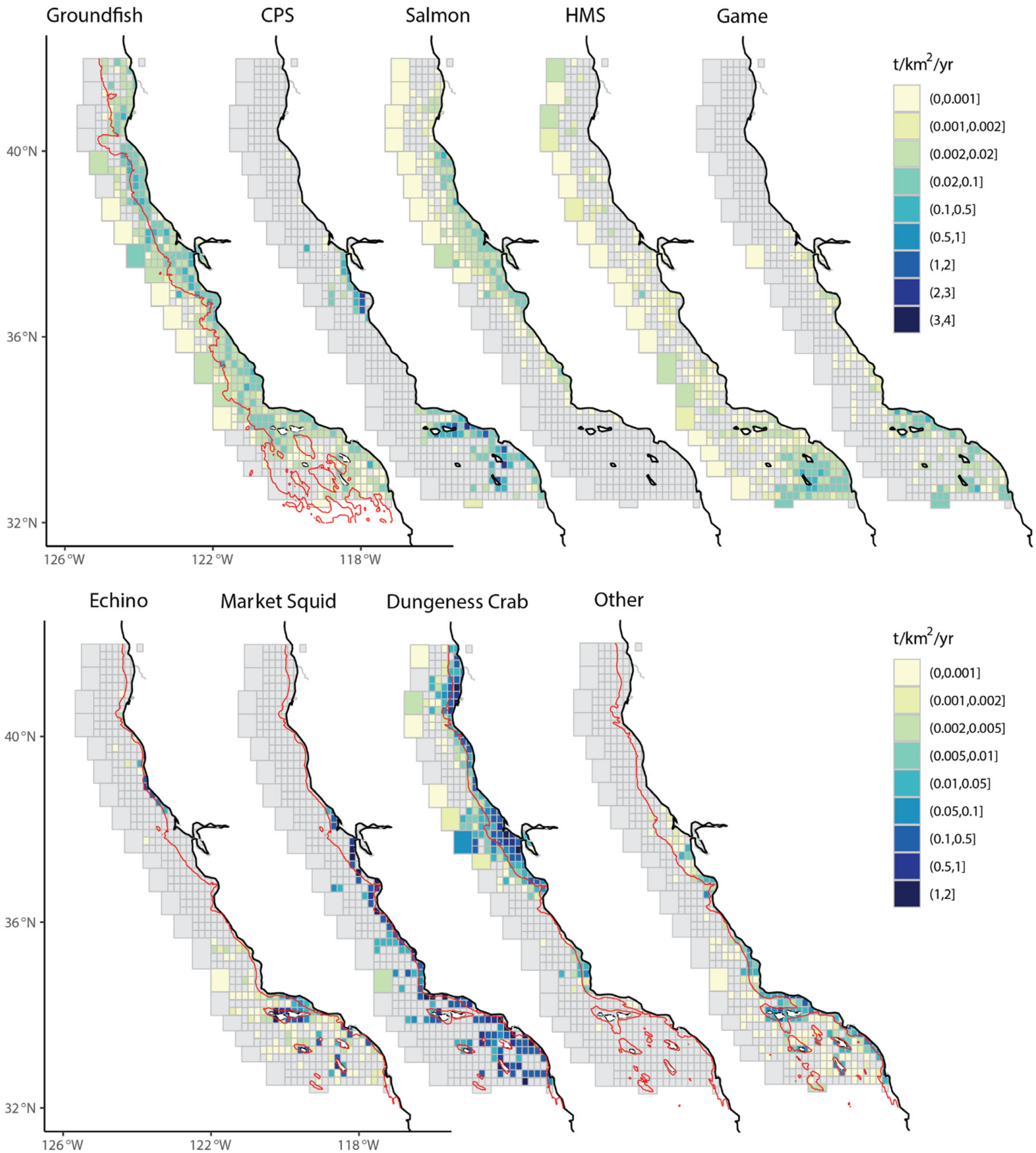

FIGURE 8. Annual average landings per unit area for (top) finfish groups (groundfish, CPS, salmon, HMS, and game fish) and (bottom) invertebrate groups (echinoderm, squid, Dungeness crab, and other crustacean) from 2005 to 2019 after applying "rule of 3." "Other crustacean" is labeled as "Other." If applicable, the prescribed depth limit is contoured in red (Miller et al. 2017; Table S1).

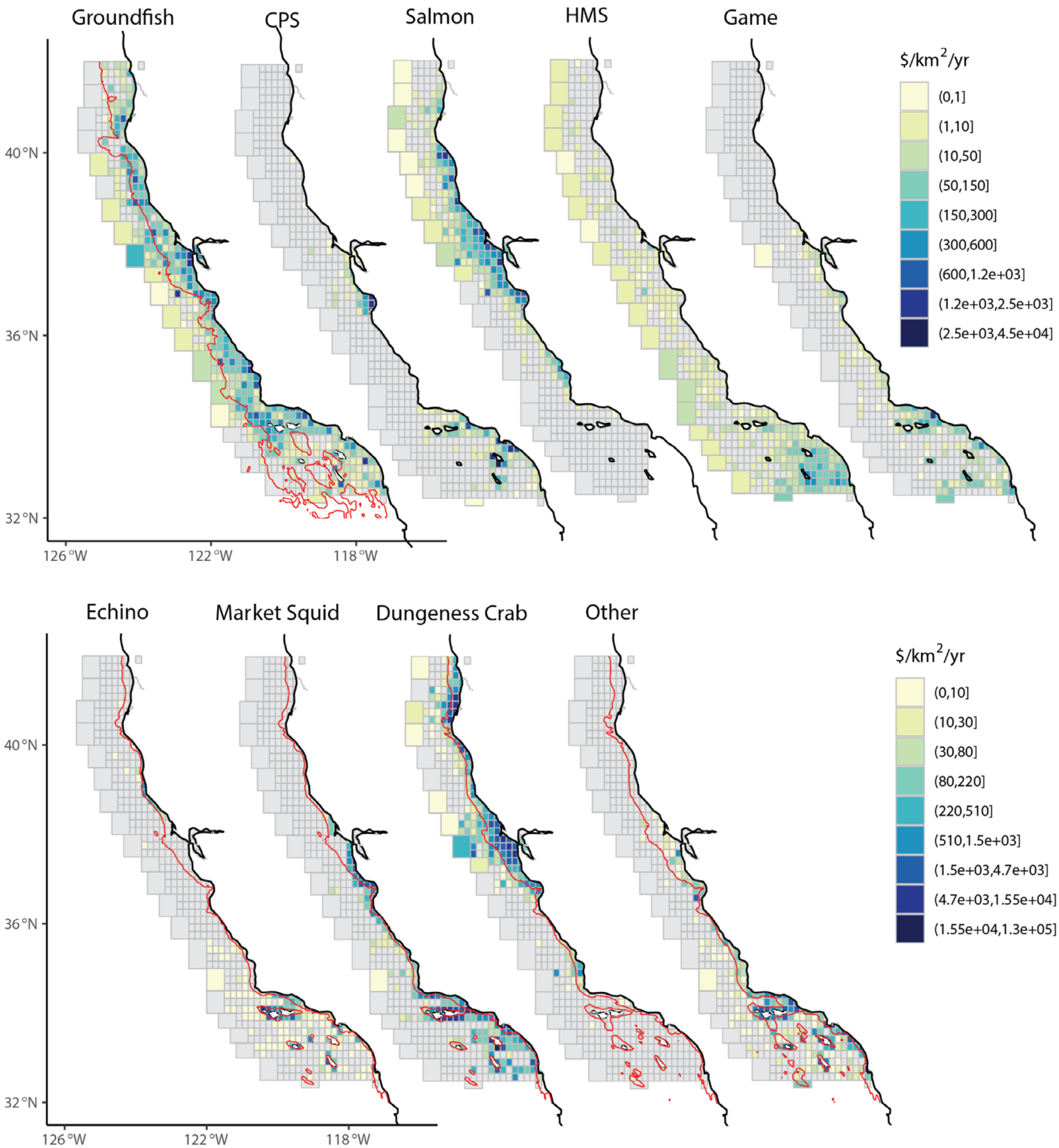

FIGURE 9. Annual average value per unit area for (top) finfish groups (groundfish, CPS, salmon, HMS, and game fish) and (bottom) invertebrate groups (echinoderm, squid, Dungeness crab, and other crustacean) from 2005 to 2019 after applying "rule of 3." "Other crustacean" is labeled as "Other."

TABLE 1. Moran's I and its *P*-value for each taxonomic group based on fishing blocks with neighbors that share at least one vertex.

Taxonomic group	Moran's I	*P*-value
Groundfish	0.09	<0.005
CPS	0.22	<0.001
Salmon	0.32	<0.001
HMS	0.48	<0.001
Game fish	0.19	<0.001
Echinoderm	0.26	<0.001
Market squid	0.12	<0.001
Dungeness crab	0.52	<0.001
Other crustacean	0.15	<0.001

contributed to over 40% of annual landings in the past 5 years.

Wind Energy Area Case Study

Using the fish ticket data, we identified fisheries that could be affected by offshore wind development (Figure 11). For the ports adjacent to a WEA, the most valuable fisheries were Dungeness crab in the Humboldt Bay port complex and groundfish in the Morro Bay/Port San Luis port complex. Landings in the self-reported fishing blocks that overlapped with the respective WEAs revealed the same general results. However, when imposing the prescribed depth limits for each fishery (Table S1; Miller et al. 2017), the relative importance of fisheries shifted substantially. The Humboldt WEA is outside the depth range of Dungeness crab, so removing that species—which is likely not caught in that WEA (Miller et al. 2017)—made groundfish and salmon the most important fisheries in the region. In the Morro Bay WEA, groundfish remained the highest value fishery and even increased in relative value due to the number of squid reported in the Morro Bay WEA that is outside the prescribed depth limit for that fishery.

DISCUSSION

This study characterizes temporal and spatial variation in California commercial fisheries landings and value of key fishery groups from 2005 to 2019. Individual fish groups exhibited substantial interannual variability in landings and values, though they did not always synchronize. Over the 15-year data set, total landings showed a downward trend, with the 2019 landings being about one-third of the 2005 landings. Despite this decline in landings, the total value of these commercial fisheries remained relatively stable. This trend was due to a steady shift toward lower-biomass, higher-value species, as well as rising prices, even after accounting for inflation. Spatially, landings and values varied among different regions in both magnitude and species composition. Southern California fisheries decreased in relative importance over the past 15 years, while the Northern and North Central regions gradually expanded their contribution to statewide landings and values. Many fisheries were also more spatially constrained (e.g., Dungeness Crab, game fish, squid), while a few were more widespread (e.g., groundfish) throughout the state.

Variation in fisheries often reflect the dynamics of socioecological systems, which are influenced by several factors, including economic conditions, regulatory frameworks, and environmental variation and stressors. For example, increasing fuel prices have been shown to correspond with a decrease in fishing effort (Kroodsma et al. 2018), and changes in regulations can have profound effects on fishery dynamics (Mamula and Kosaka 2019). Decreases in population sizes of target species can lead to fisheries collapse and closure, as happened for salmon fisheries in 2008–2009 (Figure 4; Figure S4; Richerson and Holland 2017). In addition, the impact of climate-driven environmental changes—such as MHW—on commercial fisheries and marine ecosystems can be profound and long-lasting (Suryan et al. 2021). The downward trend of the statewide landings (Figure 4A) may be evidence of long-term fisheries impacts from climate change that is projected to reduce catch potential in many temperate and subtropical regions, including waters off California (Cheung et al. 2010).

The variation in California commercial fisheries is complex since individual fish species have unique biological responses at different life stages that respond differently to changes in environmental or ecological conditions. As a result, different fishery groups are likely to display varying levels of resilience to climate change induced effects. For example, the groundfish fishery is the most geographically widespread across California (e.g., smallest Moran's I; Table 1) and includes a range of different species with differing life histories, habitat requirements, and population dynamics. As such, this broad fishery group exhibits relatively stable annual landings in each region over the past 15 years (Figure 10A). The HMS group may also be more resilient than other groups to ongoing and future climate change stressors. Even though the fishery is fairly spatially clumped (second highest Moran's I; Table 1), with most activity occurring in Southern California (Figure 8), the target species are pelagic and are thus able to migrate in response to changes in oceanographic conditions. The migratory feature of the HMS group is evidenced by the significant increase in landings from 2014 onward (Figure 10B), which coincided with warm waters associated with the North Pacific MHW and a major phase shift of both the North Pacific Gyre Oscillation (http://www.o3d.org/npgo/index.html) and Pacific Decadal Oscillation (https://oceanview.pfeg.noaa.gov/erddap/tabledap/cciea_OC_PDO.html). As with HMS, adult squid are pelagic; the decrease

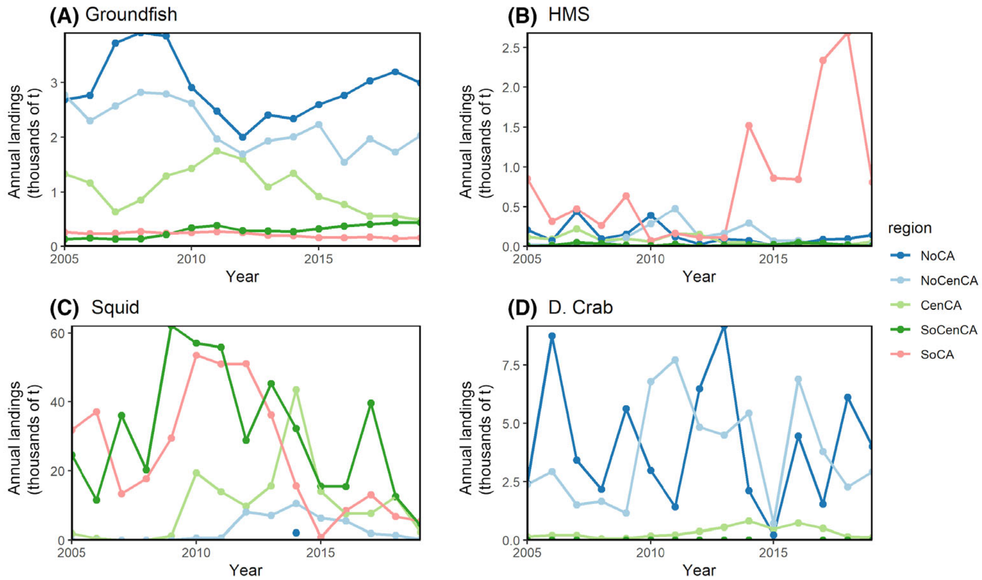

FIGURE 10. Regional annual landings (thousands of metric tons [t]) for **(A)** groundfish, **(B)** HMS, **(C)** squid, and **(D)** Dungeness crab.

in landings in the Southern and South Central regions corresponded with an increase in landings in the Central region in 2014, suggesting that squid moved poleward in response to warmer ocean waters during the North Pacific MHW (Figure 10C; Cavole et al. 2016). At the same time, adult squid lay their eggs benthically in shallow waters, potentially putting them at risk of warming and/or low dissolved oxygen/pH events, all of which that are increasing in frequency in shallow nearshore waters (Long et al. 2016).

On the other hand, a fishery like Dungeness crab—one of the most valuable in the state—may be much more susceptible to changes induced by climate change. The Dungeness crab fishery is the most spatially clumped (the highest Moran's I; Table 1), with the vast majority of fishing activity occurring in the Northern and North Central regions (Figure 7). Dungeness Crabs are mostly found in shallower waters closer to shore, where ocean acidification and hypoxia effects are more pronounced due to the upwelling of low DO and pH subthermocline waters, large algal blooms, and eutrophication (Grantham et al. 2004). For example, the Dungeness crab fishery along the Oregon coast has experienced mass die-offs from upwelling-driven hypoxic events (Grantham et al. 2004). Likewise, in California, the drop in 2015 (Figures 4 and 10D) resulted at least in part from the delayed fishery opening in response to domoic acid created by widespread harmful algal blooms (Santora et al. 2020), which also may be increasing as climate changes (Gobler 2020).

Whatever the drivers are of the patterns observed here, a changing climate will continue to impact California fisheries; the variation in California fisheries documented by this study can provide insight and a reference for evaluating the response of fisheries to future climate change. As the climate continues to change, anomalous events such as MHWs are predicted to increase in frequency and intensity (Frölicher et al. 2018) and California fisheries landings may further decline and/or redistribute as some species continue to expand poleward (Cheung and Frölicher 2020; Chaudhary et al. 2021). However, predicting future dynamics of California fisheries can be difficult, given that upwelling and productivity in the California Current may vary more in both time and space under future climate change, which can further complicate biological responses and food web dynamics in higher trophic-level species that are often the primary targets of fisheries (Brady et al. 2017; Xiu et al. 2018), potentially resulting in moving targets for management.

The findings of this study can be used to support and improve current fisheries management. The temporal and spatial variation in key fishery groups can not only help fisheries managers evaluate the effectiveness of regulations on a certain fishery, but also shed some light onto the resilience of a fishery group and the response of fishers to climate-driven oceanographic conditions (Fisher et al. 2021). Combining a better understanding of fisheries variation with near real-time environmental monitoring can further benefit the development of dynamic fisheries management approaches. Our findings can also imply the interactions between different fishery groups and across trophic levels, given interlinked food web dynamics. For example, some fish species such as squid and coastal pelagics are important prey for other top consumers such as seabirds and marine mammals; declining catch of these

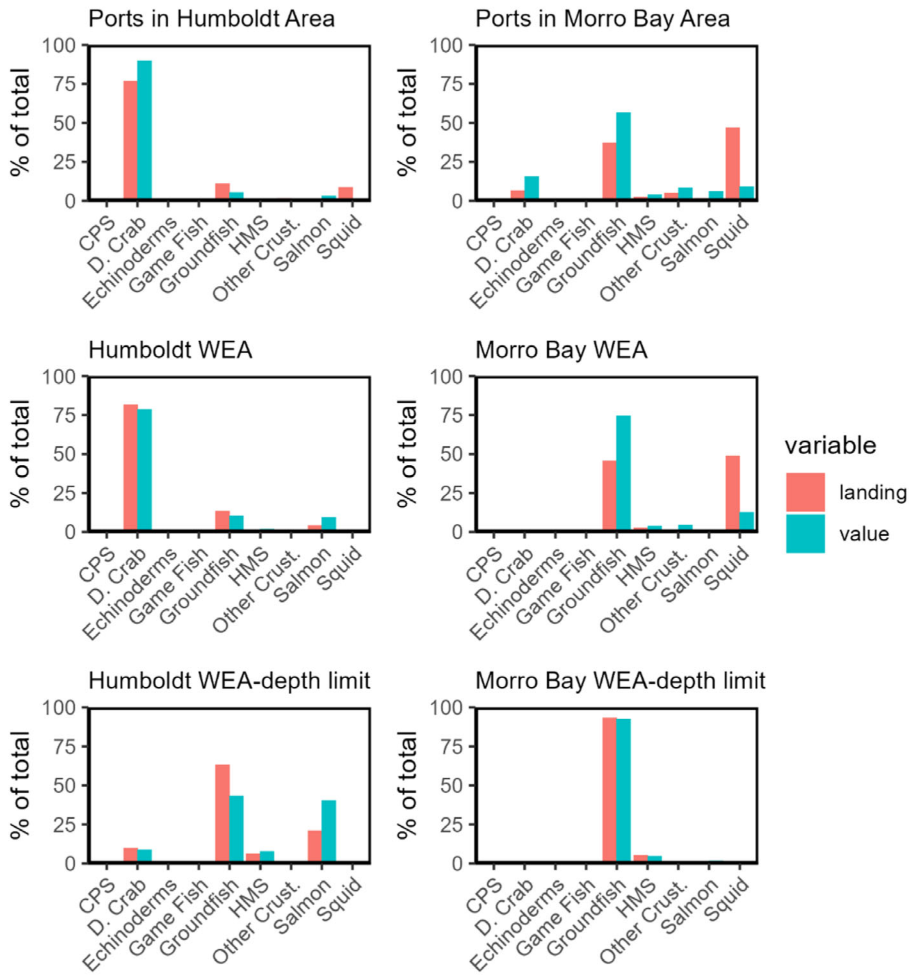

FIGURE 11. Percent of total landings and values based on fishery recorded in three-digit blocks under different conditions. (Fisheries landed in ports in the Humboldt area (i.e., Eureka, Trinidad, Shelter Cove, Crescent City, Fields Landing, King Salmon, Klamath, Humboldt Bay) (top left); fisheries landed in ports in the Morro Bay area (i.e., Avila/Port San Luis, Morro Bay, San Simeon) (top right); fisheries recorded in the blocks overlapping Humboldt Wind Energy Area (WEA) (middle left); fisheries recorded in the blocks overlapping Morro Bay WEA (middle right); fisheries in Humboldt WEA and within prescribed depth limit in Table S1 (bottom left); similar to bottom left but for Morro Bay WEA (bottom right).

species may reflect low prey availability, with potentially cascading effects across marine ecosystems (Bertrand et al. 2012). Therefore, the characteristics of multiple fishery groups documented by this study can provide useful information toward a more comprehensive stock assessment of marine ecosystems and a more advanced ecosystem-based fisheries management.

In addition to commercial fisheries, there are other ocean uses that support the blue economy, including aquaculture, tourism, offshore renewable energy, and infrastructure (Dundas et al. 2020). These analyses allowed us to identify the dominant fisheries in the two WEAs for potential offshore wind development off the coast of California, both of which are dominated by groundfish; however, the latter result only holds if the prescribed depths for Dungeness crab (Humboldt) and squid (Morro Bay) are correct.

While reported catches in the CDFW fish ticket data enable us to explore the temporal and spatial dynamics of California fisheries, there are some potential limitations. First, while the reported block information allows for the identification of spatial hot spots for different fisheries, the landings reported in the much coarser four-digit blocks (compared to the three-digit blocks seen in Figures 8 and 9) are significant. Because the four-digit blocks are essentially latitudinal bins, we are unable to calculate landings and value per unit area for them. Consequently, the landings and value per unit area may be underestimated considerably for the fishery groups that had a substantial proportion of catch reported in the much larger four-digit blocks. This includes several high-value fisheries like Dungeness crab and groundfish. Second, there was a noticeable fraction of catch reported outside of species' prescribed depth limits, including in regions that are being pursued for offshore wind energy. This mismatch could be due to changing environmental conditions not yet considered by species' depth estimates, misreporting by fishers, and other factors. While improving the precision and accuracy of fishing locations is beyond the scope of this study, it highlights the need for accurate, higher resolution spatial information to support fisheries management and science that is needed for future work. One approach for calibrating and increasing resolution in spatial information in landings data would be to combine it with other independently collected high-resolution spatial fisheries data, such as vessel monitoring systems data (Watson et al. 2018).

CONCLUSIONS

This study significantly advances our understanding of the spatiotemporal dynamics of marine commercial fisheries landings and value across the entire state of California over the past two decades, updating the research by Miller et al. (2017). These updated results confirm the shift from higher-biomass, lower-value species to lower-biomass, higher-value species that began several decades ago (Miller et al. 2017). In addition, we document clear spatial patterns and trends in fisheries activity across the state, and the data illustrate how the intensity of specific fisheries have changed statewide, possibly in response to changes in ocean climate or species range shifts. While we also demonstrate some limitations of the spatial accuracy of the fishing ticket block data, these data can help advance a number of current management challenges that intersect with fisheries across the state, including planning for a changing climate, marine spatial planning for additional users of ocean space such as offshore wind, and sustainability of fishery activity into the 21st century.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.