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The commercial groundfish fishing industry and groundfish research have a long concurrent history of activity on the Oregon continental margin. Within the non-whiting groundfish fishery, the target species are primarily flatfishes, sablefish, lingcod, and rockfishes, though landings of each have fluctuated over time. Recent work shows that over the past two decades, fishing effort has shifted offshore likely due to implementation of gear regulations, area closures, and lower catch limits. Although federal fishery-independent surveys have been conducted across most of the groundfish fishery's depth range, data is limited by years and seasons surveyed as well as absence of data in the shallowest waters (< 55 m). Fishery-dependent data covers those shallow waters and a broader temporal range, but at a coarse scale. Limitations in data coverage combined with a historical focus on deep-water groundfishes has led to a gap in understanding of dynamics within the nearshore fishery, particularly regarding the influence of environmental factors on abundance and distribution. Through this thesis, I analyzed changes in spatiotemporal dynamics of the Oregon nearshore non-whiting groundfish trawl fishery and assessed gaps in each data source over the past four decades. Statistical modeling was used to elucidate distribution shifts in species as well as temporal changes in community composition. These analyses revealed how individual species' distributions have geographically shifted over time, what environmental variables affect their spatial distribution, and how depth and habitat type strongly influence nearshore community composition.

I found that physical shelf structure drives the distribution of certain groundfish assemblages in that there are separate groups associated with different habitat types and depth

zones. Individual species had strong depth preferences grouped in either shallow (< 80 m, e.g., starry flounder and sand sole), midshelf (e.g., petrale sole and lingcod), or deep (> 120 m, e.g., *Sebastes* spp.) clusters, which explains the importance of bathymetry in groundfish assemblage composition. The large-scale climate indices tested did not explain the variability in either individual species abundance or assemblages, while temperature and depth drove abundance for most groundfish populations. It is clear from the results of this study that there have been spatiotemporal changes in the nearshore groundfish populations and assemblages during the past four decades, and that temperature is influential for some species distributions. Portions of the shelf that have experienced anomalous hypoxic events over the last two decades exhibit reductions in presence of hypoxia-intolerant species (e.g., petrale sole and lingcod), while shallow-water species that tolerate warmer water as well as low dissolved oxygen concentrations (e.g., English sole and Pacific sanddab) exhibit shoreward compressed distributions.

Visualization of both fishery-independent and -dependent data allowed for a qualitative comparison of data coverage as well as an assessment of differences in species distribution when mapping each dataset. I found that the earliest years of the NOAA surveys (1980 – 1998) have the most information gaps and had the highest potential to benefit from complementary use of fishery-dependent data for spatial and temporal analyses. This was largely due to (1) triennial rather than annual sampling and a transect-based design in the NOAA surveys, and (2) the larger spatial and temporal coverage of logbook data (inshore and latitudinal) during that period. Commonly caught species (e.g., Dover sole and petrale sole) had better spatial sampling coverage of their populations compared to species that live in shallow water and are less frequently targeted (e.g., starry flounder and sand sole). These analyses illuminate where knowledge gaps lie in both data types and how they complement one another, providing more context for future management of nearshore groundfishes.

Change in Oregon’s Nearshore Groundfish Trawl Fishery: Perspectives from Science and Industry Data

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Rebecca A. Howard, Author

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Chapter 1: Introduction to the Oregon nearshore groundfish commercial trawl fishery

1.1 **Introduction**

Groundfishes have played a vital role in Oregon's coastal economy and have so for over a century. Oregon's groundfish fishery provides a significant amount of revenue for the state, having contributed 59.5 million pounds of catch valued at $36.3 million in 2017, which translated to 1,030 jobs (Gann, 2019). Oregon has consistently received a large portion of the U.S. West Coast non-whiting (Pacific hake) groundfish landings since the early 1990s, and there are almost 40 non-whiting groundfish trawl vessels currently fishing from Oregon ports (NMFS, 2017). However, the majority of fishable groundfish stocks are currently underutilized, partially due to the collapse of the fishery in 2000 and the resulting effects on regulation and market interest (Gorman & Fergus, 2000; Warlick et al., 2018). Area closures constrained fishing for many groundfishes, strict catch limits were put in place to rebuild specific stocks, and vessels were removed from the fishery through a federal buyback program (Finley, 2017; Warlick et al., 2018; McQuaw & Hilborn, 2020). In recent years, some regulations have been relaxed or removed and may create incentives to fish nearshore habitats inshore of 200 m, which are not heavily targeted at present. This thesis assesses spatiotemporal changes in distribution, responses to environmental conditions, and data collection on federally managed groundfishes that inhabit the nearshore habitat fished by Oregon commercial trawl fishermen. Groundfishes are group of over 90 largely benthic or demersal species that are members of several taxonomic groups, also targeted by fixed gear vessels. In this research the nearshore is defined as the portion of the continental shelf inshore of the 200-meter isobath, which approximately demarcates the shelf-slope break and is the location of the 'nearshore' trawl fishery fishing grounds (Hannah et al., 2007). The continental shelf that comprises the Oregon fishing grounds extends anywhere from 13 km to almost 75 km offshore from the coast. The portion of the fishery homeported in Oregon travels as far as northern Washington and northern California to target these species. Therefore, this research covers that geographic extent. Groundfishes are caught as part of a mixed fishery and only species covered by the Pacific Fishery Management Council's (PFMC) Groundfish Fishery Management Plan (GFMP) were used for these analyses (PFMC, 2019).

1.2 **Habitat of nearshore groundfishes**

The nearshore in the California Current Ecosystem (CCE) is inhabited by numerous groundfishes, species that live on or near the seafloor (Yoklavich & Wakefield, 2015). The federally managed groundfishes are members of several different groups. The largest group, rockfishes (Scorpaeniforms), are comprised primarily of approximately 65 members of the *Sebastes* genus. Flatfishes (Pleuronectiforms) and cartilaginous sharks and skates (Elasmobranchs) are the other two groups of closely related species, encompassing twelve and six species, respectively. The roundfish group includes species like lingcod (*Ophiodon elongatus*) and sablefish (*Anoplopoma fimbria*). Other groundfishes are categorized as Ecosystem Component Species for management purposes, and this group includes species such as ratfishes (Family *Chimaeridae*) and grenadiers (Family *Macrouridae*).

The earliest studies of northern CCE shelf groundfishes and their habitat found that the seafloor in shallow water was predominantly sandy but transitioned to silt and clay at deeper sample sites. Both sediment types were found to be dominated by flatfishes, sablefish, and skates (Alverson et al., 1964; Day & Pearcy, 1968; Pearcy, 1978). Outside of the fine sediment areas, rockfishes dominate the cobble and less common high relief rocky habitat (Pearcy et al., 1989; Love et al., 2002). Although habitat and depth greatly influence groundfish distribution on the shelf, these species are also influenced by ocean conditions and basin-scale processes. The idea of oceanographic habitats has been explored by Juan-Jordá et al. (2009) in the northern CCE to evaluate groundfish associations with temperature, salinity, and chlorophyll a (Chl-*a*). The authors identified the main oceanographic habitats as (1) offshore, (2) upwelling, (3) highly variable upwelling, (4) river plumes, and (5) highly variable. They also found that groundfish presence was often more highly correlated with specific oceanographic variables such as temperature or depth, rather than these oceanographic habitats (Juan-Jordá et al., 2009). Research on CCE groundfish population dynamics has often used bottom temperature to evaluate assemblage structure (Tolimieri & Levin, 2006)), recruitment (Keller et al., 2012), and body condition (Thorson, 2015) amongst other aspects due to the availability of temperature data from surveys.

While hypoxia was not addressed by Juan-Jordá et al. (2009), nearshore CCE species are impacted by low dissolved oxygen (DO) conditions. A few shelf species have evolved physiological or behavioral adaptations to respond to hypoxia while most others have not, as they historically did not experience frequent hypoxic events (Keller et al., 2010, 2017a). Dover sole (*Microstomus pacificus*), for example, do not exhibit decreases in biomass or body condition when exposed to hypoxia and are thought to have a higher tolerance for low DO concentrations than other species (Keller et al., 2010, 2017a). English sole (*Parophrys vetulus*) and Pacific sanddab (*Citharichthys sordidus*), however, do experience decreases in body condition but have behavioral or physiological responses that allow them to respond to low DO conditions (Boese, 1988; Vetter et al., 1994; Keller et al., 2010; Love, 2011). Other species like petrale sole appear to be less tolerant and the biomass of many shelf rockfish and flatfish populations decline at specific DO thresholds (Keller et al., 2017a).

Although much of the past focus on West Coast groundfishes has been largely directed at rockfishes and other slope-dwelling species, as well as some flatfishes, the continental shelf is critical habitat for a multitude of fishes throughout varying life stages. Many of the flatfishes targeted by the groundfish fishery use the nearshore for spawning, breeding, or juvenile development. A number use both the slope and shelf habitat, annually migrating from the shallows in the summer months to the deeper, cold slope waters to spawn in the fall and winter. This is the case for both Dover sole and petrale sole (*Eopsetta jordani*), though as Dover sole age they spend less time on the shelf (Pearcy et al., 1977; Markle et al., 1992; Love, 2011). The nursery grounds for these deep-spawning flatfishes vary, with rex sole (*Glyptocephalus zachirus*) and Dover sole settlement often occurring at the shelf break or deeper, while petrale sole recruits are thought to occupy either the inner shelf or shelf break (Ketchen & Forrester, 1966; Pearcy et al., 1977; Haltuch et al., 2019; Tolimieri et al., 2020). Other flatfishes spend their entire lives on the shelf, but their juvenile life stages utilize estuaries or bays for development. English sole, starry flounder (*Platichthys stellatus*), southern rock sole (*Lepidopsetta bilineata*), and speckled sanddab (*Citharichthys stigmaeus*) are all known to spawn on the continental shelf and their offspring recruit to estuarine habitat or bays (Krygier & Pearcy, 1986; Rackowski & Pikitch, 1989; Love, 2011; Schwartzkopf et al., 2020). Estuaries are also critical habitat for multiple life stages of lingcod and cabezon (*Scorpaenichthys marmoratus*) (Love, 2011). Many species of skates (family *Rajidae*) occupy the soft sediment of the continental shelf and several are thought to spawn year-round in this region (Ebert, 2003). Although adult rockfishes within the commercial groundfish fishery are not as common on the continental shelf as they are on the slope, many utilize nearshore habitat such as kelp forests or cobble beds as nursery habitat. Other rockfishes are known to use estuarine habitat (Schwartzkopf et al., 2020). These rockfishes include species such as widow (*Sebastes entomelas*), yellowtail (*S. flavidus*), bocaccio (S. *paucispinis*), and canary (*S. pinniger*) rockfishes, all of which were once overfished by the groundfish fishery (Love, 2011; Schwartzkopf et al., 2020). It is evident that the nearshore is critical habitat for a wide range of groundfish species, many of which are commercially important and use this habitat to complete their life cycles.

1.3 **Management and policy**

The commercial non-whiting groundfish trawl fishing industry has existed in some form on the U.S. West Coast since 1876, when paired sailboats dragged trawl gear known as paranzella nets (Norman et al., 2007). Technology quickly improved with the emergence of diesel and steam powered vessels in the early 20th century (Easley, 2000). Fishing prior to 1945 was minimally regulated by the U.S. Fish Commission, later the U.S. Bureau of Fisheries, and West Coast fishermen fished in waters not yet claimed by the U.S or other nations. In 1945 the Truman Proclamation claimed the continental shelf seafloor for the U.S. as part of a global race to claim marine territory. The National Oceanic and Atmospheric Administration (NOAA) was a product of this rush for territory and was primarily used to manage the commercial fishing industry that reemerged following World War II (Hanna, 2000). In addition to domestic fishery management, the federal government sought ways to keep foreign interests out of U.S.-claimed waters and away from valuable resources like the West Coast groundfish fishery. From the 1960s through the 1980s multiple countries, including the Soviet Union, Japan, and South Korea, heavily targeted rockfishes, flatfishes, and Pacific whiting (hake) (*Merluccius productus*) (Finley, 2017). To protect U.S. fishing interests, the U.S. Exclusive Economic Zone (EEZ) was created to exclude foreign catch out to 200 nautical miles (nm). This was done in 1976 through the Magnuson-Stevens Fisheries Conservation Management Act (MSFCMA), which claimed all fishing rights within the EEZ whereas the Truman Proclamation had only claimed the seafloor. A notable exception to the foreign fleet exclusion was a set of joint ventures with Soviet, Japanese, South Korean, and Chinese vessels amongst other countries (Alverson, 1985; Mansfield, 2001; Finley, 2017).

As the federal government implemented the beginnings of modern U.S. fishery management, Oregon executed the first iteration of the Oregon Coastal Management Program

(OCMP) in 1971 through the Oregon Land Conservation and Development Commission. This program went on to set nineteen management goals by 1976, four of which focused on the coast, and included the first mention of Oregon commercial fisheries under Goal 19 which centered on ocean resources. At the same time, the OCMP goals were finalized, the federal Coastal Zone Management Act (CZMA) was approved after recommendation by the Stratton Commission. In 1977, Oregon's OCMP was authorized by NOAA to fulfill the CZMA policies (Bailey, 1997). For federal West Coast fishery management, the PFMC was created in 1976 by the MSFCMA as one of eight management councils. The councils were, and continue to be, used to determine acceptable biological catch for each species or stock complex managed, spatially or temporally restrict fishing as needed, and work with all stakeholders to fairly distribute quotas. Following its creation, the PFMC set a maximum sustainable yield (MSY) of 35-40% for most stocks in its GFMP despite lacking data (Ralston, 2002). The combination of a relatively high MSY, exclusion of foreign vessels, and a remarketing of previously undesirable species led to a dramatic increase in domestic groundfish landings in the early 1980s. In Oregon, the ports of Astoria (Warrenton), Newport, and Charleston (Coos Bay) landed and processed the majority of the non-whiting groundfish quota during this peak in fishing effort (Macomber, 2000; Warlick et al., 2018).

Despite the quick economic success of the early 1980s, landings ultimately began to decrease. State and federal agencies attempted to halt the decline, but the lack of suitable data had become clear to many fisheries scientists and managers (Easley, 2000). Oregon created the Ocean Resources Management Plan, which later resulted in the state's Territorial Sea Plan to manage state waters that extend out to 3 nm, or approximately 55 m depth (Bailey, 1997). Amendment 5 to the GFMP added the first overfishing guidelines while Amendment 6 brought about the first license limitation program, which attempted to fairly distribute quotas while still enforcing permits for a limited entry groundfish fishery (Mansfield, 2001). Joint ventures with the Soviet Union were scrapped as the U.S. built its first whiting motherships and catcher-processors (Mansfield, 2001). Limited access systems were put into place in 1994 after being contested for three years by fishermen, changing most fishing in Oregon from open access to closed access in the trawl, pot, and longline sectors (Hanna, 1995). The federal government later implemented regulations for bycatch prevention and habitat protection with the Sustainable Fisheries Act and tried to further prevent overfishing. Despite these late efforts to curb overfishing and bycatch, develop planning for Oregon waters, and protect habitat, in the early 2000s multiple species were declared overfished by the PFMC. Bocaccio (*S. paucispinis*), canary, cowcod (*S. levis*), darkblotched (*S. crameri*), widow, Pacific Ocean perch (*S. alutus*), and yelloweye rockfish along with lingcod and Pacific whiting on the West Coast were declared overfished due to the 35 – 40% MSY levels implemented in 1982 (Parker et al., 2000; Ralston, 2002; Dick & MacCall, 2010). In 2000, the Secretary of the Department of Commerce declared the groundfish fishery a disaster (Norman et al., 2007).

Following the fishery's collapse, policies were put in place to rebuild the fishery and prevent future overfishing. Several amendments to the GFMP were approved by the PFMC, three of which (Amendments 11, 12, and 13) satisfied new requirements from the MSFCMA. These GFMP amendments created the first Essential Fish Habitat (EFH) and aimed to reduce bycatch, prevent overfishing, and rebuild overfished stocks (PFMC, 2019). Rockfish Conservation Areas (RCAs) were implemented in 2002 and restricted use of bottom trawls, fixed gear, and recreational gear at certain isobaths along the West Coast to reduce catch of bocaccio, canary, and darkblotched rockfishes. These restrictions vary annually and seasonally and remained in place until the RCAs off California and Oregon were removed in 2020. Trawl footrope diameter was also limited to less than 20.3 cm inshore of about the 182-meter isobath, which reduced fishing activity on the shelf (Hannah, 2003). NOAA developed a catch reduction program in 2003 that eliminated a significant number of trawlers from the West Coast groundfish fishery through a buyback program (Norman et al., 2007; Warlick et al., 2018). Many were smaller vessels that fished nearshore waters.

Later amendments to the GFMP were largely created in response to issues with Amendments 11-13. Amendments 16-1 through 16-5 created new rebuilding plans for overfished stocks. This changed how the PFMC developed and implemented those plans, and required consideration of biological, ecological, societal, and economic factors. Amendment 17 created a timeline for modifying groundfish harvest specifications and management, which occurs every two years. Through approval of Amendment 18, bycatch monitoring and mitigation measures utilized by the PFMC were added to GFMP and the overall management framework was updated to allow for modification in response to changes in the fishery. Amendment 19 was implemented to designate habitat areas of particular concern to lessen negative effects from fishing in additional areas and updated the EFH definition. The Oregon Department of Fish and Wildlife

(ODFW) also expanded the state's groundfish policy. The ODFW Marine Resource Program implemented limited entry for nearshore groundfish under their jurisdiction (≤ 3 nm from shore) which regulated select commercial fisheries like black (*Sebastes melanops*) and blue/deacon (*S. mystinus/diaconus*) rockfishes. The ODFW also developed the Oregon Nearshore Strategy in 2005 to create a conservation plan as well as inspire further stewardship and research in the area. In 2006, the MSFCMA was reauthorized. The reauthorization led to new policy requirements for the Regional Fishery Management Councils on fishing limits, rebuilding of stocks, bycatch limitations, and more scientific input through a set of ten National Standards (Gehan & Hallowell, 2012). This created the foundation for the PFMC to implement the West Coast Groundfish Trawl Catch Share Program via Amendments 20 and 21-1 through 21-4 to the GFMP. It was put into place in 2011 and is the current system. All overfished groundfish stocks off the Oregon Coast have been rebuilt except yelloweye rockfish, and the groundfish fishery is now often cited as an example of successful ecological recovery (Bellman et al., 2005; Gleason et al., 2013; Miller & Deacon, 2017; Associated Press, 2019).

Amendment 28 to the GFMP in 2019 was responsible for the removal of the California and Oregon RCA closures (50 C.F.R. § 660.60 2019). There are still other protections in place including EFHCAs, which permanently close areas to certain types of fishing depending on what type of habitat is being protected. Block Area Closures, also a result of Amendment 28, allow the PFMC to respond to changes in the fishery and close areas temporarily. The Oregon Nearshore Strategy has been continually updated since its implementation. Current research and monitoring recommendations include the addition of fishery-independent assessments in Oregon's Territorial Sea, characterization of species and habitats, and study of temporal changes in human-nearshore interaction (ODFW, 2016). The PFMC is continuing to develop its Fishery Ecosystem Plan, first adopted in 2013, which guides management of the West Coast fisheries through an Ecosystem Based Management (EBM) lens (Pikitch et al., 2004; McLeod & Leslie, 2009; PFMC, 2013). The new EBM focus aims to incorporate all ecosystem components and is further supported by the annual California Current Ecosystem Status Reports and the California Current Integrated Ecosystem Assessments. New initiatives under consideration include "bio-geographic region identification and assessment", which emphasizes the importance of re-evaluating nearshore management (PFMC, 2017). The modern management landscape for the West Coast groundfish fishery is built on the lessons learned during the fishery's development as well as the now four decades worth of data that have been collected by industry participants and scientists.

1.4 **Fishery-independent data**

Fishery-independent research, work completed independent from the fishery, has been conducted by multiple parties and generally parallels the progression of fishery management. The first trawl surveys were conducted by the U.S. Fish and Wildlife Service in the early 1950s and several small-scale beam trawl and submersible surveys were run in the following decades (Alverson, 1953; Alverson et al., 1964; Pearcy et al., 1989; Tissot et al., 2008). In addition to these trawl efforts, NOAA implemented a bottom trawl survey to better manage the fishing effort of the groundfish fishery. Currently, this data is housed at the Northwest Fisheries Science Center (NWFSC) Fishery Resource Analysis and Monitoring Division's Data Warehouse and is publicly available (https://www.nwfsc.noaa.gov/data/map).

The first iteration of the NOAA survey began in 1977 and focused only on the continental shelf using bottom trawl gear (Fig. 1.1). This survey, known as the triennial survey, was run by the Northwest and Alaska Fisheries Science Center (NWAFSC, now the Alaska Fisheries Science Center, AFSC) and used Alaskan trawlers equipped with nylon (1977 – 1986) or polyethylene (poly) Nor'eastern (1986 – 2001) nets. Depth and transect distance were variable up until 1995 when the sample design was standardized and the AFSC began targeting a 55 to 500-meter depth range (Wilkins et al., 1998). Prior to 1995 the triennial survey did not attempt to create a picture of the entire groundfish fishery, but rather targeted certain species of interest, leading to a variation in design (Keller et al., 2017b). The triennial survey typically sampled on the Washington and Oregon continental shelf from mid-June (post-1992) or July (pre-1995) to late September. Two vessels were assigned alternate transects for a single pass down the coast and each tow was 30 minutes long (Dark & Wilkins, 1994). Beginning in 1984, the AFSC ran a simultaneous annual survey on the slope and used some of the same vessels and a similar gear configuration. The NOAA Ship *Miller Freeman* was primarily used in addition to the commercial vessels, and a different footrope than one used for the triennial survey was employed. The slope survey overlapped the triennial survey with a depth range of 184 to 1,280 m and ran until 2001. In the mid-1990s, the NWAFSC split and the newly created NWFSC was then primarily responsible for managing the West Coast groundfishes. From 1998 to 2002 the

NWFSC ran a slope survey and in 2004 it oversaw the triennial survey. The NWFSC conducted the slope and triennial surveys with a similar sample design to the AFSC but with West Coast vessels and an Aberdeen net, which has a smaller diameter footrope and lower rise opening (Fig. 1.1). The Aberdeen gear configuration also had continuous packed discs on the footrope while the poly Nor’Eastern had large discs separated by smaller discs, which changed selectivity. The NWFSC slope survey used different spacing between transects and covered a larger spatial range. The Aberdeen trawl was chosen because the smaller West Coast vessels could not tow the larger poly Nor’Eastern net and it is similar to the type of gear used by West Coast fishermen. In the late 1990s and early 2000s, the NWFSC began to convert the slope and triennial surveys into one survey, now known as the West Coast Groundfish Bottom Trawl survey (WCGBTS) which started in 2003.

The WCGBTS happens annually and uses a stratified random sampling design based on a 12,000-cell grid with cells sized 2.0 nm north-south and 1.5 nm east-west (Keller et al., 2017b). A grid is overlaid on the West Coast continental shelf and slope, and cells are selected for sampling each year. From 2003 to 2018, four West Coast vessels were chartered by the NWFSC and equipped with an Aberdeen trawl. One exception was 2004, when three vessels were used. The vessels are paired, randomly assigned 188 cells each, and then travel north to south down the coast in two passes. They typically occupy the Oregon and Washington portion of the coast from mid-May to late September. In most years 75% of the total selected stations are sampled and

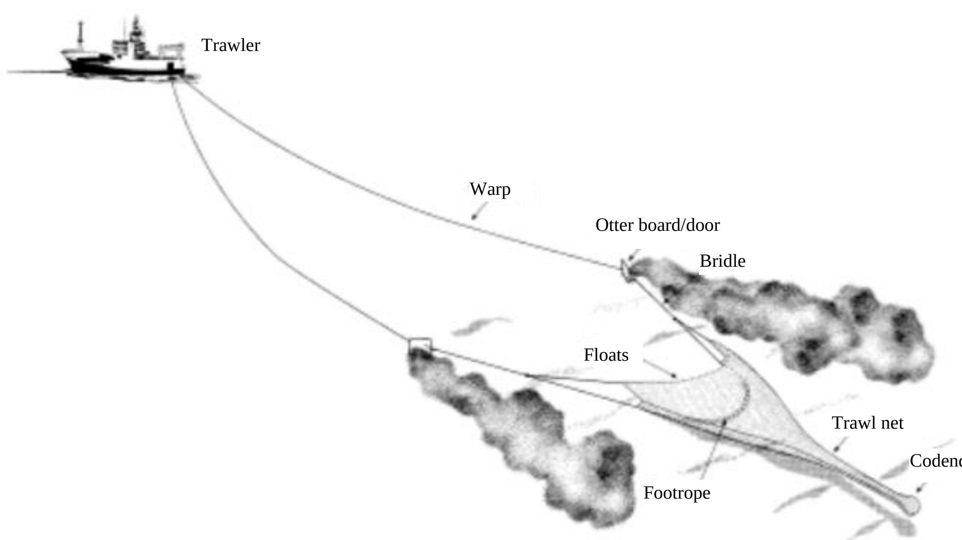

Figure 1.1: The configuration of a bottom trawl. In the context of NMFS survey sampling, the poly Nor’eastern nets had larger diameter footrope with roller bobbins when compared to the Aberdeen nets. Modified from FOOCG 2001. A Fishing Industry Guide to Offshore Operators.

cells in the area north of Point Conception are allocated to three depth strata: 40% to 55–183 m, 30% to 184–549 m, and 30% to 550–1,280 m. Satisfactory tows are 12–15 minutes long and have an average 2.2 knot bottom contact speed. The WCGBTS provides a higher degree of statistical power than the triennial survey did, as the use of transects led to issues with bands of high and low sampling (Keller et al., 2017b). Despite the difference in sampling design between the triennial survey and the WCGBTS, both surveys have been shown to be valuable for illuminating changes in species distributions (Thorson et al., 2016).

1.5 **Fishery-dependent data**

There are several sources of fishery-dependent data for the West Coast commercial groundfish fishery. Landings (fish tickets) have been recorded by management to some degree for much of the groundfish fishery's history, but logbooks provide the largest quantity of data. This information has been collected in some form since the 1970s but was required of Oregon fishermen by the PFMC beginning in 1984 (Fox & Starr, 1996). Only logbooks contain location data for such an extensive time period, making them a potential source of data for future spatiotemporal analyses as well as for this thesis. Past research has shown that while inaccuracies will always be endemic to self-reported and estimated data like the logbooks, the information these records contain is nonetheless useful (Sampson, 2011). Captains record length of tow, depth fished, location of trawl setting and retrieval, and species retained, amongst other details (Sampson et al., 1997). The species records specifically can make individual species analyses difficult due to lack of data on discards, misidentification, and possible mismeasurement of catch, as fishermen use estimation to record catch weights (Sampson, 2011).

The first work to evaluate both the NOAA survey and fishery-dependent datasets was completed by Fox and Starr in 1996, in which they used GIS to compare commercial trawl catch data (logbook) to the triennial survey. They found that the differences between datasets included lack of spatial overlap in certain regions and a discrepancy in Dover sole biomass estimates, likely a result of gear differences, but that logbooks could be complementary to the survey data (Fox & Starr, 1996). Later work used logbook and fish ticket information to assess patterns of fishing effort and visualize spatial and temporal extent of certain fisheries (Macomber, 2000; Hannah, 2003; Bellman et al., 2005; Bellman & Heppell, 2007). There is infrequent use of fishery-dependent data for study of groundfish populations outside of fish tickets, which provide landings information. However, the logbook data generated by Oregon groundfish fishermen provides a more consistent time series and for certain species, a larger spatial range of information than NOAA survey data. This gives the data potential to fill in gaps in fishery-independent data and the combined use of both data types has been employed in other regions as well as the U.S. West Coast for spatiotemporal analyses (Pecquerie et al., 2004; Guy et al., 2013; Murray & Orphanides, 2013; Pennino et al., 2016). In 2001 the West Coast Groundfish Observer Program (WCGOP) was established to collect data aboard groundfish vessels to help manage the fishery in the wake of overfishing. With the creation of the West Coast Groundfish Trawl Catch Share Program, members of the limited entry fleet were then required to carry an observer on every trip. This has provided an additional source of fishery-dependent data with a spatial component and is useful for stock assessments as there is no conflict of interest and randomized sampling is used.

1.6 **Climate and oceanography in the northern California Current**

In the last four decades, the CCE has experienced novel climate regimes and changes in regional oceanographic conditions (Hare & Mantua, 2000; Di Lorenzo et al., 2010; McClatchie et al., 2016a; Harvey et al., 2019). Two marine heatwaves and multiple anomalous hypoxia events have affected groundfishes targeted by Oregon commercial fishermen in particular, signaling new challenges and more uncertainty for marine resource managers (Chan et al., 2008; Keller et al., 2010; Joh & Di Lorenzo, 2016; Sobocinski et al., 2018; Harvey et al., 2019). Many fishes are sensitive to shifts in oceanic conditions (Hare & Mantua, 2000; Litzow, 2006; Szuwalski & Punt, 2013; Litzow & Mueter, 2014). Fluctuations in oceanic and atmospheric forcing lead to changes in regional oceanographic conditions such as temperature, salinity, upwelling, and DO and can sometimes happen rapidly and persist in the form of a regime shift (Hare & Mantua, 2000; Peterson & Schwing, 2003; Pierce et al., 2012; Di Lorenzo et al., 2013; Jacox et al., 2014; Litzow & Mueter, 2014).

To better understand how changing ocean conditions have impacted the CCE, there has been investigation into large scale climate patterns. El Niño/Southern Oscillation (ENSO) is one of the most well-known climate patterns and it connects equatorial Pacific circulation with the northeastern Pacific (Rasmusson & Carpenter, 1982). Warm ENSO phases are known as El Niño, and cool as La Niña, and there are two varieties of El Niño patterns (Kao & Yu, 2009).

Eastern Pacific (EP) El Niño is associated with positive sea surface temperature anomalies (SSTa) in the eastern tropical Pacific due to high sea surface atmospheric pressure over the western tropical Pacific and low sea surface pressure in the eastern tropical Pacific (Rasmusson & Carpenter, 1982; Larkin & Harrison, 2005). Central Pacific (CP) El Niño is associated with warmer water in the central tropical Pacific and has a similar pressure pattern but shifted farther west (Larkin & Harrison, 2005; Ashok et al., 2007; Hu et al., 2016). CP El Niño may become more common due to global warming (Ashok & Yamagata, 2009). Recent research has shown shifts between El Niño and La Niña conditions can correlate with changes in zooplankton composition, northward movement of southern species, and changes in larval fish community composition during strong El Niño events (Mantua et al., 1997; Goericke et al., 2004; Leising et al., 2014; McClatchie et al., 2016b).

The Pacific Decadal Oscillation (PDO) climate index was first described in the 1990s as the first principal component of monthly SSTa in the North Pacific (Mantua et al., 1997). Positive phase PDO is typically correlated with anomalously high sea surface heights (SSHa) and warm SSTa throughout the CCE, while negative phase indicates the reverse (Mantua et al., 1997; Chhak et al., 2009). More recently, the North Pacific Gyre Oscillation (NPGO) climate index has been described as the second principal component for SSHa (Di Lorenzo et al., 2008). NPGO is correlated with Chl *a*, sea surface salinity anomalies, wind, and certain nutrient concentrations (Chhak et al., 2009; Di Lorenzo et al., 2008, 2009). Positive phase NPGO is associated with enhanced central CCE upwelling due to stronger coastal winds in the winter months that usually lead to cooler temperatures in this area (Di Lorenzo et al., 2008; Chenillat et al., 2012; Macias et al., 2012). ENSO and PDO, however, are correlated with changes in upwelling throughout most of the CCE (Macias et al., 2012). Additionally, CP El Niño and NPGO exhibit similar patterns and are considered linked, while EP El Niños are more connected to the PDO (Alexander et al., 2002; Di Lorenzo et al., 2010). Transitions between climate index phases can also be linked to regime shifts, which affect variability in species' biomass, recruitment, and abundance (Litzow, 2006; Keller et al., 2012; Litzow & Mueter, 2014). It has been well-established that there was a regime shift driven by the combined PDO shift from negative to positive and NPGO shift from positive to negative in 1976/1977 (Hare & Mantua, 2000; Litzow & Mueter, 2014). Additional regime shifts have been detected for 1988/1989 and cautiously for 2007/2008 (Peterson & Schwing, 2003; Litzow & Mueter, 2014).

While climate indices largely describe interannual and interdecadal variation in the northeastern Pacific, regional oceanography on shorter timescales is also important. Because the CCE is an eastern boundary current system, hypoxia has always been a feature because upwelling sometimes brings water up from deep oxygen minimum zones (OMZ; > 500 m water depth) to the shelf. However, anomalously low DO events were first documented in 2002 and it is not thought that hypoxia of this severity occurred before 2000 (Grantham et al., 2004; Chan et al., 2008; Rabalais et al., 2010). These events are the result of both increased respiration and shoaling, movement of the OMZ shoreward driven by strong upwelling (Grantham et al., 2004; Bograd et al., 2008; Rabalais et al., 2010). Portions of the northern CCE seem particularly vulnerable to hypoxia, including the area near Heceta and Stonewall Banks where high primary productivity, and therefore respiration, is common (Grantham et al., 2004; Barth et al., 2005; Adams et al., 2013) (Fig. 1.2). Anomalous ocean warming is another recent oceanographic phenomenon in the CCE. Beginning in winter of 2013 and lasting until 2016, a warm mass of

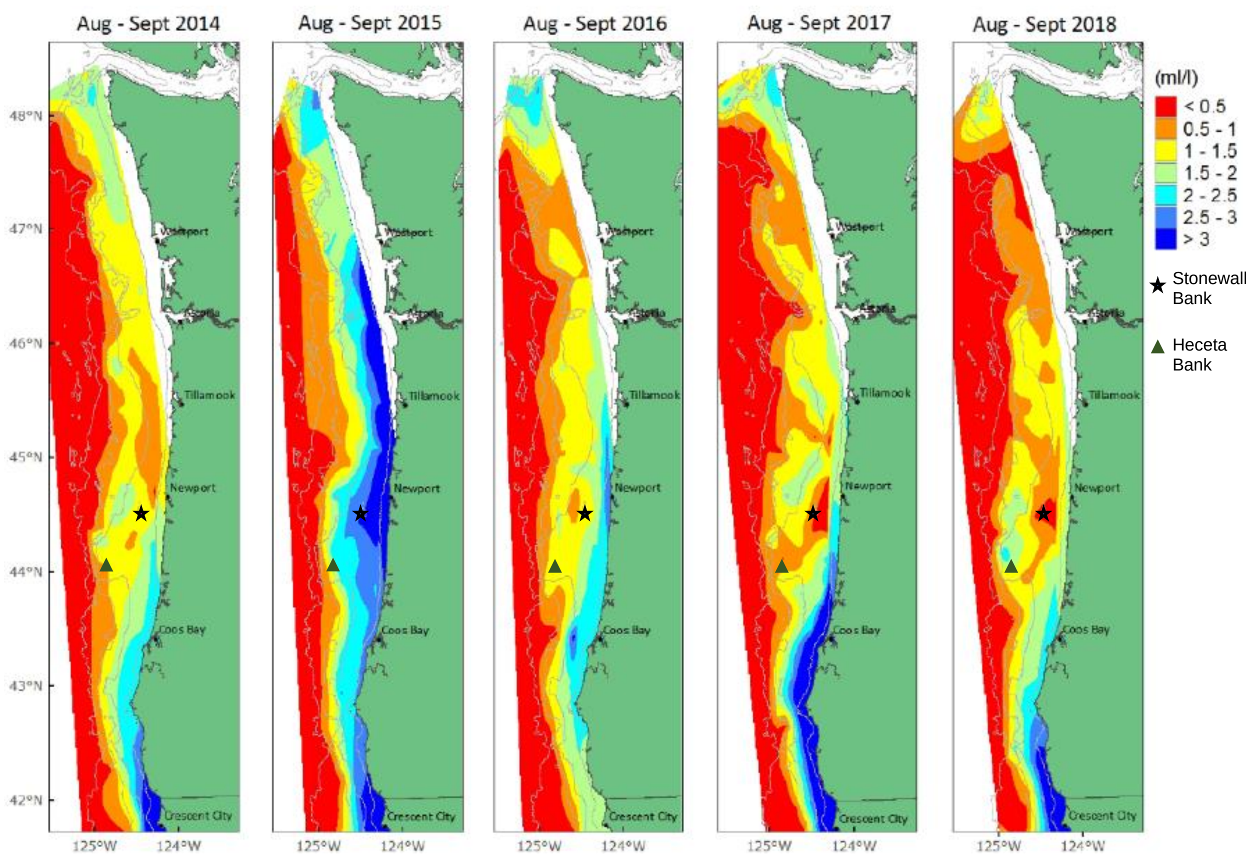

Figure 1.2: Dissolved oxygen concentrations off the Oregon and Washington Coasts. Notable areas of hypoxia (≤ 1.4 mL/L) on the shelf include the area near Heceta and Stonewall Banks (west of Newport) and northern Washington. Adapted from: PMFC 2019 Ecosystem Status Report.

water formed in the Gulf of Alaska (GoA) and gradually extended south to the CCE. This marine heatwave was formed by high atmospheric pressure over the GoA which led to reduced heat loss to the atmosphere, reduced vertical oceanic mixing, and lack of upper ocean cold advection (Bond et al., 2015). No SSTa of this size had been seen since the 1980s, though other smaller heatwaves occurred in the 1950s, 60s, and 90s (Bond et al., 2015; Di Lorenzo & Mantua, 2016). The 2013 – 2016 anomaly led to mass strandings of marine mammals, harmful algal blooms, northward movement of southern species, and fisheries closures (Cavole et al., 2016). Along the CCE, the warm water mass dissipated at the end of 2015, with some effects lingering into 2016 (Gentemann et al., 2017). The persistence of this heat wave is thought be caused by ENSO teleconnections and atmospheric variability in the CCE, preceded by warm water in the GoA (Di Lorenzo & Mantua, 2016; Jacox et al., 2018). Warm water conditions in the GoA reappeared in 2018, leading to another marine heatwave that ended in early 2020 (Amaya et al., 2020).

1.7 **Groundfish assemblages**

While individual species analyses are useful, understanding species interactions and co-occurrence is crucial for fishery management. In one of the first attempts to identify groundfish assemblages off the coast of Oregon, Jay (1996) identified over fifteen common nearshore clusters in the AFSC triennial survey data. Some of the dominant indicator species for these assemblages, as determined by abundance, included Dover sole, Pacific whiting, rex sole, sablefish, arrowtooth flounder (*Atheresthes stomas*), shortspine thornyhead (*Sebastolobus alascanus*), darkblotched rockfish, English sole, Pacific sanddab, and spiny dogfish (*Squalus suckleyi*) (Jay, 1996). Further research using the triennial survey to assess assemblage structure concentrated entirely on rockfishes, as this was the initial intent of the survey. Shelf rockfishes that dominated the assemblages identified in these studies had distributions centered at 150 m depth and included canary, yellowtail, widow, sharpchin (*Sebastes zacentrus*), rosethorn (*S. helvomaculatus*), yelloweye (*S. ruberrimus*), greenstriped (*S. elongatus*) and redstripe rockfishes (*S. proriger*) (Weinberg, 1994; Williams & Ralston, 2002). While Williams and Ralston's study region included only a small portion of Oregon Coast waters, Weinberg's results indicated that shelf waters sampled by the triennial survey likely encompassed similar species regardless of latitude. These early investigations of groundfish assemblage structure using the triennial survey provided a baseline understanding of slope and shelf community composition.

Following the transition to the NWFSC annual survey, there has been one study that used both iterations of the NOAA surveys to determine shelf and slope assemblage structure. The two surveys are not often used together due to differences in sampling methods, gear, and vessel type, among other discrepancies. Cope and Haltuch (2012) compared the two surveys in the context of assemblage presence and found that both surveys consistently included three assemblages. These persistent groupings were (1) a Dover-whiting-rex-slender sole (*Lyopsetta exilis*) complex that also included arrowtooth flounder, spotted ratfish (*Hydrolagus colliei*), sablefish, spiny dogfish, longnose skate (*Raja rhina*), and sandpaper skate (*Bathyraja kincaidii*); (2) an English sole-Pacific sanddab complex that included petrale sole, lingcod, spiny dogfish, and spotted ratfish; and (3) a chilipepper (*Sebastes goodei*) and shortbelly (*S. jordani*) rockfish complex that included stripetail (*S. saxicola*), bocaccio, and greenstriped rockfishes (Cope & Haltuch, 2012). As noted by the authors, identification of assemblages can help with bycatch management and is especially useful if the groupings persist temporally.

1.8 **Chapter summary**

In this thesis I assess (1) the relationship between oceanographic variability and nearshore groundfishes in the region fished by Oregon commercial groundfish trawl fishermen over the course of the entire WCGBTS (1977 – 2018) and (2) the combined use of fishery-independent (WCGBTS) and -dependent (logbooks and fish tickets) data for spatiotemporal analysis of the same region. In doing so I provide a more in depth look at nearshore groundfish population dynamics, factors that drive assemblage structure, and the utility of two very different data sources for study of Oregon fishing grounds.

In Chapter 2, I use data collected by the WCGBTS to examine what regional and basin-scale factors impact the nearshore (≤ 200 m water depth) groundfish species and assemblages found on the continental shelf. This is done by several methods. Ordination methods provide perspective on assemblage structures present during both the annual and triennial surveys and what environmental variables influence those groupings. Statistical modeling of individual species allows for analysis of correlations with climate indices and habitat characteristics recorded by the surveys as well an assessment of sudden shifts in distribution over time. In Chapter 3, I determine how fishery-independent and -dependent datasets for the Oregon nearshore fishing grounds can complement one another for spatiotemporal analyses.

Spatiotemporal visualization of the two data types is the primary tool used in this chapter and is complemented by a quantitative assessment of data overlap throughout the study region. Logbook and fish ticket data for Chapter 3 were obtained from the ODFW and the usage of those data in this thesis meets the requirements of the confidentiality agreement for data handling and display. This chapter provides context for what each dataset is lacking on both spatial and temporal scales over the same time frame as the preceding chapter. Chapter 4 then synthesizes Chapters 1-3 to explain how the nearshore has changed over the past four decades and how research like this thesis present can inform management of a nearshore fishery.

1.9 **References**

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Chapter 2: The effects of climate, oceanography, and habitat on the distribution and abundance of northern California Current nearshore groundfishes

Abstract

The California Current Ecosystem has been subject to a changing climate for many decades, leading to shifts in community structure and species distributions. In the northeastern Pacific, novel climate regimes have been detected and anomalous events like hypoxia and marine heatwaves have been observed in the nearshore. These changes have the potential to impact marine species like groundfishes and therefore their associated U.S. West Coast fisheries. Using data collected by the NOAA West Coast Groundfish Bottom Trawl Survey, this study examines what environmental factors impact the nearshore (≤ 200 m) groundfish populations and assemblages found on the continental shelf. The shelf habitat and associated communities are underrepresented in the literature despite their ecological and economic importance. Non-metric multidimensional scaling was used to assess change in assemblage structure between the earlier and later years of the survey. Generalized additive modeling was used to test for any sudden shifts in population distribution over time as well as determine what environmental and temporal covariates are influential for individual species of groundfishes. I found that physical shelf structure drives the distribution of specific groundfish assemblages, with a separation between habitat types and depth zones. Individual species had strong depth preferences grouped in either shallow (< 80 m, e.g., starry flounder and sand sole), midshelf (e.g., petrale sole and lingcod), or deep (> 120 m, e.g., *Sebastes* spp.) clusters, which demonstrates the importance of physical habitat on groundfish assemblage composition. The large-scale climate indices tested were not significantly correlated with either species abundance or groundfish assemblages, while temperature and depth were correlated with abundance for most groundfish populations. It is clear from the results of this study that there have been spatiotemporal changes in the nearshore groundfish populations and assemblages, and that temperature is influential on an individual species basis. Portions of the shelf that have experienced anomalous hypoxic events over the last two decades exhibit reductions in predicted probability of presence of hypoxia-intolerant species (e.g., petrale sole and lingcod), while shallow-water species that tolerate warmer water as well as low dissolved oxygen concentrations (e.g., English sole and Pacific sanddab) exhibit shoreward compressed distributions. With the removal of the trawl Rockfish Conservation Area off the coast of Oregon and changes in gear requirements, there is possibility for an increase in fishing

effort on the continental shelf, an area historically fished more heavily by bottom trawl fishermen. This research provides more context for management of the potential revitalization of the nearshore groundfish fishery.

2.1 **Introduction**

The U.S. West Coast continental shelf provides resources for coastal communities and habitat for the numerous species targeted by the Oregon non-whiting groundfish bottom trawl fleet. The fishery is a multispecies industry that has existed in some form since the beginning of the 20th century. It provides a significant amount of revenue for the state, and in 2017 contributed 59.5 million pounds of product valued at $36.3 million, which translated to 1,030 jobs (Gann, 2019). Oregon has consistently landed a large portion of the U.S. non-whiting groundfish quota since the early 1990s and there are almost 40 trawl vessels currently fishing these stocks from Oregon ports (NMFS, 2017). However, the majority of fishable groundfish stocks are currently underutilized, particularly in the wake of the recovery of the fishery during the last two decades (Gorman & Fergus, 2000; Warlick et al., 2018). Following dramatic changes in West Coast groundfish management and policy over the last two decades, some regulations have been relaxed or removed. This may now create incentives to fish nearshore habitats, which are not highly targeted.

For the current research, the nearshore is defined as the portion of the continental shelf inshore of the 200-meter isobath, which approximately demarcates the shelf-slope break and extends anywhere from 17 km to almost 75 km offshore. The fishery in this area has been referred to as the “beach fleet” or the nearshore trawl fishery (Hannah et al., 2007; Sjostrom et al., 2020). Many of the nearshore species live their entire lives on the shelf, including many of the flatfishes (Family *Pleuronectidae*) that dominate the sandy sedimentary habitat common to this region. Others migrate between slope and shelf habitat seasonally or occupy rocky habitat near the shelf-slope break (Day & Pearcy, 1968; Vetter & Lynn, 1997). Beginning in January 2020, the trawl Rockfish Conservation Area (RCA) that had restricted bottom-contact fishing in critical rockfish (*Sebastes* spp.) habitat along the shelf break since 2002 was removed from waters off Oregon and California (50 C.F.R. § 660.60 2019). The RCA removal allows vessels using bottom-contact gear to access species found on the outer shelf. With the imminent possibility of increased fishing pressure by Oregon fishermen on the continental shelf, it is necessary to provide a baseline of abundance, distribution, and their changes over time for nearshore groundfishes. Portions of the continental shelf are understudied compared to the slope and this research aims to fill a gap in knowledge about shelf groundfishes. Using NOAA Alaska Fisheries Science Center (AFSC) and Northwest Fisheries Science Center (NWFSC) survey data, in this study I assess (1) how assemblage composition of the nearshore has changed over time and what environmental factors or large scale climate patterns drive those changes, as well as (2) which groundfish species dominate the nearshore habitat, how their distributions have shifted over time, and what environmental factors drive their spatial presence and abundance. Evaluating the nearshore Oregon groundfishes and the environmental variables that influence these species adds information that is lacking for future U.S. West Coast groundfish management under federal and state jurisdictions.

In the last four decades, the northeastern Pacific has experienced novel climate regimes and changes in regional oceanographic conditions (Hare & Mantua, 2000; Di Lorenzo et al., 2010; McClatchie et al., 2016; Harvey et al., 2019). Many fishes are sensitive to changes in oceanographic conditions (Hare & Mantua, 2000; Litzow, 2006; Szuwalski & Punt, 2013; Litzow & Mueter, 2014). Fluctuations in oceanic and atmospheric forcing lead to changes in regional chemical and physical oceanographic conditions such as temperature, salinity, upwelling, and dissolved oxygen (DO) (Hare & Mantua, 2000; Peterson & Schwing, 2003; Pierce et al., 2012; Di Lorenzo et al., 2013; Jacox et al., 2014; Litzow & Mueter, 2014). In the Gulf of Alaska and Bering Sea, multiple fish species respond to these changes, including groundfish populations (Szuwalski & Punt, 2013; Litzow et al., 2018; Puerta et al., 2019). In the North Pacific and other regions, several regime shifts have been described but they are notoriously difficult to predict and lead to a great deal of uncertainty for managers (Scheffer et al., 2001; Carpenter & Brock, 2006; deYoung et al., 2008).

In addition to decadal scale community restructuring, fish populations respond to environmental change on a seasonal and interannual basis and move to different habitats to spawn or feed each year (Cushing & Dickson, 1976; Levin et al., 1994; Ottersen et al., 2004, 2010; Maxwell et al., 2015). Two marine heatwaves and multiple anomalous hypoxia events have affected groundfishes targeted by Oregon commercial fishermen, signaling new challenges and more uncertainty for marine resource managers (Chan et al., 2008; Keller et al., 2010; Joh & Di Lorenzo, 2016; Gentemann et al., 2017; Sobocinski et al., 2018; Harvey et al., 2019; Amaya et al., 2020). Research on the effects of environmental variability on West Coast groundfishes has primarily been focused on individual species responses, rather than assemblages (Keller et al., 2010, 2015; Thorson et al., 2016; Tolimieri et al., 2018; Haltuch et al., 2019), though there are some examples (Tolimieri & Levin, 2006). NMFS survey temperature data indicates that the southern, narrow portion of the Oregon shelf experiences the warmest bottom water temperatures while the coldest are near Washington state. However, in the 1990s there was a transition to warm waters across the inner shelf (Fig. 2.1). DO levels and hypoxia became a significant focus of research following an anomalous hypoxic event in 2002 off the Oregon Coast (Grantham et al., 2004). A few shelf species have evolved physiological or behavioral adaptations to respond to hypoxia while most others have not, as they historically did not experience frequent hypoxic events (Keller et al., 2010, 2015, 2017a). Declines in biomass and species richness for the West Coast groundfishes during the early 21st century have been found to be correlated with the Pacific Decadal Oscillation (PDO). This is particularly true in the case of weakly recruiting species and makes it unlikely that the observed decreases in biomass and richness can be entirely explained by high fishing pressure in the 1980s and 90s (Keller et al., 2012). Combined with simultaneous fluctuations in market preference, policy, and overfishing, elucidating the ecological and societal consequences of distributional shifts in

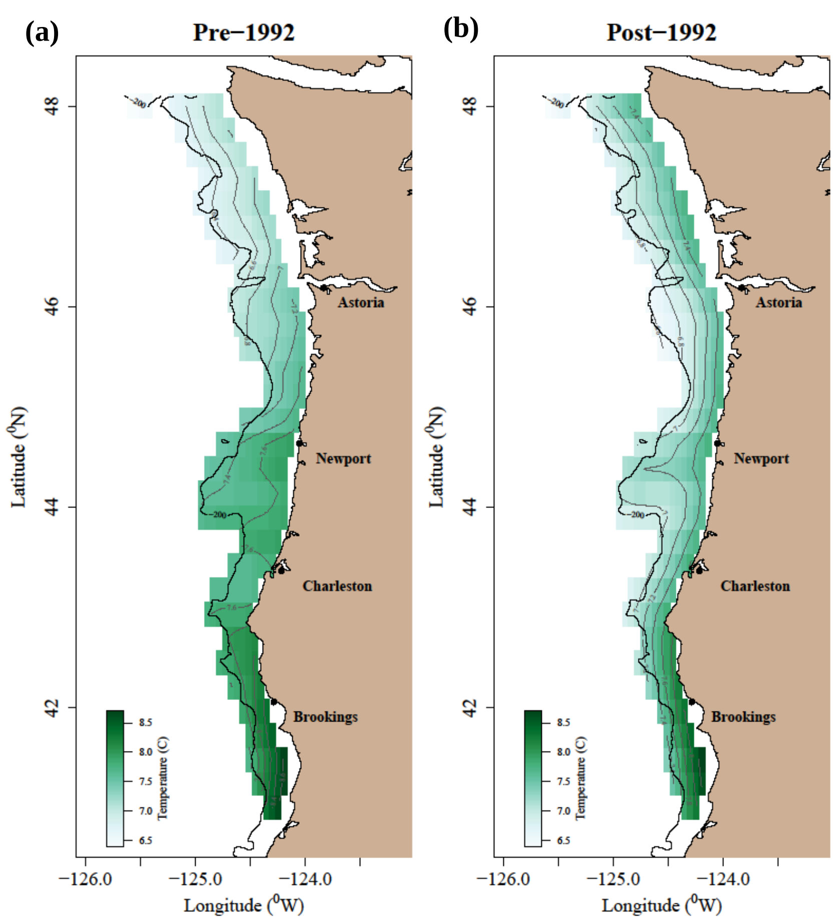


Figure 2.1: Bottom temperatures (a) before and (b) after 1992 on the continental shelf. Gray lines depict the temperature contours as predicted by a threshold GAM using bottom temperatures recorded by the NOAA triennial and annual survey data. 1992 was identified as the threshold year, at which point there was a general shift from profile (a) to (b).

groundfishes is a significant challenge faced by West Coast fisheries scientists and managers (Warlick et al., 2018; Sjostrom, 2019).

Scientific research has been conducted alongside the development of the industry, beginning when the groundfish fishery gained domestic interest and catch rates substantially increased. The first nearshore groundfish surveys in the 1970s and 1980s were completed by beam trawl, bottom trawl, and submersible. Those surveys focused on characterizing the populations of fishes found off the Oregon Coast (Alverson et al., 1964; Pearcy et al., 1977, 1989). These were soon followed in 1977 by development of a NOAA AFSC-led triennial survey on the continental shelf with a transect sample design (referred to hereafter as the triennial survey), as well an annual slope survey beginning in 1984 (Keller et al., 2017b). In 2003, the NOAA NWFSC implemented an annual shelf and slope survey conducted using a randomly sampled grid (referred to hereafter as the annual survey), replacing the former AFSC surveys (Fig. 2.2). Although fishing by the remaining vessels continued to some degree in the nearshore, the fishery offshore has drawn more scientific attention than the shallow shelf. Therefore, much of the focus on West Coast groundfish research has been aimed toward the offshore slope-dwelling groundfishes, especially Pacific whiting (hake) (*Merluccius productus*).

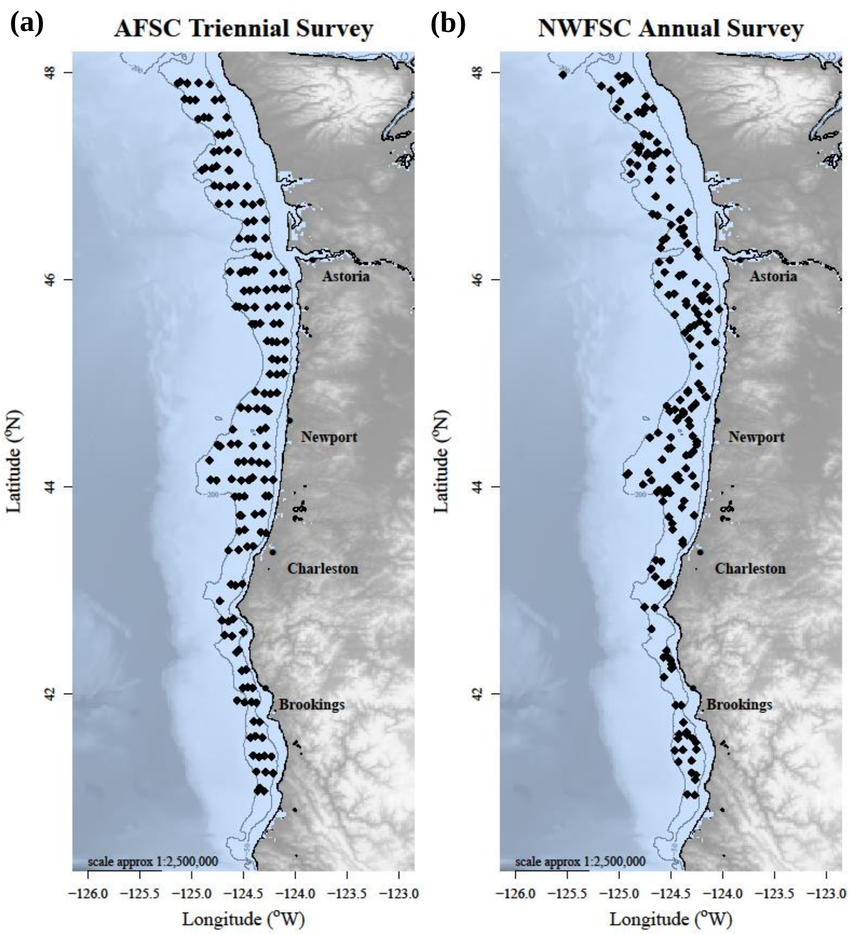


Figure 2.2: Representative depictions of the (a) triennial and (b) annual surveys. Black diamonds represent tow locations for one year. Grey lines depict the 50-meter and 200-meter isobaths.

Although commercial fishing on the

West Coast has a long history, catches in the nearshore groundfish fishing industry peaked in the 1970s and 1980s (Easley, 2000; Warlick et al., 2018). During this time, technological advances allowed movement of fishing effort offshore as vessels were able to stay at sea longer and consumers increasingly demanded west coast seafood. Offshore movement of the fleet increased in the 1990s and continued after the groundfish fishery's collapse in 2000. The collapse brought about a new period of restrictive management in the form of area closures, gear constraints, and stricter limitations on catch as well as a federal vessel buyback program that removed many of the small, nearshore vessels that make up the beach fleet (Warlick et al., 2018). The remaining groundfish vessels continued to fish predominantly on the slope in the 2000s and 2010s. This was done in order to not catch choke species, stay out of permanent and temporary RCAs, and avoid using the selective flatfish trawl and small footrope required shoreward of 182 m depth.

While individual species analyses are useful, understanding species interactions and co-occurrence is crucial for fishery management. In one of the first attempts to identify groundfish assemblages off the coast of Oregon, Jay (1996) identified over fifteen common nearshore clusters in the AFSC triennial survey data. Some of the dominant indicator species for these assemblages, as determined by abundance, included Dover sole (*Microstomus pacificus*), Pacific whiting, rex sole (*Glyptocephalus zachirus*), sablefish (*Anoplopoma fimbria*), arrowtooth flounder (*Atheresthes stomias*), shortspine thornyhead (*Sebastolobus alascanus*), darkblotched rockfish (*Sebastes crameri*), English sole (*Parophrys vetulus*), Pacific sanddab (*Citharichthys sordidus*), and spiny dogfish (*Squalus suckleyi*) (Jay, 1996). Both Weinberg (1994) and Williams and Ralston (2002) used the triennial survey to identify rockfish assemblages, though Williams and Ralston only looked at part of the northern California Current Ecosystem. Shelf rockfish assemblages identified in these studies had distributions centered at 150 m depth and included canary (*S. pinniger*), yellowtail (*S. flavidus*), widow (*S. entomelas*), sharpchin (*S. zacentrus*), rosethorn (*S. helvomaculatus*), yelloweye (*S. ruberrimus*), greenstriped (*S. elongatus*) and redstripe (*S. proriger*) rockfishes (Weinberg, 1994; Williams & Ralston, 2002).

The two survey datasets are not often used together due to differences in sampling methods, gear, and vessel type. Only one study has used both versions of the NOAA surveys to identify assemblages. Cope and Haltuch (2012) compared the two surveys in the context of assemblage presence and found that both surveys consistently included three groups. These were (1) a Dover-whiting-rex-slender sole (*Lyopsetta exilis*) core complex that also included arrowtooth flounder, spotted ratfish (*Hydrolagus colliei*), sablefish, spiny dogfish, longnose skate (*Raja rhina*), and sandpaper skate (*Bathyraja kincaidii*); (2) an English sole-Pacific sanddab complex that included petrale sole (*Eopsetta jordani*), lingcod (*Ophiodon elongatus*), spiny dogfish, and spotted ratfish; and (3) a chilipepper (*S. goodei*)-shortbelly (*S. jordani*) rockfish complex that included stripetail (*S. saxicola*), bocaccio (*S. paucispinis*), and greenstriped rockfishes (Cope & Haltuch, 2012). Identification of assemblages can help with bycatch management and is especially useful if the groupings persist temporally.

The continental shelf and slope serve as habitat for many flatfish species throughout varying life stages, including species that occupy the infrequently studied area inshore of 55 m depth that is not covered by the surveys. Many of the flatfishes targeted by the groundfish fishery, both in the past and present day, use the nearshore for spawning or juvenile development. A number use both the slope and shelf habitat, conducting annual migrations from the shelf in the summer months to the deeper, cold slope waters to spawn in the fall and winter. This is the case for both Dover sole and petrale sole, though as Dover sole age they spend less time on the shelf (Pearcy et al., 1977; Hunter et al., 1990; Jacobson & Hunter, 1993; Love, 1996). The nursery grounds for these deep-spawning species vary, with juvenile rex sole typically found near the shelf/slope break while petrale sole and Dover sole recruits can be found on shallower portions of the shelf (Ketchen & Forrester, 1966; Pearcy et al., 1977; Markle et al., 1992). Other flatfishes spend their entire lives on the shelf and juveniles utilize estuaries for development. English sole, starry flounder (*Platichthys stellatus*), rock sole (*Lepidopsetta bilineata*), and speckled sanddab (*Citharichthys stigmaeus*) are all known to spawn on the continental shelf with their offspring recruiting to estuarine habitat (Krygier & Pearcy, 1986; Rackowski & Pikitch, 1989; Love, 1996; Schwartzkopf et al., 2020).

Roundfishes and rockfishes also use the shelf for spawning, breeding, and juvenile development. Juvenile sablefish are found on the shelf, and estuaries are known to be critical habitat for multiple life stages of lingcod and cabezon (Love, 1996; Schirripa & Colbert, 2006). Many species of skates (family *Rajidae*) occupy the soft sediment of the continental shelf and several are thought to spawn year-round in this region (Ebert, 2003; Bizzarro et al., 2014). Although adult commercially important rockfishes are not as abundant on the inner shelf as they are on the outer shelf and slope, many use nearshore habitats like kelp forests or cobble beds as nursery habitat whereas others use estuarine habitats (Schwartzkopf et al., 2020). These rockfishes include species such as widow, yellowtail, bocaccio, and canary rockfishes, which have been consistently targeted off the Oregon Coast, and were declared overfished at the collapse of the fishery (Love, 2011; Schwartzkopf et al., 2020). It is evident that the nearshore is critical for a wide range of groundfish species, many of which are commercially important and use the shelf habitat to complete their life cycles.

2.2 **Data and Methods**

2.2.1 NOAA West Coast Groundfish Bottom Trawl Surveys

Survey data from both the triennial (1977 – 2001) and annual (2003 – 2018) version of NOAA groundfish surveys (Fig. 2.2) were used. For the triennial survey, Alaskan class trawl vessels equipped with a Poly Nor'Eastern trawl were used to sample transects running perpendicular to the coast. Sampling depth, transect spacing, and timing of the survey were variable, but tow time was consistent at 30 minutes. In 1980 the minimum depth was set to 55 m, changed from a minimum of 91 m in 1977. Up until 1995, sampling occurred from July to September or October; after 1995, sampling began in June and ended in August. The NWFSC annual survey began in 2003, combining the slope and shelf surveys operated by the AFSC. It uses four paired West Coast class trawlers equipped with an Aberdeen trawl and stations are selected using a stratified random sampling of cells placed along the U.S. West Coast shelf and slope. The first pass for the survey occurs from May to August and the second pass occurs from August to October with a tow time of 15 minutes. Both the triennial and annual surveys cover the region trawled by the Oregon commercial groundfish fishery, but the sampling density is greater for the annual survey. Several other surveys conducted by the AFSC and NWFSC were not included in these analyses due to sampling primarily on the continental slope or because they were only conducted for a short time. Due to differences in sampling methods for each survey, abundances cannot be compared across surveys; however, assessments of distribution based on presence/absence have proven useful (Thorson et al., 2016).

Data from the NOAA surveys was obtained from the NWFSC/FRAM Data Warehouse (url: https://www.nwfsc.noaa.gov/data/) as a dataset with characteristics from each tow and a dataset with species composition information. Tow ID numbers were used to match tows to the species composition data and all surveys other than the annual and triennial surveys were removed. To include only data on the continental shelf, data collected at 200 m depth,

Table 2.1: Number of hauls containing each species were summed for each survey to determine occurrence. Only species that occurred in over 1% of hauls are listed below. Depth and temperature ranges were calculated using both survey datasets. Bolded species were selected for individual analyses.

		No. of Hauls		% Occurrence			
Common Name	Scientific Name	NWFSC	AFSC	NWFSC	AFSC	Depth (m)	Temp. (°C)
Rex sole	***Glyptocephalus zachirus***	**2327**	**1778**	**97%**	**92%**	**78 - 438**	**5.8 - 8.1**
Dover sole	***Microstomus pacificus***	**2258**	**1687**	**94%**	**87%**	**82 - 711**	**5.7 - 8.1**
Petrale sole	***Eopsetta jordani***	**2219**	**1206**	**92%**	**62%**	**72 - 192**	**6.7 - 8.3**
Spotted ratfish	*Hydrolagus colliei*	1963	853	82%	44%	78 - 307	6.3 - 8.1
English sole	***Parophrys vetulus***	**1902**	**1245**	**79%**	**64%**	**70 - 201**	**6.7 - 8.3**
Arrowtooth flounder	***Atheresthes stomas***	**1883**	**1269**	**78%**	**65%**	**90 - 406**	**5.9 - 8.1**
Longnose skate	*Raja rhina*	1862	518	77%	27%	91 - 459	5.7 - 8.1
Lingcod	***Ophiodon elongatus***	**1596**	**892**	**66%**	**46%**	**77 - 213**	**6.7 - 8.3**
Pacific sanddab	***Citharichthys sordidus***	**1536**	**1149**	**64%**	**59%**	**68 - 137**	**7.0 - 8.5**
Greenstriped rockfish	*Sebastes elongatus*	1296	910	54%	47%	108 - 215	6.6 - 8.1
Sablefish	***Anoplopoma fimbria***	**1236**	**1247**	**51%**	**64%**	**107 - 957**	**5.5 - 8.0**
Big skate	*Beringraja binoculata*	1086	174	45%	9%	68 - 169	6.8 - 8.5
Sandpaper skate	*Bathyraja kincaidii*	1002	193	42%	10%	108 - 447	5.6 - 7.7
Spiny dogfish	*Squalus suckleyi*	985	1087	41%	56%	79 - 311	6.4 - 8.2
Darkblotched rockfish	*Sebastes crameri*	791	787	33%	41%	120 - 357	6.1 - 7.9
Flathead sole	*Hippoglossoides elassodon*	693	493	29%	25%	98 - 183	6.6 - 7.8
Yellowtail rockfish	*Sebastes flavidus*	549	629	23%	32%	98 - 188	6.7 - 7.8
Canary rockfish	*Sebastes pinniger*	548	589	23%	30%	79 - 195	6.7 - 8.2
Stripetail rockfish	*Sebastes saxicola*	504	246	21%	13%	120 - 230	6.6 - 8.3
Pacific cod	*Gadus macrocephalus*	330	269	14%	14%	74 -194	6.7 - 7.8
Rosethorn rockfish	*Sebastes helvomaculatus*	314	199	13%	10%	65 - 107	6.0 - 7.8
Curlfin sole	*Pleuronichthys decurrens*	276	79	11%	4%	62 - 94	7.1 - 8.6
Splitnose rockfish	*Sebastes diploproa*	270	211	11%	11%	160 - 381	5.9 - 7.7
Sharpchin rockfish	*Sebastes zacentrus*	253	219	11%	11%	144 - 299	6.3 - 7.9
Rock sole	*Lepidopsetta bilineata*	247	51	10%	3%	64 - 112	7.0 - 8.1
Shortspine thornyhead	*Sebastolobus alascanus*	212	371	9%	19%	196 - 1020	5.3 - 7.5
Pacific Ocean perch	*Sebastes alutus*	184	182	8%	9%	160 - 402	5.8 - 7.6
Butter sole	*Isopsetta isolepis*	162	27	7%	1%	61 - 83	7.1 - 8.7
Redbanded rockfish	*Sebastes babcocki*	166	122	7%	6%	170 - 372	5.9 - 7.5
Yelloweye rockfish	*Sebastes ruberrimus*	159	109	7%	6%	92 - 199	6.7 - 8.1
Kelp greenling	*Hexagrammos decagrammus*	145	46	6%	2%	69 - 122	7.1 - 8.7
Chilipepper	*Sebastes goodei*	152	30	6%	2%	120 - 235	6.7 - 8.8
Blackspotted/Rougheye	*Sebastes aleutian. / melanost.*	141	190	6%	10%	139 - 425	5.6 - 7.5
Sand sole	*Psettichthys melanostictus*	113	64	5%	3%	60 - 79	7.3 - 8.6
Greenspotted rockfish	*Sebastes chlorostictus*	121	28	5%	1%	99 - 175	7.0 - 8.2
Widow rockfish	*Sebastes entomelas*	131	160	5%	8%	131 - 312	6.2 - 7.9
Shortbelly rockfish	*Sebastes jordani*	109	124	5%	6%	115 - 234	6.7 - 8.4
Redstripe rockfish	*Sebastes proriger*	126	156	5%	8%	100 - 221	6.6 - 8.0
California skate	*Raja inornata*	73	2	3%	-	67 - 103	7.4 - 9.2
Starry skate	*Raja stellulata*	84	6	3%	30%	70 - 157	6.9 - 8.6
Pygmy rockfish	*Sebastes wilsoni*	83	89	3%	5%	97 - 180	6.8 - 8.1
Starry flounder	*Platichthys stellatus*	44	18	2%	-	62 - 78	7.2 - 8.6
Silvergray rockfish	*Sebastes brevispinis*	45	83	2%	4%	95 - 255	6.3 - 7.7
Quillback rockfish	*Sebastes maliger*	45	18	2%	-	65 - 107	7.1 - 8.1
Bocaccio	*Sebastes paucispinis*	53	137	2%	7%	103 - 229	6.8 - 8.5
Black rockfish	*Sebastes melanops*	6	27	-	1%	60 - 79	7.1 - 8.6

approximately the shelf/slope break, or shallower was retained. Logbook data that tracks activity of Oregon commercial groundfish fishermen was used to set latitude bounds of 41°N and 48°N in order to include only waters they consistently fish. Pacific whiting and species not managed by the Pacific Fishery Management Council (PFMC) as part of the Groundfish Fishery Management Plan, along with invertebrates, were removed. Of those species remaining, only those present in over 1% of all tows were kept. This was done for each survey individually, resulting in 47 and 44 species retained for the annual and triennial surveys, respectively (Table 2.1).

2.2.2 Environmental Data

Covariates tested include bottom temperature, depth, day of year, the Pacific Decadal Oscillation (PDO) monthly index, and the North Pacific Gyre Oscillation (NPGO) monthly index. Bottom temperature and depth were recorded during both the annual and triennial surveys. For the triennial survey, depth and temperature were measured by a bathythermograph attached to the headrope. For the annual survey, net performance and position were recorded by Simrad Integrated Trawl Instrumentation and P144 Catch Monitoring Systems while temperature was measured by a SeaBird SBE 39 recorder on the wing. Depth was measured by a depth sensor on the headrope, with a final value recorded as sum of trawl headrope depth and distance from seafloor. Day of the year was used to assess seasonal shifts. PDO monthly values were retrieved from the University of Washington Cooperative Institute for Climate, Ocean, and Ecosystem Studies (url: http://research.jisao.washington.edu/pdo/PDO.latest) and matched to the trawl characteristic dataset using month and year. A similar method was used for the NPGO, with monthly values retrieved from the North Pacific Gyre Oscillation webpage (url: http://www.o3d.org/npgo/).

2.2.3 Data Analysis

To assess both assemblages and individual species, both multivariate and univariate statistical methodologies were used. All analyses were performed using the R programming language (R Core Team, 2019). Eight species were selected for individual analyses: sablefish, Pacific sanddab, petrale sole, Dover sole, English sole, arrowtooth flounder, rex sole, and lingcod. These eight were selected because they were consistently caught throughout the entire survey time series, have either current or historic commercial importance, and live predominantly in nearshore water during the months surveyed. Petrale sole and lingcod were the only species selected that were classified as overfished by the PFMC, which occurred in 1999 and 2009 respectively, and the stocks were considered rebuilt in 2005 for lingcod and 2014 for petrale sole (Haltuch et al., 2018; Wetzel, 2019). Flatfishes were the primary species selected due to their prevalence in the nearshore and because they make up the majority of catches in the nearshore groundfish fishery (Sjostrom, 2019).

Non-metric multidimensional scaling (NMS) was chosen to look at assemblage structure and environmental drivers of community composition in the nearshore environment. Initial exploratory analyses were conducted to determine any appropriate data adjustments, which resulted in a log(x+1) transformation. NMS was chosen due to its utility with data that does not exhibit linear relationships between variables and is zero-inflated, both of which are characteristic of the survey data (McCune & Grace, 2002; Keller et al., 2017b). To perform NMS, a Bray-Curtis (Sørensen) dissimilarity matrix was created using species matrices for each survey where trawls were rows and species were columns. Stress, the difference in distance between the reduced ordination space and the original dissimilarity matrix, was minimized for the species matrices to the lowest possible value until a final, low-stress matrix was achieved. The final ordination plots show similar points clustered together while points or clusters that are different are further away from other points and clusters. Bray-Curtis distances were chosen because of their relative insensitivity to outliers and ability to deal with large variation in species abundance (Clarke, 1993; McCune & Grace, 2002). Each axis of the ordination is orthogonal and explains patterns in the resulting plot of sample units. Ties were not penalized in this analysis, as they were infrequent (< 1%).

Initial exploratory NMS ordinations for both surveys used groundfish species with a frequency of occurrence over 1% and an environmental matrix of the climate and oceanographic variables. Both species richness and the Shannon-Wiener diversity index were calculated once the final ordination for each survey was plotted to assess any gradients regarding those two metrics. Richness was calculated as the number of species in a given tow and the Shannon-Wiener index as $H' = -\sum_i^S p_i \ln(p_i)$ (Hill, 1973). Analyses were performed using the vegan package in R (Oksanen et al., 2019). To assess any potential a-priori groupings in the NMS ordinations, two categories were created for both the PDO and NPGO to denote negative and positive phases. Years were also categorized for each sample, with 25 years total. To test whether there was a relationship between the groups and climate variables or year, a multiple response permutation procedure (MRPP) was used. This is a nonparametric procedure that calculates the chance-corrected within-group agreement and a corresponding p-value (McCune & Grace, 2002).

Generalized additive models (GAM) were used to assess spatiotemporal relationships between individual species and the marine environment. GAMs are regression models that incorporate smooth terms and can capture nonlinear relationships. Non-stationary GAMs, known as threshold GAMs (TGAM), exhibit two or more eras during which the functional relationships between species' population and smoothed terms can change (Ciannelli et al., 2004). Both stationary GAM and TGAM formulations incorporating regional oceanographic and climate covariates were tested for each species. TGAMs were used to assess spatial shifts before and after a threshold year in order to determine if there was movement of species and if this movement occurred at a certain point in time. TGAMs created for each species contained data for the duration of the survey, including both the triennial survey and the annual survey data from 1977 to 2018, and focused on presence/absence. The stationary model formulation used for comparison with the TGAM is as follows:

(Eq. 1) $$l(\mu)_{y,lat,lon} = \alpha_y + s_1(J_{y,lat,lon}) + s_2(lat_y, lon_y)$$

where l is a link function (*logit* for presence/absence data), and μ indicates the probability of presence for each species at station. Latitude and longitude (lat, lon), year (y), and day of the year (J) are smooth functions (s) for each covariate. Presence/absence data follow the Bernoulli distribution, with mean equal to μ and variance equal to μ(1- μ). This stationary formulation was then compared to the TGAM:

(Eq. 2) $$l(\mu)_{y,lat,lon} = \alpha_y + s_1(J_{y,lat,lon}) + \begin{cases} s_2(lat_y, lon_y), \text{if } y < t \\ s_3(lat_y, lon_y), \text{if } y \geq t \end{cases}$$

The TGAM formulations use a threshold year (t) to separate different periods of time. The TGAM tests all possible threshold years between the upper and lower quantiles of data in the combined survey dataset (1986 to 2015) for all species by minimizing Akaike's Information Criteria (AIC). The regions with significant change in spatial distribution were identified by computing the difference in predicted probability of presence plus or minus the 90% confidence intervals before and after the threshold year. Significant changes in the predicted probability of presence were those that did not include the zero value. For the two species with high frequency of occurrence throughout both surveys (see Table 2.1, Dover sole and rex sole), the year factor was removed because models fit with year resulted in predictions that greatly deviated from the observations, likely due to model overfitting when the majority of the observations were presence. The ΔAIC between the stationary GAM formulation and TGAM was calculated and TGAM was selected for a given species if ΔAIC was positive. To validate the TGAM results, the predicted probability of presence before the threshold was subtracted from the predicted probability of presence after the threshold for each species and the resulting confidence interval was calculated to determine areas of significant increase or decrease in predicted probability of presence. Then, for corresponding areas, observed change in presence for each species was calculated and compared to the model predicted change.

Stationary GAMs using CPUE or presence/absence as the response variable were fitted for each of the eight species to determine relationships between individual species and environmental or climatic variability (Table A.1). For the presence/absence models, the same formulation in Equation 1 was used and a comparison was made between the model with day of the year and without. CPUE models using bottom temperature as recorded by the surveys were formulated as follows:

(Eq. 3) $$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$$

The same explanatory variables used in the TGAM formulations were used here with the addition of year (y), depth (D), and bottom temperature (T) as smooth terms. For the climate indices (PDO and NPGO) the GAM formulation was as follows, with year replaced by the climate index (C):

(Eq. 4) $$CPUE_{y,lat,lon} = s_1(C) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$$

The full models containing each environmental or climate covariate was compared to a null model with the covariate removed. The model with the lowest AIC was selected as the best model. To validate the TGAM results, the predicted probability of presence before the threshold was subtracted from the predicted probability of presence after the threshold for each species and the resulting confidence interval was calculated to determine areas of significant increase or decrease in predicted probability of presence. Then for corresponding areas, observed change in presence for each species was calculated and compared to the model predicted change.

2.3 **Results**

Frequency of occurrence for each species was variable between the triennial and annual surveys. In general, occurrence was lower for flatfish during the triennial survey and many rockfishes were caught less frequently during the annual survey. All skates except the starry skate were caught more often by the annual survey than the triennial survey and there was a larger change in frequency of occurrence between surveys for skates than the other groups. Occurrence for roundfish and other miscellaneous species was variable.

The final annual and triennial survey ordinations were two-dimensional with a stress of 0.17 and 0.18, respectively (Fig. 2.3). A two-dimensional ordination was chosen due to a reduction in stress at two dimensions. Depth was the only environmental gradient strongly related to either ordination. Other gradients assessed were latitude, day of the year, the climate indices, year, and temperature and an $r^2 < 0.2$ was used as a cutoff when determining gradient strength (McCune & Grace, 2002). In both final ordinations, a depth gradient was primarily represented by axis 1 and while not explicitly quantified for this analysis, axis 2 seemed linked to habitat types. Flatfishes were grouped together on axis 2 for both ordination plots, indicating their association with the inshore sedimentary habitat, while the rockfishes were dispersed along the entire axis illustrating a diversity in habitat preference. In the annual survey ordination, species diversity and richness increased along axis 1. For the triennial survey, species diversity and richness increased along axis 1 and decreased along axis 2. MRPP results for year, PDO, and NPGO indicated no likely relationship between any of those variables and species abundance for either survey, though year had slightly stronger relationship to abundance than did than either climate index (Table 2.2). When the two final survey ordinations were compared, it was evident that there was little change in assemblage structure in shallow and sandy habitat whereas in areas

Table 2.2: MRPP test results for the annual and triennial surveys. Categorical variables tested were year, PDO, and NPGO, all of which showed no relationship in visual assessment using the ordination plot. The A value indicates the amount of variance in each group, with A = 0 representing within-group randomization expected by chance and A = 1 representing within-group homogeneity. For community ecology an A > 0.3, for example, would mean there is substantially less randomization than expected by chance. The table shows there is little difference between positive and negative phase groupings for PDO and NPGO or between years.

	Annual Survey		Triennial Survey	
Variable	A value	p-value	A value	p-value
year	0.017	0.001	0.055	0.001
PDO	0.0023	0.001	0.017	0.001
NPGO	0.0029	0.001	0.010	0.001

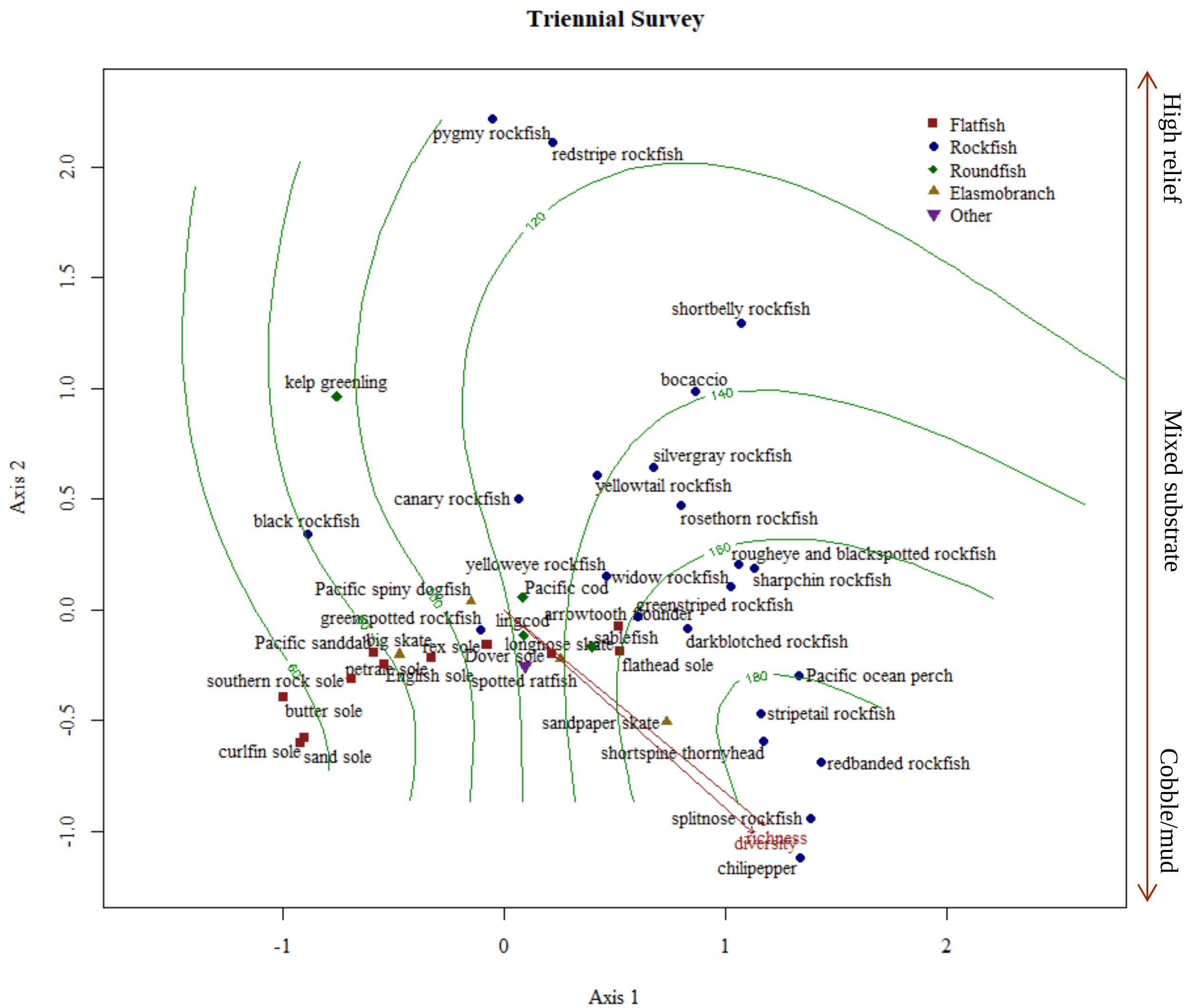


Figure 2.3: Final NMS ordination for both surveys. Green lines represent the depth gradient, and each species symbol indicates their PFMC management/taxonomic group. The habitat gradient is depicted on the right y axis and the diversity and richness gradients are represented by red arrows along which the variable increases.

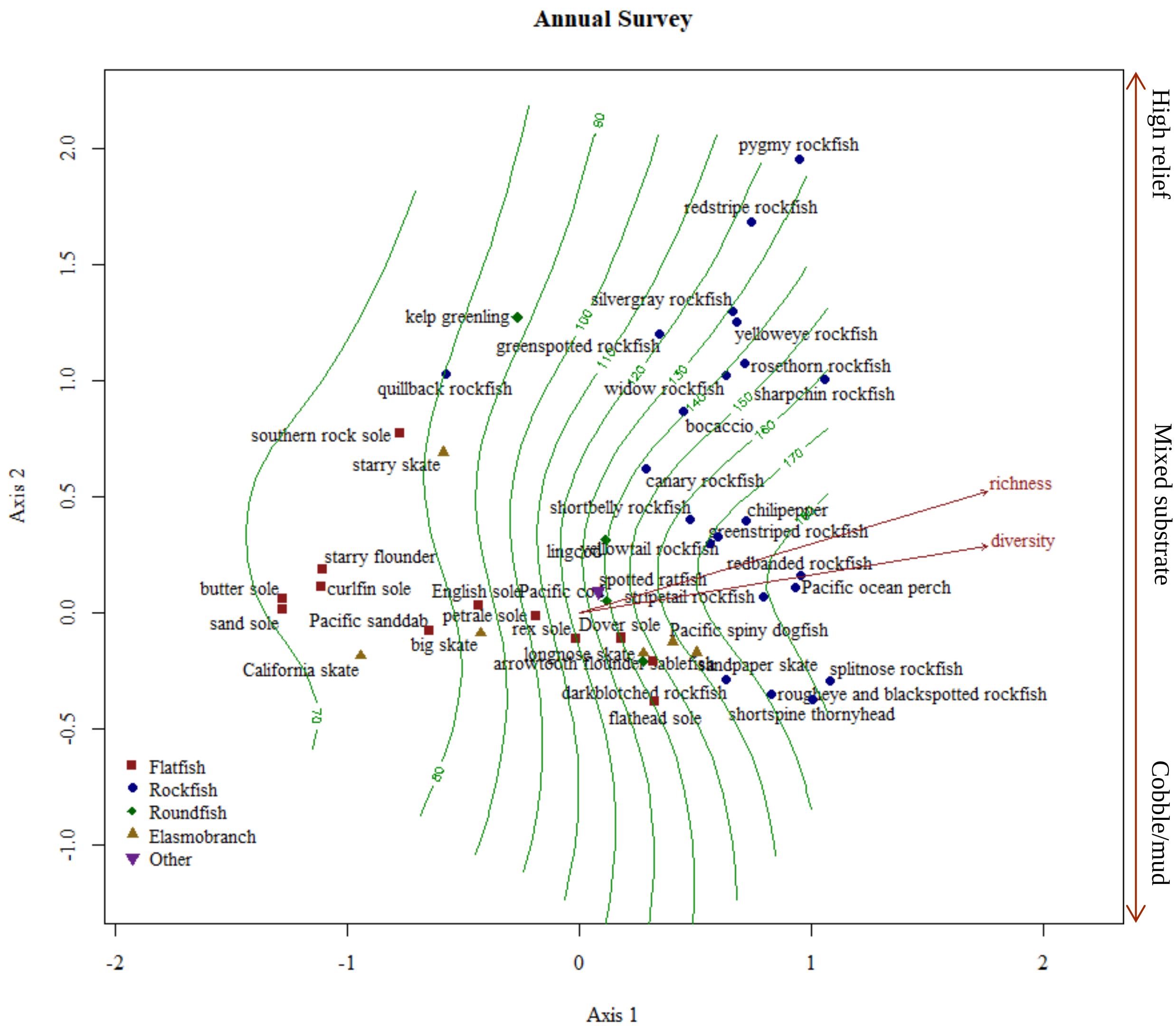


Figure 2.3 continued.

Table 2.3: TGAM results for eight groundfish species. Deviance explains the goodness of fit of the model. ΔAIC indicates the difference in AIC between the reference model and the model containing the threshold.

Species	Threshold Year	Deviance	ΔAIC
Petrale Sole	2011	28.5%	53.9
Lingcod	2009	11.3%	46.4
Arrowtooth Flounder	2007	36.5%	27.0
Sablefish	2003	24.5%	11.3
English Sole	1995	35.0%	64.0
Dover Sole	1995	23.1%	154.8
Pacific Sanddab	1989	57.4%	73.0
Rex Sole	1989	19.9%	49.9

of the shelf deeper than 120 m, composition differed between the two (Fig. 2.3).

The distribution of some groundfish populations has significantly changed during the time frame considered, but the year of change (threshold) depends on the species. The earliest distributional changes were in 1995 for Dover sole and English sole and 1989 for Pacific sanddab and rex sole. All other species had shifts that occurred during the annual survey (year ≥ 2003, Table 2.3). Petrale sole had the most recent change in 2011. For sablefish and petrale sole there were multiple years with locally minimum AIC values and when inspected, these secondary threshold years resulted in similar changes in distribution as those observed in the primary threshold year. For sablefish, although 2015 had the lowest AIC value, 2003 was chosen instead because it was not at the boundary of the upper quantile of data in the combined survey dataset used for the TGAM analyses and distribution maps from both 2003 and 2015 indicated the same distributional pattern for sablefish. The petrale sole model had low AIC values in both 1998 and 2011, but the primary threshold year was retained (2011). The four species with early threshold years (Dover sole, rex sole, English sole, and Pacific sanddab) had steady increases in AIC values following their respective threshold years (Fig. 2.4).

All species except Dover sole had a predicted reduction in the predicted probability of presence after the threshold year on the continental shelf near Heceta and Stonewall Banks (Fig. 2.5). A reduction inshore was statistically significant for lingcod and Petrale sole while offshore reduction was significant for arrowtooth flounder, English sole, and Pacific sanddab (Table A.3). There was an observed decrease in presence inshore in the original data for rex sole and sablefish in the same region as lingcod and petrale sole, but these decreases were not statistically significant. Petrale sole distributional patterns were the most strikingly different before and after the threshold, with more predicted areas of catch located in shallow waters before 2011. After 2011 there are noticeable predicted decreases in the northern and central inshore areas of the shelf. Arrowtooth flounder, Dover sole, and lingcod had predicted reductions in presence off the coast of Washington while there were increases predicted for sablefish, English sole, rex sole, and Dover sole off southern Oregon/northern California. This southern increase was exclusively seen in species with early threshold years. Dover sole and rex sole both had general increases in predicted probability of presence, but this was only significant throughout the study region for Dover sole. It was additionally evident that the two inshore species, English sole and Pacific sanddab, have more compressed distributions following their respective threshold years. After

1995 it appeared that catches of English sole were compressed shoreward except in areas south of Charleston, OR. The Pacific sanddab population was predicted to be concentrated inshore of the 100-meter isobath.

Individual species distribution models for the eight species (Eq. 3) resulted in the inclusion of year for the final model for all species. In the annual survey final models, the temperature covariate was kept for the Pacific sanddab, lingcod, sablefish, arrowtooth flounder, rex sole, and Dover sole (Table 2.4). For three of these species – lingcod, rex sole, and sablefish – the relationship between abundance and temperature was very weak, but I still retained

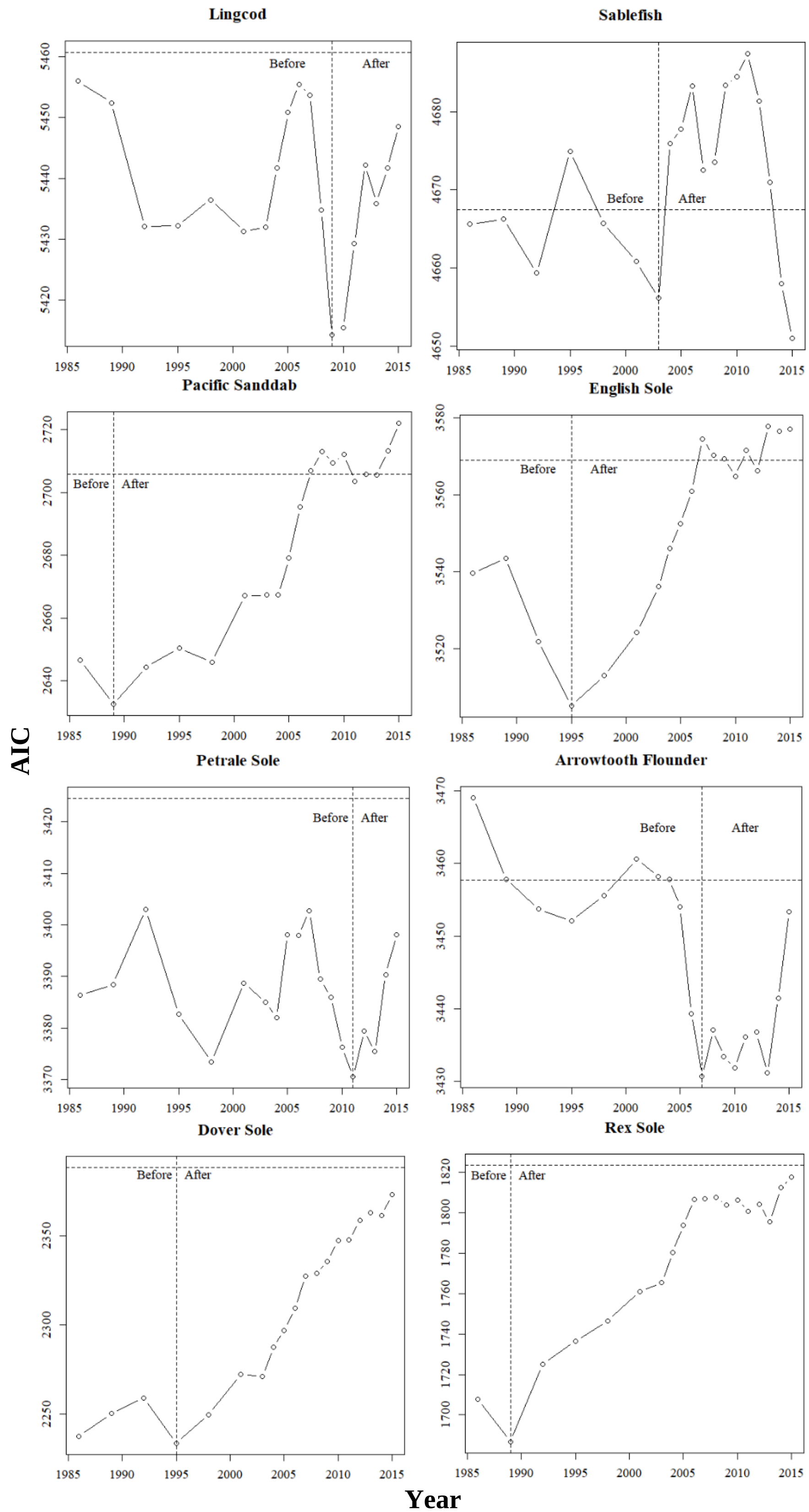


Figure 2.4: AIC plots for TGAM for eight species. The vertical dashed line depicts the selected threshold.

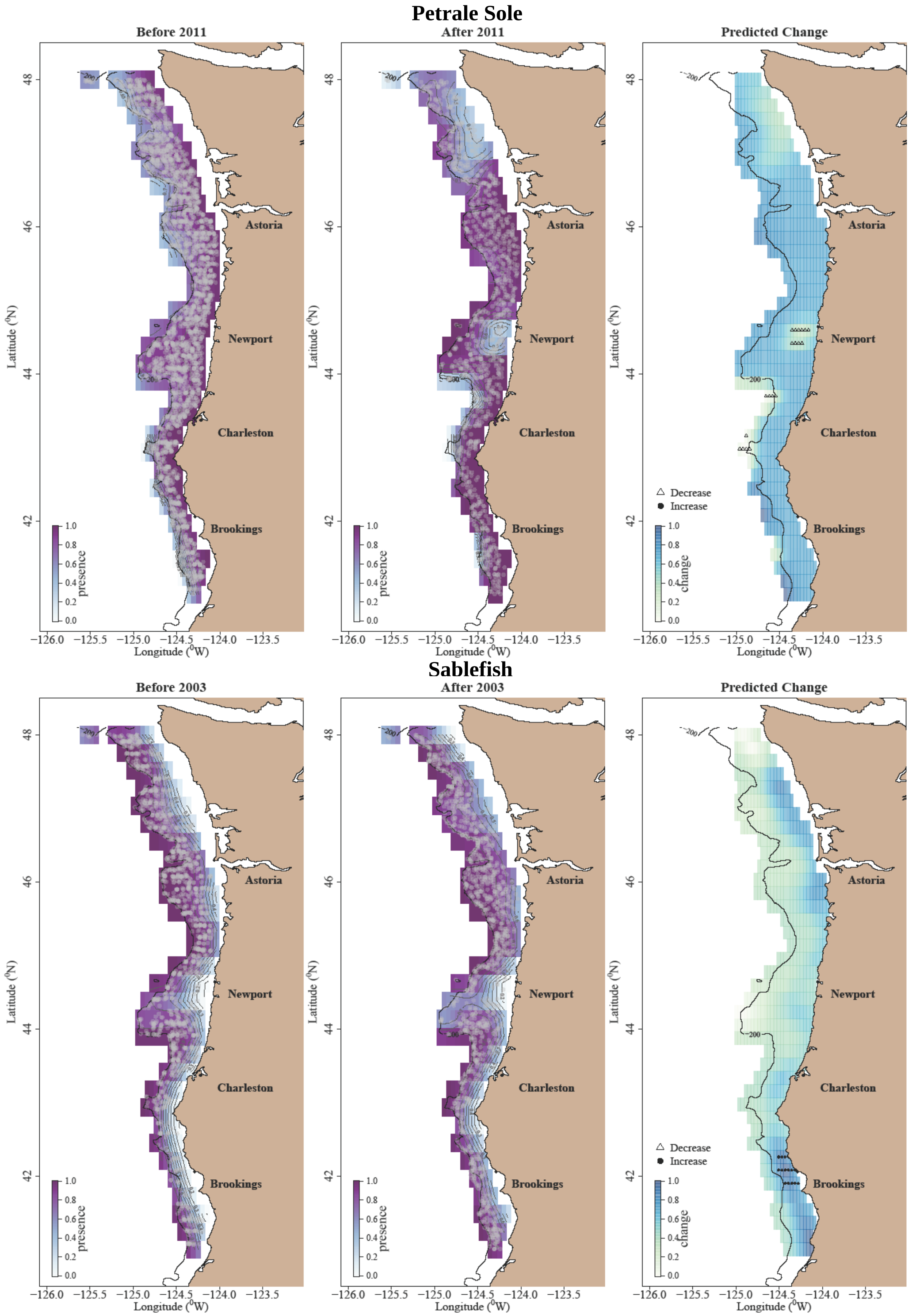


Figure 2.5: Model output for TGAMs. The left and middle panels display model predicted probability of presence prior to and after the selected threshold year overlaid with survey tow locations (gray circles). The right panel depicts differences in probability of presence before and after the threshold year and is overlaid with areas of statistically significant decrease (open triangle) or increase (filled circle) in probability of presence following the threshold year.

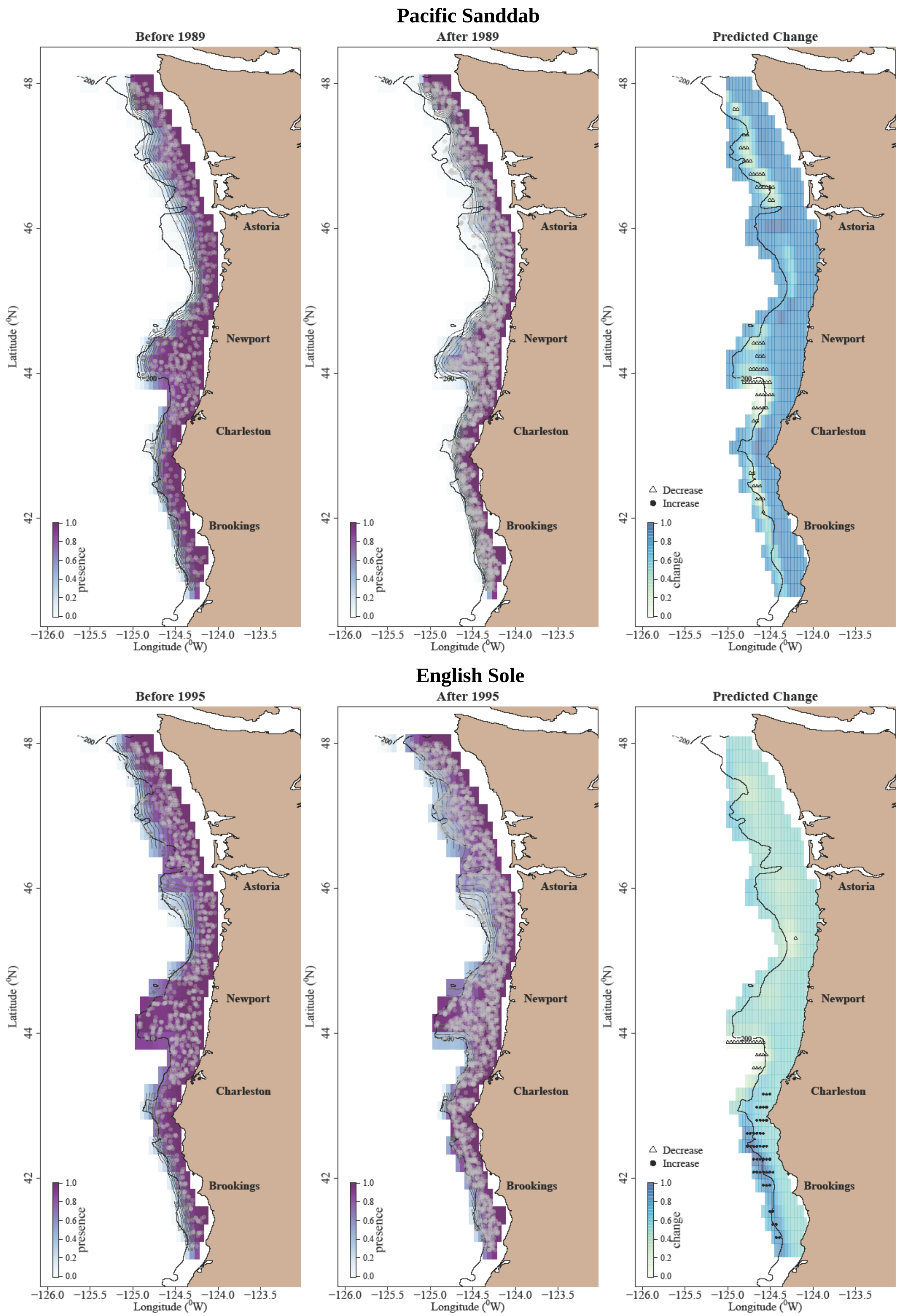
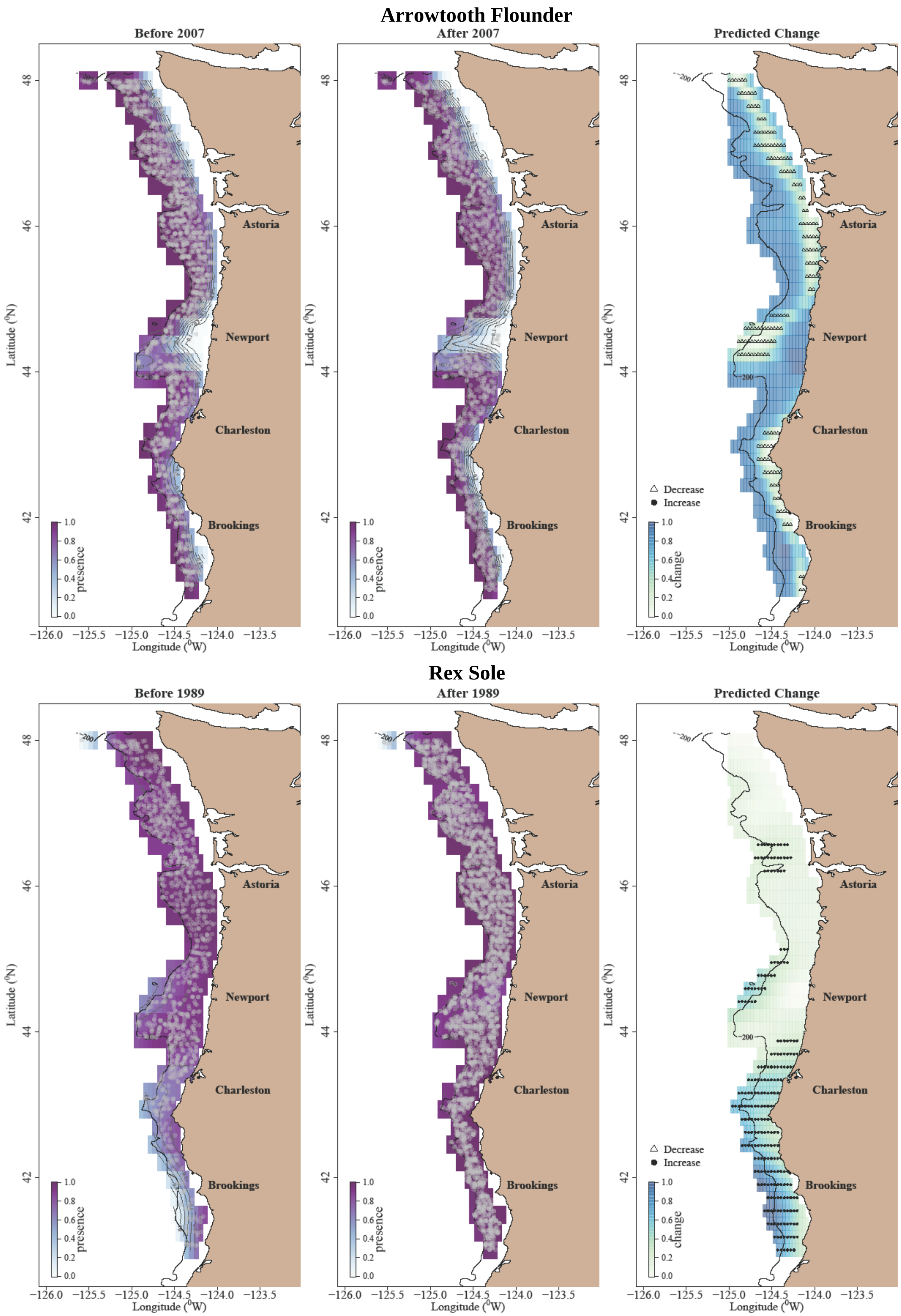


Figure 2.5 continued.



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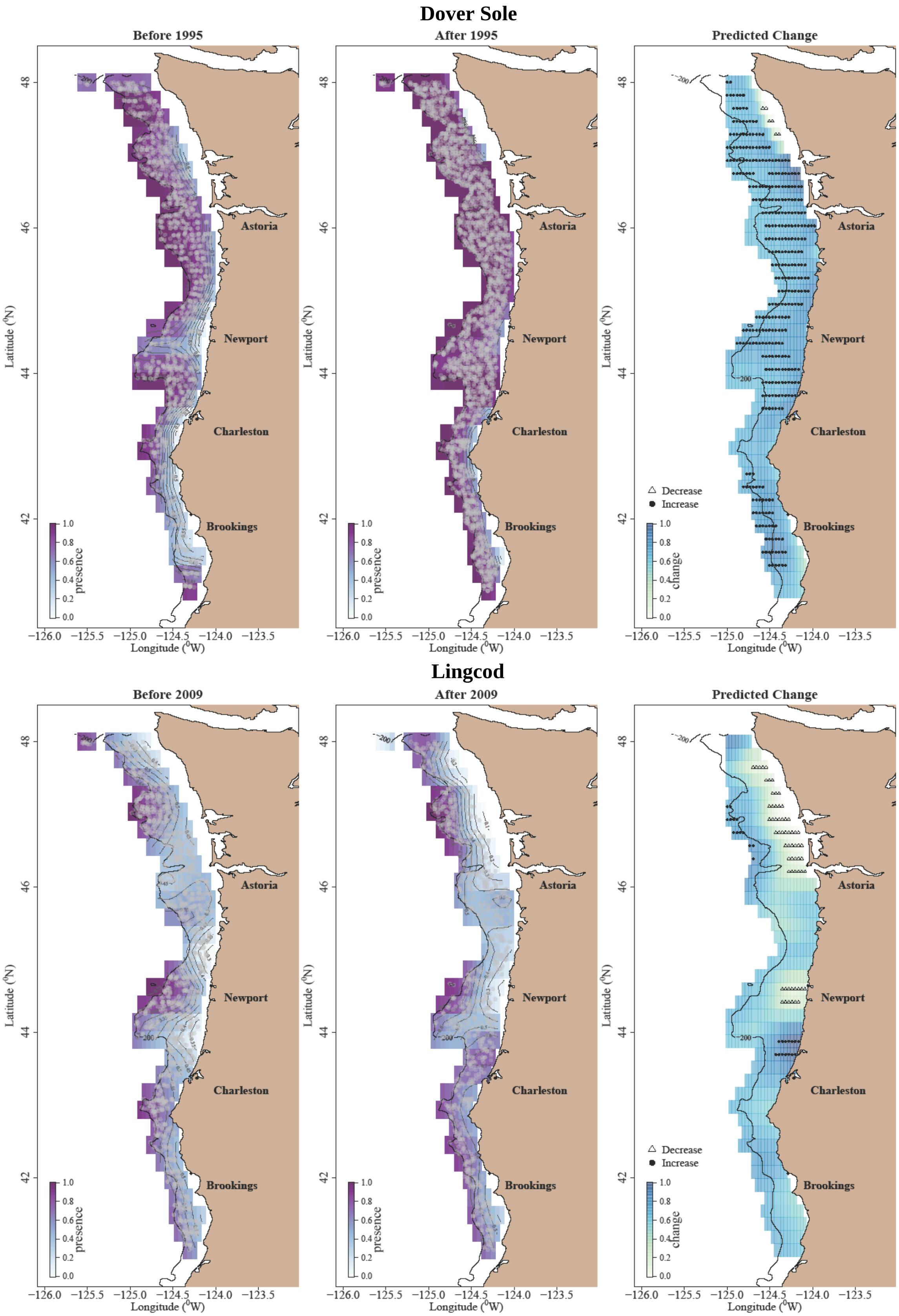

Figure 2.5 continued.

Table 2.4: GAM formulations for individual species using the annual survey data. Deviance explains the goodness of fit of the model. ΔAIC indicates the difference in AIC between the reference model and the model containing the threshold.

Species	Best Model for Annual Survey	ΔAIC	GCV	Deviance	Adj. R^2
Pacific Sanddab	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	6.91	1.69	46.4%	0.45
English Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1.48	1.45	31.2%	0.30
Lingcod	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	0.51	0.64	15.0%	0.13
Petrale Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1.96	0.84	22.9%	0.22
Arrowtooth Flounder	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	7.38	0.80	43.6%	0.42
Dover Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	4.57	0.90	55.1%	0.54
Rex Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	3.25	1.04	34.3%	0.33
Sablefish	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	0.58	0.82	15.4%	0.13

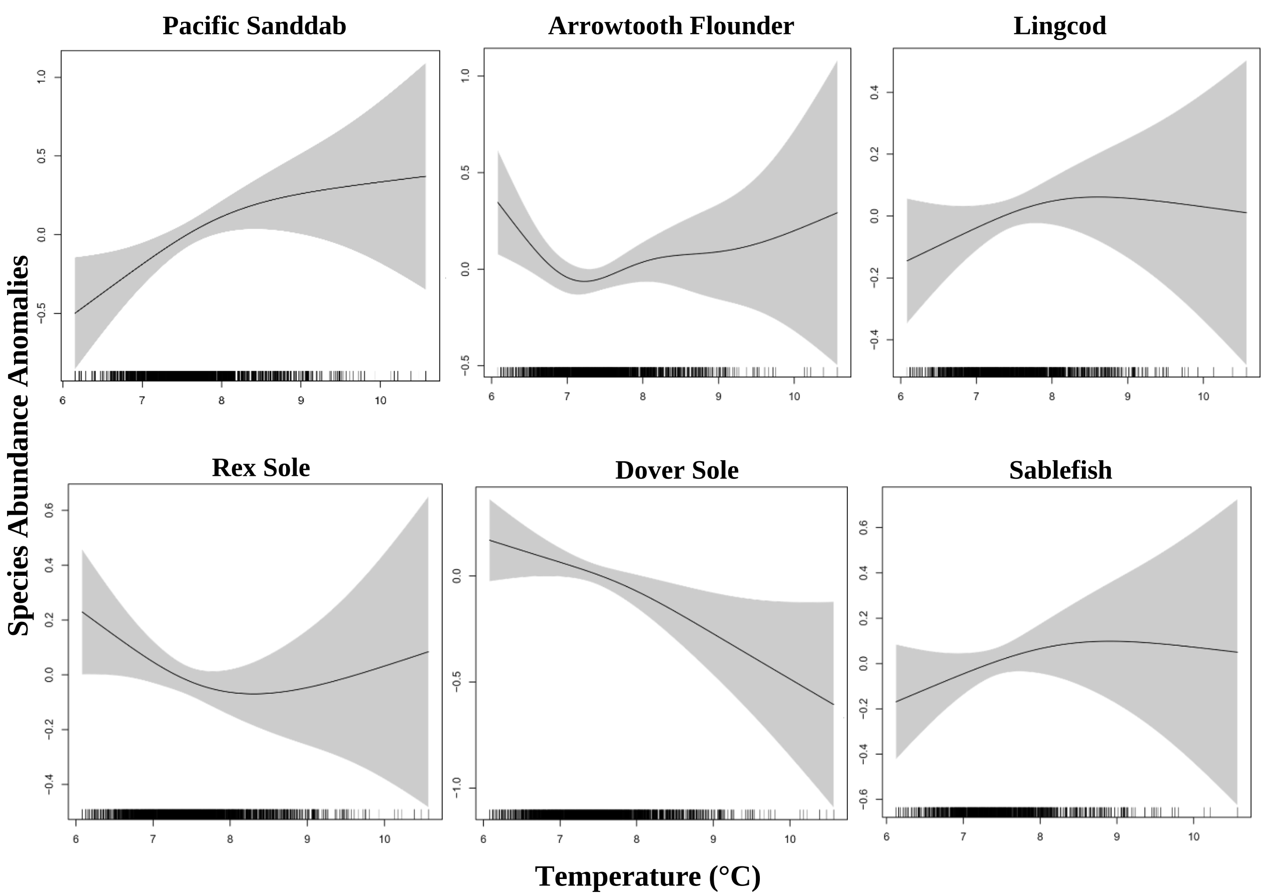

Figure 2.6: Effect of temperature on six species for which temperature was included as a covariate in each selected stationary GAM formulation for the annual survey.

temperature in the model because its removal caused an increase of the AIC. None of the climate indices were selected for any species or survey. Depth was a significant covariate for all models. For the annual survey GAMs that included temperature, Pacific sanddab, lingcod, and sablefish all showed some level of increase in abundance up to 9°C, and the opposite was true for rex sole (Fig. 2.6). Dover sole exhibited an almost linear decrease in abundance with increasing temperature, while arrowtooth flounder had a dip in abundance at about 7°C. For the triennial survey, temperature was kept in models for five species: Pacific sanddab, sablefish, arrowtooth flounder, English sole, and rex sole. English sole exhibited an increase in abundance up to about 8°C (Fig. A.1). Two species were best represented by models

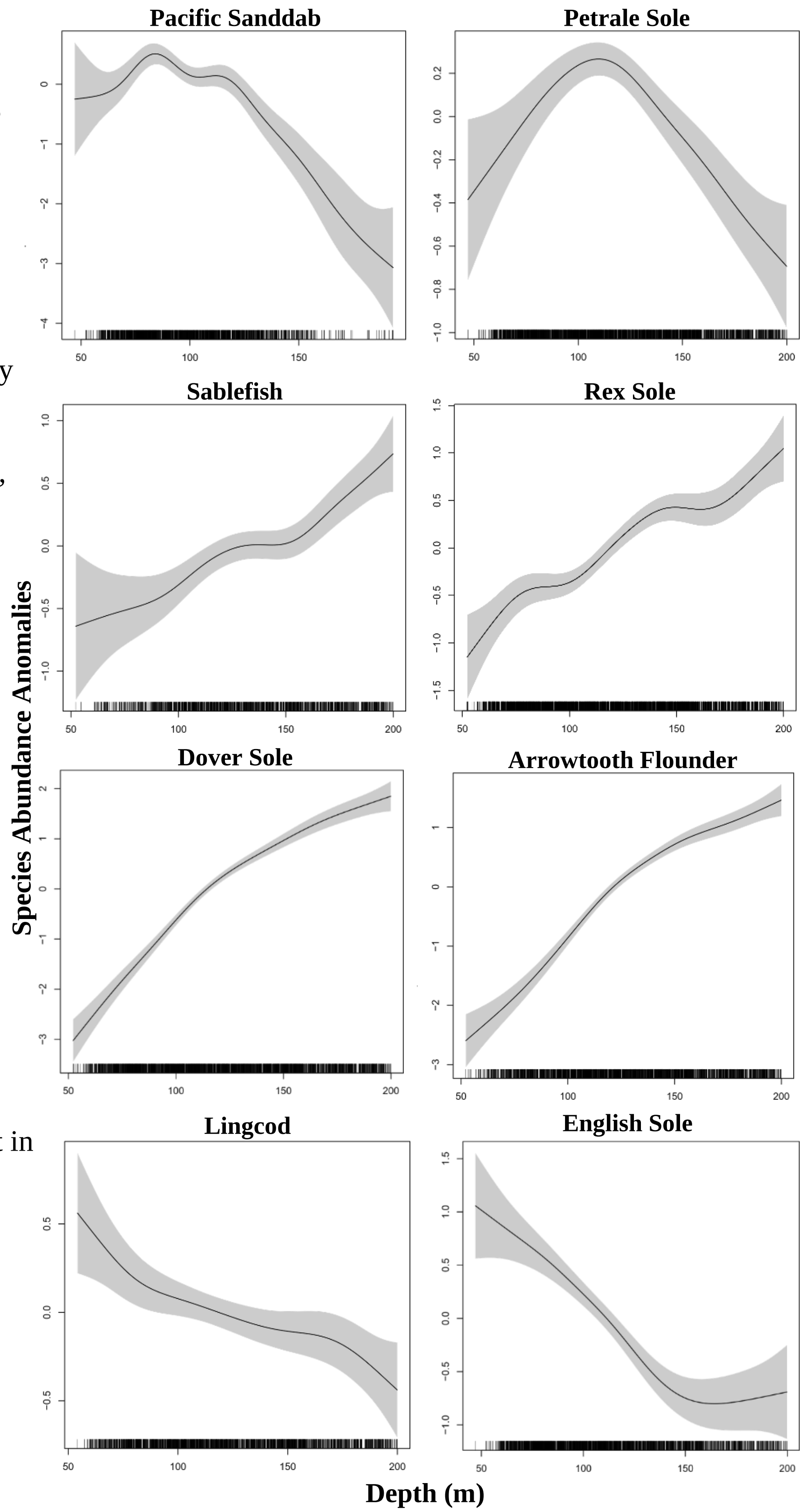

Figure 2.7: Effect of depth on eight species for each selected stationary GAM formulation for the annual survey.

that included temperature but had weak relationships with temperature (Table A.2). These species were Pacific sanddab, which had slight peak in abundance at about 8°C, and rex sole, which exhibited an increase in abundance with increasing temperature. The arrowtooth flounder triennial survey model showed a similar relationship to the annual survey model results, with a dip in abundance at 8°C and a sharp increase up to 7°C. For the annual survey there was a clear trend of increasing abundance with increasing depth for arrowtooth flounder, rex sole, Dover sole, and sablefish (Fig. 2.7). Both English sole and lingcod showed trends of increasing in abundance with decreasing depth. Petrale sole had a peak in abundance at about 100 m depth while Pacific sanddab had steadily high abundance up to about 120 m depth at which point abundance quickly decreased. These patterns in depth were similar for the triennial survey though there was a sharp peak in abundance for rex sole at about 180 m depth and petrale sole abundance steadily declined with increasing depth (Fig. A.2). In general, all species had strong relationships with depth, and inner to mid-shelf species had either a weak relationship with temperature or their abundance increased with increasing temperature, whereas deeper water species' abundances increased with decreasing temperature.

2.4 **Discussion**

This study aimed to characterize nearshore groundfishes and their relationships to the marine environment over the last four decades. There were differences between the annual and triennial survey data regarding frequency of occurrence of certain species. However, some of those differences may be due to differences in the survey design rather than actual changes in species occurrence. The change in frequency of skate occurrence between the triennial and annual surveys indicates higher catchability for skates with the current annual survey sampling configuration. Starry skate is the only skate species represented here that has an affinity for rocky habitat, so the species' unique habitat preference, and therefore lower frequency of occurrence in the annual survey, may be a result of the change to a smaller footrope that cannot handle as rough of habitat (James et al., 2014; Bizzarro et al., 2014; Keller et al., 2017b). While the triennial survey footrope was better able to trawl over low relief rocky habitat, the tows were longer (30 minutes) than the annual survey (15 minutes), leading to a greater possibility of net hang-ups on high relief habitat. Therefore, the annual survey could access areas close to high relief areas of the seafloor which may lead to increased catch of species that live near this type of habitat.

Changes over time of sample design may have led to the apparent TGAM threshold years in 1989 (rex sole and Pacific sanddab) and 1995 (Dover sole and English sole). The early years of the triennial survey were characterized by variability in transect distance and selection of depth bins, but the sampling design was standardized in 1995 (Keller et al., 2017b). The same explanation is possible for the sablefish model, with a threshold year of 2003 coinciding with the year the annual survey began.

The NMS and MRPP results indicated that depth has consistently been the primary influence on shelf groundfish assemblages, and the GAM output further illustrates individual species' strong correlation with this covariate (Fig. 2.7, A.2). This is in congruence with recent work that found juvenile groundfish communities to be primarily depth structured, as well as with past multivariate analysis of survey data came (Williams & Ralston, 2002; Sobocinski et al., 2018; Haven, 2019). In addition to depth, there is also likely a relationship between assemblage species composition and habitat. Much of the shelf habitat is sand, silty mud, or a mixture of the two sediment types but there are several rocky banks offshore (Kulm et al., 1975; Romsos et al., 2007). Thus, the nearshore flatfishes are best defined by two groups with differing depth and sediment preference while most rockfishes are found on or near rocky habitat.

Shallow-water flatfishes include sand sole, butter sole (*Isopsetta isolepis*), Pacific sanddab, curlfin sole (*Pleuronichthys decurrens*), starry flounder, southern rock sole, and English sole. They co-occur with some skate species that inhabit the sandy habitat that characterizes the inner shelf. The mid-shelf flatfishes were not tightly clustered in the triennial ordination, but the results indicated that Dover sole, arrowtooth flounder, and flathead sole consistently co-occur on the mud and mud/sand habitat on the mid to outer shelf. Petrale sole and rex sole are also found in the mid-shelf region. Therefore, the shallow-water flatfish assemblage appears to associate with sandy habitat and shows little distributional change over time, while the mid-shelf flatfish assemblage likely occurs on silty or muddy habitat and has experienced a more visible shift in distribution. Other species associated with sedimentary habitat were also primarily grouped with the flatfishes along axis 2, which demonstrates the high proportion of sand and mud habitat present in the nearshore. Inshore species notably excluded from this cluster were the kelp greenling (*Hexagrammos decagrammus*), an inner-shelf reef species, and the starry skate, both species that prefer hard substrate (James et al., 2014; Berger et al., 2015). Southern rock sole off the West Coast is known to inhabit substrate with grain size ranging from sand to large rocks (Alverson et al., 1964), and with the survey sampling design change it is possible that more were captured near rockier habitat after 2003, which potentially explains the southern rock sole position in the annual survey ordination.

The rockfish species spread along axis 2 indicates slight differences in habitat preference, ranging from cobble mixed with mud to high relief rocky reefs. Many of the rockfishes were also associated with tows with high diversity and richness, likely due to an intermingling of shelf and slope species at these deeper, rocky sample sites. From these analyses, it is evident that depth and habitat on the continental shelf are related to species abundance and co-occurrence. Neither depth nor bottom type change rapidly over time, therefore keeping overall community composition the same. The consistency in assemblage structure over time has been noted in prior studies and some clusters of shelf species previously identified were visible in the ordination plots (Weinberg, 1994; Williams & Ralston, 2002; Cope & Haltuch, 2012; Jay, 1996). However, because this research focuses only on the shelf, there is more detail about which flatfishes are grouped together and the importance of habitat for rockfishes is evident.

On an individual species level, the predicted reduction in presence for all species except Dover sole in the wide portion of the shelf between 44 and 45°N is striking, particularly because this occurs to some degree for seven species despite a wide range of threshold years. Reductions were present near Stonewall Bank for lingcod, arrowtooth flounder, sablefish, rex sole, and petrale sole and south of Heceta Bank for English sole and Pacific sanddab. A possible explanation is anomalous summer hypoxia, a seasonal phenomenon first detected in 2002 (Grantham et al., 2004; Chan et al., 2008). These anomalous hypoxic events occur in areas on the shelf that do not regularly experience low DO, unlike portions of the continental slope that are regularly hypoxic. The prevalence of these events is driven by the upwelling of deep, low-oxygen water combined with an increase in respiration following phytoplankton blooms (Huyer et al., 1979; Rabalais et al., 2010; Adams et al., 2013). DO levels have not been consistently measured throughout the shelf region but the data that does exist and recent analyses indicate that portions of the shelf between 44 and 45°N have experienced low DO conditions since the early 2000s (Peterson et al., 2013; Keller et al., 2017b; Harvey et al., 2019). The midshelf habitat near Heceta and Stonewall Banks now regularly experiences low DO during the summer months due to weak currents and inshore accumulation of phytoplankton (Barth et al., 2005; Adams et al., 2013). With the continuation of hypoxic events in the summer months off the coast of Oregon over the last two decades, it appears that portions of this habitat have become less suitable for these species. In recent years, the most extreme hypoxia has been present around Stonewall Bank where there have been predicted or observed reductions in petrale sole, lingcod, sablefish, and rex sole. Three of those species (petrale sole, lingcod, and rex sole) have previously been found to have negative relationships with DO or declines in body condition (Keller et al., 2010, 2015, 2017a; Leeuwis et al., 2019; Harvey et al., 2019). Arrowtooth flounder abundance has also been found to decline with decreasing DO and also exhibited decreases in predicted and observed presence for this region (Keller et al., 2017a).

Those species responses to low DO contrast with Dover sole, English sole, and Pacific sanddab, all of which have been previously found to persist even under low DO conditions (Keller et al., 2010). Pacific sanddab are known to modify their behavior to avoid hypoxic areas and English sole alter their ventilation volume and rate when exposed to hypoxic waters, though both still experience reductions in body condition in low DO concentrations (Boese, 1988; Keller et al., 2010; Bancroft, 2015). Dover sole are adapted to live in hypoxic conditions, possibly explaining their continued or increased presence despite the decrease in DO (Keller et al., 2010; Love, 2011). The compressed distribution exhibited by the two inshore species (Pacific sanddab and English sole) and predicted increase in Dover sole presence may be explained by avoidance of the hypoxic area south of Heceta Bank or to take advantage of high productivity inshore of Heceta Bank (Barth et al., 2005; Ressler et al., 2005). There is also a predicted reduction in presence near the Washington Coast for many species, including Dover sole, and this is another region that regularly experiences seasonal hypoxia (Peterson et al., 2013). It is possible that the reason for the predicted decrease in Dover sole presence in the inshore area near Washington is a result of recent small recruitment events rather than hypoxia, as Dover sole are hypoxia tolerant (Vetter et al., 1994). Four of the largest recruitment years for Dover sole occurred prior to 1995, the threshold year, while four of the smallest occur after 2002 (Hicks & Wetzel, 2011). As Dover sole age they move to deeper waters, meaning that in the period of time after 1995 there was likely a reduction in occurrence of young Dover sole in the shallowest portion of the nearshore (Jacobson & Hunter, 1993). Older, larger Dover sole return to the shelf during the summer months, which may explain the increase in observations in other areas. While overall community composition has not noticeably shifted over time, there has likely been a change in this geographic region due to the influence of hypoxic waters.

As illustrated by the potential change in individual species distribution in response to hypoxia, the response of individual species to environmental variability influences their distributions over time and space, providing further detail about shelf groundfish communities. Because much of the shelf is used for early life stages of groundfishes, shifts in distribution on the shelf are often more indicative of changes in the population of younger individuals occupying this habitat. The four species for which catch increases with depth – Dover sole, rex sole, sablefish, and arrowtooth flounder – all ontogenetically migrate off the shelf and onto the slope over their lifetimes, meaning that most of the individuals caught by the surveys on the shelf are likely younger than those caught further offshore (Vetter & Lynn, 1997; Jacobson et al., 2001; Doyle et al., 2018). Dover sole spawning stock biomass increased during the early 2000s as a result of a large recruitment event in 1999 and lower fishing pressure (Hicks & Wetzel, 2011). This potentially explains the increase in predicted presence seen in the TGAM results. It is unlikely that the rex sole increase in presence has an identical explanation, as rex sole has never been exploited heavily and overall biomass declined in the early 2000s (Keller et al., 2012). There is little information about past rex sole recruitment events off the West Coast and it is possible that despite an overall decline in biomass, there may have been an increase population of the younger life stages that occupy the shelf resulting from a large recruitment event similar to Dover sole.

As indicated by the GAM results, temperature is an important driver for each of those four species' nearshore populations. The results revealed a strong relationship between arrowtooth flounder CPUE and temperature, with the species preferring cold water. This is expected given prior research in the Gulf of Alaska that showed small (<400 mm) arrowtooth flounder density increased with cooler water (Doyle et al., 2018). Similar relationships were also evident for rex and Dover soles. The sablefish relationship to temperature is similar to that of English sole and Pacific sanddab, potentially because warmer temperatures are known to increase juvenile sablefish growth rates and possibly improve survival (Sogard, 2011; Tolimieri et al., 2018).

The shallow water flatfishes and lingcod differ from the midshelf and shelf-slope break species in that their populations are contained almost entirely to the shelf. Compressed distributions of Pacific sanddab and English sole are potentially a result of their depth limitations or requirement of estuarine habitat and shallow-water habitat as nursery grounds (Krygier & Pearcy, 1986; Rooper et al., 2006). Both species are known to have higher tolerance for warmer waters, which was corroborated by the GAM results, and they serve as important prey species for sablefish, lingcod, skates, and other piscivorous species (Steiner, 1979; Gunderson et al., 1990; Buckley et al., 1999; He et al., 2013). The combination of habitat compression and hypoxia and warmer temperature tolerance for these two species may ultimately lead to reduced predator-prey overlap if species like lingcod and sablefish are unable to occupy shallow-water habitat. For both petrale sole and lingcod, there was little change in distribution outside of anomalously hypoxic areas and petrale sole results indicated no relationship with bottom temperature. Therefore, both may have populations primarily driven by DO concentrations and depth on the shelf and they may not have been affected by changes in temperature on the shelf (see Fig. 2.1).

Changes in the northern California Current nearshore groundfish communities over the past four decades have created a modern shelf ecosystem different from the one fished prior to changes in regulation and management in the 2000s. Hypoxia has displaced fish from portions of the shelf near Newport and the Washington Coast and there is an observed greater physical separation between shallow water flatfish populations and their mid-shelf counterparts due to distributional shifts. Although the shallow-water flatfishes (e.g., English sole, Pacific sanddab, sand sole) were previously fished more consistently, currently most are not targeted. All the shallow water flatfishes except English sole and starry flounder are managed as part of the Other Flatfish Complex, a group that is infrequently assessed. In the past, these species were more commonly fished by the nearshore fleet of trawl vessels. Currently, only about 10% of the annual catch limit for the Other Flatfish Complex is fished each year due to the reduction in nearshore fleet size, processing facilities, and change in market preference (Sjostrom, 2019; PFMC, 2020). With increased access due to the RCA reopening in 2020 there is potential for more fishing pressure on the continental shelf. This could lead to increased catches of shallow-water flatfishes as well as other shelf species.

Currently the Oregon groundfish fleet catches nearly the entirety of available petrale sole and sablefish quota each year. Sablefish is considered a choke species, restricting catch of lingcod, Dover sole, and other flatfishes (McQuaw & Hilborn, 2020). This lack of quota utilization for all species besides sablefish and petrale sole has been augmented by area closures like the RCA (lingcod and Dover sole) and a lack of market incentive (flatfishes) (Warlick et al., 2018; Sjostrom, 2019; McQuaw & Hilborn, 2020). Increased access to the shelf has the potential to provide opportunities for portfolio diversification for Oregon trawl fishermen but this will likely be hampered by a lack of market interest and the reduction of processing facilities, both largely a result of the implementation of the West Coast Groundfish Trawl Catch Share Program and efforts to rebuild overfished stocks (Errand et al., 2017; Sjostrom, 2019). In addition, shifts in distribution can change access to target species. While there has been an increase in sablefish, Dover sole, rex sole, and English sole survey catch off the southern Oregon/northern California coast, and in the case of sablefish a southern distributional shift (Selden et al., 2020), this area has few processing facilities for non-whiting groundfishes (Errand et al., 2017). Organizations like Positively Groundfish and the Eat Oregon Seafood Initiative aim to increase consumption of West Coast seafood products and certain rockfish species have renewed market interest (McQuaw & Hilborn, 2020). It is unclear if whether will be similar economic revivals for the shallow-water species like English sole and Pacific sanddab. Both have populations found partially outside of the survey sampling range and were previously of more commercial interest.

With a potential increase in fishing effort on the continental shelf, it is important to understand how environmental variability is impacting nearshore groundfish population dynamics and community structure. Additional focus on inner-shelf species, such as starry flounder or sand sole, will provide more context for future management should those species become more frequently caught. For analysis of species that live in areas infrequently sampled by NOAA surveys, like the inner-shelf species or those that migrate on and off the shelf seasonally, logbook and landing records along with local ecological knowledge may address some of the gaps.

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Chapter 3: Visualization and overlap of fishery-independent and fishery-dependent data for assessment of the Oregon nearshore flatfish fishery

Abstract

The commercial non-whiting groundfish fishing industry and corresponding research activity have a long concurrent history on the Oregon continental shelf. Although federal fisheries-independent surveys have been conducted across most of the groundfish fishery's depth range, data is limited by years and seasons surveyed as well as absence of data in the shallowest waters (< 55 m). Fishery-dependent data (logbooks) covers those shallow waters and a broader temporal range, but it is self-reported. Limitations in data coverage combined with a historical focus on continental slope-dwelling groundfishes has led to a gap in understanding of dynamics within the nearshore fishery. In this chapter I analyzed spatial and temporal changes in catch, as well as gaps in fishery and scientific survey data, for six flatfishes in the Oregon nearshore non-whiting groundfish trawl fishery. Visualization of both fishery-independent (NOAA survey) and -dependent (logbook and landings) data allowed for a qualitative comparison of data coverage as well as an assessment of differences in species distribution when mapping data in each dataset. These analyses illuminate where knowledge gaps lie in both data types and how they complement one another, providing more context for future management of nearshore groundfishes. I found that the earliest years of the NOAA surveys (1980 – 1998) have the most information gaps and had the highest potential to benefit from complementary use of fishery-dependent data for spatial and temporal analyses. This was largely due to (1) triennial rather than annual sampling and a transect-based design in the NOAA surveys, and (2) the larger spatial and temporal coverage of logbook data (inshore and latitudinal) during that period. Commonly caught species, like Dover sole and petrale sole, had better spatial sampling coverage of their populations compared to species that live in shallow water and are less frequently targeted, such as starry flounder and sand sole. Overlap between datasets was variable but often highest near the two largest ports: Astoria and Newport, OR. There is limited previous work that uses logbook data for visual analyses, and it primarily assesses rockfishes. Only one previous comparison has been made between the two data sources. This work provides a new perspective by comparing four decades of NOAA survey data and logbooks to illustrate the potential utility of fishery-dependent data for future analyses of Oregon flatfishes.

3.1 **Introduction**

Fishery-independent and fishery-dependent data are typically the two primary sources of information used by fishery scientists for assessing population distributions over time and space. Both have their advantages and disadvantages depending on the methods applied, but their combined use is undeniably valuable for the management of many fisheries. For many regions, mapping of species distributions can only be reliably done using fishery-independent data, as locations are not always recorded correctly or at all in fishery-dependent sources (Hilborn & Walters, 1992). In those areas where location data is more reliably documented by fishermen, mapping is still not a common practice due to inherent biases present in fishery-dependent data, whereas there is standardization and fixed sampling design built in to fishery-independent data (Hilborn & Walters, 1992; Maunder & Punt, 2004) There can also be issues with fishery-independent surveys. These largely stem from a lack of time and funding, which can restrict the spatial and temporal extent of sampling but can also be caused by inadequate survey design (Hilborn & Walters, 1992). Therefore, research is needed in specific regions or fisheries to determine whether it is possible or necessary to combine fishery-dependent and -independent data in order to take advantage of the strengths of both.

Several recent studies have examined the differences between fishery-dependent and fishery-independent spatial information and shown that it may be possible to use certain fishery-dependent datasets to map or predict species distributions. For example, fishery observer and survey data in the western Mediterranean Sea have been shown to display similar distribution patterns of elasmobranch bycatch species despite differences in temporal and spatial coverage of the datasets (Pennino et al., 2016). Nonetheless, Pennino et al. did find that there were differences in predictive ability of each data type for temporal and spatial presence and absence. Earlier studies indicate that the combination of various sources of fishery-independent and -dependent data can provide a more complete picture of population distributions (Pecquerie et al., 2004), allow for a better understanding of bycatch-fishery interactions (Lyons et al., 2013; Murray & Orphanides, 2013), and be valuable for stock assessment models (Booth, 2000).

In Oregon, data has been collected by fishermen for decades through logbook and landing documents. This data includes records of set and retrieval locations for fishing gear, weight and number of each species caught, and length of time of the tow, amongst other information. Despite the existence of this long time series, Oregon fishery-dependent data is infrequently used to assess population distributions. Instead, the NOAA West Coast Groundfish Bottom Trawl Surveys have been used predominantly and fishery observer data is used to obtain bycatch estimates (Bjorkland et al., 2015; Stock et al., 2019). The NOAA trawl surveys were initiated in 1977, and logbook records that contain usable spatial data began around the same time, in 1980. The first work to look at both West Coast groundfish fishery-independent and -dependent data was done by Fox and Starr (1996). In their study, they compared commercial trawl catch data (logbook) to the NOAA surveys, which at that time were conducted triennially, using Geographic Information System (GIS) mapping. They found that differing results between the datasets included lack of spatial overlap in certain regions and a discrepancy in Dover sole (*Microstomus pacificus*) biomass estimates, likely a result of gear differences, but that the datasets were overall complementary (Fox & Starr, 1996). Later work used logbooks and fish ticket information, data for commercial landings, to assess patterns of fishing effort as well as visualize spatial and temporal extent of certain fisheries (Macomber, 2000; Hannah, 2003; Bellman et al., 2005; Bellman & Heppell, 2007). Despite the infrequent use of fishery-dependent data for study of groundfish populations, the logbook data generated by Oregon groundfish fishermen provides a more consistent time series and, for certain species, a larger spatial range of information than NOAA survey data, making these data potentially invaluable for filling in holes in fishery-independent data. Sampson (2011) found that while there are issues with accuracy in the logbooks, information from tows on the continental shelf is typically consistent with landings data and bathymetric maps, but this becomes less true on the slope. Gaps in fishery-independent data exist temporally prior to 2003, when the NOAA surveys began to run annually, as well as seasonally because the survey only happens from late spring to early fall. Spatially, the survey is limited to depths deeper than 55 m, cutting off much of the inner shelf, though some of this area is fished commercially (Sjostrom, 2019).

The Oregon nearshore commercial bottom trawl fishing grounds, here defined as inshore of ≤ 200 m depth, or on the continental shelf, are the focus of this study. The area inshore of approximately 55 m depth is understudied compared to the slope and remaining portion of the shelf. Recently there has been renewed interest in nearshore commercial trawling, which had declined following the collapse of the groundfish fishery in 2000. A large portion of the shelf seafloor is sedimentary, with sand being the predominant grain type in the shallowest waters (Romsos et al., 2007). Therefore, the shelf is habitat for many flatfishes, including those most heavily targeted by the fishery like petrale sole (*Eopsetta jordani*) and Dover sole. Many flatfishes use the shelf to complete their life cycles (Pedersen, 1975; Jacobson & Hunter, 1993; Abookire & Bailey, 2007; Toole et al., 2011) while others spend their entire lives in the nearshore (Krygier & Pearcy, 1986; Richmond, 1983). This makes them the dominant group fished by Oregon nearshore bottom trawlers (Sjostrom, 2019). Additionally, flatfishes display much different behavior near trawl gear when compared to roundfishes, so selection of only flatfish species for analysis allows for a better comparison between species (Ryer, 2008). Flatfishes are also historically more consistently identified to species in the logbook data than most rockfishes. With the possibility of increased fishing activity in the nearshore, more information on species distributions in this region will contribute to future management efforts. Therefore, this research assesses the feasibility of using the fishery-dependent and -independent data jointly to add to existing knowledge. Based on the previous research conducted using logbook and fish ticket data, as well as the limitations of the NOAA surveys, I expected to find a greater amount of fishery-dependent data in nearshore habitats as well as more spatial and seasonal coverage. I also expected to find that there is greater disagreement between the two data sets when considering shallow water species, as these species likely occupy habitat not sampled by the NOAA surveys.

3.2 **Methods**

3.2.1 Fishery-dependent data

Logbook and landings data were obtained from the Oregon Department of Fish and Wildlife (ODFW). Logbook records included information for catches of individual species, tow time, average depth of tow, offload port, gear type, and location of each tow. Catches for each species were recorded as the original hail weight and an adjusted weight. Hail weight is the original weight recorded by the vessel captain. For adjusted weight, ODFW applied five classifications for each trip or tow to make any appropriate corrections to the hail weight to obtain these values. These corrections were made using the fish ticket pounds and depended on what errors were identified in the data. For example, this may have included adding information to a logbook record for a species without a hail weight but that was recorded on the fish ticket. Because hail weights were not recorded in early years, the adjusted weights were used.

To prepare the data for analysis, I limited the logbook records to only fishing grounds fished by Oregon commercial fishermen. Only tows completed using the three most common nearshore groundfish gear types were retained and these included unspecified bottom trawl, sole net, and selective flatfish trawl (Sjostrom, 2019). Tows with missing critical data, such as set latitude or longitude, were removed. A locally estimated scatterplot smoothing curve (LOESS), a type of nonparametric regression, was used to replace all depth measurements. Due to numerous previously identified inaccuracies with depth reporting in the logbooks, and the variability in technological capabilities over time, it was deemed best to replace the depth values rather than remove inaccurate records (Sampson, 2011; Sjostrom, 2019). Bathymetric data for the LOESS curve was obtained from the NOAA ETOPO1 global relief model (Amante & Eakins, 2009). The final model (adj. $r^2 = 0.99$), which used a 2^{nd} degree polynomial and 0.01 span, was then used to predict depths for the recorded locations of each logbook tow. Tows with depths greater than 200 m or shallower than 10 m were removed, providing a dataset with 85,143 hauls. Landings information (fish tickets) and logbooks were joined using individual tow catch ID numbers and the weights from the tickets were used to calculate total landings over time. All analyses and data processing was completed using R statistical software (R Core Team, 2019).

3.2.2 Fishery-independent data

Survey data from both the triennial (1977 – 2001) and annual (2003 – 2018) iterations of NOAA groundfish surveys were available for analyses. For the triennial survey, Alaskan class trawl vessels equipped with a Poly Nor’Eastern trawl were used to sample transects running perpendicular to the coast. Sampling depth, transect spacing, and timing of the survey were variable, but tow time was consistent at 30 minutes (Dark & Wilkins, 1994; Keller et al., 2017). Up until 1995, sampling occurred from July to September or October; after 1995, sampling began in June and ended in August. The annual survey began in 2003 and it uses paired West Coast class vessels equipped with an Aberdeen trawl, which is towed for 15 minutes at each station. Stations are selected using a stratified random sampling of cells placed along the U.S. West Coast shelf and slope (Keller et al., 2017). The first pass for the survey occurs from May to August and the second pass occurs from August to October. Both the triennial and annual surveys cover the region trawled by the Oregon commercial groundfish fishery, but the sampling density is greater for the annual survey. Several other surveys conducted by NOAA were not included in these analyses because they sample primarily on the continental slope or were only conducted for a few years. Data from the NOAA surveys were obtained from the NWFSC/FRAM Data Warehouse (url: https://www. nwfsc.noaa.gov/data/) as a dataset containing characteristics from each tow and a dataset containing information on species composition. Tow ID numbers were used to match tows to the species composition data. Only data collected at 200 meters depth or shallower was retained, with the shallowest depth at approximately 55 meters. Using the logbook records, the data was trimmed to only waters consistently fished by Oregon commercial fishermen, between 42 and 47°N. Because complete logbook data was only available between 1981 and 2017, the survey data used below were limited to this time period as well, leaving 4,343 tows for the analyses.

3.2.3 Species selection and visualization

Six species of flatfish were chosen for analysis: petrale sole, Dover sole, sand sole (*Psettichthys melanostictus*), starry flounder (*Platichthys stellatus*), English sole (*Parophrys vetulus*) and Pacific sanddab (*Citharichthys sordidus*). Petrale sole and Dover sole are the flatfishes most consistently caught by both the survey and commercial fishery, with distributions known to span much of the shelf. Starry flounder and sand sole are two shallow-water species not commonly caught by the surveys or fishery while English sole and Pacific sanddab are mid-shelf species with some commercial importance (Table 3.1). All shallow and midwater species have potential for market expansion. Pacific sanddab catch is not separated out from speckled sanddab (*Citharichthys stigmaeus*) in logbook records, but speckled sanddabs, a similar but smaller species, are assumed to be infrequently encountered by commercial trawl vessels (He et al., 2013). Therefore, the unspecified sanddab grouping was used to assess catch of Pacific sanddab.

I gridded maps of species catch and overall fishing effort for four decades (1981 – 1989, 1990 – 1999, 2000 – 2009, 2010 – 2017) using both survey and logbook data. In addition, Icreated time series of total commercial catches over time and average catch-per-unit-effort (CPUE). I constructed maps with a grid covering 42° to 47°N latitude and 125° to 123.9°W longitude comprised of cells with dimensions of 20 north-south intervals and 15 east-west intervals to allow for fishing location confidentiality. To investigate tow distribution, maps of overall fishing effort were created for each decade. For individual species maps I used a log(x+1) transformation of CPUE, and each grid cell represented the mean transformed CPUE in that area

Table 3.5: Species below were selected for analyses. Values represent the number of hauls that contained each species.

Species	Survey	Logbook
Dover sole	3,925	53,460
petrale sole	3,422	56,207
English sole	3,135	54,618
Pacific sanddab	2,678	20,681
sand sole	174	20,608
starry flounder	62	19,315

during the decade depicted. CPUE was used rather than total catch because tows conducted by fishermen can be of varying length, which typically leads to larger catches for longer tows. The logbook CPUE was calculated as kilograms per hour (kg/hr) using the recorded tow time and catch weight, while the survey CPUE was recorded as kilograms per hectare (kg/ha). A linear regression of transformed CPUE against vessel length showed little to no relationship between length and catch, which indicated that CPUE does not significantly change with vessel length (Fig. B.1). Mean CPUE for each grid cell was calculated as the sum of the log transformed CPUE in that area for each decade divided by the number of tows made in that area for the same time period. For comparison between datasets, the logbook data was restricted to the months the survey operates.

Fishery-independent and -dependent maps and plots for each species were first compared visually to determine if differences or similarities were present in spatial distribution or mean CPUE over time. Dover sole and petrale sole were used to compare commercial fishery catches during the time the survey samples to the days fished outside of that time. Both species are known to seasonally migrate on and off the shelf, making them ideal to assess any differences in distribution that are missed by the survey (Ketchen & Forrester, 1966; Pedersen, 1975; Jacobson & Hunter, 1993; Abookire & Bailey, 2007). Contour plots were created using the ggplot2 stat_density_2d function to display patterns of spatial distribution by only depth and latitude, rather than geographically (Wickham, 2016). Only points of presence for each species were used and plots were divided into the same four decades as above.

3.2.4 Quantitative comparison

To further assess the level of overlap between the fishery-independent and -dependent data, I calculated the local index of collocation (LIC). The LIC is a correlation coefficient that is not sensitive to zero-inflation and assesses the overlap of two data sources over the same spatial bounds (Bez & Rivoirard, 2000; Pianka, 1973). The LIC has previously been used to determine overlap with respect to population abundance (Kotwicki & Lauth, 2013; Petrik et al., 2015; Carroll et al., 2019), predator-prey interactions (Trenkel et al., 2005; Carroll et al., 2019), and fishing effort (Bez et al., 2011; Pointin et al., 2019). Values range between 0 and 1, with lower values indicating less collocation between the two datasets. The total LIC for a given decade can be calculated as follows (Pianka, 1973; Petigas et al., 2017; Carroll et al., 2019):

(Eq. 1)
$$LIC_{total} = \frac{\sum_i^n (D_i * I_i)}{\sqrt{\sum_i^n D_i^2 \sum_i^n I_i^2}}$$

In the above equation, D represents the fishery-dependent data (untransformed CPUE) while I represents the fishery-independent data (untransformed CPUE). To look at spatially explicit overlap I modified Equation 1 to use CPUE in each grid cell for a given species. This is essentially the contribution of overlap per cell to the total overlap (Equation 1) across the study region, providing a spatially explicit value (Carroll et al., 2019):

(Eq. 2)
$$LIC_{spatial} = \frac{D_{cell} * I_{cell}}{\sqrt{\sum_i^n D_i^2 \sum_i^n I_i^2}}$$

In areas shallower than 55 meters depth only logbook data is available, so for comparison purposes the fishery-independent mean CPUE value for unsampled grid cells was artificially set to 0 as there was no survey data.

3.3 **Results**

3.3.1 Fishing effort and catch

Average CPUE generally either increased over time (Pacific sanddab, Dover sole, petrale sole, survey English sole) or remained relatively constant (sand sole, starry flounder, logbook English sole) (Fig. B.2). The logbook data indicate a marked decrease from 2015 to 2017 in CPUE for Pacific sanddab that is not present in the survey data. The two inshore species (starry flounder and sand sole) had large spikes in average CPUE in the early 2000s and irregular

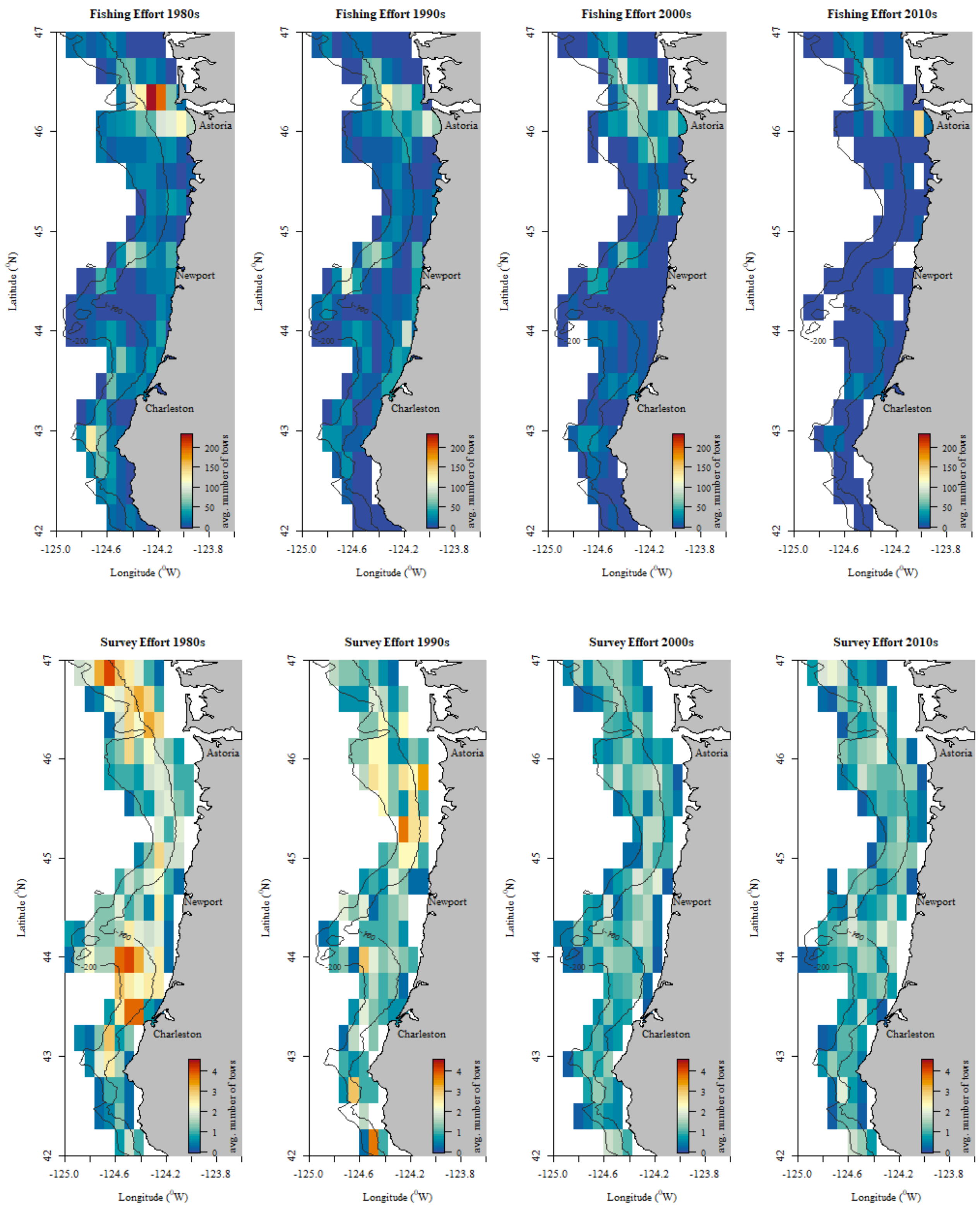

Figure 3.3: The top four panels depict fishing effort by Oregon commercial fishing vessels. The bottom four panels depict survey sampling effort over the same time period. Each grid cell represents average fishing effort per year for each decade.

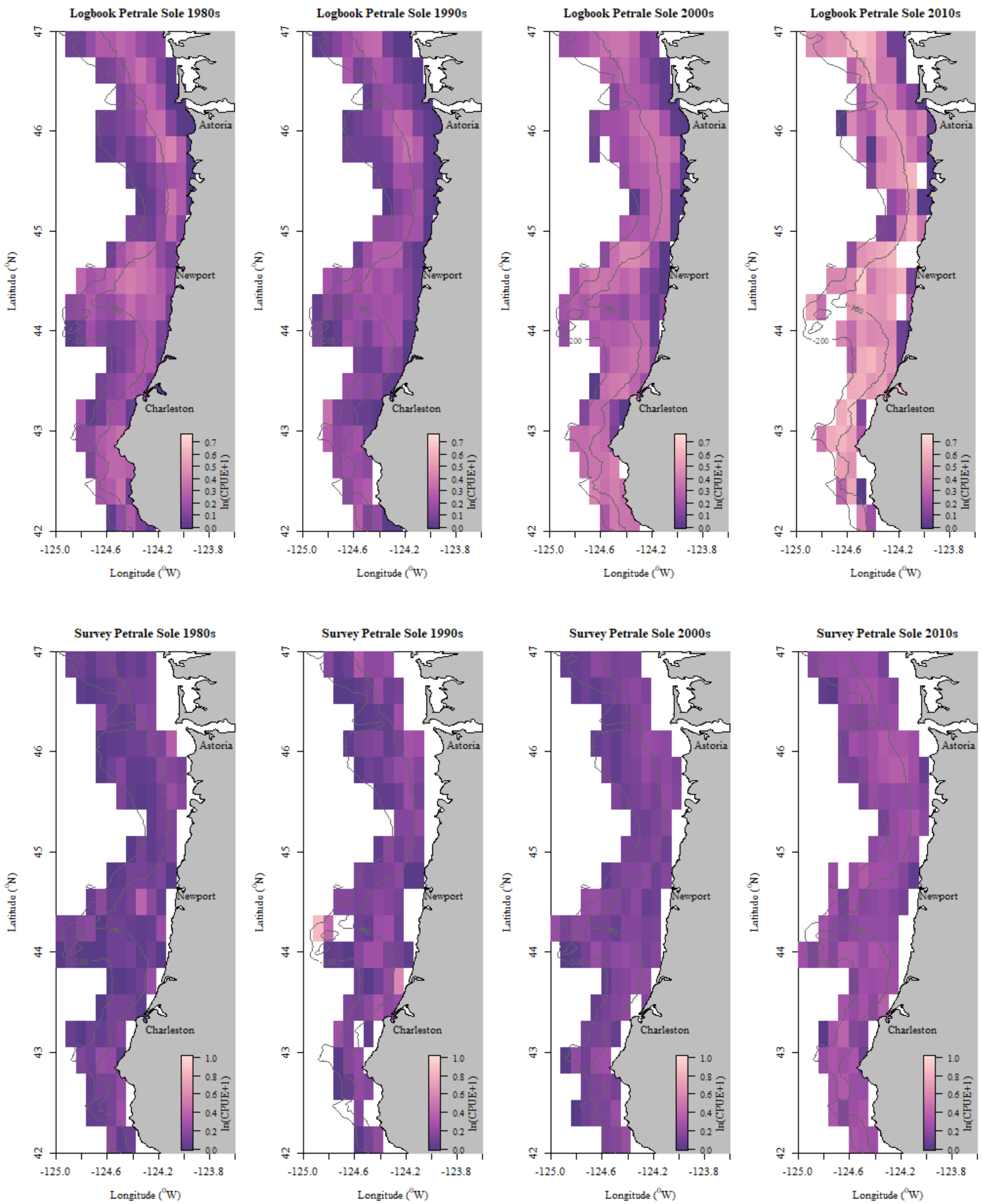

Figure 3.2: The panels above depict the spatial distribution of CPUE for petrale sole over four decades. The top four panels depict data from logbooks and the bottom four panels depict data from the NOAA surveys. Grid cells indicate average log transformed CPUE in each area.

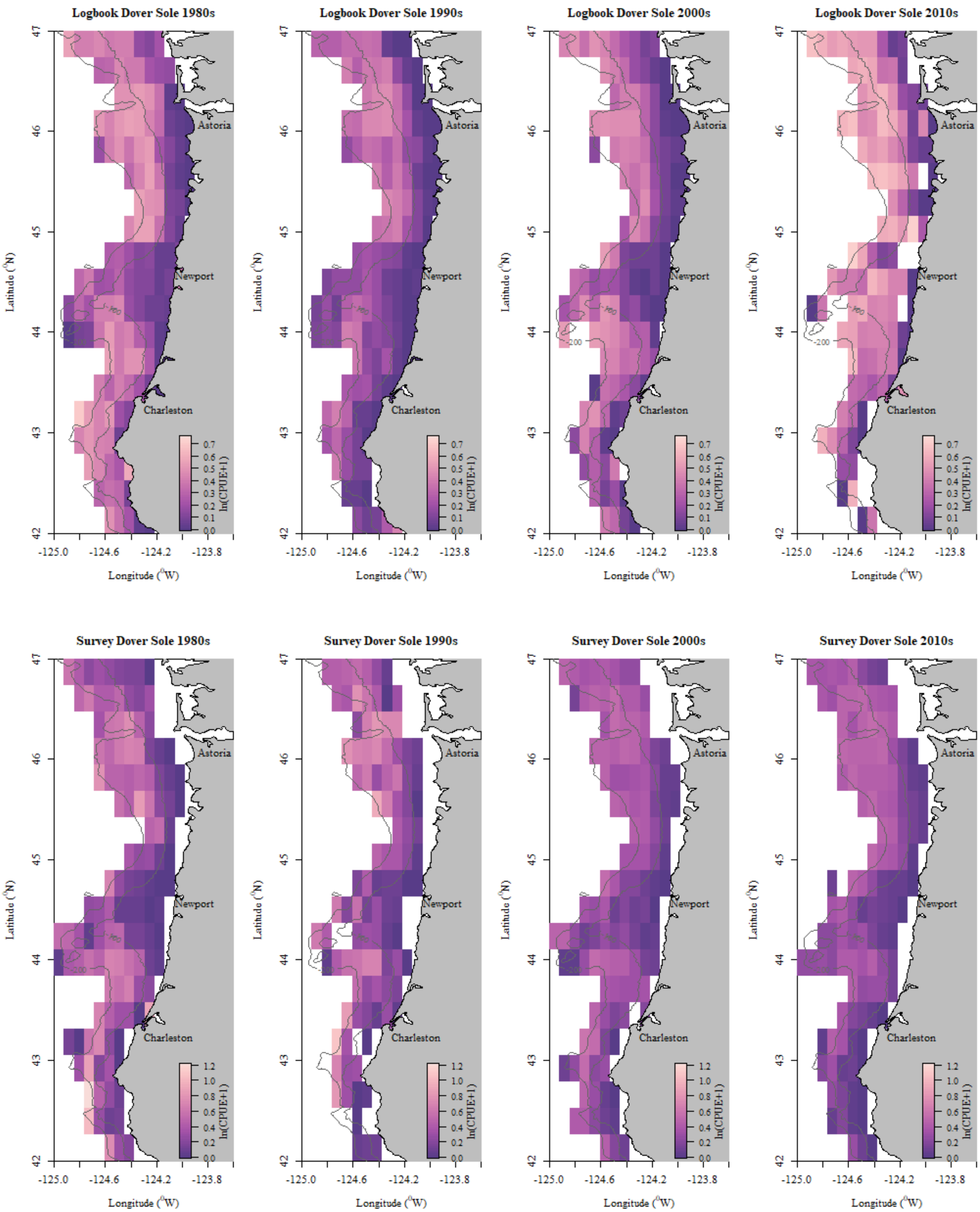

Figure 3.3: Same as figure 3.2 but for Dover sole.

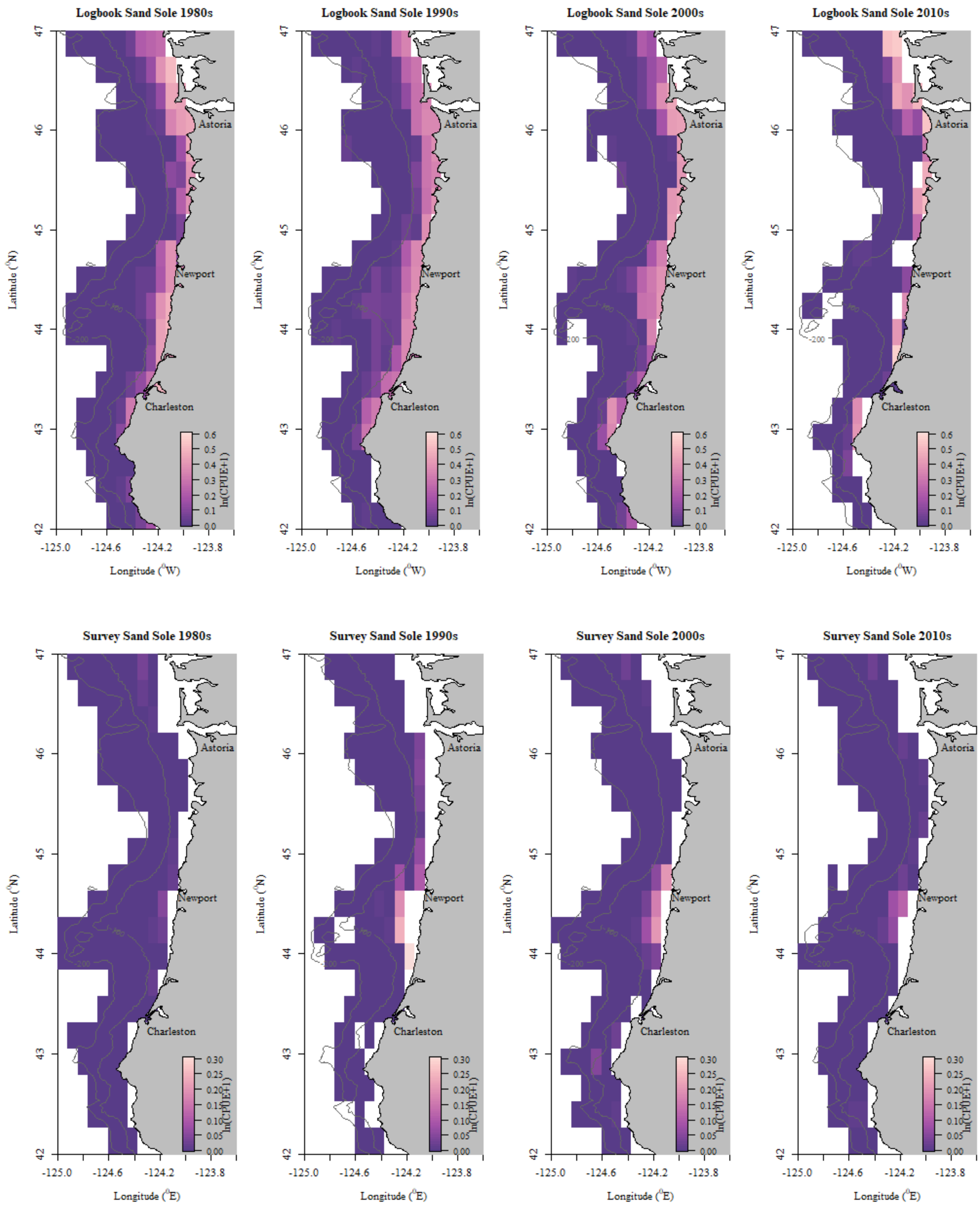

Figure 3.4: Same as figure 3.2 but for sand sole.

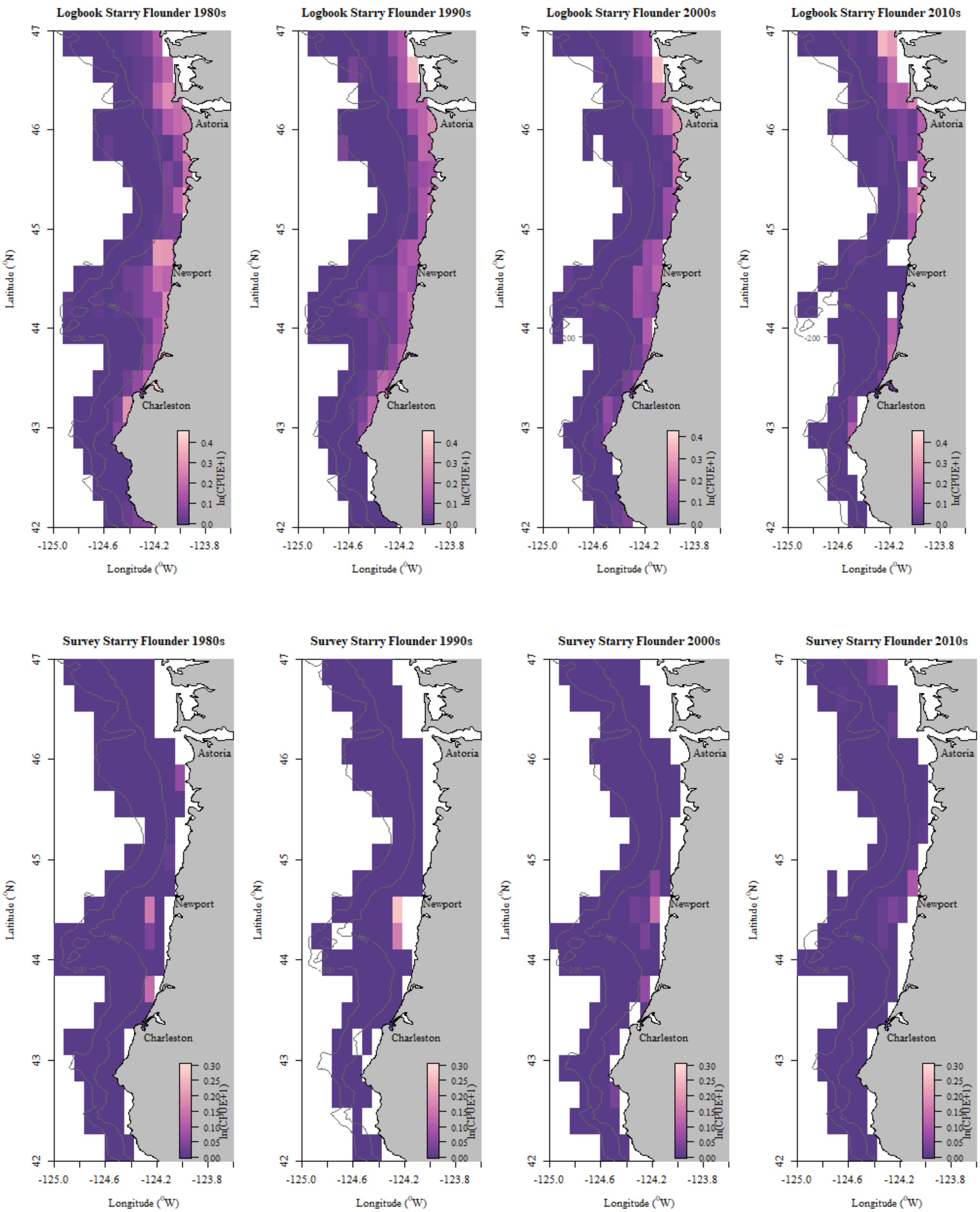

Figure 3.5: Same as figure 3.2 but for starry flounder.

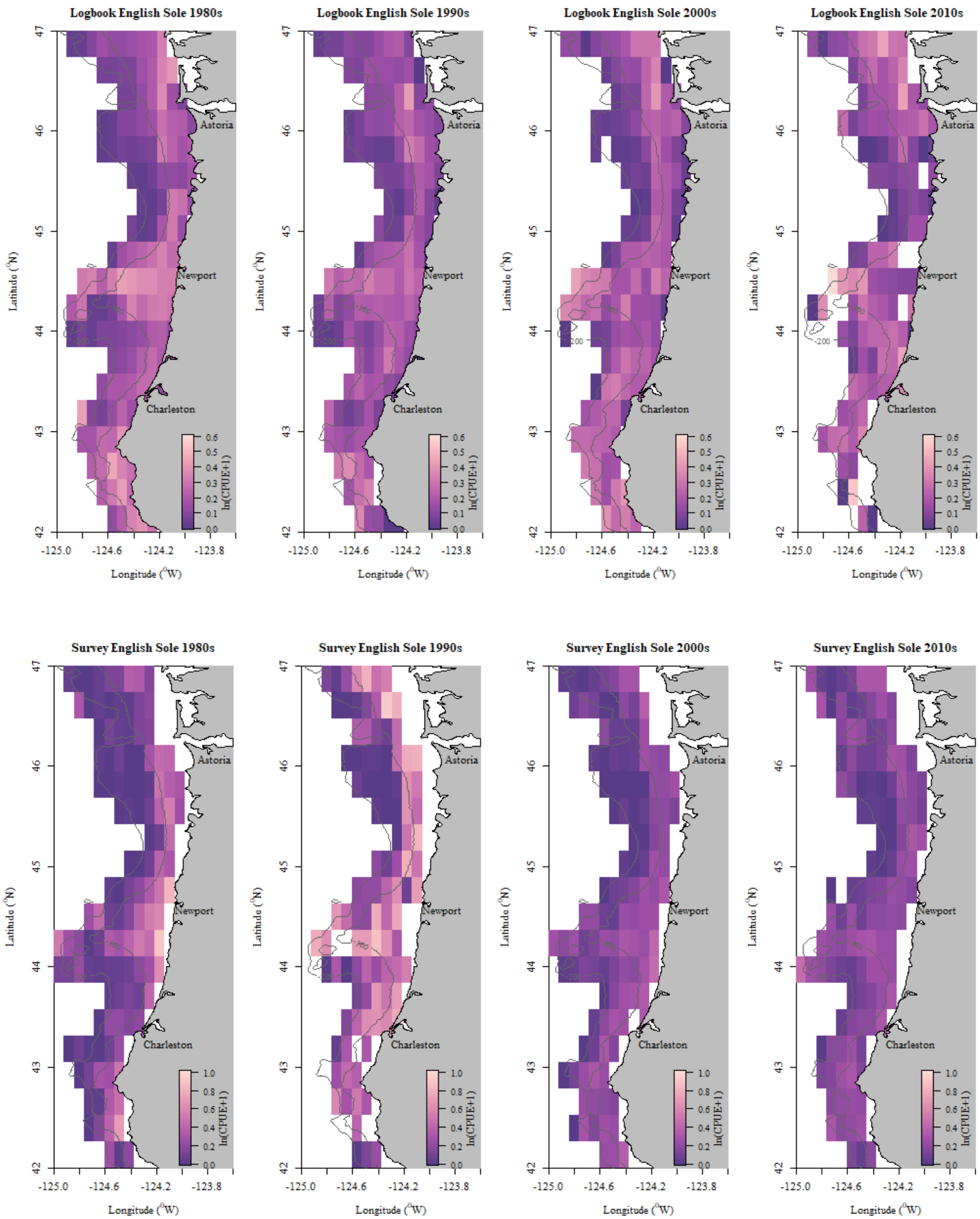

Figure 3.6: Same as figure 3.2 but for English sole.

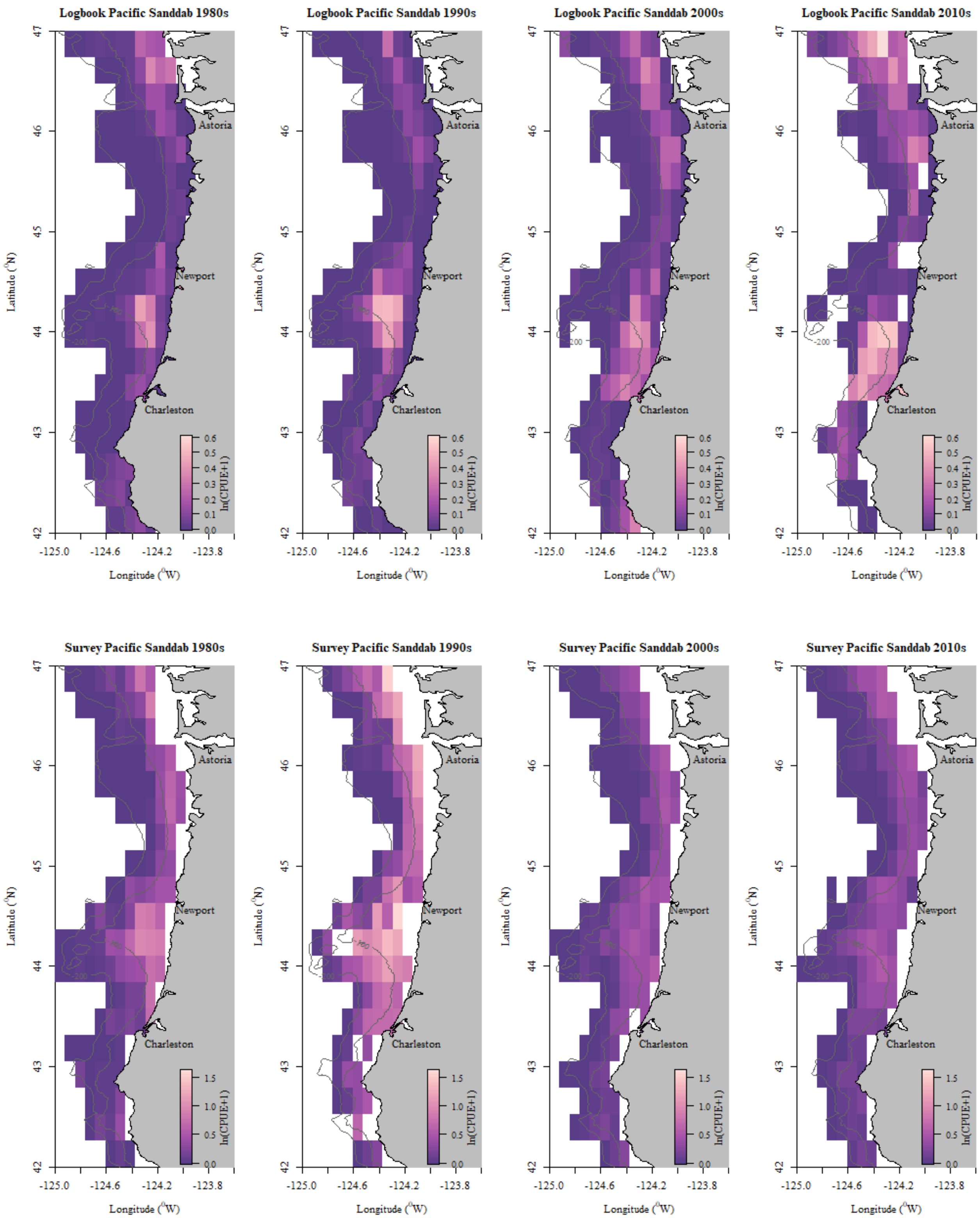

Figure 3.7: Same as figure 3.2 but for Pacific sanddab.

changes in CPUE over time (Fig. B.2). There were decreases in total nearshore catch for Dover sole, English sole, sand sole, and starry flounder (Fig. B.3). Petrale sole exhibited an increase in total catch during recent years, and Pacific sanddab total catches have stayed relatively consistent, save for a spike in the mid-1990s (Fig. B.3).

Overall fishing effort was distributed differently in space in the fishery-independent and fishery-dependent data, as well as when comparing the triennial and annual surveys (Fig. 3.1). Fishing effort on the inner shelf decreased. More effort shifted offshore and northward toward Astoria, OR over time and there was a decrease in effort across the entire region. This is not unexpected given the general decrease in catch for most species, and previous research reported a similar shift for management groupings (Fig. B.3; Sjostrom 2019). Fishing

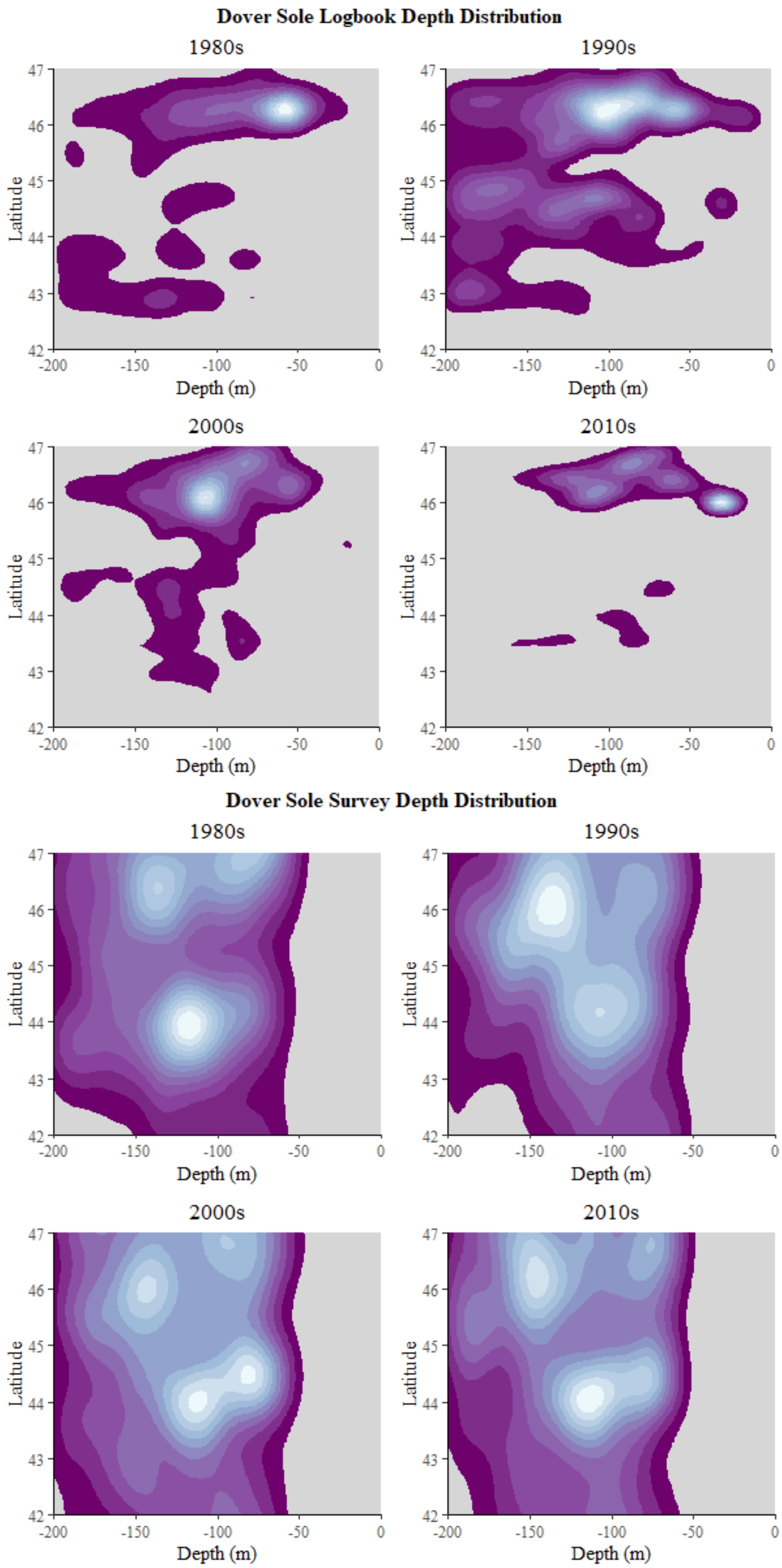

Figure 3.8: Contour maps depicting depth distribution of Dover sole for the logbooks (upper four panels) and for the survey (lower four panels).

effort in the most recent years (2010-2017) appears to have significantly decreased, with most effort located off the coast of northern Oregon and southern Washington. The survey fishing effort is more evenly distributed, though there was higher average effort and patchy distribution during the triennial survey decades (1981-1989 and 1990-1999). In the most recent two decades (2000-2009 and 2010-2017), effort is far more evenly distributed across the shelf, which was expected with the change from transects to stratified random sample design.

3.3.2 Spatiotemporal visualization of catch

Difference in spatial distribution of catches between the two data types and two groups of species was clear geographically. Maps for the two commonly caught species, petrale sole and Dover sole, had similar patterns of spatial distribution of average CPUE per year over time within each

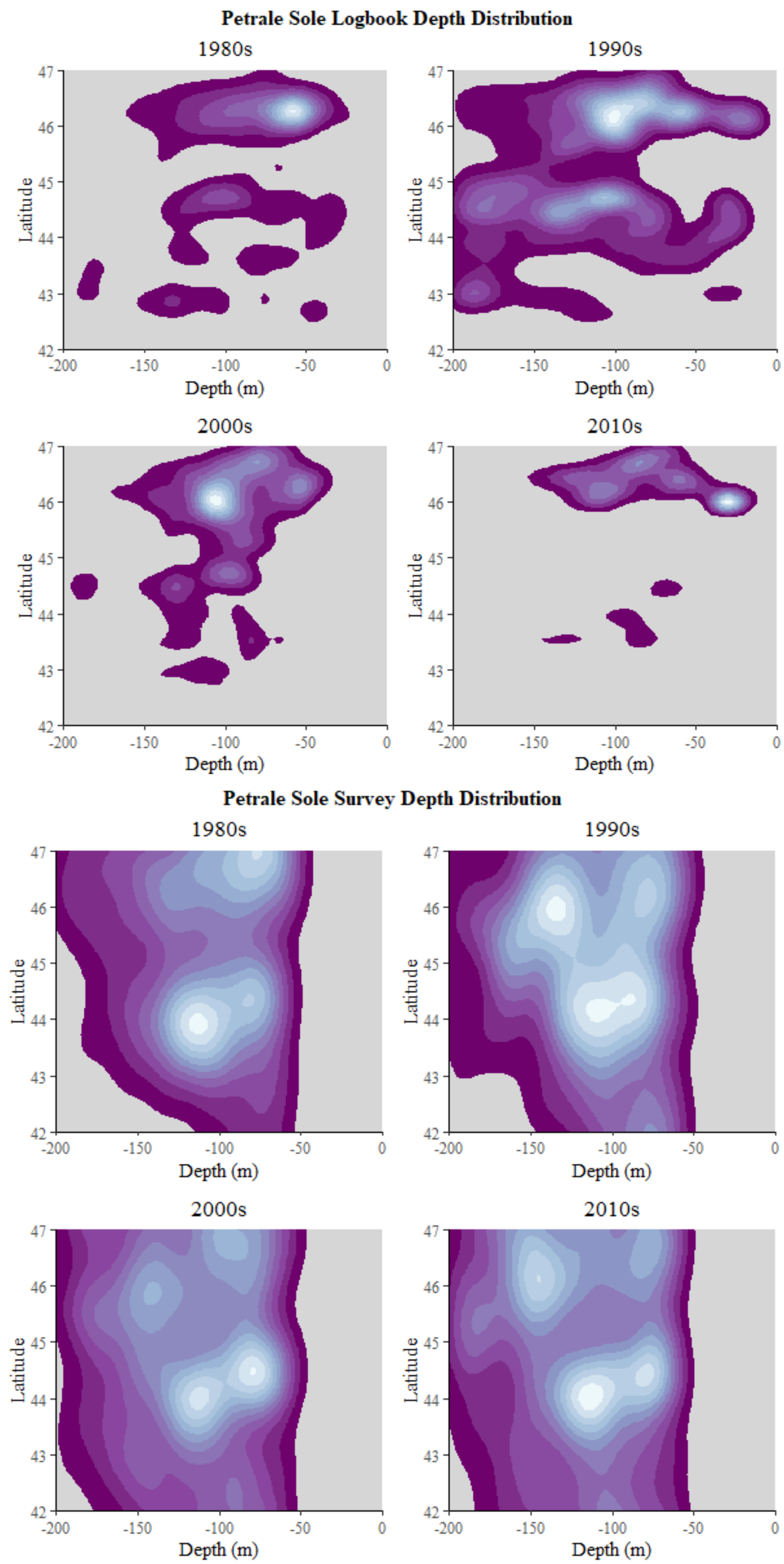

Figure 3.9: Same as figure 3.8 but for petrale sole.

data type (Fig. 3.8 and 3.9). The highest average logbook CPUE of petrale sole was centered along the 100-meter isobath throughout much of the shelf, whereas average survey CPUE was similar throughout the study area (Fig. 3.2). Dover sole logbook and survey CPUE were highest near the outer edge of the shelf, and in the most recent decade, CPUE was highest north of 45°N (Fig. 3.3). For the inshore shallow-water species, the logbook data indicate that nonzero CPUE occurred almost entirely in areas shallower than 100 m. Sand sole CPUE was consistent across the four decades throughout this depth range in the logbooks (Fig. 3.4). Average logbook CPUE of starry flounder was highest near Astoria and decreased southward (Fig. 3.5). Both species were sporadically caught by the survey, and the primary location of tows containing either species was near Newport. Tows containing the final two species, English

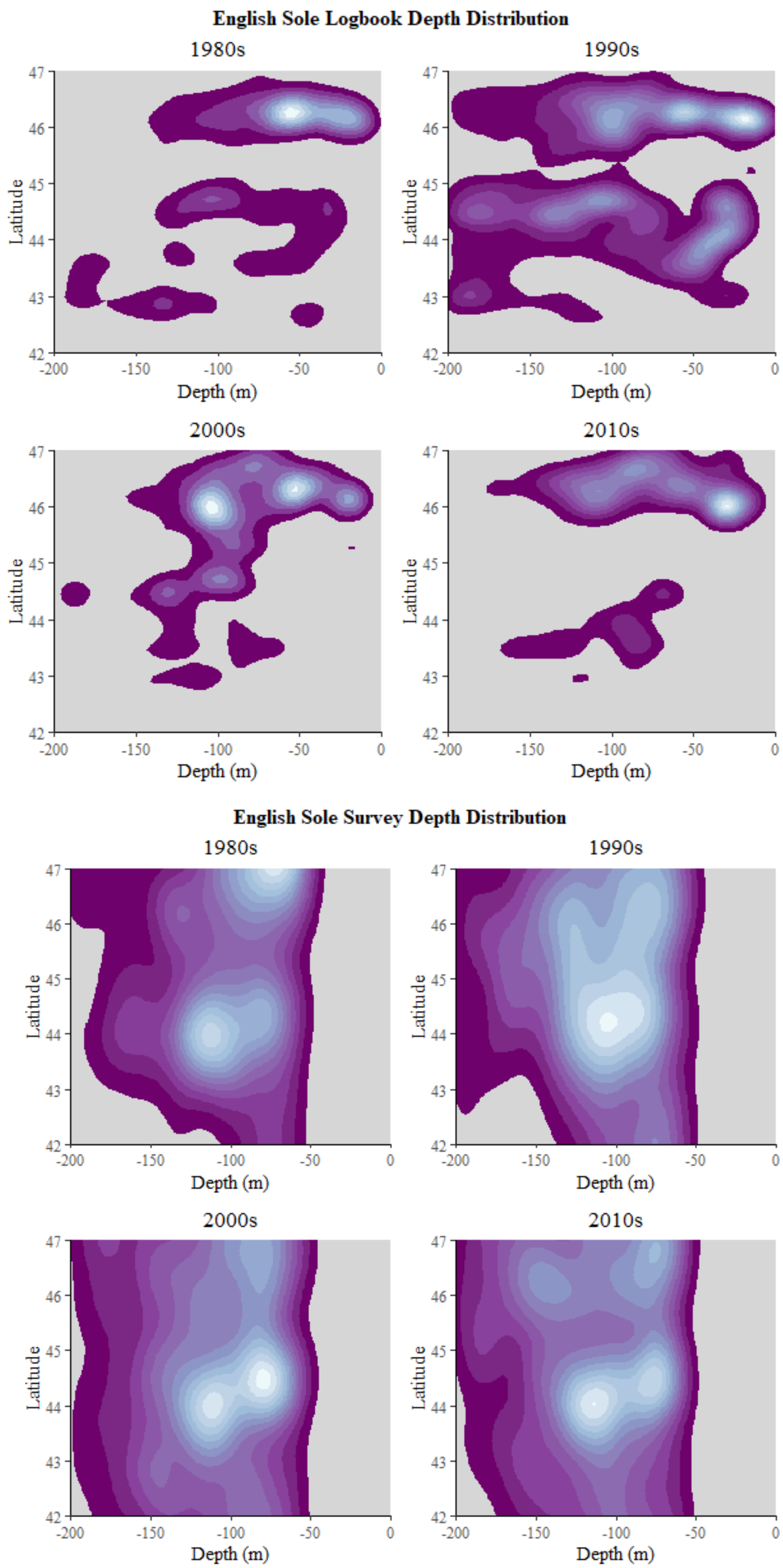

Figure 3.10: Same as figure 3.8 but for English sole.

sole and Pacific sanddab, were more common across the study area than for the inshore species. Pacific sanddab average CPUE was highest off the shelf near Charleston and Newport, though this patch of higher CPUE appeared to shift south over time in the logbook data (Fig. 3.6). There were also high catches north of Astoria. English sole logbook CPUE was highest in the southern portion of the shelf and on the wide section near Newport (Fig. 3.7).

Depth contour plots and maps revealed the discrepancy in the coverage of spatial sampling between the two data types. All species commonly caught by the survey (petrale sole, English sole, Dover sole, and Pacific sanddab) had survey catches distributed evenly throughout much of the sampling area (Fig. 3.8 – 3.11). Patches of high presence were visible in areas where the shelf is about 44° and 46°N. Dover sole, English sole, and petrale sole were present in samples throughout all depths and latitudes sampled by

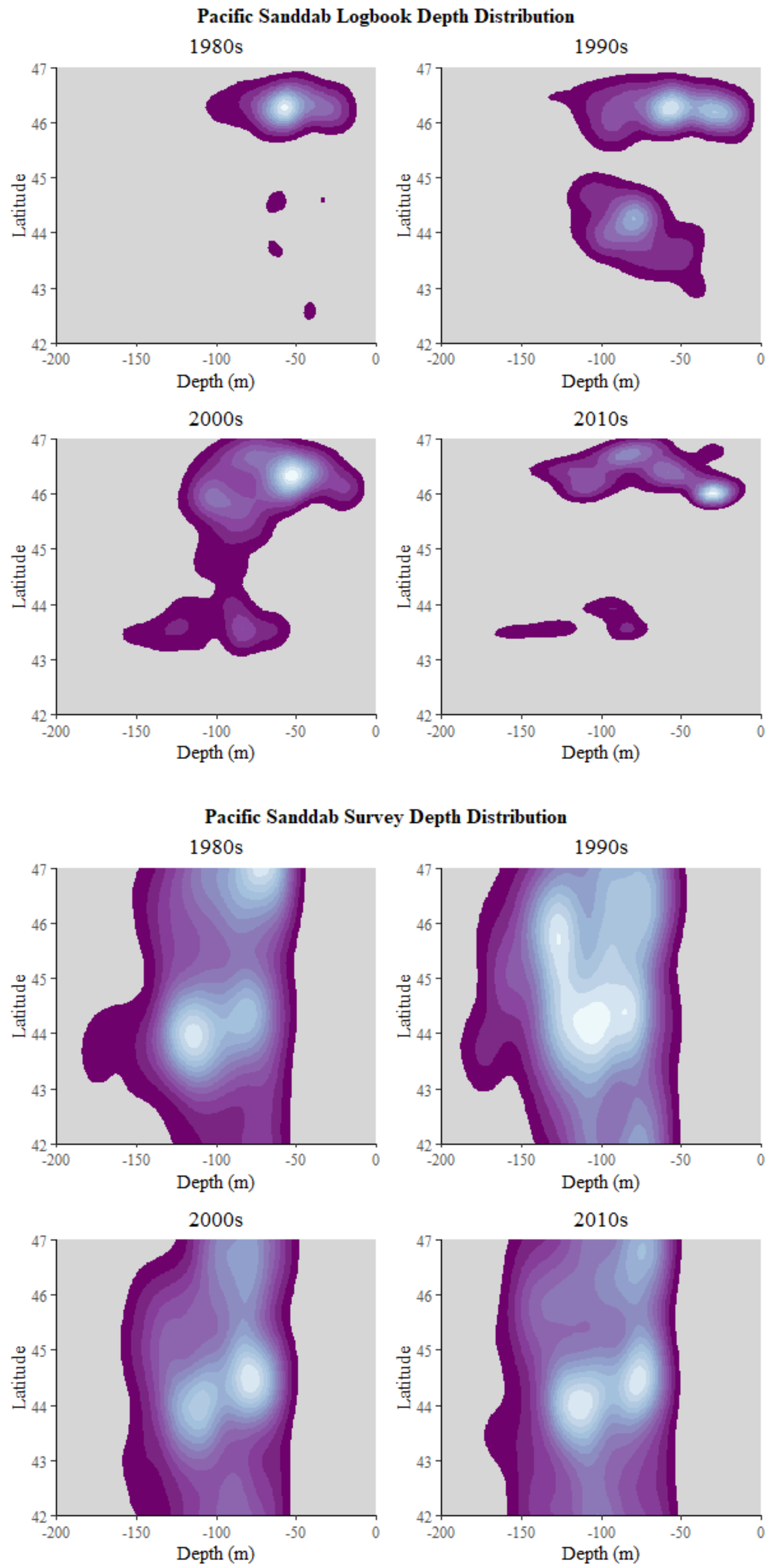

Figure 3.11: Same as figure 3.8 but for Pacific sanddab.

the survey wider, such as those centered at but were caught in specific patches by the commercial fishery (Fig. 3.8 – 3.10). Pacific sanddab were caught consistently latitudinally by the survey but had a clear maximum depth limit at about 150 m (Fig. 3.11). Recorded logbook catches for the infrequently caught shallow-water species, starry flounder and sand sole, occurred almost exclusively inshore of the 70-meter isobath (Fig. 3.12 and 3.13). High catch areas for English sole and Pacific sanddab in the logbook data also occurred in shallow water, but substantial catches did extend farther offshore than for the shallow-water species (Fig. 3.10 and 3.11). Dover sole and petrale sole were found on the shallow portion of the shelf (inshore of 55 m), but most catches were in deeper water (Fig. 3.8 and 3.9). In recent years, the shallow water distribution of these species has been found entirely near Astoria. The 55-meter depth cutoff for the

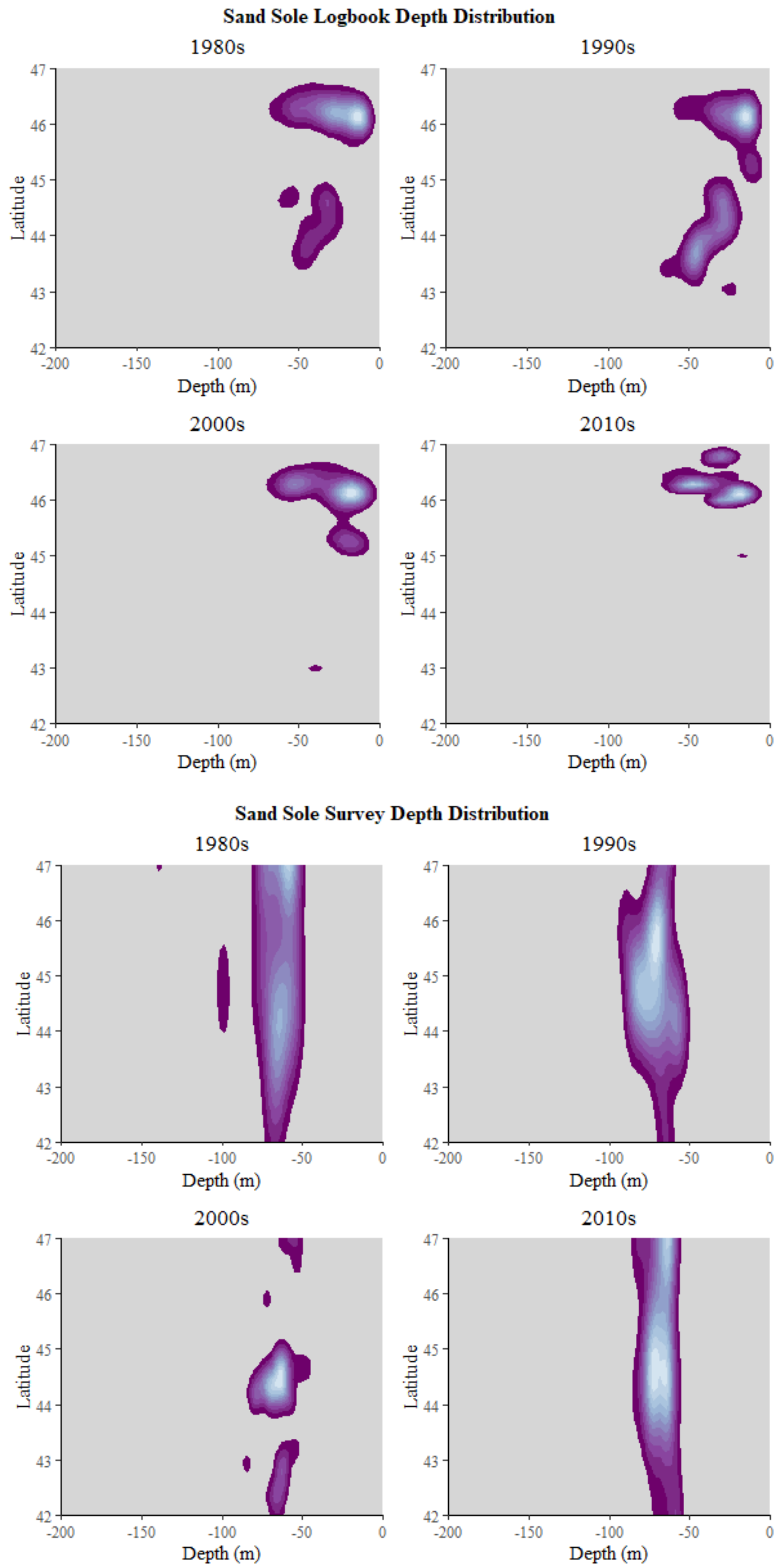

Figure 3.12: Same as figure 3.8 but for sand sole.

survey is clearly visible in the survey contour plots for these two species as well as English sole and Pacific sanddab. With the logbooks, there is obvious movement northward of overall fishing effort.

3.3.3 Seasonal Variation

The seasonal variation maps for Dover sole indicated a difference between population distribution during the “winter” (November – April) and “summer” (May – October). During the summer, the mapped Dover sole mean CPUE values for each decade were higher when compared to the winter (Fig. 3.14). Most nonzero values for Dover sole mean CPUE were found on the outer shelf during the winter whereas there were shallower catches during the summer. Maps for petrale sole generally showed similar patterns of mean CPUE for each decade when comparing the winter and summer (Fig. 3.15). However, mean CPUE values for petrale sole were lower on the

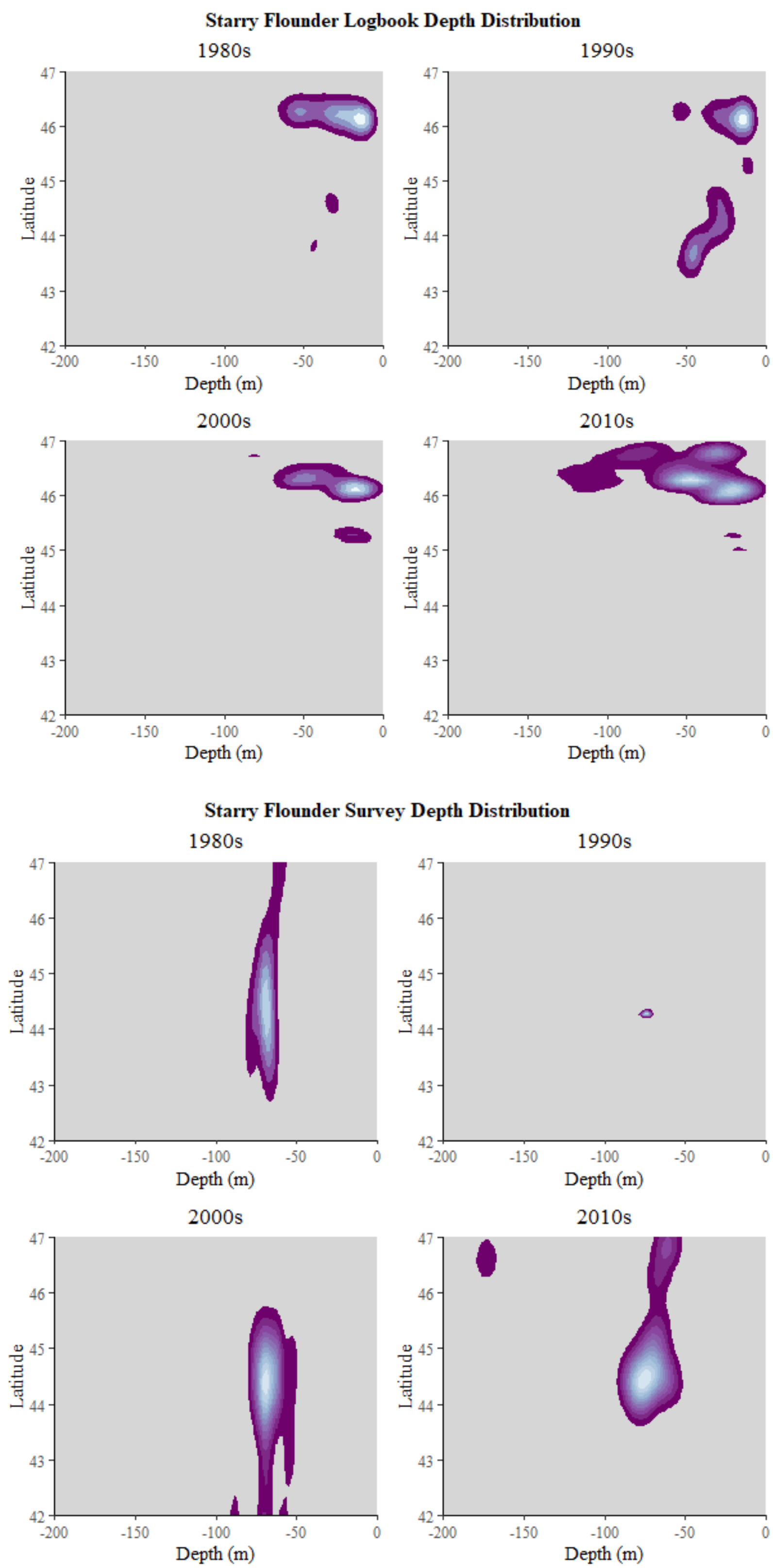

Figure 3.13: Same as figure 3.8 but for starry flounder.

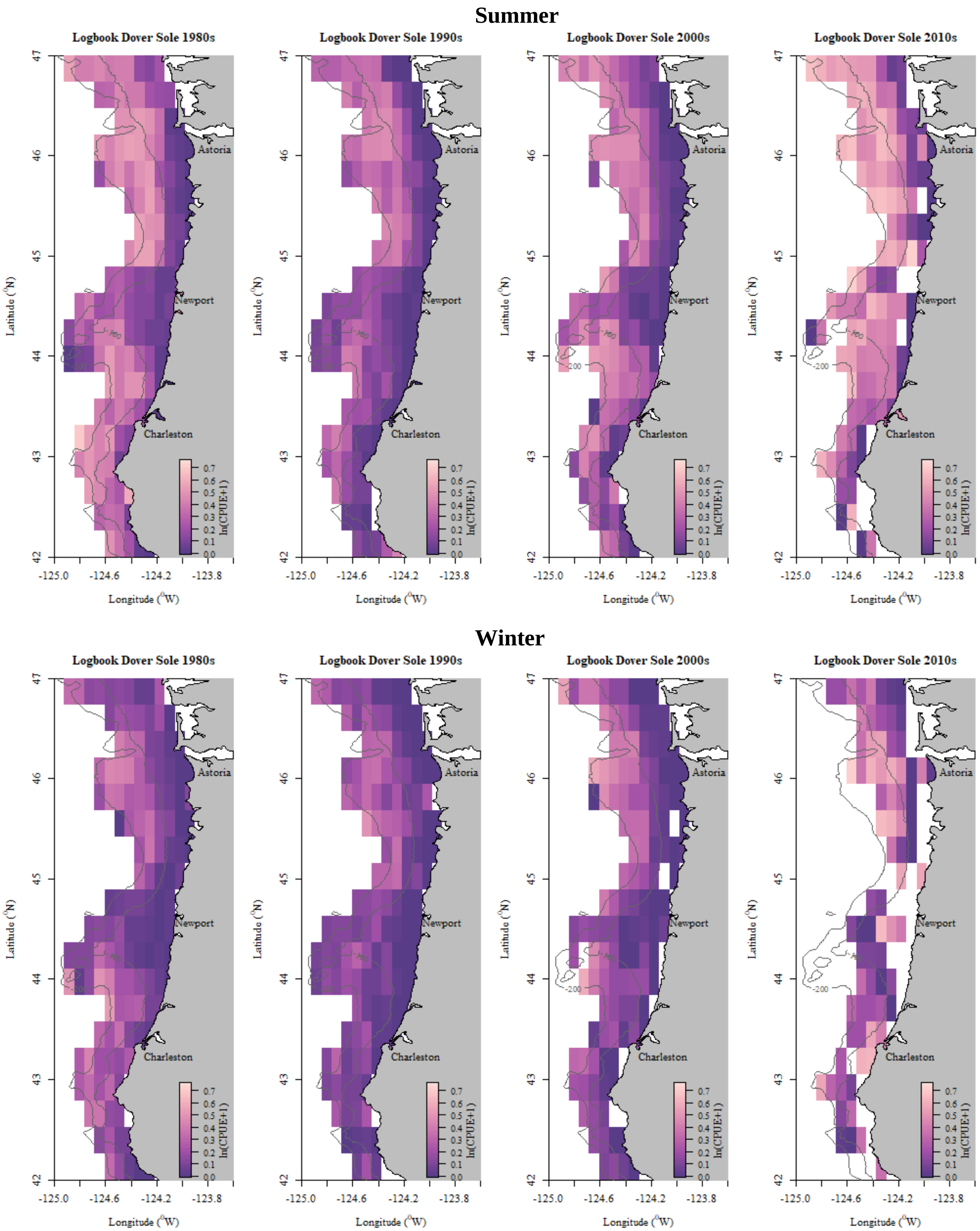

Figure 3.14: The panels above depict the spatial distribution of Dover sole over four decades for two different times of the year using logbook data. The bottom four panels depict data from the portion of the year not sampled by the survey, which ranges from October to mid-May. The top four panels depict tows conducted during the same months the survey samples. Grid cells indicate average CPUE in each area.

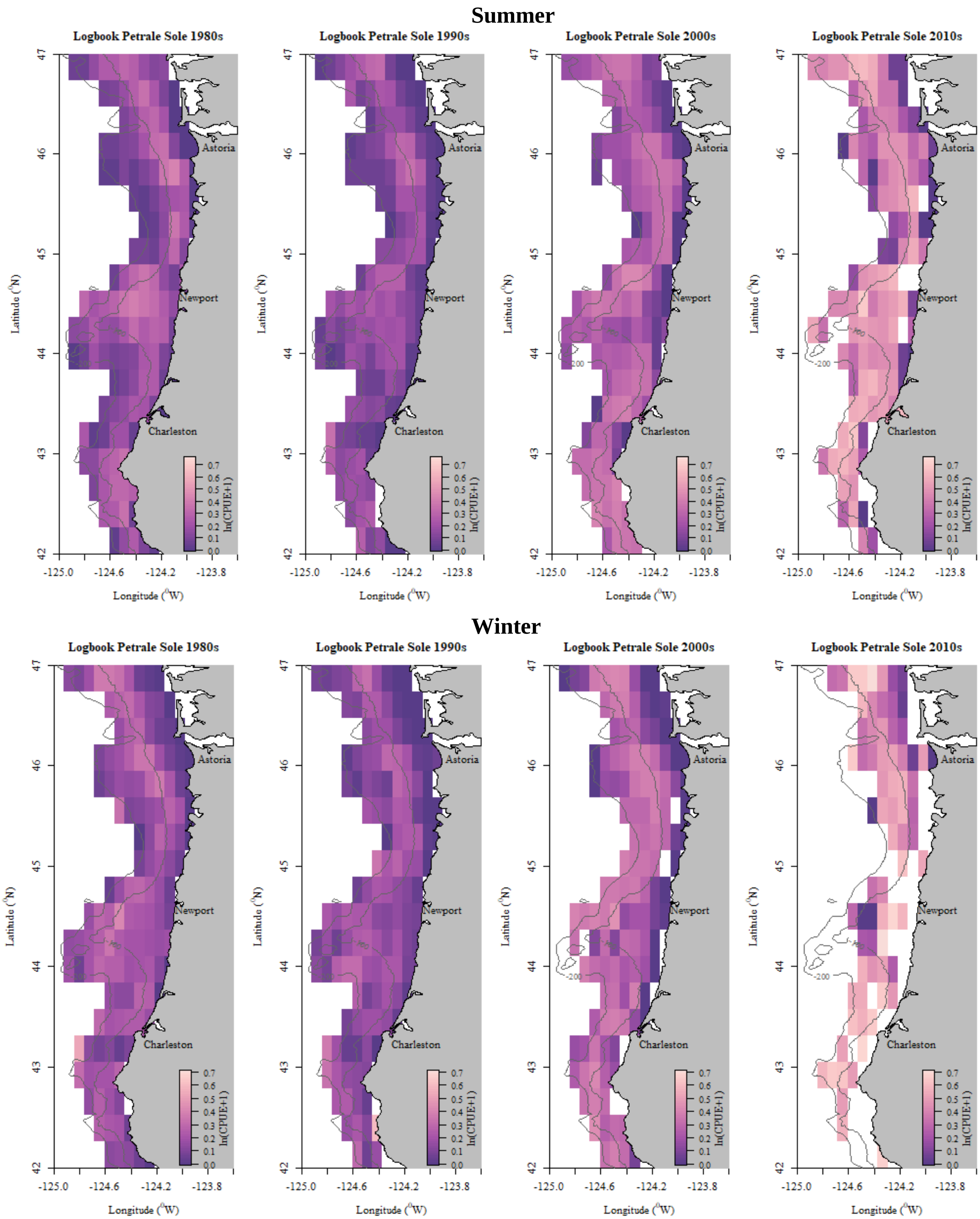

Figure 3.15: Same as figure 3.14 but for petrale sole.

Table 3.6: Average LIC values calculated for each decade for each species. Lower values indicate less overlap between the fishery-dependent and -independent data.

Species	1980s	1990s	2000s	2010s
starry flounder	0.09	0.01	0.03	0.02
petrale sole	0.14	0.40	0.76	0.54
sand sole	0.17	0.18	0.33	0.02
English sole	0.38	0.35	0.52	0.36
Pacific sanddab	0.55	0.59	0.57	0.67
Dover sole	0.70	0.75	0.79	0.61

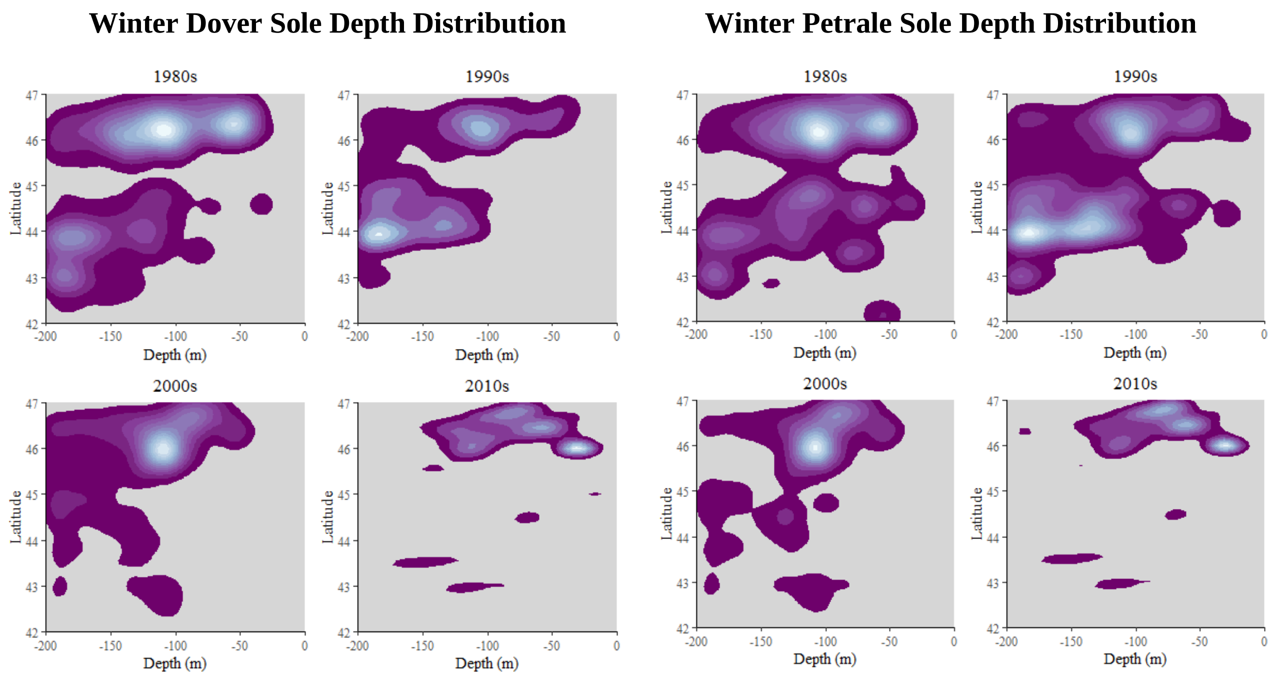

Figure 3.16: Contour maps depicting logbook depth distribution of Dover sole and petrale sole for the "winter" months (November – April).

inner shelf north of 45°N in the winter and there were higher values on the outer shelf during winters in the 1980s and 90s. Contour plots for both species showed that there were more catches in deeper water during the winter compared to the summer (Fig. 3.8, 3.9, 3.16).

3.3.4 LIC

Maps of LIC indicated highly variable levels of overlap between fisher-independent and -dependent data, depending on the species. Dover sole had the highest and most consistent degree of total overlap per decade, followed by Pacific sanddab and petrale sole except for the 1980s, when LIC for petrale sole much lower (Table 3.2). English sole had an intermediate amount of

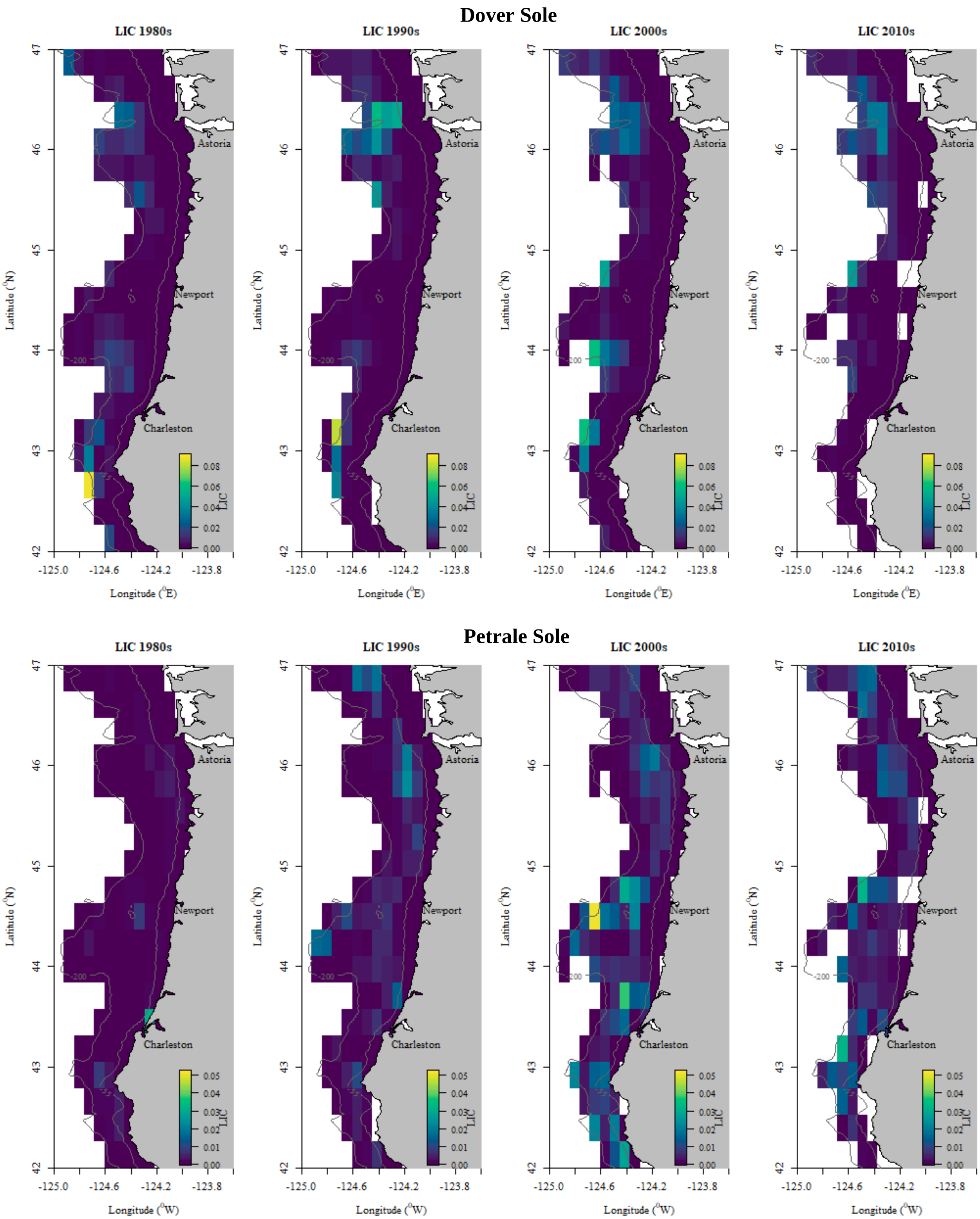

Figure 3.17: The four panels for each species depict average LIC in each grid cell for each decade. Darker colors indicate less collocation while lighter indicate higher LIC. The contour lines delineate the 200- and 55-meter isobaths.

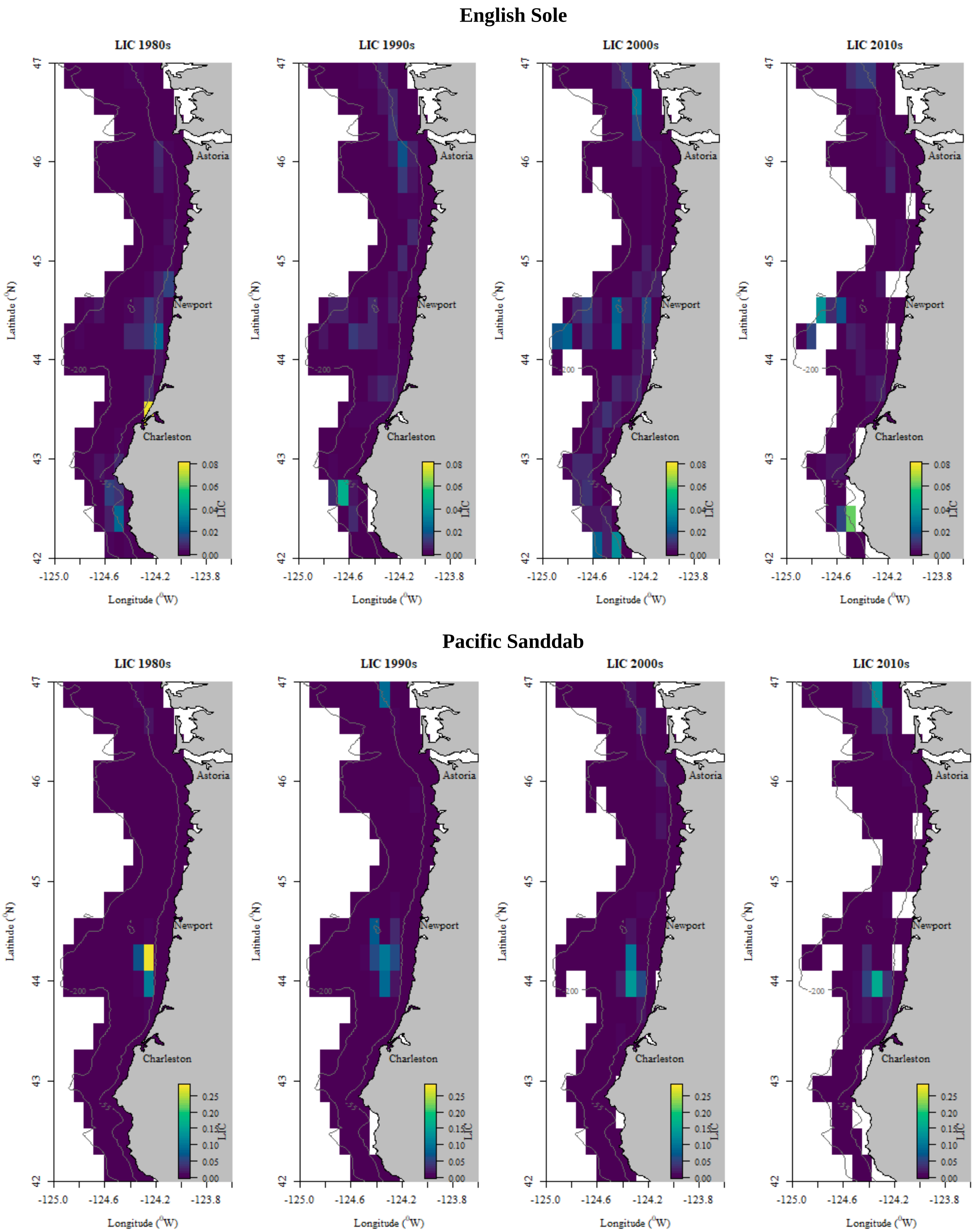

Figure 3.17 continued.

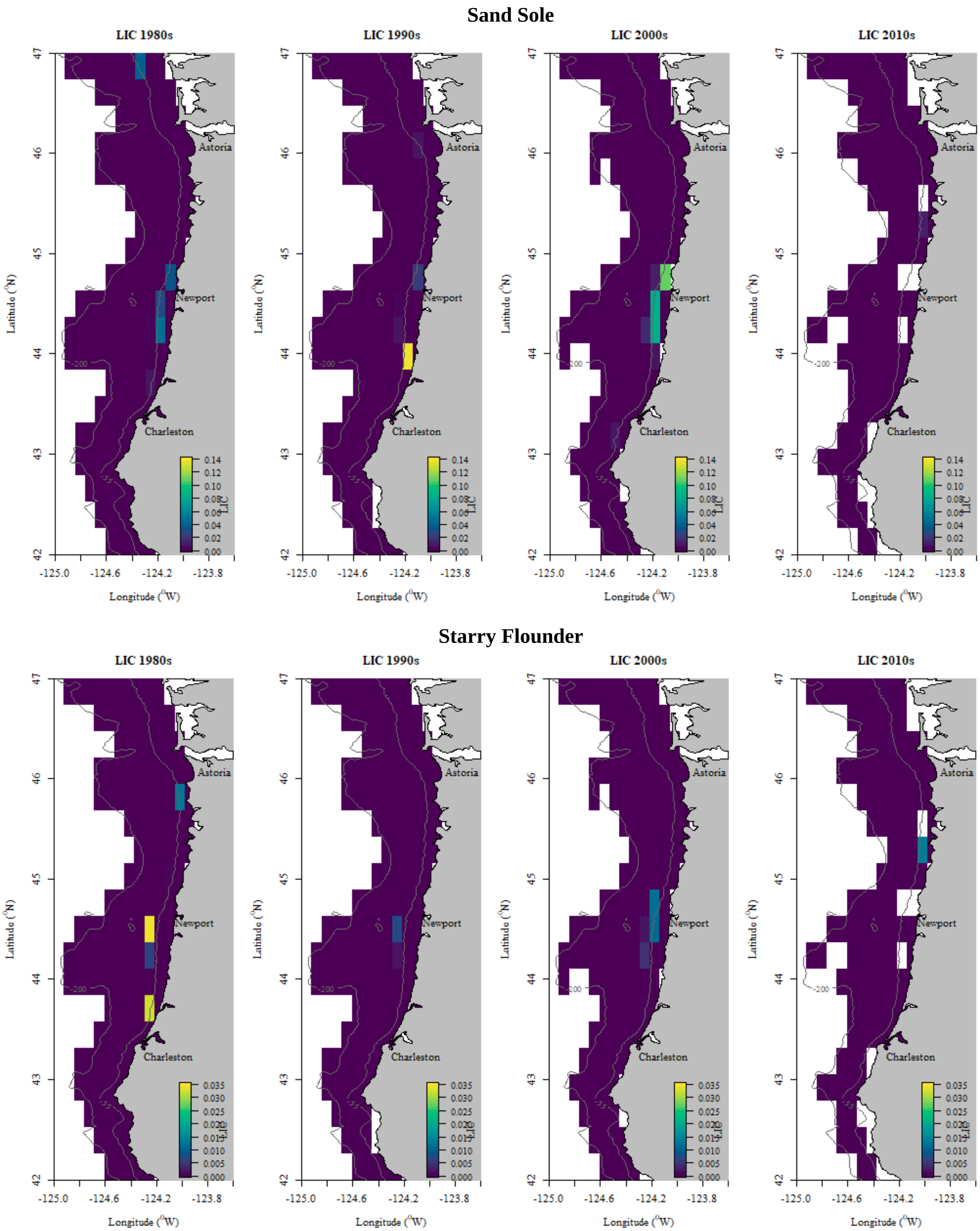

Figure 3.17 continued.

total overlap, and the total LIC values for sand sole and starry flounder were low in each decade. Maps for each species provided a more detailed image of where collocation occurred. Petrale sole and Dover sole both had spatial overlap between data sources on much of the shelf between the 55- and 200-meter isobaths (Fig. 3.17). The highest spatially explicit LIC values for Dover sole were located near the 200-meter isobath, whereas high values for petrale sole were more evenly dispersed throughout the 55- to 200-meter depth range. Pacific sanddab had some of the highest total LIC values of all the species, though the spatially explicit values were largely centered around the mid-latitude area of the shelf similarly to sand sole and starry flounder. English sole had more variable spatial overlap than Pacific sanddab and the average total LIC values for each decade were lower than those for Pacific sanddab.

3.4 **Discussion**

Fishery-dependent and -independent data have been shown to be complementary when mapping fish distribution in other regions (Pecquerie et al., 2004; Stallings, 2009; Murray & Orphanides, 2013; Lyons et al., 2013) and this seems to also be the case here for certain time periods and some Oregon nearshore flatfishes. The logbooks provide a large quantity of self-reported data, while the NOAA datasets are smaller but created through random sampling, so they have more uniform spatial coverage. Visualization of the fishery-independent and -dependent effort associated with the Oregon nearshore trawl fishing grounds illuminated clear spatiotemporal disparities between the datasets. This lack of agreement happens for several reasons. First, NOAA has never sampled inshore of the 55-meter isobath and there were fewer surveys in the 1980s and 90s, when the surveys were triennial, than in the 2000s and 2010s. Secondly, even though the fishery targets the inshore and was active every year, total fishing effort during the 2000s and 2010s tapered off and is concentrated in the north. This leaves a noticeable gap in fishery-dependent data in the southern locations and an overall data gap for inshore locations in the recent decades. There are challenges associated with bringing these data sources together for future analyses, but this research showed there is potential.

Northerly movement of fishing effort in recent decades toward Astoria and Newport happened because this is where most of the fleet is homeported and where factories that process non-whiting groundfish are located. This concentration of effort around larger ports or those with processing plants illustrates one reason why the NOAA surveys can provide more spatially consistent and statistically useful data for specific species. Although in general there is more fishing near ports, in the 1980s and 90s these ‘biases’ toward specific ports were less evident. Numerous processing facilities were still available to fishermen at most ports prior to the intensified regulation and management that followed the fishery’s collapse in 2000 (Hanna, 2000; Warlick et al., 2018). Management and policy changes in the early 2000s led to consolidation and a federal buyback of vessels, resulting in only five major processing facilities for non-whiting groundfish. Therefore, the time period most suitable for potential use of fishery-dependent data to fill in fishery-independent gaps for specific species is likely during the 1980s and 90s. For spatial analyses, this likely requires use of preferential sampling models to account for vessels targeting or retaining specific species (Diggle et al., 2010; Pennino et al., 2016). Caution should be taken when using logbook data for the 1980s and 90s because the technology available was less advanced and therefore less accurate, compliance was variable, and bycatch was not recorded (Sampson, 2011; Sjostrom, 2019). For the most recent two decades, the survey changed to a grid-based stratified random sampling with better spatial coverage (Fig. 3.1). Because the logbook data are concentrated in the north, fishery-dependent data may be more redundant than complementary in the 2000s and 2010s for species that inhabit much of the shelf (e.g., petrale sole, Dover sole).

Throughout the four decades studied it was evident that the survey has not sampled much of the habitat occupied by shallow-water flatfishes (<55 m). While starry flounder and sand sole are not among the most heavily targeted flatfishes, they have been caught consistently by commercial trawl vessels, albeit in smaller amounts than other species. Fisheries for both species are considered data-poor by the PFMC, and there is uncertainty about the status of either species (PFMC, 2018). There is not presently a dedicated fishery for starry flounder and sand sole, though they were once more frequently pursued as part of a nearshore mixed flatfish fishery (Fig. B.2; Alverson et al. 1964; PFMC 2018). Lack of data in the survey (see Table 3.1) has made it difficult to determine whether there have been shifts within starry flounder and sand sole populations, and this could be partially remedied by the use of logbook data.

There was very little overlap between datasets when comparing starry flounder and sand sole catches, but logbook data indicates both species are present throughout the inshore portion of the shelf. The location of these catches suggests that the NOAA surveys largely miss both populations by not sampling shallower areas, and therefore that stock assessments do not factor in the area where both are typically commercially caught. No discernible changes in population distribution were picked up by the survey that would help explain the inshore shift in high logbook catch rates for both species. Either a distributional shift in these populations or a change in preference for fishing location is possible, but it is unclear which is occurring. However, even without this fishery-independent information, similar types of habitat compression have been documented for English sole and Pacific sanddab (see Ch. 2), so this may also be the case for starry flounder and sand sole. Additionally, maps of overall fishing effort do not indicate an overall trend in recent decades toward fishing shallow waters, which may point to other factors not addressed in this thesis. Both species are predicted to be vulnerable to climate change (Cheung & Oyinlola, 2018). This is due to their potential exposure to changing ocean conditions as well as their life history characteristics, as both rely on the shelf or estuaries to complete their life cycle (Orcutt, 1950; Pearson & McNally, 2005). With the limited information used to create these visualizations, it is not possible to say whether the shifts seen in both shallow-water species are due to changes in chemical or physical oceanographic dynamics in the nearshore. There also appear to be potential external factors driving the changes in mean CPUE for these species, as evidenced by the nearly aligned peaks in CPUE in the early 2000s (Fig. B.2). One possible explanation for this could be simultaneous large recruitment events. In the California Current Ecosystem, there were multiple other groundfish species with large recruitment in 1999. If this was also the case for sand sole and starry flounder, that could have led to the spike in catches in the 2000s, as both species grow quickly in their first few years and then enter the fishery (Orcutt, 1950; Hettman, 1979; Richmond, 1983).

Data comparison and visualization of the four other species presented very different results from the shallow-water species. Two of those species are petrale sole and Dover sole. Petrale sole is the only flatfish species that was previously categorized as overfished by the PFMC and for which nearly all quota is caught each year (PFMC, 2018; Wetzel, 2019). Both petrale sole and Dover sole nearshore populations have experienced distributional changes in recent decades (Ch. 2). The petrale sole population off Oregon and Washington has decreased in areas that now regularly experience hypoxia but increased in numbers in other spots. There has been an overall increase in presence of Dover sole, especially on the northern shelf (Ch. 2). These changes may explain the increase in logbook mean CPUE per year of Dover sole near Astoria seen in the most recent decade and the increase in logbook CPUE for petrale sole off the southern Oregon Coast since the 1990s (Fig. 3.2-3.3). Although there is not consistently catch of either species in the shallowest portion of the shelf, the depth distribution plots show that the shallow portion of both populations is missed by the NOAA surveys, especially near Astoria. Thus, increased sampling inshore of the 55-meter isobath could provide new information for these species. This is especially necessary for detecting any population expansion shoreward, which may be occurring for both species given their increase in presence on the shelf and recent higher logbook CPUE inshore (Fig. 3.2-3.3). For Dover sole, and to a degree petrale sole, there is also information missed by the survey due to the timing of sampling. While most fishing does occur during the summer months, there is fishing happening outside of those months and the community composition is likely different in the winter due to seasonal migrations. However this may not be the case for all migratory species, as there were only minor differences between seasons for petrale sole, and earlier research determined that summer sampling is adequate for most population assessments (Fox & Starr, 1996).

The final two species, Pacific sanddab and English sole, portrayed somewhat of a middle ground between the other four species. Survey data indicated that both species are predominantly found on the inner shelf, but this was not necessarily true based on the logbooks. The narrow band of Pacific sanddab commercial catches with patches of high CPUE possibly suggests that there are specific geographic areas where either Pacific sanddab are targeted or retained, or where there are high density clusters. Recent research found a similar distributional pattern for juvenile Pacific sanddab, indicating that these patches in the logbook data are likely groups of juveniles in nursery grounds (Tolimieri et al. 2020). High CPUE English sole commercial catches were variable and may be associated with either ports or proximity to the estuaries where English sole live as juveniles (Krygier & Pearcy, 1986; Gunderson et al., 1990). Despite the similar inner shelf spatial distributions for English sole and Pacific sanddab, overlap metrics were surprisingly different. The variable overlap between datasets with Pacific sanddab and English sole, as well as Dover and petrale sole, was unexpected. A high total LIC did not necessarily predict an even distribution of high spatially explicit LIC values, nor did it correspond to the frequency of catch in either dataset (see Table 3.1). This showed that total overlap does not necessarily correspond to how heavily the species is targeted (high LIC ≠ heavily fished) and that fishery-dependent data may be valuable for filling in spatial gaps not just for shallow water populations, but also for species like petrale sole and Pacific sanddab.

Assessment of the utility of combining these data sources for spatiotemporal analyses should therefore be determined on an individual species basis. Species with low spatially explicit or total LIC values, shallow distributions, or seasonal variability would be potential candidates for future work as long as they are reliably identified to species within logbook records.

With renewed interest in revitalizing the nearshore fishery, it is crucial for managers to understand the current and past ecology of Oregon's continental shelf. Should species like starry flounder and sand sole become increasingly targeted or caught as bycatch, spatiotemporal data from logbooks could allow for better future assessment and a more complete historical baseline dataset. English sole and Pacific sanddab are perhaps more likely that the other species to gain market interest in Oregon, given their previous importance as part of the nearshore fishery (He et al., 2013; Cope et al., 2015). In the case of Pacific sanddab, the species has had a moderate resurgence in popularity in California. While over 90% of the petrale sole quota is caught each year, this is not true for Dover sole because sablefish is a choke species and there is little market interest. Despite this, there are current efforts to increase Dover sole quota utilization, particularly for the northern region, so the Oregon nearshore may experience more fishing activity as a result (SaMTAAC, 2019). Additionally, there are ongoing attempts to increase consumption of Oregon seafood through industry-driven groups like Positively Groundfish and Oregon Sea Grant's Eat Oregon Seafood initiative. Utilizing fishery-dependent and -independent data can assist in this endeavor, providing more context for potential bycatch interactions and changes in community composition due to distributional shifts over time. This is not only useful for groundfishes with directed fisheries, but also for those caught less frequently.

3.5 **References**

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Chapter 4: Conclusion

In this thesis I analyzed changes in spatiotemporal dynamics of nearshore (< 200 m depth) commercially important groundfishes in the northern California Current. I also assessed gaps in fishery-independent (NOAA surveys) and -dependent (logbooks and fish tickets) data sources for the Oregon non-whiting groundfish trawl fishery over the past four decades. Activity in the groundfish fishery declined substantially following the collapse of the industry in 2000 and during the resulting rebuilding period. Recent interest from fishermen to fish waters shallower than 200 m off the Oregon Coast sparked the creation of an Oregon Sea Grant project that aims to characterize nearshore groundfish communities, which is a component of this thesis. I found that physical shelf structure is a driver of groundfish assemblages in that there are separate groups associated with different habitat types and depth zones. While climate indices were not influential, temperature and depth affect the abundances of multiple groundfish populations. Reductions in the presence of hypoxia-intolerant species in hypoxic regions were discernible over a four-decade period while the population distributions of hypoxia and warm water-tolerant species shifted inshore. Visualization of fishery-independent and -dependent data showed that survey data in the 1980s and 90s had the most spatiotemporal information gaps and highest potential for complementary use of logbook data in future analyses. Species commonly caught by the surveys had better spatial sampling coverage of their distributions compared to shallow water species that are less frequently targeted. Overlap between logbook and survey datasets was variable but was often highest near ports. The nearshore Oregon groundfish trawl fishery faces challenges from climate change, lack of market interest, and reductions in fleet and processing plant numbers. The three preceding chapters, summarized in Figure 4.1, provide context for future management of a sustainable fishery by characterizing the nearshore groundfishes and the changes in abundance and distribution these species exhibited during the last four decades. In the following sections I provide examples of issues facing Oregon’s groundfish fishery, such as increased resource use on the continental shelf and climate change, as well as give recommendations for future management and science in the modern nearshore.

4.1 **Expanding Oregon nearshore fisheries**

There is currently potential to expand the groundfish fishery into the nearshore due to recent regulatory changes and this research provides a baseline understanding of the groundfishes inhabiting the continental shelf and the data available to study them. In the U.S. West Coast non-whiting groundfish trawl fishery, approximately 187 million pounds of quota out of 247 million pounds went uncaught in 2017 (Gann, 2019), which makes further development of the fishery both in Oregon and the nearshore possible. The lack of utilization is largely a result of changes in regulation and management following the period of fishery expansion and overexploitation that led to the rebuilding of the 2000s and 2010s (Hanna, 2000; Warlick et al., 2018). Now that the majority of formerly overfished groundfish stocks have recovered, the trawl Rockfish Conservation Area (RCA) closures off the Oregon and California Coasts have been lifted as of January 2020, and gear restrictions are now less strict for the shelf, there is renewed interest in the nearshore from current fishery participants. The removal of the trawl RCA allows access to a strip of the continental shelf along the shelf-slope break, bringing with it the potential to target the now-rebuilt rockfish stocks that were protected by the RCA. There also appear to have been recent increases in nearshore presence of commercially important flatfishes like Dover sole and rex sole (Chapter 2), and fewer gear restrictions may provide

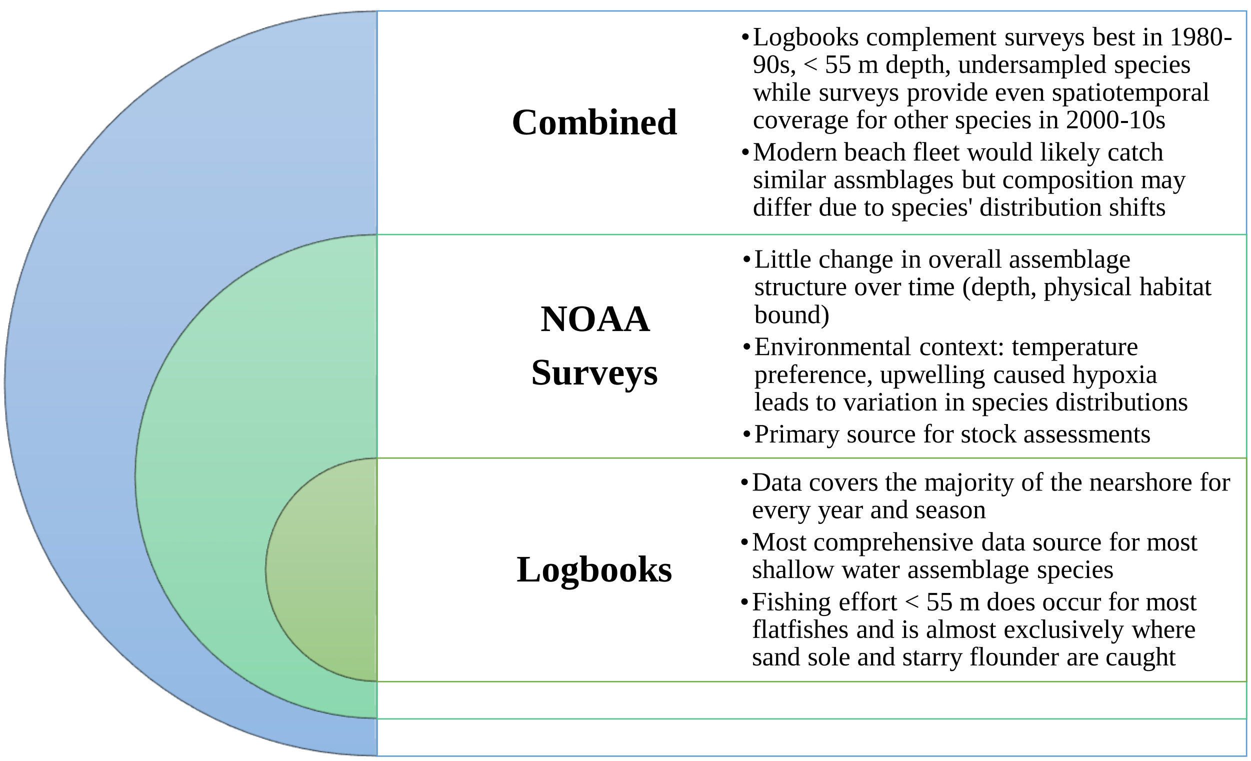

Figure 4.4: Summary of the thesis main points. Logbooks and NOAA surveys independently provide critical knowledge but when combined lead to additional information and fill in gaps. Data obtained from logbooks influence what survey data is collected to manage the fishing industry.

incentive to fish the shelf. Although there is clear potential for revitalization of the nearshore groundfish fishery, the industry will face economic, social, and environmental obstacles should it grow.

Expansion of the groundfish fishery into the nearshore would likely lead to catches of similar fish today when compared to the 1980s and 90s but we have a limited understanding of how specific groundfish populations respond to oceanic change. This research showed that groundfish assemblages present in the nearshore have remained consistent over time and can be corroborated by past studies that assessed species groupings (Rogers & Pikitch, 1992; Jay, 1996; Williams & Ralston, 2002; Cope & Haltuch, 2012). However, population-level responses to environmental change are diverse and due to data availability, it is uncertain which nearshore groundfishes are more vulnerable to climate change and overfishing. As a result of this research, it is known that petrale sole, sablefish, lingcod, arrowtooth flounder, and rex sole have likely experienced distribution shifts out of areas subject to low dissolved oxygen concentrations, and several groundfishes exhibit relationships between bottom temperature and abundance (Chapter 2). It is possible that this is true for other groundfish populations. The restructuring of Oregon's groundfish fishery in the wake of the fishery's collapse and the reduction of the "beach fleet", Oregon's nearshore bottom trawl fleet comprised of small vessels, led to reduced fishing effort in the nearshore and likely contributed to the lack of shelf groundfish research (Warlick et al., 2018; Sjostrom et al., 2020). Because the NOAA surveys are limited to 55 meters depth and species of less commercial importance receive a smaller amount of scientific attention, many stocks are considered data moderate or data poor, making it difficult to investigate the population dynamics of nearshore groundfishes (Dick & MacCall, 2010; Cope et al., 2015). It is also challenging to predict how these populations will respond to fluctuations in the environment. Logbook data can fill in some of the gaps present in scientific data collection, particularly for those species that dominate the trawlable sandy inshore habitat, but this is not possible for all groundfishes. Rockfishes, for example, were not historically identified to species in logbook records. The addition of more surveys in the area inshore of 55 meters depth would be especially valuable for further research on how exploitation of nearshore assemblages would affect groundfish populations in a changing climate.

The groundfish fishery often interacts with non-groundfish species. Therefore, incidental take of protected and prohibited species and bycatch restrictions are a worry for the future of the nearshore trawl fishery. In recent years concerns have been raised in the West Coast fisheries over gray and humpback whale entanglement and albatross interactions, though the non-whiting trawl fishery is considered to pose minimal risk to most marine mammals and seabirds (Guy et al., 2013; PFMC, 2019). However, there are other bycatch concerns, including Chinook salmon (*Oncorhynchus tshawytscha*) and Pacific halibut (*Hippoglossus stenolepis*). Chinook salmon and Pacific whiting occupy similar habitat, with Chinook salmon being more frequently caught incidentally by the Pacific whiting fishery, but Chinook salmon have historically also restricted catches in the bottom trawl fishery (NMFS & PFMC, 2019). Pacific halibut, managed by the International Pacific Halibut Commission (IPHC), are most often encountered as bycatch in bottom trawl gear in Oregon's non-whiting groundfish fleet (Jannot et al., 2020). Halibut bycatch has been mitigated by using bycatch reduction devices and the Pacific Fishery Management Council (PFMC) implementing temporary Block Area Closures (BAC) to prevent bottom trawling (Lomeli & Wakefield, 2013; NMFS & PFMC, 2019). Pacific halibut is typically found in areas also inhabited by nearshore flatfishes during the summer months and is most commonly caught as bycatch near the shelf-slope break (Jannot et al., 2020), while some Chinook salmon stocks either spend their first year or their entire ocean phase on the shelf (Trudel et al., 2009). Increased bycatch of Chinook salmon and Pacific halibut will be a potential problem if fishing increases in the nearshore.

In the flatfish fisheries, bycatch of groundfish species like rockfish, juvenile sablefish, and skates are a concern. Juvenile sablefish bycatch is an issue because they count toward the sablefish quota allocations but are too small to market, and they inhabit the shelf until they join the larger adults at the shelf break (Haltuch et al., 2019). Rockfish are long-lived and multiple stocks were once overfished, which has led to lower catch limits. Skates pose a challenge, both as a bycatch species and a target species, because little is known about the West Coast species' population distributions and migration patterns, which is necessary for assessment at biologically relevant spatial scales (Bizzarro et al., 2014; Matta et al., 2017). Frequency of occurrence between the annual and triennial NOAA surveys was highly variable for most skate species (Chapter 2), making inconsistent catchability throughout time an obstacle for analyses, and they are not historically identified to species in the logbooks. Several skate species seem to occupy similar depths to the PFMC-managed flatfishes assessed in this research but are thought to primarily inhabit the mid-shelf to the shelf break (Bizzarro et al., 2014). Although all groundfish are managed together, certain stocks can restrict catch of other species.

While there is opportunity for Oregon's nearshore trawl fishery to expand, the industry will face economic challenges. Sablefish and petrale sole are fully exploited, but the majority of groundfish stocks, despite commanding a high price (lingcod) or interest (Dover sole) from the industry, are not fully utilized due to a lack of market, choke species, or area closures (e.g., RCA, Essential Fish Habitat Conservation Areas) (McQuaw & Hilborn, 2020). Choke species are those that have low available quota and may prevent other quotas from being met once all the choke species quota is caught. Underutilized species are not targeted despite previous interest or their potential to provide an alternative. For example, the shallow-water assemblage of flatfishes, which includes English sole, Pacific sanddab, curlfin sole, sand sole, starry flounder, and rock sole, was once targeted as a mixed-species fishery and all are suitable for consumption. The ex-vessel price over the last five years for commercially caught groundfishes ranged from $0.10/lb or less for arrowtooth flounder and butter sole to a high of $1.19/lb for petrale sole, with most priced somewhere in between (PacFIN, 2020). A few rockfish species have maintained some level of market interest, but it is still low compared to halibut and salmon, with lower ex-vessel prices for trawl as opposed to hook and line caught fish. Dover sole and lingcod, amongst other species, have underutilized quotas in recent years due in part to sablefish bycatch when targeting Dover sole and area closures like the RCA that affect lingcod (Hicks & Wetzel, 2011; Oken & Essington, 2016). There is potential for the beach fleet to target these species as part of a mixed nearshore flatfish fishery or by fishing the re-opened RCA area. This will depend on whether ongoing marketing efforts such as Positively Groundfish and initiatives, including Oregon Sea Grant's Eat Oregon Seafood are successful in re-popularizing these species. Another obstacle to full utilization of many groundfish species is the few remaining processing plants that can process non-whiting groundfishes outside of those in Newport and Astoria.

The revitalization of the nearshore trawl fishery will require cooperation with other coastal industries that use resources on the continental shelf, some of which could be directly impacted by an increase in nearshore bottom trawl activity. Wave energy technology is currently being tested on the continental shelf near Newport and has the potential to become part of Oregon's energy portfolio. Any bottom contact gear, like trawl nets, has the potential to snag or damage undersea fiber-optic cables and scientific equipment. Most cables terminate in northern Oregon, near fishing grounds used by Astoria-based vessels, and agreements between fishermen and the cable companies are facilitated by the Oregon Fishermen's Cable Committee. The Dungeness crab fishery also operates on the continental shelf, which may lead to additional conflict within the fishing industry. Tourism and recreation are a growing part of the Oregon nearshore economy. These industries may benefit from future growth of the nearshore fishery, as sustainably sourced local seafood has become more important to consumers and may be of interest to those that visit Oregon's coastal communities (Konefal, 2013). Although there is low impact from trawling in sand and mud habitats, and small amount of bottom trawl activity in the northern California Current compared to historic activity, there will be concerns about the consequences of bottom trawling on the nearshore ecosystem from these sectors, as there would still be ecological impacts from increased fishing pressure (Pitcher et al., 2017; Hiddink et al., 2017; Amoroso et al., 2018). Recreational fishing, whale watching, and sightseeing amongst other attractions bring visitors to the Oregon Coast, all of whom are connected to the commercial fishing industry by their shared interest in Oregon's coastal waters. There are a multitude of resource users that interact with Oregon's nearshore and cooperation between interest groups will be necessary moving forward.

4.2 Climate change and vulnerability

While there has been little change in the overall assemblage structure of groundfishes on the shelf over the past four decades, there has been variation in species' population distributions in response to changes in water temperature and dissolved oxygen (Chapter 2). In the coming decades, the northern California Current System (CCS) will likely experience increased upwelling intensity during the spring (Rykaczewski et al., 2015; Wang et al., 2015). This upwelling can bring colder bottom water temperatures on the shelf and anomalous hypoxia events may become more prevalent (Adams et al., 2013; Peterson et al., 2013). Cold temperatures may push shallow-water flatfishes, like English sole and Pacific sanddab, that prefer warmer water inshore while allowing deep-water species, such as Dover sole and rex sole, to expand their distributions shoreward. For some English sole and Pacific sanddab, this effect may have led to increased southern presence in recent decades, as the bottom waters in the area south of Cape Blanco are typically warmer than the rest of the Oregon fishing grounds during the sampling period but have become cooler in recent decades (Chapter 2, Fig. 2.1). Hypoxia is now more prevalent seasonally in the area of the shelf near Heceta and Stonewall Banks and inshore off the southern coast of Washington (Harvey et al., 2019). In those areas, there have been notable reductions in presence for hypoxia-intolerant species like petrale sole and lingcod, though it is not certain that hypoxia is the only cause for these decreases (Chapter 2). It is difficult to ascertain whether similar changes in distribution are occurring for shallow water species like sand sole and starry flounder as data from NOAA surveys is limited and logbook data is self-reported with incomplete spatial coverage (Chapter 3). It is possible that population distributions of species like starry flounder and sand sole have compressed shoreward, as seen with English sole and Pacific sanddab in Chapter 2. Logbook data visualization in Chapter 3 indicates that this may be the case, but with uncertainty due to lack of discard records and a change in overall fishing effort.

Policy makers and resource managers will need to find ways to adapt in a changing climate as there will be societal and economic consequences. Fishing communities in the Pacific Northwest are poised to face numerous challenges in the coming decades, and the resiliency of these communities is being assessed through the PFMC's Climate and Communities Initiative (Blanchard et al., 2012; Barange et al., 2014; Moore et al., 2018; Free et al., 2019). This initiative is part of the PFMC's application of its Fishery Ecosystem Plan (FEP), which looks at the California Current System through an Ecosystem Based Management (EBM) lens for future management purposes (Lester et al., 2010). Within an EBM framework, managers consider how policy decisions, environmental change, consumer preference, and ecological shifts will affect the whole industry, rather than one species (Pikitch et al., 2004; McLeod & Leslie, 2009; Long et al., 2015). Issues identified by the PFMC include range shifts, warming seas, hypoxia, and "ecological surprises", which they define as unexpected, significant ecosystem changes. In the nearshore, uncertainty about the future increases due to the lack of nearshore research. Managers have little knowledge about environmental impacts on shallow water species like English sole, sand sole, and Pacific sanddab, potential targets for the nearshore fleet (Dick & MacCall, 2010; Cope et al., 2015). Recent research predicts that Pacific sand sole, petrale sole, and starry flounder may be especially vulnerable to climate change, while English sole, flathead sole, Pacific sanddab, rex sole, rock sole are likely less vulnerable (Cheung & Oyinlola, 2018). Groundfish fishermen may choose to diversify their fishing portfolios even further than they already do by targeting those species less vulnerable to climate change, making fishing communities more resilient to future environmental change (Kasperski & Holland, 2013; Cline et al., 2017; Strawn, 2019).

4.3 Oregon nearshore policy and management

The modern policy and management landscape of the Oregon nearshore non-whiting groundfish fleet came to be in the wake of overexploitation and the resulting rebuilding period (Warlick et al., 2018). Today the fishery is known as a success story, with all but the yelloweye rockfish stock rebuilt and many certified sustainable by independent non-profit organizations (Associated Press, 2019). The PFMC and ODFW continue to adapt their management strategies and recommendations using EBM to ensure continued sustainability. This has led to a new focus on the nearshore through ODFW's Oregon Nearshore Strategy and potential future objectives in the PFMC FEP. The Nearshore Strategy focuses on Oregon's Territorial Sea (< 3 nm from land) and provides recommendations for future research, conservation, education and outreach, and monitoring. One goal of Oregon's Nearshore Strategy is to address the lack of regular surveys, such as those conducted in federal waters, to reduce the lack of data as a management barrier (ODFW, 2016). This thesis provides evidence that inner shelf fishery surveys would improve the monitoring and management of shelf groundfishes in the northern California Current as well as the greater California Current Ecosystem (CCE). Logbook data can supplement the survey data in areas where research is not regularly conducted for species like sand sole and starry flounder, but consistently surveying in areas shallower than 55 meters depth would provide more statistically useful data that could be used in stock assessments (Chapter 3). The PFMC's FEP encompasses all of the U.S. waters of the CCE, rather than solely the shallowest waters encompassed by Oregon's Nearshore Strategy. However, because the federal management of the CCE by the PFMC uses an EBM framework, there is a potential need to incorporate the nearshore. Factoring the nearshore into groundfish management may be re-evaluated in future, either as part of an FEP initiative or through an evaluation separate from the FEP. (PFMC, 2017). The PFMC FEP goals, designed to help augment individual species management, include increased understanding of the environmental drivers of change in species distribution, population dynamics, and changes in fishing trends over time (PFMC, 2013). This thesis contributes to these PFMC FEP objectives by further supporting past research showing that several groundfish species' abundances in nearshore waters are associated most strongly with depth and bottom temperature (Tolimieri & Levin, 2006; Juan-Jordá et al., 2009; Keller et al., 2012, 2014) and that there have been statistically significant shifts in species' distributions (Bradburn et al., 2011; Sobocinski et al., 2018; Tolimieri et al., 2020; Selden et al., 2020) over the last four decades.

4.4 **Future directions**

The research in this thesis investigated the gaps in available data for the Oregon nearshore groundfish fishery, and the connections between changing oceanographic conditions and the distribution and abundance of Oregon's nearshore groundfishes. Combining fishery-independent and -dependent data sources brings together the expertise of the resource users, managers, and scientists that interact with the fishery. Further research into the economic viability of fishing the nearshore and the addition of inner shelf surveys should account for these differing perspectives and can lead to more successful future resource management by including all stakeholders in the research process. This is crucial for Oregon fishing communities as the climate continues to change. The work preceding this thesis used interviews in addition to logbook and fish ticket data to capture trends and changes in the nearshore groundfish fishery over the last four decades (Sjostrom, 2019). Local ecological knowledge (LEK), the knowledge of fishery participants, provides different and possibly complementary perspectives to scientific ecological knowledge when conducting fisheries research on data-poor stocks like sand sole, Pacific sanddab, and many of the shelf rockfishes (Beaudreau & Levin, 2014). LEK has the potential to contribute to further investigations of poorly understood groundfish such as rockfishes and shallow-water flatfishes that do not have consistently available logbook data or were infrequently caught by NOAA surveys. Additionally, LEK may provide more detail about historic nearshore catches of these species and can add to the already available logbook data for the shallowest shelf waters.

4.5 **References**

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Appendix A: Chapter 2 Figures and Tables

Table A.1: Six GAM formulations were tested for each species and survey. The final model is in bold.

Model Formulation	AIC	GCV	Deviance	Adj. R^2
English Sole Annual Survey				
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	**5979.6**	**1.45**	**31.2%**	**0.299**
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	5981.1	1.46	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	5980.0	1.45	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	5981.2	1.46	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	5991.3	1.46	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	6009.5	1.48	-	-
English Sole Triennial Survey				
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2094.6	1.23	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	**2062.6**	**1.17**	**50.0%**	**0.477**
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2105.6	1.25	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	2084.6	1.21	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2108.7	1.25	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	2098.7	1.24	-	-

Model Formulation	AIC	GCV	Deviance	Adj. R^2
Pacific Sanddab Annual Survey				
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	5065.3	1.70	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	**5058.4**	**1.69**	**46.4%**	**0.449**
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	5077.1	1.72	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	5072.3	1.71	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	5073.8	1.71	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	5070.1	1.71	-	-
Pacific Sanddab Triennial Survey				
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2007.4	1.33	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	**2006.4**	**1.33**	**60.5%**	**0.585**
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2077.1	1.48	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	2074.8	1.48	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2095.2	1.52	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	2089.5	1.51	-	-

Model Formulation	AIC	GCV	Deviance	Adj. R^2
Dover Sole Annual Survey				
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	6083.6	0.905	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	**6079.1**	**0.904**	**55.1%**	**0.543**
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	6202.4	0.955	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	6193.7	0.951	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	6206.5	0.957	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	6198.1	0.953	-	-
Dover Sole Triennial Survey				
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	**2248.5**	**0.848**	**44.3%**	**0.419**
$\mathbf{CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	2249.0	0.849	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2275.9	0.876	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	2277.9	0.878	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}}$	2282.6	0.883	-	-
$\mathbf{CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}}$	2281.1	0.882	-	-

Table A.1: Continued

Model Formulation	AIC	GCV	Deviance	Adj. R^2
Petrale Sole Annual Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	**5816.9**	**0.841**	**22.9%**	**0.216**
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	5818.8	0.842	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	6042.3	0.933	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	6044.1	0.934	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	6044.2	0.934	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	6046.1	0.935	-	-
Petrale Sole Triennial Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	**1131.7**	**0.327**	**24.4%**	**0.21**
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1132.3	0.327	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1136.4	0.329	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1135.4	0.328	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1137.3	0.329	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1138.1	0.330	-	-

Model Formulation	AIC	GCV	Deviance	Adj. R^2
Lingcod Annual Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	3745.5	0.639	-	-
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	**3745.0**	**0.639**	**15.0%**	**0.128**
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	3771.5	0.649	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	3770.2	0.649	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	3771.4	0.649	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	3770.9	0.649	-	-
Lingcod Triennial Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	**669.5**	**0.236**	**23.4%**	**0.194**
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	670.0	0.236	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	680.9	0.242	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	680.9	0.242	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	668.6	0.236	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	667.6	0.235	-	-

Model Formulation	AIC	GCV	Deviance	Adj. R^2
Sablefish Annual Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	3214.0	0.824	-	-
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	**3213.3**	**0.824**	**15.4%**	**0.129**
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	3245.5	0.844	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	3243.7	0.843	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	3229.6	0.833	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	3229.7	0.833	-	-
Sablefish Triennial Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1813.4	1.28	-	-
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	**1808.1**	**1.27**	**25.1%**	**0.215**
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1813.9	1.29	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1814.2	1.29	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1814.6	1.29	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1811.8	1.28	-	-

Table A.1: Continued

Model Formulation	AIC	GCV	Deviance	Adj. R^2
Rex Sole Annual Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	6561.6	1.043	-	-
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	**6558.5**	**1.042**	**34.2%**	**0.329**
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	6589.5	1.056	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	6584.6	1.054	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	6594.9	1.058	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	6594.0	1.058	-	-
Rex Sole Triennial Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	2440.4	0.916	-	-
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	**2439.6**	**0.916**	**40.7%**	**0.384**
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	2520.6	1.003	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	2509.8	0.990	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	2547.6	1.034	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	2539.4	1.024	-	-

Model Formulation	AIC	GCV	Deviance	Adj. R^2
Arrowtooth Flounder Annual Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	4835.8	0.799	-	-
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	**4828.4**	**0.796**	**43.6%**	**0.424**
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	4887.9	0.822	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	4879.1	0.818	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	4911.8	0.832	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	4896.6	0.826	-	-
Arrowtooth Flounder Triennial Survey				
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1305.1	0.466	-	-
$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	**1288.6**	**0.455**	**55.6%**	**0.527**
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1325.2	0.481	-	-
$CPUE_{y,lat,lon} = s_1(PDO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1310.3	0.506	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	1401.8	0.543	-	-
$CPUE_{y,lat,lon} = s_1(NPGO) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1349.8	0.477	-	-

Table A.2: GAM formulations for individual species using the triennial survey Data. Deviance explains the goodness of fit of the model. ΔAIC indicates the difference in AIC between the reference model and the model containing the threshold.

Species	**Best Model for Triennial Survey**	**ΔAIC**	**GCV**	**Deviance**	**Adj. R^2**
Pacific Sanddab	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	1.0	1.33	60.5%	0.585
English Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	32	1.17	50.0%	0.477
Lingcod	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	0.5	0.236	23.4%	0.194
Petrale Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	0.6	0.327	24.4%	0.21
Arrowtooth Flounder	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	16.5	0.455	55.6%	0.527
Dover Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	0.5	0.848	44.3%	0.419
Rex Sole	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + s_5(T_{y,lat,lon}) + \varepsilon_{y,lat,lon}$	0.8	0.916	40.7%	0.384
Sablefish	$CPUE_{y,lat,lon} = s_1(y) + s_2(lat_y, lon_y) + s_3(J_{y,lat,lon}) + s_4(D_{lat,lon}) + \varepsilon_{y,lat,lon}$	5.3	1.27	25.1%	0.215

Table A.3: Comparison of predicted frequency of occurrence and actual data frequency of occurrence. The probability of presence before the threshold was subtracted from the probability of presence after the threshold for each species and the resulting confidence interval was calculated to determine areas of significant increase or decrease in presence. Actual change in presence for each species was calculated and compared to the model predicted change. Yellow highlighted cells are areas that had increases in presence rather than the decreases predicted by the model. Precise locations are available in manuscript figure 2.4.

Species	Location	Predicted Mean Δ	Survey Data Mean Δ
Dover Sole	N. Inshore/Offshore	0.082	0.12
	Heceta Bank	0.10	0.13
	S. Offshore	0.19	0.33
English Sole	C. Offshore	-0.43	-0.026
	S. Offshore/Inshore	0.37	0.64
Arrowtooth Flounder	N. Inshore	-0.32	0.068
	Heceta Bank	-0.47	-0.017
	S. Inshore	-0.48	-0.069
Petrale Sole	Heceta Bank	-0.32	-0.17
	S. Offshore	-0.26	0.032
Pacific Sanddab	N. Offshore	-0.41	-0.014
	Heceta Bank	-0.52	-0.064
	S. Offshore	-0.44	-0.19
Rex Sole	N. Offshore	0.16	0.09
	Heceta Bank	0.39	1.00
	S. Offshore/Inshore	0.39	0.19
Lingcod	N. Inshore	-0.40	-0.16
	Heceta Bank	-0.32	-0.34
	S. Inshore	0.28	0.49
Sablefish	N. Oregon	0.33	0.24

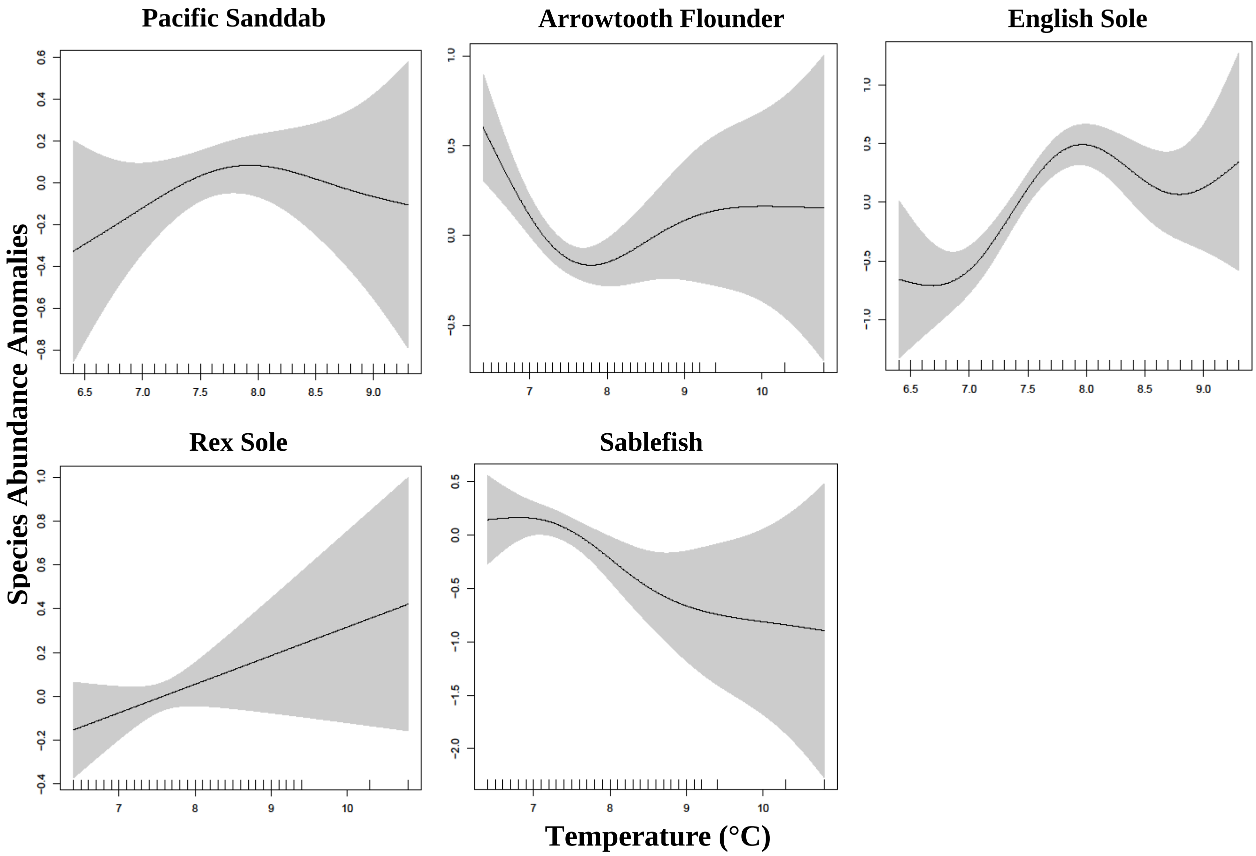


Figure A.1: Effect of temperature on five species for which temperature was included as a covariate in each selected stationary GAM formulation for the triennial survey.

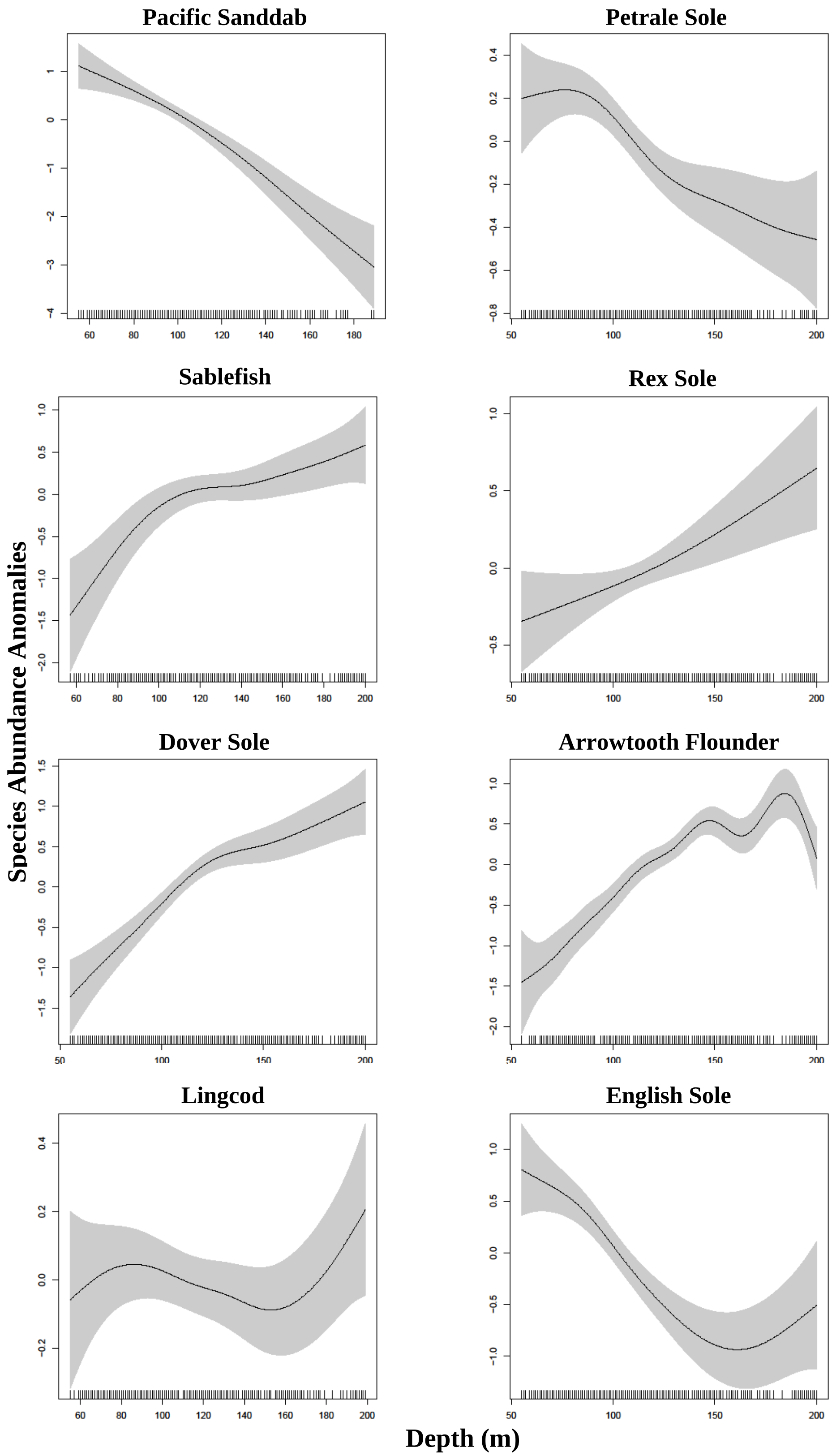


Figure A.2: Effect of depth on eight species for each selected stationary GAM formulations for the triennial survey.

Appendix B: Chapter 3 Figures

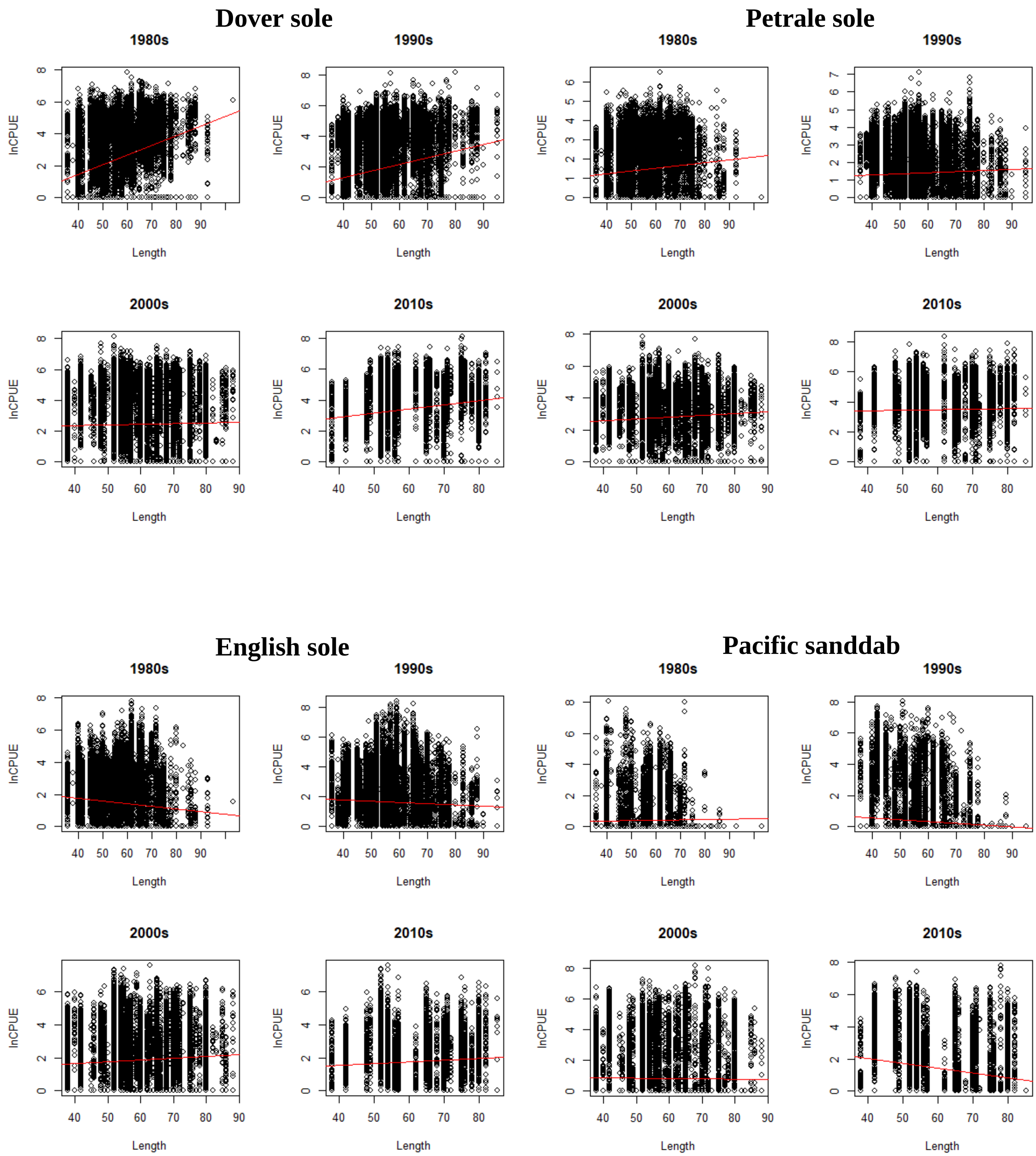


Figure B.1: Linear regression of log(x+1) and vessel length for each species and decade.

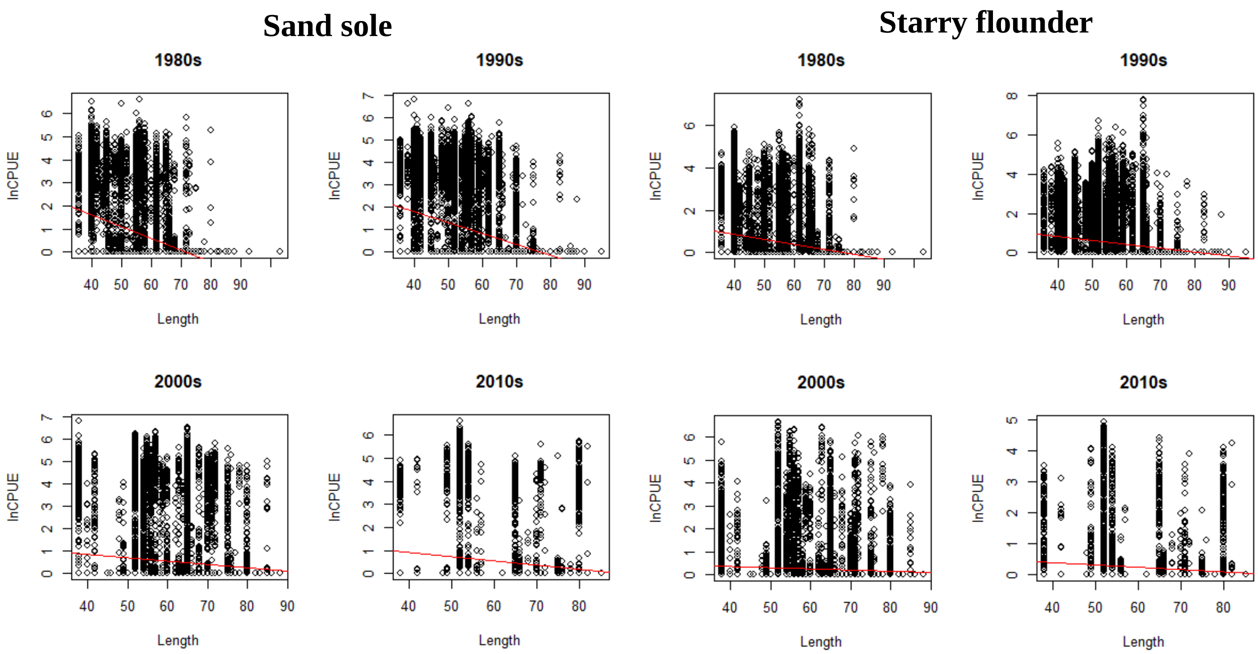


Figure B.1 continued.

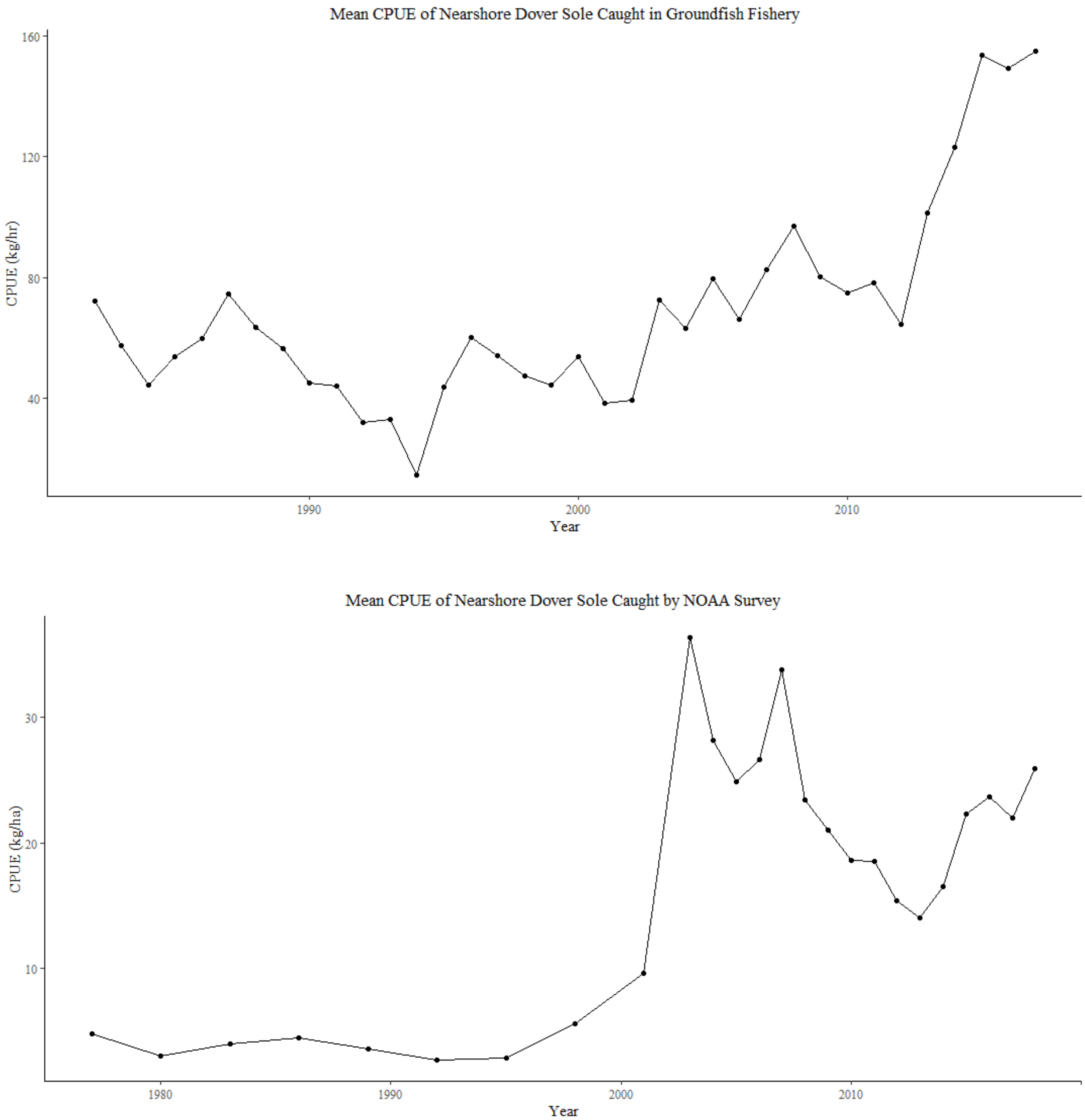
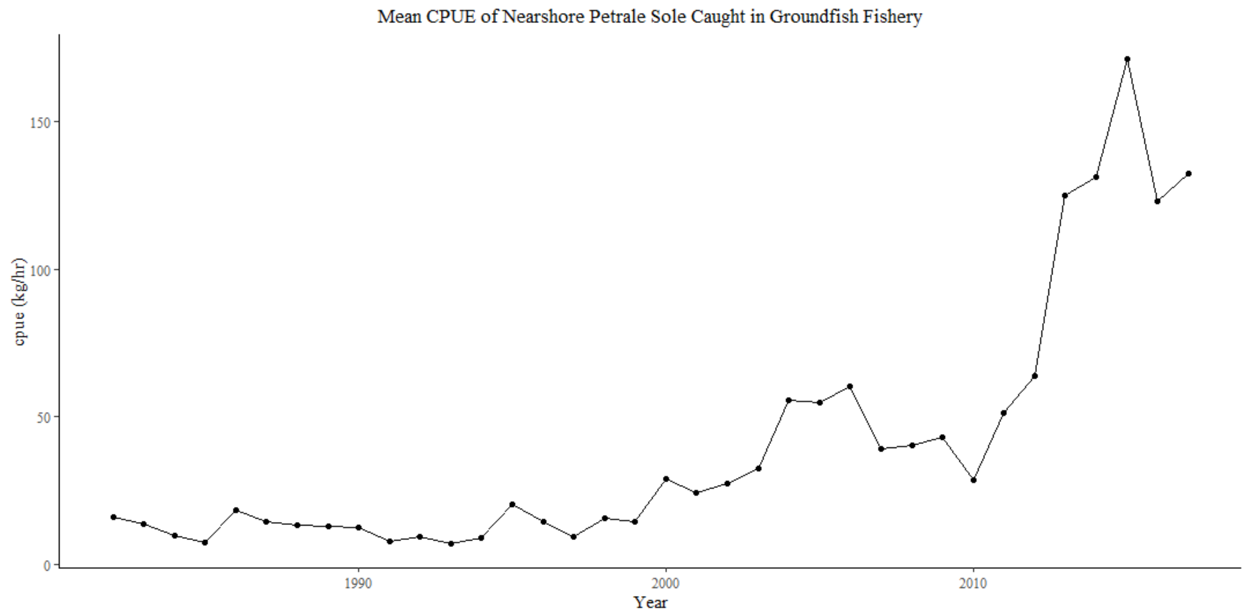
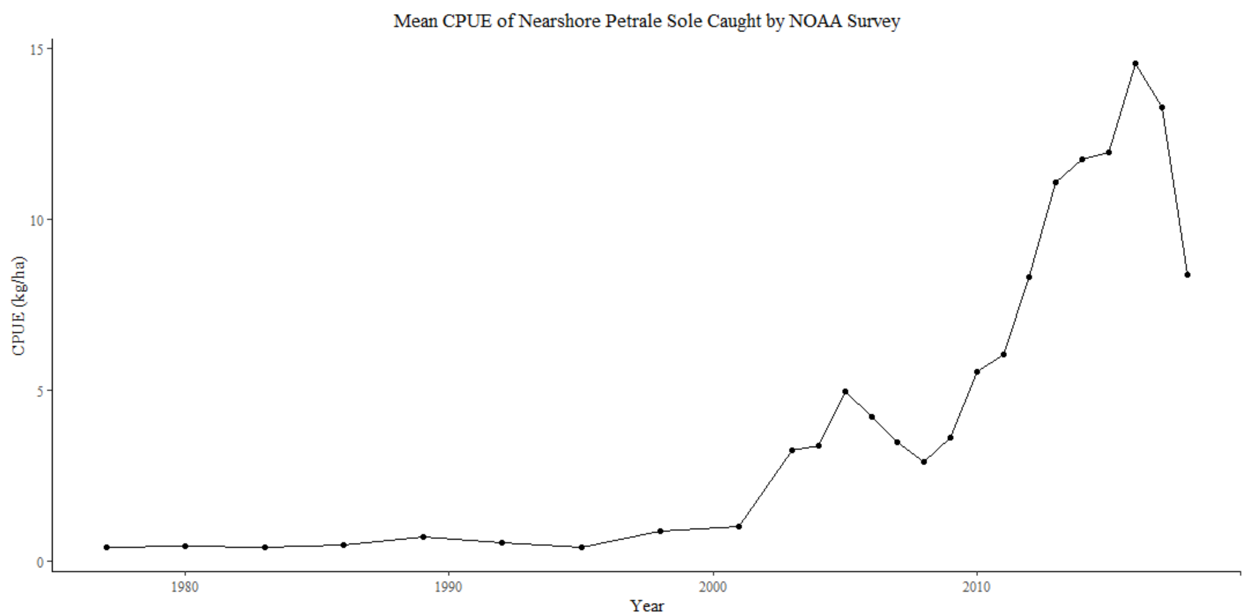


Figure B.2: Mean CPUE for the logbooks (top panel) and the surveys (bottom panel) for each of the six species.





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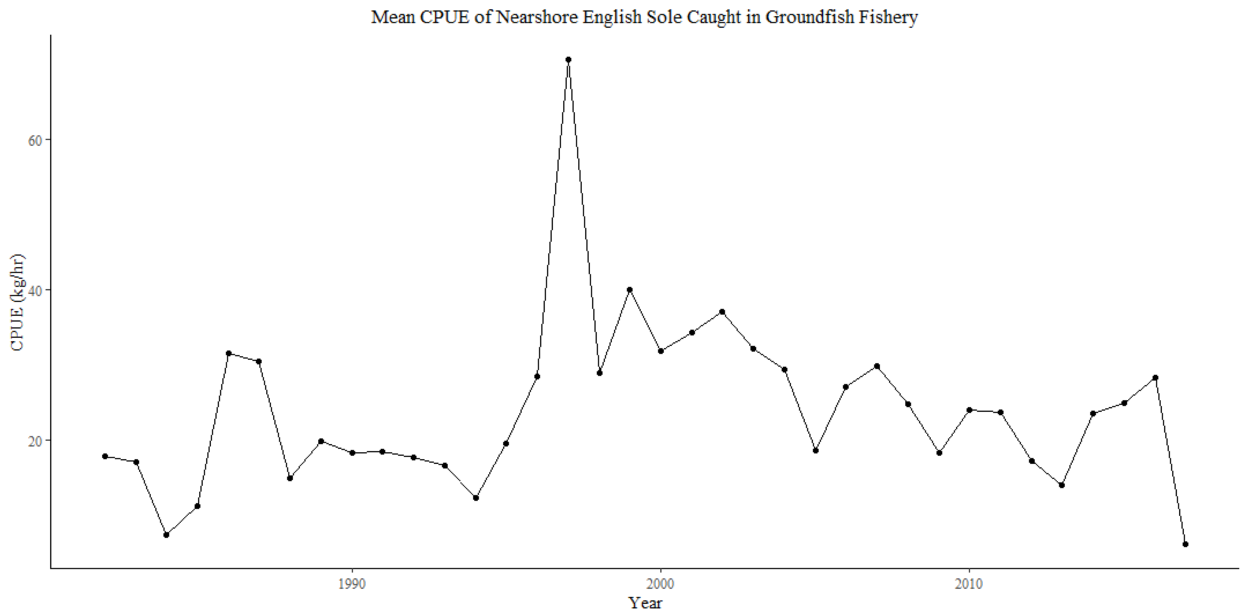


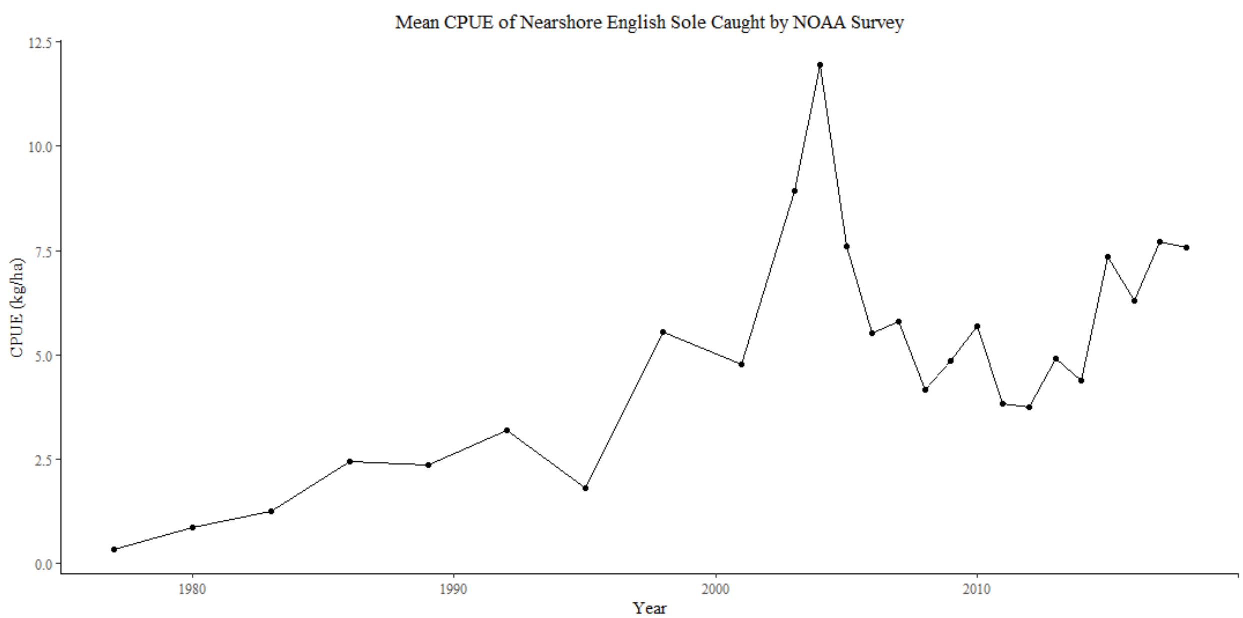
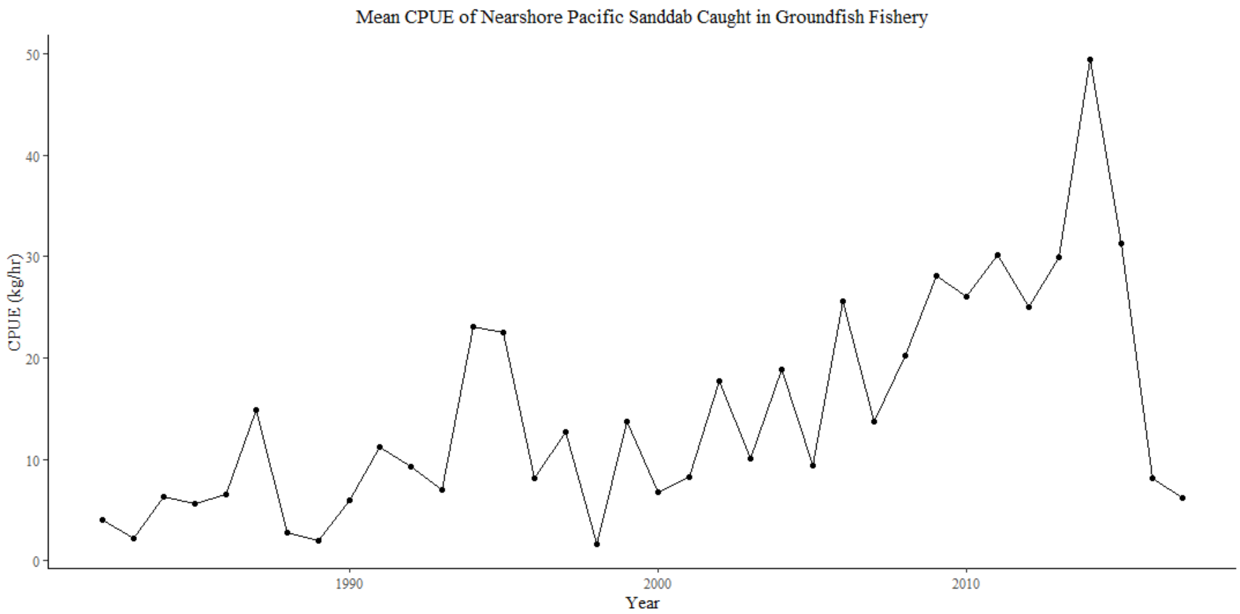


Figure B.2 continued.



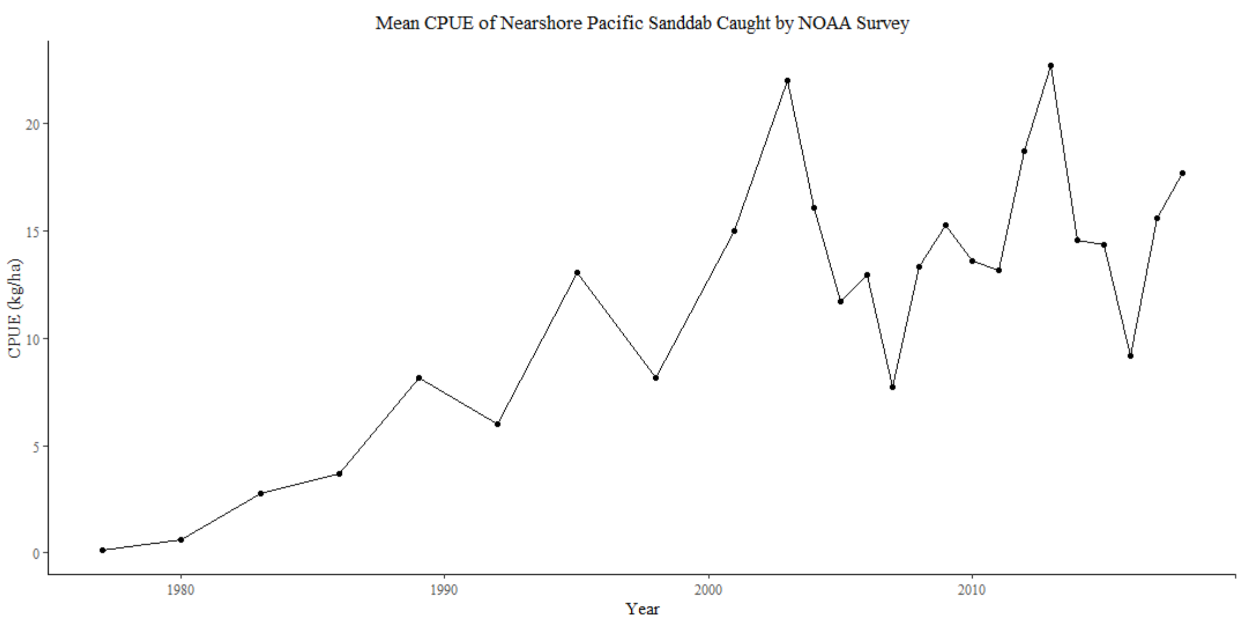
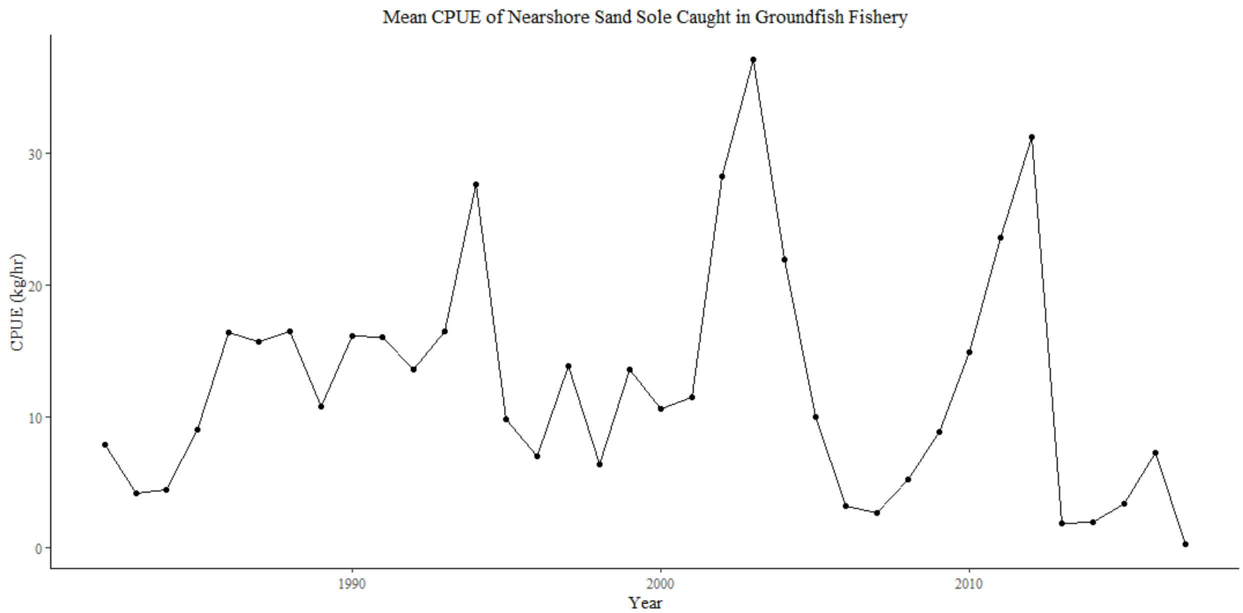


Figure B.2 continued.



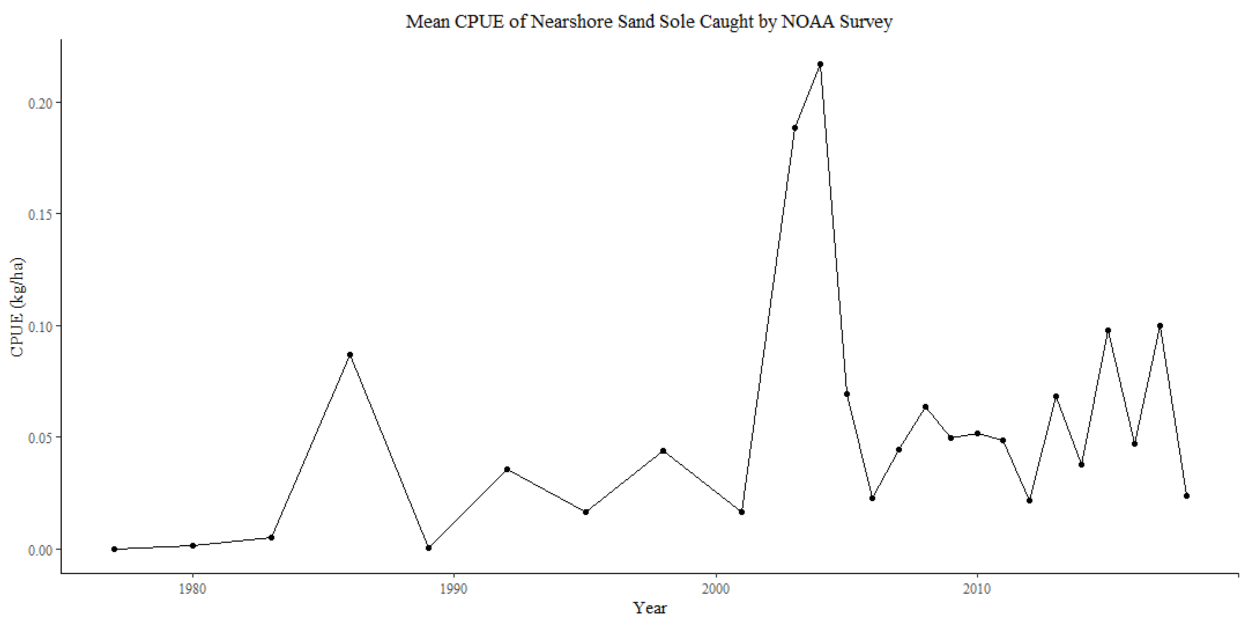
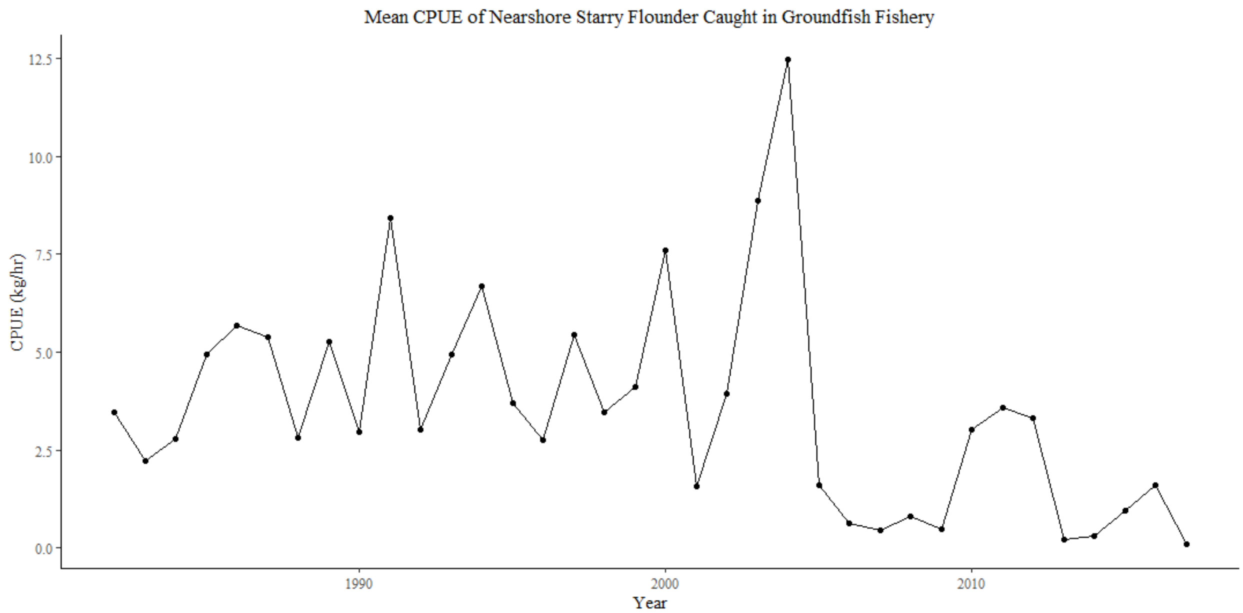


Figure B.2 continued.



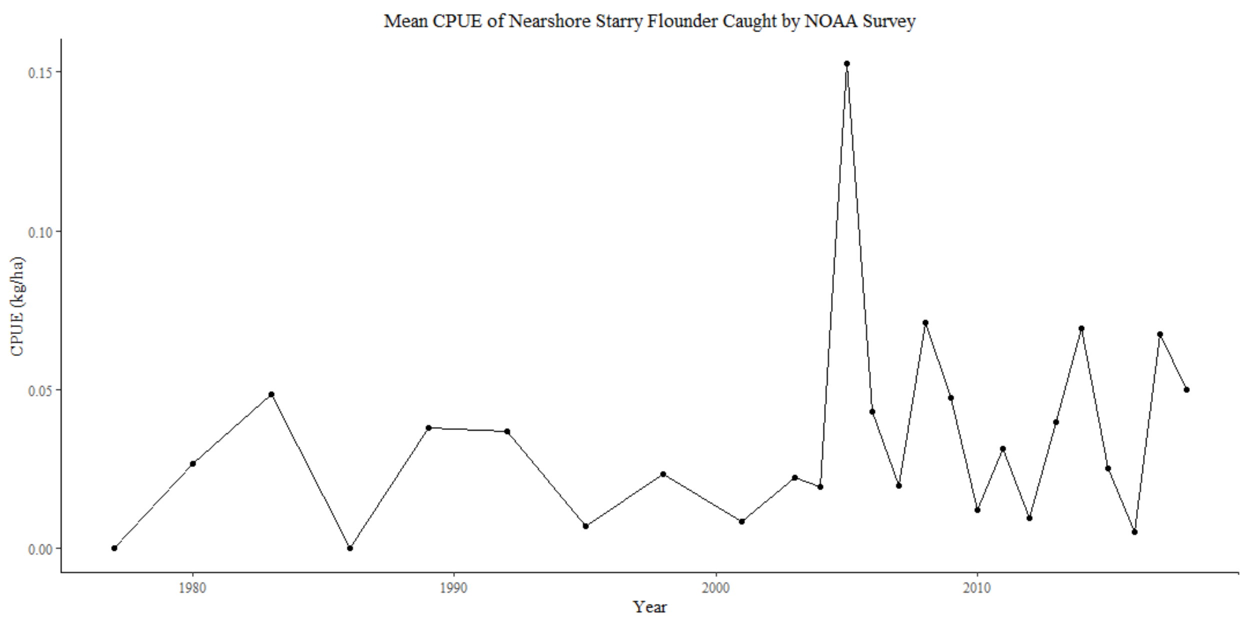


Figure B.2 continued.

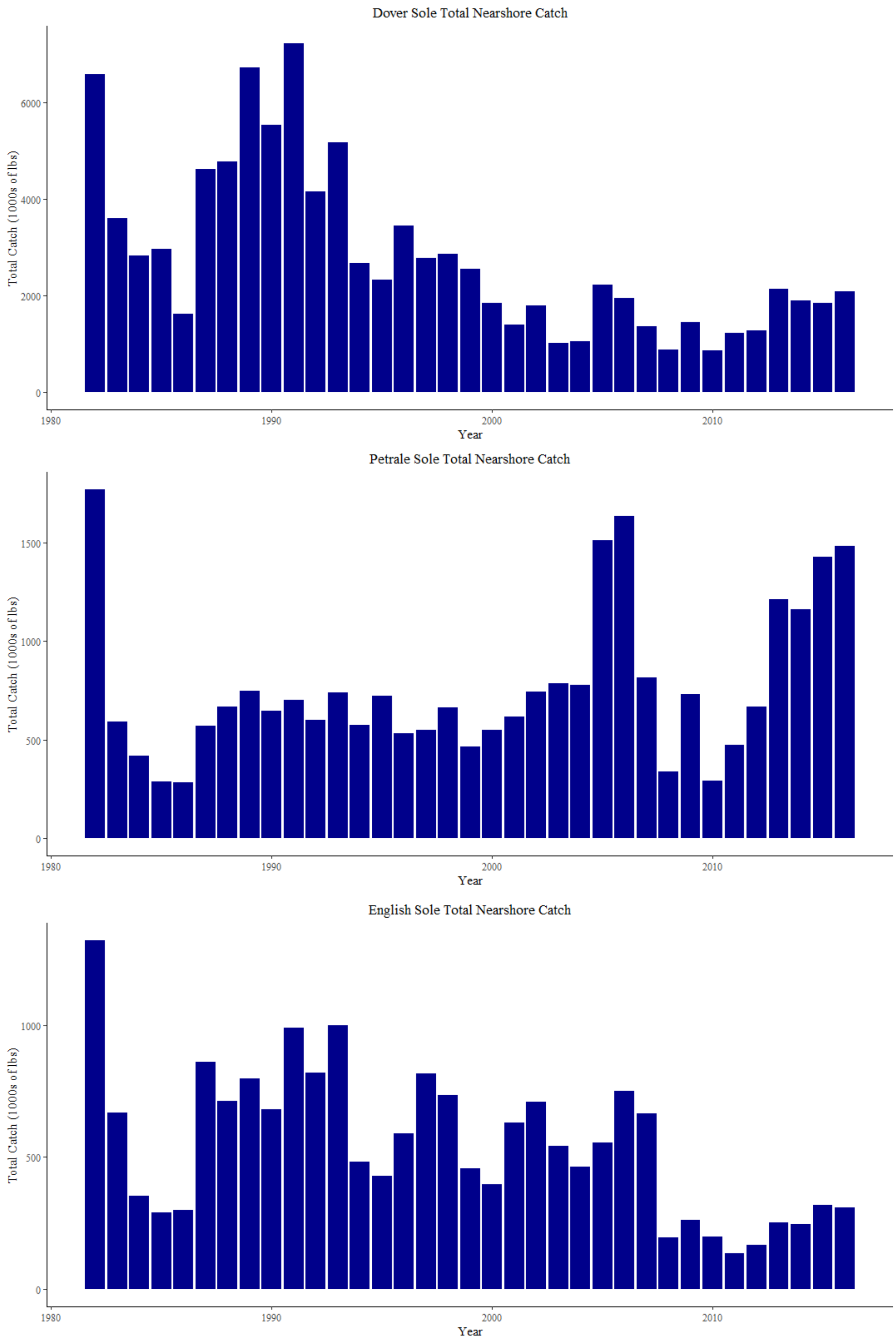


Figure B.3: Total nearshore catch for all species in 1000s of pounds.

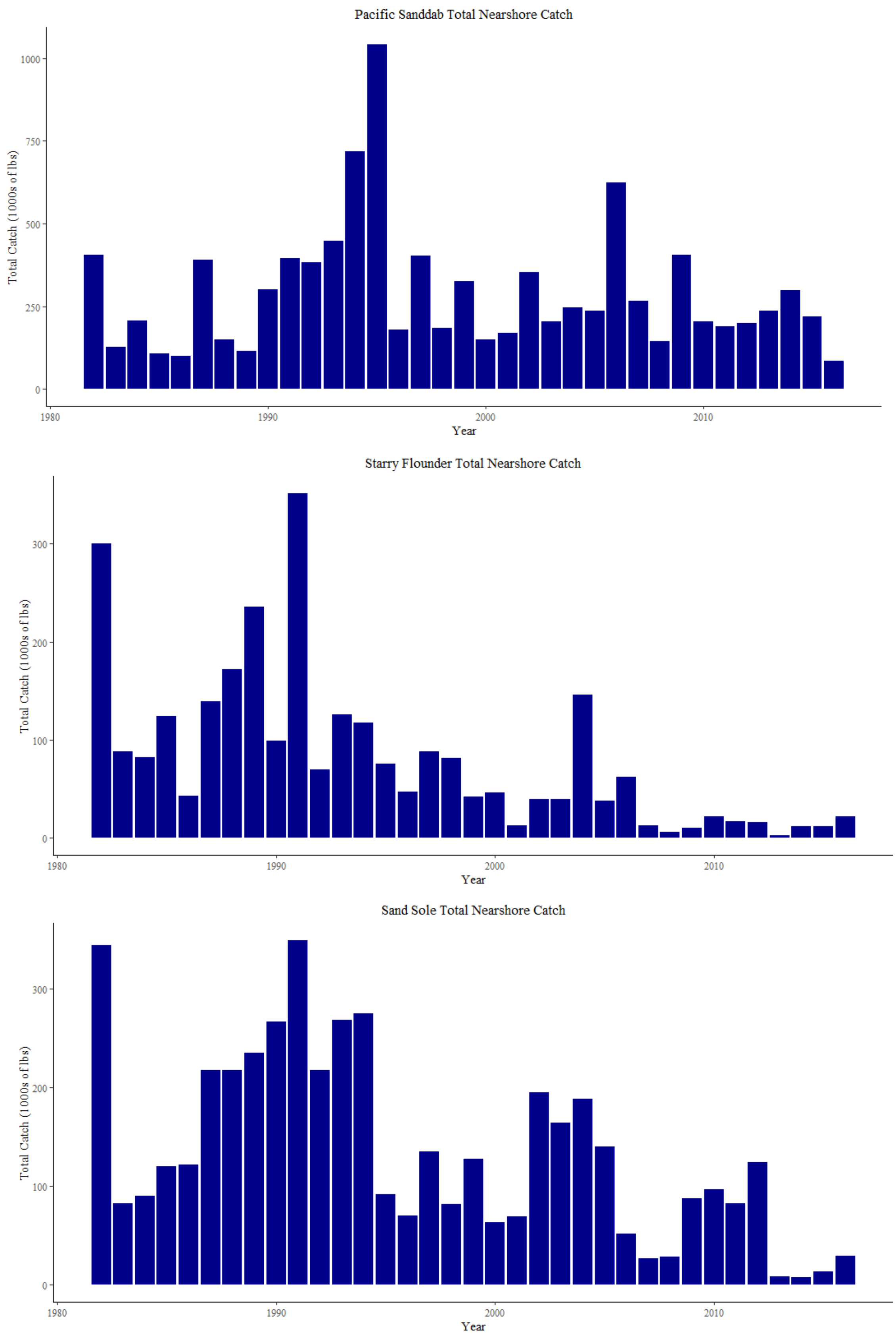


Figure B.3 continued.

Appendix C: ODFW Data Agreement

Oregon Department of Fish & Wildlife, Marine Resources Program
Data Request Form Guidance and Instructions

Some commercial fishing information held by ODFW is confidential under Oregon law (ORS 192.501), and may not be released to the public unless the public interest requires disclosure in the particular instance. In practice, ODFW finds that purposes that are clearly in the public interest are fish stock assessments and analyses for use by regional fishery management councils and/or federal or state agencies in developing or evaluating fishery management measures.

Most other proposed uses are not usually considered to meet the public interest standard. However, some proposed projects appear to have significant potential value to resource managers even if the project is not being undertaken at their request. Requesters are encouraged to contact ODFW staff prior to submitting a formal data request, in order to discuss their specific needs and identify appropriate data that may be available.

The following items will aid in evaluating a request. Including as many as possible/appropriate, as well as other relevant information, in a written data request is recommended. Please replace the Red example text in the form with your actual request information.

Project working title: **Collaborative Fisheries Research Project of Nearshore Groundfish Assemblages**

Names: **Lorenzo Ciannelli, David Fox, Waldo Wakefield, Robert Eder, Flaxen Conway and Anja Sjostrom**

Affiliation: **Oregon State University, NOAA, and ODFW.**

Contact:
Lorenzo Ciannelli,
lciannelli@coas.oregonstate.edu
541-737-3142

Goal(s)
Reconstruct a more accurate picture of the nearshore groundfish assemblages with the potential for management applications and future collaborative research using fish ticket and logbook data, focused fisheries interviews and long-term scientific beam trawl data.

Purpose
To combine survey based estimates of groundfish community composition in the nearshore with the local ecological knowledge of fishermen to assess large scale spatial and long scale temporal changes in these assemblages.

Approach
Summarize the fish ticket data for landings, year, season, port of landing, and species and logbook data for fishing effort. Following this, conduct semi structured interviews with fishermen to fill in and missing data and address causation and shifts in nearshore use from 1969-present. These data will be compared to an analysis of historical and current beam trawl survey data collected by NWFSC and others. Ultimately this combined data will be incorporated into ODFW's nearshore ecological data atlas.

Spatial resolution
Highest currently and consistently available spatial resolution.

Temporal resolution
Highest currently and consistently available temporal resolution.

Temporal extent
1969-2017.

Models
- Spatial maps of catch by location by time period, boat size and seasons.
- Frequency distribution and cumulative density function of standardized catch by depth, time, location and other oceanographic variables.
- Spatial maps of composition by time period, boat size and seasons.
- Spatial maps of standardized catch of most frequently occurring species.

Fishery data requirements
- Port of departure
- Vessel size (exact size not required – bins/classes ok), horsepower if possible
- Catch (weight) by species per haul (Hailed catch)
- Location latitude/longitude or Loran A, Loran C if not converted for start of stop
- (Set depth & bottom depth) Average depth if available
- Date of haul
- Length of haul (hours/mins)
- Gear type per haul, size of net
- Mean depth of haul
- Composition of catch if available

Timeframe for use of data
3/2018-3/2022

Research products
A clearer understanding of the feasibility of using scientific ecological and local ecological data in assessing the nearshore fishing effort and groundfish assemblages. This will produce an initial publication, reports and presentations at conferences and industry meetings. Our hope is to produce insights into how collaborative scientific ecological and local ecological knowledge research can be incorporated at a management level as well.

Data security
Data will only be accessed and stored on devices owned and operated by those who sign the data request form and will be kept in locked offices on locked computers at all time. No confidential information will be disclosed when discussing the data in meetings and any figures produced will not display information granted in confidentiality.

Oregon Department of Fish & Wildlife

CONFIDENTIAL DATA USE AND NON-DISCLOSURE AGREEMENT

DISCLOSER:	The Oregon Department of Fish and Wildlife
ADDRESS:	2040 SE Marine Science DR, Newport, OR 97365
REQUESTER:	Lorenzo Ciannelli
ORGANIZATION:	CEOAS
ADDRESS:	Oregon State University 104 CEOAS Admin Bldg Corvallis, OR 97331
REQUESTER:	Anja Sjostrom
ORGANIZATION:	CEOAS
ADDRESS:	Oregon State University 104 CEOAS Admin Bldg Corvallis, OR 97331
REQUESTER:	Flaxen Conway
ORGANIZATION:	CEOAS
ADDRESS:	Oregon State University 104 CEOAS Admin Bldg Corvallis, OR 97331
REQUESTER:	Waldo Wakefield
ORGANIZATION:	NOAA, National Marine Fisheries Service
ADDRESS:	Fishery Resource Analysis and Monitoring Division-Northwest Fisheries Science Center 2032 SE OSU Dr. Newport, OR, 97365

EFFECTIVE DATE: This agreement is effective immediately upon signature by all parties.

RECEIVER has requested to use the following data:

- Individual Oregon Fish Ticket (live and dead landings) and associated data (gear type, port, weight, etc) for bottom trawl-caught fish species.
  - Indexed to logbook and market sample data, as available
  - Contains both
    - Raw landings data by available market category, and
    - Species-comp applied aggregated data, as available

- Oregon Trawl Logbook and associated data (port of departure, vessel size, catch (weight/species haul), latitude/longitude, depth, length of haul (hours/min), gear type per haul, ~~net size~~) for bottom trawl-caught fish species, all available years.
  - Indexed to fish ticket and market sample data, as available
  - Contains both
    - Raw logbook data with reported hails, and
    - Fish ticket-adjusted hails, as available

- Information on vessels (length, horsepower, etc) with fish tickets for bottom trawl-caught fish species, all available years.

- Market sample data (species, length, weight, sex, etc.) for bottom trawl-caught fish species, all available years.

- Complete EDCP database (e.g., haul-level/vessel-level data). This includes but is not limited to:
  - Catch information at the haul level retained and discarded (weights and counts, where counts are available). This should include target and discarded species.
  - Vessel and gear information, including net type and specifications
  - Biological data (i.e., length) that can be associated with haul, gear type, and mesh size

The Oregon Department of Fish and Wildlife (DEPARTMENT) recognizes the confidentiality of these data and that this information is exempt from public disclosure under ORS 192.501-505, and may only be publicly released under such circumstances as required by the Public Records Law. The DEPARTMENT finds pursuant to this same statute that it is in the public interest in this case to allow disclosure of the specified information to the individuals named in this Agreement for the limited purpose described below. Therefore, the DEPARTMENT agrees to allow RECEIVER to use the data described above on the following conditions:

(1) These data will be used only for the following purpose:

The nearshore groundfish assemblage project.

(2) The timeframe for the use of these data and results of this project are:

March 2018-February 2020

(3) RECEIVER agrees that these data will be treated as confidential and handled with the utmost security. The data shall not be disclosed in any manner that identifies the individual or enterprise from which the data were originally collected.

(4) RECEIVER agrees not to distribute the data, and shall limit access to the individuals named on the top of this form. All individuals who are allowed access to the provided data must abide by the conditions set forth in this agreement and by signing this agreement agree to be bound by these conditions.

(5) RECEIVER agrees to gain approval by the DEPARTMENT of all products (publications, reports, presentations, maps, etc.) which include any representation of the confidential data, including products in which the data are summarized or aggregated to a non-confidential level, prior to public display, release, or

distribution. **ODFW requires two weeks for this review.** The purpose of the DEPARTMENT's review is solely to ensure that the confidentiality of the source data is preserved.

(6) RECEIVER agrees not to present specific location or identity data (e.g., vessel or processor), either in graphical or tabular format, where any vessel fished without aggregating by a minimum of 3 (e.g., vessels) and additional approval by the DEPARTMENT.

(7) RECEIVER agrees to hold the DEPARTMENT harmless for any damages or liability incurred as a result of the violation of any of the terms of this agreement.

(8) Reports, manuscripts or other print or video material shall contain an acknowledgement of the DEPARTMENT for providing the requested information.

(9) A copy of this agreement shall remain with the requested data, whether it resides in an electronic or printed format.

(10) RECEIVER agrees to promptly destroy or return all of the original raw data provided upon completion of work or should funding for project not be secured for the purpose described above.

(11) RECEIVER agrees to notify the DEPARTMENT if the general timeframe for the project, as described in box (2) above is significantly altered.