Exploring the role of oceanographic features in the spatial distribution of Pacific halibut and other longline-caught fishes off the west coast from southern Oregon to Queen Charlotte Sound, British Columbia

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Abstract

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Knowing how groundfish distribute in relation to ocean conditions is of primary importance to fishery managers as they are tasked with estimating stock size and designing effective monitoring programs amidst a changing climate. This research examined near-bottom environmental data alongside Pacific halibut survey catch data for the years 2006-2009 on the continental shelf of Oregon, Washington, and southern British Columbia. The objectives of the research were: 1) characterize summer environmental and fish distribution conditions at depth observed during the setline survey throughout the study area; 2) explore ranges and possible tolerance thresholds for temperature, DO, salinity, and pH for Pacific halibut and six other species commonly caught during the survey including arrowtooth flounder, spiny dogfish, sablefish, longnose skate, lingcod, and yelloweye rockfish; 3) identify the primary environmental factors affecting distribution of these species and model the observed relationships; and 4) assess the ability of the longline survey to adequately account for target species across environmental gradients.

All of the organisms except sablefish were found in increasing numbers from south to north and occupied varying depth strata. Upwelling-induced seasonal hypoxia (i.e. DO < 1.4 ml/L) is a feature of the study area and all of the organisms except sablefish exhibited apparent species-specific DO minimum thresholds between 0.75 ml/L – 1.0 ml/L, i.e. where animals were found above, but not below these thresholds. Ordinary least squares (OLS) multiple regression analysis indicated a variety of variables unique to each species as significant in predicting distribution, with temperature, DO, and pressure as the most common. Poor model performance led to the use of two other methods, geographically weighted regression (GWR) and tree regression, to examine regional variation and mitigate the effect of correlated explanatory variables. The tree regression model, which allows for predictor variable correlation, was a comparable or better fit than OLS and GWR for all species except Pacific halibut, where GWR, using DO as a predictor variable, was the best fit. GWR addresses regional variation of processes. Results here suggest that many of the animals, including halibut, use avoidance as a coping mechanism for below-threshold DO. However, given that GWR yielded the best fitting model for halibut, low (but above threshold) DO may also be contributing to catchability differences in the survey. Multivariate analysis was used to examine the relationship among the environmental variables and to examine species assemblages in relation to these variables. Depth and latitude were of primary importance in describing relationships.

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Chapter 1: Background, objectives, and sampling methods

Background

Fishery managers are becoming increasingly aware of fluctuating oceanographic conditions and their impacts on the survival, recruitment, growth, and distribution of fishes. Modern oceanographic monitoring takes place in a variety of ways: for example through the use of free drifting gliders, moorings, and satellite imaging of the ocean surface. Until recently, there was very little oceanographic information collected coincident with commercial fishing or scientific fisheries surveys due to high costs, difficult sampling protocols, or lack of monitoring tools appropriate for non-scientific vessels. Technological developments in recent years have allowed the collection of oceanographic information at depth in a more cost and time-effective manner, making it possible to collect these data relatively easily alongside fishery or survey data, and ultimately couple oceanographic measurements with species catch data.

As awareness of climate change and the impact of climate variability has increased, the need for environmental and biological baselines has followed suit. Knowing how fishes distribute in relation to basic oceanographic metrics can help resource managers better assess stocks and design monitoring programs (e.g. Mueter et al. 2007 and Perry et al. 2005).

The study area for this research spans from southern Oregon (latitude 42^{o}00’ N) to Queen Charlotte Sound (latitude 52^{o}10’ N) along the continental shelf of North America to depths of 500 m. These waters tend to be nutrient-rich due to several unique climatic and oceanographic features that can directly or indirectly influence the distribution of fishes found in the area (Fig. 1.1a). The study area encompasses a transition zone for large-scale upper ocean currents and gyre systems in the northeast Pacific Ocean. The North Pacific Current flows eastward, entering the North American continental shelf zone near Vancouver Island, British Columbia and feeds the California Current System to the south and the Alaska Current to the north (Sverdrup et al. 2003). The coast experiences seasonal wind-driven upwelling, weaker to the north and stronger to the south (NOAA 2011). In the south, due to frequent periods with north winds in spring and summer and a southward flowing upper ocean current, upwelling events dominate oceanographic processes along the shelf. In addition, several other physical features contribute to the oceanographic conditions on the shelf such as the northward flowing California undercurrent, submarine canyons, and riverine and estuarine outflow (Hickey and Banas 2003) all of which are explored in more detail in the following sections. To the north of Vancouver Island is Queen Charlotte Sound, close to the origin of the Alaska Current. It also receives nutrient-rich fresh water via the Strait of Georgia and Queen Charlotte Strait on the east side of Vancouver Island (Crawford et al. 2007).

Key water mass characteristics that include dissolved oxygen (DO), temperature, salinity, and pH (acidity) also vary across the study region. These characteristics and their causes and consequences are described in more detail below.

Dissolved oxygen

DO is naturally low in deeper water and thus upwelled water, (i.e. cold, nutrient-rich water coming up from depth) for two primary reasons. The first is due to decreased ventilation with the atmosphere compared to the upper ocean mixed layer (Whitney et al. 2007). Second, low DO can develop in shallow, nutrient-rich waters where primary production supply exceeds the zooplankton demand; as the excess phytoplankton dies and sinks, bacterial respiration depletes the already poorly oxygenated deep water of its remaining oxygen, resulting in a hypoxic condition (Gray et al. 2002). Eutrophication through nutrients supplied by excess fertilizers and other agricultural run-off is commonly found in the Gulf of Mexico, the Black Sea, and Chesapeake Bay (Diaz and Rosenburg, 2008), for example, but can also naturally occur in coastal upwelling zones (Rosenburg et al. 1991).

Upwelling-induced hypoxia has been found to occur off the coasts of Peru (Diaz and Rosenberg 2008), South Africa (Bailey 1991), and the U.S. West Coast (Connolly et al. 2010, Chan et al. 2008). Within the study area, hypoxia has been shown to occur regularly off the coast of Washington and less commonly off Oregon's mid and outer shelf (Connolly et al. 2010), but was recently detected on a regular basis (since 2002) on Oregon's inner shelf (Chan et al. 2008). Upwelling occurs when Ekman transports move surface water away from the coast, and are then replaced with deeper waters (Bakun 1990). Seasonally, coastal upwelling is caused each spring and summer off the North American coast when prevailing winds are equatorward and Ekman transports are offshore, with deep, cold, high salinity, nutrient rich, low pH, and DO-poor water being brought on to the continental shelf (Hickey and Banas 2003, Chan et al. 2008).

Hypoxia in deep waters over the continental shelf typically occurs off the west coast beginning in mid-summer and can persist for several months (Connolly et al. 2010). Within the study area, it is found off the coasts of Washington and Oregon and although less common, has been documented intermittently in the historical record further north off of Vancouver Island (Irvine and Crawford 2008). To date, the most notable hypoxic event recorded within the study area and time frame occurred in 2006 where waters along Heceta Bank off Oregon were hypoxic from mid-June until mid-October. During this period, hypoxia deteriorated into shelf anoxia which persisted for several weeks, resulting in large kills of stationary and slow moving invertebrates and crustaceans (PISCO, retrieved October 13, 2011). Waters off Washington also experienced hypoxia outside of the historical extremes in the summer and fall of 2006 (Connolly et al. 2010).

The exact mechanism for upwelling-induced hypoxia has not yet been fully explained, but Bakun (1990) predicted that as CO_2 and other greenhouse gas levels rise in the earth's atmosphere, inhibited nighttime cooling and enhanced daytime heating would lead to intensified continental thermal lows. These would then lead to increased onshore-offshore pressure gradients and resulting intensified alongshore winds, ultimately resulting in accelerated coastal upwelling. The accelerated upwelling would then presumably trigger the intense algal blooms associated with hypoxia. In fact, Barth et al. (2007) examined the coastal upwelling in 2005 off the Oregon coast and found that although the spring transition, and therefore the onset of seasonal upwelling, was delayed due to slack winds well into the summer, when the north winds did commence, they lasted longer in each cycle and were stronger than average. This resulted in larger and more persistent plankton blooms, and eventually hypoxia.

It is also theorized that due to rising global temperature and the increased stratification of the world's oceans as a result, the oxygen minimum zones (OMZs) are expanding bringing cold, low oxygen water closer to the continental shelf, thus facilitating the annual recurrence of upwelling-induced hypoxia even in years of moderate upwelling winds (Keeling et al. 2010). Whitney and Freeland (1999) and Whitney et al. (2007) reported that water measurements taken at Ocean Station Papa off Vancouver Island, B.C. (OSP located at 50^{o}N, 145^{o}W) over a 50-year period (1949 – 1999), clearly showed wide inter-annual variability, but also a longer term shoaling of the hypoxic OMZ boundary. If Keeling et al.'s (2010) hypothesis is true, then the expectation would be that more hypoxic areas will emerge along continental shelf regions of low to moderate upwelling strength as the OMZs expand.

Many studies have shown that marine macro fauna have varying, but generally dramatic, responses to hypoxic conditions. Rabalais et al. (2002) found that benthic organisms are especially vulnerable to environmental stressors because they are immobile. Mobile organisms have several responses such as reduced or increased swimming speed (Metcalfe and Butler 1983), reduced growth and metabolism (Gray et al. 2002), and changes in the intensity of predatory behavior which could eventually result in changes to trophic pathways (Pollock et al. 2007). Pihl et al. (1991) and Gray et al. (2002) found that some animals were able to simply move out of the way of suboptimal conditions. However, such behavioral responses can lead organisms to experience habitat compression or overlap with other species and/or habitats not normally encountered (Diaz and Rosenberg 2008). In some cases, fishes and invertebrates are pushed into very shallow water nearshore to escape hypoxia and experience habitat displacement, increased vulnerability to predators, and severe physiological stress (Rabalais et al. 2002). Top predators may be pushed to unfamiliar territories, but also to increased prey concentrations, so perhaps benefitting to some degree.

Within the study area, the DO at depth is typically low even in non-hypoxic areas – between 1.4 ml/L and 3 ml/L (NODC 2011) – and the demersal fishes in the area are presumably adapted to these lower oxygen levels. Hypoxic conditions on the mid to inner shelf, below 1.4 ml/L, appear seasonal in nature and it is reasonable to assume that fishes in this study are less adapted to these lower levels and thus may move to more oxygenated waters when confronted with hypoxia as has been seen in other fish species (e.g. Rabalais et al. 2001a, 2001b; Prince et al. 2010). The exact tolerance point may be different for different species and is examined in this analysis.

Temperature

Because of coastal upwelling in the spring and summer, marine waters near the North American west coast are typically cooler on the continental shelf than offshore. However, deep water over the shelf is also transported to the region from the south by the California Undercurrent, making it warmer than it would otherwise be (Hickey et al. 1991). Whitney and Freeland (1999) found a long-term trend toward warming and freshening of surface waters in the north Pacific as measured at OSP based on observations taken between 1956 and 1997. Low temperatures are also a characteristic of the OMZ. If the OMZ continues to shoal as discussed in Whitney and Freeland (1999), then it may be that water along the continental shelf at depth will cool over time because of reduced mixing with warmer surface waters.

This study examines the role of temperature in the distribution of groundfishes and uses number per unit effort (NPUE) as a measure. There is evidence suggesting that temperature affects egg and larval development as well as fish bioenergetics and behavior. For example, Hurst (2007) found that temperature was negatively correlated with swimming speed and positively correlated with cohesiveness of schooling in walleye pollock. Stoner et al. (2006) and Stoner and Sturm (2004) noted behavioral changes related to feeding in Pacific halibut and sablefish. Perry et al. (2005) documented a northward contraction of several species in the North Sea correlating to rising water temperature in the area. Oregon and Washington are near the southernmost range for halibut and some of the other fishes encountered on the survey used in this analysis. It is reasonable to think that a depth integrated increase in temperature on the shelf over time could move the southern boundary of the range for selected species further north and vice versa for a depth average decrease in water temperature.

Salinity

Salinity together with temperature dictates the density of the oceanic layers. The world's oceans average a salinity of 33-37 practical salinity units (psu) (NODC 2011) with higher values at depth and lower values at the surface where precipitation or freshwater input from rivers and streams exceeds evaporation. There is also significant seasonal variability in salinity dependent on prevailing seasonal sub-surface currents (Bingham et al. 2010). A warming and freshening trend has been observed at OSP according to data collected from 1956-1997 (Freeland et al. 1998) and Whitney et al. (2007) also reported that stratification in the upper ocean strengthened over the observation period of 1956-2006. The direct effect of variations in salinity or strengthening of density stratification on adult macrofauna is unclear although some research shows that salinity may be important in the egg and larval stages of development (e.g. Parley et al. 1984; Lough, R. G. 1970) .

Acidity

Ocean acidification, a topic of increasing study in recent years, refers to the oceanic uptake of anthropogenic CO_2 resulting in decreased pH and a lowered $CaCO_3$ saturation state (Feely et al. 2008). Some models predict that globally averaged seawater pH will decrease by 0.35 by 2100 (Elderfield 2002). Because the projected decrease is due primarily to the uptake of anthropogenic CO_2 from the atmosphere, the surface ocean and shallow water of the shelf will be affected first, because of more prevalent ventilation, followed by the deeper waters of the ocean basin (Elderfield

2002). Deeper shelf waters receive input from deep upwelling sources and are naturally lower in pH. Expansion of the OMZs (water which is also naturally lower in pH) could also increase acidity on the continental shelf (Keeling et al. 2010). The upwelling current system along the West Coast is highly variable and organisms living there are likely acclimated to lower pH periodically (Hauri et al. 2009). However in recent years, with the increased oceanic uptake of anthropogenic CO_2, the areal extent of this lower pH bottom water has expanded, reaching depths as shallow as 40 m over the west coast's continental shelf (Feely et al. 2008). Demersel shelf fishes routinely experience a lower pH and lower saturation level than those at the surface and may be resilient to future changes as long as that range of variability is not exceeded (Hauri et al. 2009).

Research objectives

This project is focused on four primary objectives:

Objective 1. Characterize summer environmental and fish distribution conditions at depth observed during the setline survey throughout the study area.

This is achieved by a thorough accounting of survey timing, range, and oceanographic conditions encountered during the survey for each year. Observed species distributions are described using number caught per unit of gear (NPUE) and plotted against latitude and depth.

Objective 2. Explore ranges and, where evident, tolerance thresholds for temperature, DO, salinity, and pH for Pacific halibut and six other species commonly caught during the survey.

The environmental data are coupled with species data as one large data set (i.e. ignoring spatial and temporal effects) to look at overall trends in species abundance as a function of environmental factors. Single variable scatterplots and Loess smoothed regression lines are used to evaluate relationships between fish distributions and temperature, salinity, pH, and DO.

Objective 3. Identify the primary environmental factors affecting distribution of Pacific halibut and six other species commonly caught on the survey, and model the observed relationships.

Here, spatial statistics, ordinary least squares (OLS), and geographically weighted regression models (GWR) are used to model species distributions as a function of environmental variables. The collinearity of environmental variables is explored. In addition, multivariate statistics and tree regression models are used to evaluate relationships between and among species complexes and environmental variables.

Objective 4. Assess the ability of the longline survey to adequately account for target species across environmental gradients.

This will be accomplished through a comprehensive look at the different models described above in terms of strengths and weaknesses; and diagnosing root causes for model mis-specification/errors.

Data collection methods

The geographic location of this research spanned from southern Oregon's continental shelf (latitude 42^{o}00' N) northward to Queen Charlotte Sound (latitude 52^{o}10' N) in depths 30-500 m. As part of a survey conducted by the International Pacific Halibut Commission (IPHC), longline fishing gear is laid out on a grid over the continental shelf (Fig. 1.1b). Species counts were conducted as the gear was pulled from the water. Catch data were then converted to numbers per unit effort (NPUE, numbers per skate) at that geographic location. Just prior to haul back of gear, a water column profiler was deployed to obtain coincident environmental data (specifically temperature, salinity, DO, and pH). The environmental data were then coupled with the NPUE of species at each station. All sampling occurred in the summer months of June, July, and August.

Study area and time frame

The IPHC annual longline survey includes a series of stations on a 10x10 nmi grid covering the area from 30-500 m depth along the continental shelf.

The selected area encompasses four adjacent IPHC survey regions, and includes 168 gridded survey stations (Fig. 1.1). The survey targets halibut using longline gear, though a large number of other species are caught also. Profiler measurements near the bottom provide direct habitat information applicable to the species caught in the longline survey. This study includes data from the years 2006-2009, and all stations were fished in all years, but not all stations were profiled in all years. Only those stations both fished and profiled in a given year were used. Table 1.1 summarizes data collected for these analyses which totaled 527 total rows of data over the four year time span.

The region definitions used here vary slightly from the IPHC defined regions (IPHC 2008) of the same name in order to better reflect natural geographic and oceanic boundaries. A summary for each region is described here.

Oregon – defined as the continental shelf off the coast of Oregon from 42°N to the Columbia River (46°10’N). The Oregon continental shelf was surveyed in the years 2007-2009. The depth of stations profiled varied substantially with near bottom profiler readings ranging from 46 to 536 m.

Washington – defined as the Columbia River (46°10’N) to the Strait of Juan de Fuca (48°20’N). The IPHC has surveyed the region annually, but did not begin oceanographic measurements off the Washington coast until 2008, resulting in only two years of data (2008 and 2009). The depth of stations profiled ranged from 32 m to 383 m.

Vancouver Island – defined as Strait of Juan de Fuca to the northwest end of Vancouver Island (50°40’N). Near-bottom profiler readings for this area ranged in depth from 29-389 m. The IPHC surveyed and profiled this region for all study years. However, pH was not measured until 2009 and pH data are not used here.

Queen Charlotte Sound – defined as north Vancouver Island (50°40”N) into Queen Charlotte Sound (52°10’N), and is the northernmost region for this study. The IPHC surveyed and profiled the region in all study years, 2006-2009. PH was not measured until 2009, however, in that year, the instrument was damaged so no data were collected. Near-bottom depth readings ranged from 34 to 368 m.

Species data collection

Each survey station was fished annually during the summer months with standardized gear and bait. Specific survey dates for each area were roughly the same from year to year. The gear was a longline consisting of skates (1800-foot sections), equipped with 100 number 3 circle hooks (also known as 16/0) each spaced 18 feet apart (IPHC 2008). The number of skates fished at each station varied by year ranging from five to seven. A 5-10 pound groundline weight was placed between each skate to help the gear stay on the bottom and minimize seabird predation on the baits during setting. Each hook was baited with ¼ to 1/3 pound pieces of #2 semi-bright chum salmon (*Oncorhynchus keta*). When setting the gear, the goal was to place the center of the groundline at the station coordinate. The gear was set and allowed to soak for a minimum of five hours before retrieval. Upon retrieval, all halibut were sampled and accounted for. In Oregon and Washington, only the first 20 hooks of each skate were assessed for species occurrence (20% of the hooks per set), recorded, and extrapolated to the entire string of gear. In British Columbia 100% of hooks were assessed for species occurrence.

Oceanographic data collection

For this study, we exclusively used profiler instruments manufactured by Seabird Electronics Inc., Bellevue, Washington to collect environmental data. The first unit purchased was an SBE19® model which collected pressure (db), temperature (^{o}C), salinity (psu), and dissolved oxygen (ml/L) at half second intervals as it traveled to depth through the water column. The second unit purchased and used off the U.S. west coast was an updated SBE19*plus*® model which recorded readings every quarter second and was equipped to collect the information listed above as well as pH and chlorophyll *a* concentrations. The newest units, purchased in 2009, were the third generation model (SBE19*plus*V2®) and collected all the information described here at quarter second intervals. Data for this study includes collection with all three models. The units were kept in excellent working condition with annual calibrations and servicing just prior to the survey season as well as detailed maintenance of the instruments throughout the survey period.

The deployment assembly was the result of work done in the early 2000s (Hare 2001) and consisted of floats attached to the top of the profiler along with a line connecting it to the deck of the vessel at all times, and a 40-pound anchor at the bottom linked to the profiler via a weak link. The float and anchor assembly allowed the profiler to drop through the water column at a rate of approximately 1-2 m/s. For each deployment, the profiler was placed at the surface and allowed to freefall to the bottom, recording 2-4 oceanographic measurements per second as it descended. The anchor hit bottom first, rendering the profiler and float assembly positively buoyant. Momentum allowed the profiling unit to continue to descend briefly to within 5-10 m of hard bottom, but was pulled upward by the floats and thereby never impacted the bottom. On deck, the line went slack indicating that the assembly had hit bottom, and the profiler was subsequently retrieved. If the anchor became attached to the bottom, the weak link allowed retrieval of the profiler and floats. All profile casts were taken immediately prior to hauling the fishing gear for each station, and the data were subsequently uploaded to an onboard laptop computer. Only profiles recorded during the descent were utilized.

A water column profile was taken at each station within the study area, but not all stations were profiled in all years. Reasons for no data at a station included: 1) the region was not surveyed that year (see summary Table 1.1), 2) heavy weather or tides led to a decision by the vessel captain and/or biologist not to deploy the unit, or 3) data were lost or corrupt after the fact.

Species selection

A total of 63 different species were identified over the four-year study. In order to keep the analysis statistically manageable, a subset of six species in addition to Pacific halibut were selected for investigation of NPUE relationships with environmental data.

Halibut were the primary focus of the survey, and catch per unit effort for halibut was based on all deployed hooks. For all other species, hook occupancy (presence/absence by species) was recorded for all deployed hooks in the two British Columbia regions, and in the Oregon and Washington regions a 20% subsample of hooks was used. There was some question as to whether a subsample could be accurately extrapolated to the entire string of gear, but Menon (2004) found that the 20% hook sub-sample was sufficient to estimate the number per unit effort (NPUE), (i.e. the average number of animals per skate of gear), of more common species but had the potential to profoundly under or overestimate the more rare species. Keeping this in mind, the criteria for selecting the study subset was as follows:

1) Organisms were present in all study regions.

2) Total counts exceeded 200 animals.

3) Any organisms that may have been snagged such as sea stars or other invertebrates were excluded from consideration.

After halibut, the six species selected for inclusion in this analysis encompassed six major species groupings including flatfish, sharks, skates, deep sea groundfish, rockfish, and greenling. Redbanded rockfish were more frequently caught than lingcod, but were passed over because the most common rockfish, yelloweye, had already been selected. Besides halibut, the species included in this analysis are: arrowtooth flounder (*Atheresthes stomias*), spiny dogfish (*Squalus suckleyi*), longnose skate (*Raja rhina*), sablefish (*Anoplopoma fimbria*), yelloweye rockfish (*Sebastes ruberrimus*), and lingcod (*Ophiodon elongates*) (Table 1.2).

Figures

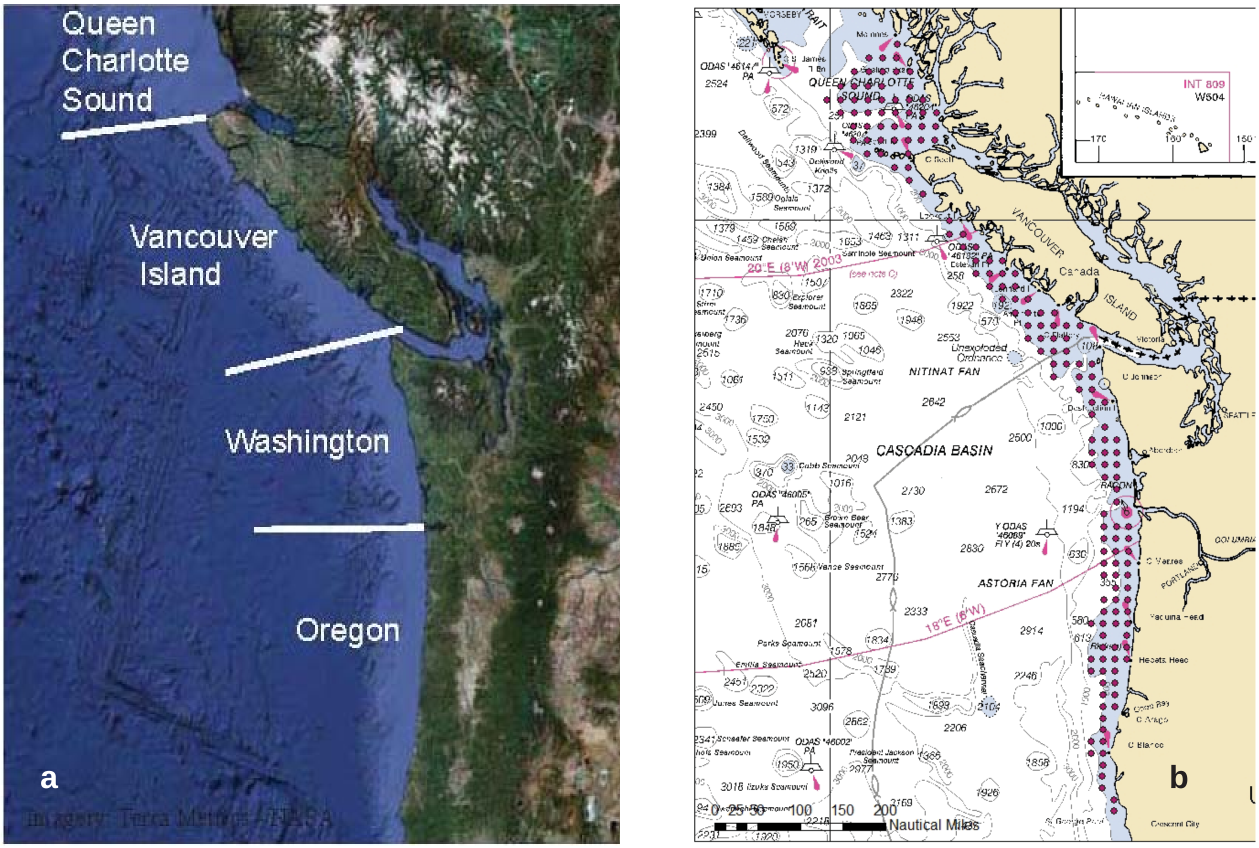


Figure 1.1 The study area encompasses four geographic regions: Oregon, Washington, Vancouver Island, and Queen Charlotte Sound (panel a). Approximate station locations for data collection are illustrated in panel b. Inshore of the 200-m depth contour is highlighted in blue.

Tables

Table 1.1. Number of sampling sites and type of oceanographic data collected by year and region. The pH sensor was not added until 2007 on the instrument used in the southern portion, and 2009 on the instrument used in the northern portion.

Year	Sample number	Region	Pressure, temp, salinity	DO	pH
2006	0	Oregon			
	0	Washington			
	33	Vancouver Island	X	X	
	42	Queen Charlotte Sound	X	X	
2007	56	Oregon	X	X	X
	0	Washington			
	32	Vancouver Island	X	X	
	40	Queen Charlotte Sound	X	X	
2008	55	Oregon	X	X	X
	24	Washington	X	X	X
	36	Vancouver Island	X	X	
	42	Queen Charlotte Sound	X	X	
2009	57	Oregon	X	X	X
	26	Washington	X	X	X
	38	Vancouver Island	X	X	X
	46	Queen Charlotte Sound	X	X	X
Total	527	4 regions			

Table 1.2. Total number of each species encountered during the four-year study (listed from most frequent to least frequent). Note that some areas/sets were sampled at 100% and others subsampled at 20% for species other than Pacific halibut. The total number of animals for all species represents an extrapolation in the sub-sampled sets to 100%. Species used for this study are highlighted.

Species	Number	Species	Number
Spiny dogfish	44,291	Sleeper shark	23
Pacific halibut	13,085	Sea whip	22
Sablefish	12,448	Yellowmouth rockfish	15
Yelloweye rockfish	2,876	China rockfish	13
Longnose skate	2,873	Coral	13
Arrowtooth flounder	2,246	Dover sole	11
Redbanded rockfish	1,625	Flathead sole	11
Lingcod	1,250	Sea cucumber	11
Blue shark	982	Wolf eel	11
Sea stars	751	Greenspotted rockfish	10
Sunflower sea star	628	Gastropod	9
Roundfish (unident)	401	Rosethorn rockfish	8
Rougheye rockfish	368	Slender sole	8
Big skate	328	Sponge	8
Quillback rockfish	297	Rock sole	6
Soupfin shark	243	Aleutian skate	5
Canary rockfish	114	Greenstriped rockfish	5
Sun sea star	109	Pacific hagfish	5
Silvergray rockfish	91	Sand dab	4
Shortspine thornyhead	88	Sea urchin	4
Pacific hake	80	Red tree coral	3
Sea anemone	80	Vermillion rockfish	3
Spotted ratfish	68	Skate (unident)	2
Shortraker rockfish	65	Bivalve	1
Bocaddio rockfish	64	Copper rockfish	1
Yellowtail rockfish	62	Great sculpin	1
Sixgill shark	49	Grenadier	1
Fish-eating star	44	Kamchatka coral	1
Pacific cod	44	Okhotsk skate	1
Petrale sole	43	Sandpaper skate	1
Scallop	42	Shark (misc.)	1
Sea pen	37	Starry flounder	1
Thorneyhead	32	Tiger rockfish	1
Basketstar	28	Walleye pollock	1
Octopus	25		

Chapter 2. Summary of environmental and species data collected during the IPHC longline survey 2006-2009

Background

The neritic waters of the West Coast encompass dynamic oceanographic systems that include major ocean currents, seasonal and intermittent coastal upwelling, a prominent, stationary eddy feature, freshwater inputs, and a narrow continental shelf with numerous undersea canyons and banks. Specifically, the North Pacific Current feeds the California Current system (CCS), from Vancouver Island southward, and the Alaska Current system from Vancouver Island northward. Within the CCS is the southward flowing California Current, the northward flowing California Undercurrent, the Vancouver Island Coastal Current (Hickey et al. 1991) which flows northwestward along the coast of Vancouver Island to mid-shelf, and alongshore winds in spring and summer that periodically cause offshore Ekman transports and coastal upwelling (Hickey and Banas 2003, 2008) (Fig. 2.1). Generally, upwelling is strongest to the south and decreases northward primarily due to weakened and highly variable upwelling favorable coastal winds to the north (Hickey 1979). Upwelling off the coast consists in large part of water from the California Undercurrent that is relatively high in salinity, temperature, and nutrients, and low in DO and pH (Hickey and Banas 2003, 2008; Feely et al. 2008).

In some instances, the bathymetry affects the magnitude of the impact from the currents. For example, although upwelling favorable winds are weaker in Washington than in Oregon, Hickey and Banas (2003) showed that the numerous submarine canyons of the Washington shelf act as conduits for deep, nutrient-rich water to flow up onto the shelf, allowing delivery of more nutrients than would be possible without canyons. Shelf width, coastally trapped waves, and nutrients from the Juan de Fuca Eddy have also been identified as contributors to the highly productive nature of the Washington shelf waters (Hickey and Banas 2003, 2008; MacFadyen 2008). Elevated productivity helps explain why upwelling-driven hypoxia has been regularly observed on the Washington continental shelf since the 1950s (Connolly et al. 2010).

Average near-bottom DO concentrations are generally lower in the south, off Oregon and Washington, than further north off Vancouver Island and in Queen Charlotte Sound. Since hypoxia off the west coast is directly linked to upwelling and respiration, this can be expected given that coastal upwelling decreases with latitude, and primary production is greatest off the SW Washington coast (Connolly et al. 2010).

The Strait of Juan de Fuca and Strait of Georgia along with the Puget Sound are already a dynamic, interconnected system and combined, they are called the Salish Sea (USGS 2009; BC Geographical Names 2010). The Salish Sea is influenced by strong tidal currents year-round, and in summer, the Fraser River is at peak flow making up more than 70% of the fresh water input on average (Herlinveaux and Tully 1961). The water flowing into the Salish Sea from the Pacific Ocean is more saline and more dense, entering the Strait of Juan de Fuca through a deep channel that crosses the shelf. Within the Salish Sea, the seawater mixes with the freshwater, but a pycnocline remains present. Duxbury (1979) and Hickey and Banas (2003) found that the gravitational circulation caused by upwelling and downwelling can cause increased estuarine flushing in summer months. Holbrook et al. (1980) found that the inflow of sea water into the Strait of Juan de Fuca is deep (greater than about 50 m depth on average) while the outflow of less saline estuarine water (brackish water) is more shallow (up to 50 m depth on average). The outflow feeds the Vancouver Island Coastal Current that exists from the surface to depth of about 50 m along the coast to the mid-shelf region (Hickey et al. 1991).

Long term average environmental conditions on the continental shelf bottom obtained from the National Ocean Data Center’s World Ocean Atlas 2009 (NODC 2011) show that temperatures tend to range from about 4-8^{o}C during the month of July. Average salinity is higher offshore and again, where the shelf is narrow, at 34.5 psu and above. Along the wider shelf areas and closer to freshwater sources such as the Strait of Juan de Fuca, the Columbia River, and the Strait of Georgia, the average near-bottom salinity in July is about 34 psu (NODC 2011). Long-term averages of bottom DO indicate that it ranges from near 0 to 3 ml/L, but in most shelf areas is 1-3 ml/L (NODC 2011). Data collected at a sampling transect off Newport, Oregon (called the NH line) from 1960-71 and 1997-2009 indicated a trend of decreasing DO in the deeper water of the slope and outer shelf (Pierce et al. 2012). Recent literature suggests that Oregon's inner shelf had not experienced regularly occurring significant levels of hypoxia prior to 2002 (Keller et al. 2010) but has been detected off Washington for some time (Connelly et al. 2010).

Environmental features

The Oregon continental shelf is influenced by several oceanographic and bathymetric features. The Columbia River at the north end of the region provides a substantial freshwater input (Hickey et al. 2010) that peaks in May-June-July. However, since the freshwater is less dense than the more saline ocean water, it likely has more effect at the surface and little or no direct effect at depth where the stations were located. Coastal hypoxia in varying degrees has been a documented feature in the area since 2002 (Chan et al. 2008, Connolly et al. 2010; Pierce et al. 2012). Environmental data were collected from 2007-2009 during the IPHC longline surveys and station depths ranged from 46 to 536 m.

The Washington continental shelf, like that in Oregon, experiences seasonal upwelling and is made up of a wide range of bathymetric features from wide to narrow shelf, steep slope, and submarine canyons. It is unique in that it is sandwiched between two major freshwater inputs; the Columbia River to the south and the Strait of Juan de Fuca to the north. Low DO in mid to late summer and fall has been a fairly regular feature of the mid to outer shelf since measurements began in the 1950s (Connelly et al. 2010). The IPHC has surveyed the region annually, but did not begin oceanographic measurements off the Washington coast until 2008, resulting in only two years of data (2008 and 2009). The depth of stations profiled ranged from 32 m to 383 m.

The continental shelf along the west side of Vancouver Island is narrow and steep in many places. It is also the meeting place for several oceanographic features: from the west the North Pacific Current splits north and south to become the Alaska Current and the California Current, respectively. Brackish water from the Strait of Juan de Fuca feeds the Vancouver Island Coastal Current from the east (Hickey et al. 1991). The Juan de Fuca Eddy occurs in the southern portion of the region as a result of Strait outflow, winds, topography, and tides (MacFadyen and Hickey 2010). Near-bottom profiler readings for this area ranged in depth from 29-389 m. Hypoxic zones are less common on the shelf in this region than further south, but have been documented in the historical record (Irvine and Crawford 2008). The IPHC surveyed and profiled this region for all study years.

The north end of Vancouver Island into Queen Charlotte Sound makes up the northernmost region for this study. The area is unique in that the shelf is relatively broad and slightly sheltered by Vancouver Island to the south and the Queen Charlotte Islands to the north. Brackish water flows into the area from the Strait of Georgia which is fed prominently by the Fraser River and freshwater discharge from coastal marshland (Crawford et al. 2007). Hypoxia is rare here. The IPHC surveyed and profiled the region in all study years, 2006-2009. Near-bottom depth readings ranged from 34 to 368 m.

Study organisms

Seven species were chosen for this study. These are all demersal fishes that live along the continental shelf and were caught during a standardized survey using commercial longline gear. They are Pacific halibut (*Hippoglossus stenolepis*), arrowtooth flounder (*Atheresthes stomias*), spiny dogfish (*Squalus suckleyi*), longnose skate (*Raja rhina*), sablefish (*Anoplopoma fimbria*), yelloweye rockfish (*Sebastes ruberrimus*), and lingcod (*Ophiodon elongates*). A summary of what is currently known regarding the geographic range, environmental habitat, and fishery for each these fishes follows.

Pacific halibut

Pacific halibut are a demersal flatfish that can grow up to eight feet long and weigh 500 pounds. More typically, adult halibut are significantly smaller, ranging in size from about 80 cm and up and weighing 10-20 pounds or more but are still large enough that predation on adult halibut is not thought to be a significant issue. Halibut are highly mobile and can swim long distances in relatively short periods of time (IPHC 1998). In summer, Pacific halibut are found on the continental shelf in depths <500 m, from northern California to the Gulf of Alaska and the Bering Sea, the Aleutian Islands, and the coasts of Russia and Japan, preferring temperatures in the 3-8^{o}C range (IPHC 1998). In winter, halibut migrate to deeper water off the slope to spawn. They are opportunistic feeders, but common prey items range from crustaceans such as crabs to smaller fishes (IPHC 1998).

Halibut, like other fishes may have several mechanisms for coping with adverse environmental conditions, at least in the short term. As previously mentioned, some fishes can alter their metabolism to withstand lower pH (Fabry et al. 2008) which will not necessarily negatively affect the organism in the short term, but could if the fish is exposed to these conditions over longer periods. The same may be true for low DO concentrations, especially for demersal fishes that are often found in deep water where DO tends to be naturally low. Still, because the fish are highly mobile, simply moving to a more satisfactory environment where possible may be a preferred coping mechanism.

Halibut are a fully exploited species in the NE Pacific, caught commercially, for sport, as well as for subsistence use (IPHC 1998). The survey that collected these data is designed to target adult and older juvenile halibut on their summer feeding grounds and the gear used is similar to that used in the commercial halibut fishery (IPHC Unpub.)

Arrowtooth flounder

Arrowtooth flounder is a flatfish that is often times found coincidentally with Pacific halibut. Arrowtooth can be found from central California to the Bering Sea along the continental shelf and upper slope commonly to about 400 m depth, but as deep as 900 m (Stark 2012). Arrowtooth can grow up to three feet in length and, as a population, have experienced rapid growth in biomass since the 1990s (Witherell 2000 and NOAA 2011). However, a commercial fishery for this species has been elusive. Degradation of the flesh is swift after mortality due to an enzyme (Witherell 2000), and delivering a fresh product to market has proven difficult. However, recent advances with additives that arrest the enzyme activity have shown promise and a directed fishery is developing in the north Pacific (NOAA 2012). Arrowtooth is both a predator and competitor for other groundfish and because of its large biomass, it is important to understand how the population responds to changing climate variables.

Spiny dogfish

Spiny dogfish are a small shark found off the west coast of North America from Baja, California to the Bering Sea. Studies are currently being conducted to establish depth and geographic distributions, which are largely unknown (Tribuzio et al. 2008). Dogfish exhibit schooling behavior and are known for their ability to hunt for food in “packs” (Bester 2011b). Dogfish found in the north Pacific were thought to be the same species as dogfish in other geographic locations (*Squalus acanthius*) until very recently when it was classified as its own species (S. *suckleyi*) (NOAA 2012). This organism is demersal but can occasionally be found throughout the water column in search of prey. They are opportunistic feeders, but common prey items consist of smaller fish such as herring and eulachon. Females do not mature until about 34 years of age and gestation is close to two years yielding a litter of up to nine pups (Tribuzio et al. 2008).

Dogfish are found coincidentally with larger fish such as halibut and arrowtooth flounder (DFO 2010) and can be a nuisance species for longline fishers targeting more commercially valuable animals like halibut and sablefish. In the NE Pacific, only a limited directed dogfish fishery has existed to present. Because the species has been deemed vulnerable to overfishing based on the life history traits of slow growth and low reproductive rates (DFO 2010), knowing how this animal responds to environmental factors may be critical to future stock assessments.

Longnose skate

Longnose skates are one of a number of skate species off the west coast of North America. They range from Baja, California to Unalaska Island in the eastern Pacific in depths commonly to 350 m, but observed as deep as 675 m (Allen and Smith 1988). The longnose skate lives on the bottom but is capable of swimming up into the water column. These animals often bury themselves partially in the substrate for camouflage and pounce on top of prey items as they swim by. They eat small fish and crustaceans, but their relationship to larger co-habitants like the fishes in this study is unclear (Bester 2011b).

The longnose skate has been fished commercially for some time off California (Martin and Zorzi 1993) and more recently further north into the Gulf of Alaska (Gaiches et al. 2003), but the fishery remains small. Holden (1974) concluded that skates were potentially vulnerable to overfishing due to slow growth rates and low reproductive rates thus as this species is further exploited, providing quantitative links between longnose skate distribution patterns and environmental factors will gain importance in stock assessments.

Sablefish

Sablefish are a demersal species that are long-lived and widely distributed in the north Pacific and Bering Sea from the waters of Japan to Baja, California (NOAA 2012). Sablefish are commonly found in depths to 700 m, but have been observed to 2740 m (Allen and Smith 1988). Kimura et al. (1998) first suggested (and has now been widely accepted) that there are two distinct populations, one north of Vancouver Island in the Alaska Gyre and one south in the California Current, with population mixing occurring off of Vancouver Island and the northern Washington coast. This idea is now widely accepted. Sablefish are opportunistic feeders and prey on invertebrates and other fishes (NOAA 2012). Like halibut and arrowtooth, sablefish spawn in the winter along the continental slope. Sablefish are considered a valuable food fish and are fully exploited in a lucrative commercial fishery in the NE Pacific Ocean.

Lingcod

Lingcod can be found from Baja, California to the Aleutian Islands, and are commonly found in depths to 300 m, but have been observed as deep as 475 m (Allen and Smith 1988). Lingcod are not known for their migratory behavior, but diurnal movements to locate food (i.e. shallows at night and deeper water during the daylight hours (Wilby 1937)) show that lingcod are capable of moving substantial distances. Both flatfish and dogfish are known food sources for lingcod (Shaw and Hassler 1989). This species supports a moderate commercial and sport fishery off the west coast of the U.S. and Canada.

Yelloweye rockfish

Yelloweye rockfish range from Baja, California to Prince William Sound, Alaska. They are most commonly found in depths from 50-400 m, but have been observed as deep as 475 m (Orr et al. 1998). This species has been fished commercially and for sport for some time, but its long life-span (and slow replacement) makes it particularly vulnerable to overfishing and has recently elicited concern among managers about the population's health. In 2010, NOAA listed yelloweye as threatened in the Puget Sound and Georgia Basin (NOAA 2010) affording the species special protections. In Canada, yelloweye are included in the rockfish Marine Conservation Area plans that are designed to protect the populations (DFO 2011c).

Characterizing the habitat: observations during the study years 2006-2009

Environmental data were collected at each fishing station on the 10x10 nmi grid depicted in Figure 2.2. Water column profilers were used to collect pressure (a proxy for depth), temperature, salinity, DO, and pH. For this study, only the bottom-most observations were used in order to characterize the conditions experienced by the demersal animals caught on the adjacent gear. Bathymetry is highly variable. The area includes wide, relatively shallow, shelf regions (e.g. off Oregon), steep drop-offs (e.g. off of northern Vancouver Island), and cross-shelf canyons (e.g. off northern Washington) (Fig. 2.3) In addition to water column profiles, bottom type information at each station location was obtained from the United States Geological Survey (USGS 2012) and Fisheries and Oceans Canada (DFO 2012).

Oceanographic observations

Iso-surface maps for each measured variable are shown in Figures 2.4a-d which depicts temperature, salinity, DO, and pH, respectively, in each sampled year. Iso-surface plots were generated using Ocean Data View software (Schlitzer 2010). Temperature was generally cooler to the north than to the south and cooler offshore than inshore during the study period. Salinity was well within the normal bounds for the area, but both DO and pH showed more extreme values that are discussed at length in this report. A description of the data by year is illustrated as box and whisker plots in Fig. 2.5. These plots illustrate the high degree of variability across the study area. It is important to note when considering these results that 2006 encompassed data in the area north of Washington state only while the other three years included at least a portion of stations to the south of Vancouver Island.

Between Washington and Vancouver Island where Vancouver Island temperatures tended to be slightly higher than off Washington. The outflow from the Strait of Juan de Fuca is warmer and fresher than the seawater off the coast, and is visible off southern Vancouver Island in the temperature and salinity panels (Fig. 2.4 a and b). In Queen Charlotte Sound there is lower saline, warmer water found at more shallow depths, near discharge points of local rivers, and near the inflow point from the Strait of Georgia described in Crawford et al. (2007).

DO in the water column is affected by both biological and physical processes and can change fairly quickly. Hypoxia (<1.4 ml/L) occurs in the summer months and into the fall in areas off of Washington and Oregon (Connolly 2010; Chan et al. 2008) and DO levels are generally at their lowest later in the summer season because of the biological drawdown from respiration (B. Hickey, pers. comm.) The IPHC survey operates within the months of June, July, and August with some flexibility within that time frame so it is possible that the survey can miss all or part of a hypoxic event during the survey period. Hypoxic conditions were observed during the IPHC survey in both Oregon and Washington in 2007-2009 while no hypoxia was observed off Vancouver Island and Queen Charlotte Sound in any year (Fig. 2.4c). There were no DO samples collected by IPHC in 2006 in the southern regions, but there were in the Vancouver Island and Queen Charlotte Sound areas. Although IPHC did not collect samples off the U.S. coast in 2006, sampling done by Oregon State University identified severe hypoxic conditions off of Oregon that year (OSU 2008, Chan et al. 2008).

Upwelling further north off the B.C. coast was stronger than normal, but still weaker than further south and did not give rise to hypoxia or even particularly lower than normal DO levels within the bounds of the survey. However, the Vancouver Island portion of the survey was conducted in early June, so given that oxygen levels were extremely low later in the summer and into the fall further south, it is likely that the survey was simply too early to detect it if it developed to the north later that summer. In fact, a look at the data from a regularly sampled transect off of Vancouver Island, called Line P (DFO 2011b), supports this possibility. The data show that in September of that year, an inshore Line P station (Station 2, 48^{o}36.08N and 126^{o}00.03W, 114 m depth) had a near-bottom DO level of about 0.5 ml/L, which is clearly hypoxic.

Another look at how hypoxia develops temporally further north is illustrated when looking at DFO trawl survey data for Vancouver Island and Queen Charlotte Sound collected in 2006-2007 (Olsen et al. 2007, 2009a, 2009b; Workman et al. 2008). In 2006, the DFO survey dates correspond closely to IPHC survey dates and show a similar pattern and degree of DO on the shelf stations, although there is clearly lower DO water further offshore as sampled by the trawl survey (Fig. 2.6a). However, in the following year, the trawl survey dates are approximately one month later into the summer than the longline survey dates and near-shore DO is clearly lower in several locations during the trawl survey (Fig. 2.6b).

Salinity tended to decrease with latitude. This overall pattern may partly reflect the freshwater discharge from the Strait of Juan de Fuca, the Strait of Georgia, and the various coastal rivers and marshland in the northern areas (Crawford et al. 2007), weaker upwelling in the north, and also the weakening California undercurrent which brings warmer, salty water from south to north. In Oregon and Washington, salinity trended downward according to the summertime measurements taken from 2006-2009.

Acidity was measured from 2007-2009, illustrating the wide degree of variability experienced by fishes in the area. Clearly present (Fig. 2.4d) are particularly low pH waters in the upwelling zone off Oregon and Washington. This finding agrees with Feely et al. (2008) who found that corrosive waters (undersaturated with carbonate) were upwelled off the west coast of the U.S in summer of 2007. The majority of studies to date have focused on acidification effects to shell-forming organisms. However, recent studies (e.g. Munday et al. 2010, Simpson et al. 2011, Ferrari et al. 2012) have documented behavioral changes in larval and juvenile stage reef fishes whereby predator detection and evasion is severely impaired. Very recently, P. Munday (James Cook University, Centre of Excellence for Coral Reef Studies, Australia, results reported at *The Ocean in a High-CO2 World: Ocean Acidification* symposium) also documented behavioral changes in predators that resulted in prey switching. It is yet unclear if sensory impairment was the impetus for the switch in these adult fishes. This is very recent line of study and more work is needed to examine the subject of adult fish behavior related to ocean pH in the north Pacific.

Species catch observations

The seven species chosen for this study were selected specifically because they were the most commonly caught species on the survey, making up 92% of the catch over the four year period. They share similarities in that they are all considered predators, are relatively large (and thus catchable by the survey longline gear), share similar prey preferences, and many have similar spawning habits. The survey was designed as a tool to assess halibut abundance and therefore extends across the full summer range for halibut. Most of the animals are generally contained within the 500 m depth boundary in summer also, with the exception of spiny dogfish where range is yet unknown, and sablefish which are routinely also found much deeper. The study area intersects the known geographical ranges for all of the study species with the closest range endpoint being central California for Pacific halibut, and some species ranging as far south as the Baja Peninsula. All of the animals had a northern range of at least the central Gulf of Alaska and most range farther west to as far as the coast of Japan.

Catches were standardized into number per unit effort (NPUE), i.e. number of animals caught per one hundred hooks, so they could be compared across years and regions. An accounting of NPUE by year shows that average catches differed by species, but were similar from year to year within species (Fig. 2.7). Spiny dogfish were clearly the most abundant followed by halibut and sablefish, respectively. The remaining four species consistently had mean NPUEs less than one.

NPUE clearly changed with latitude over the boundaries of the study area (Fig. 2.8), with Oregon and Washington to the south providing fewer animals than the British Columbia coast further north. Sablefish NPUE was an exception, with catch rates having no obvious relationship with latitude. Animal distributions matched well with the summer depth ranges established in the literature for each (described in the previous section) with sablefish found in deeper depths and the other animals generally found in depths less than 300 m (Fig. 2.9). NPUEs were also mapped against each environmental variable (Figs. 2.10a-d; temperature (^{o}C), salinity (psu), DO (ml/L), and pH, respectively). Salinity appeared to provide some structure with the majority of animals found at higher salinities. The temperature, DO, and pH panels showed that there were some patterns within species, but no obvious patterns with all species combined. These relationships are considered in detail in the next Chapter.

Figures

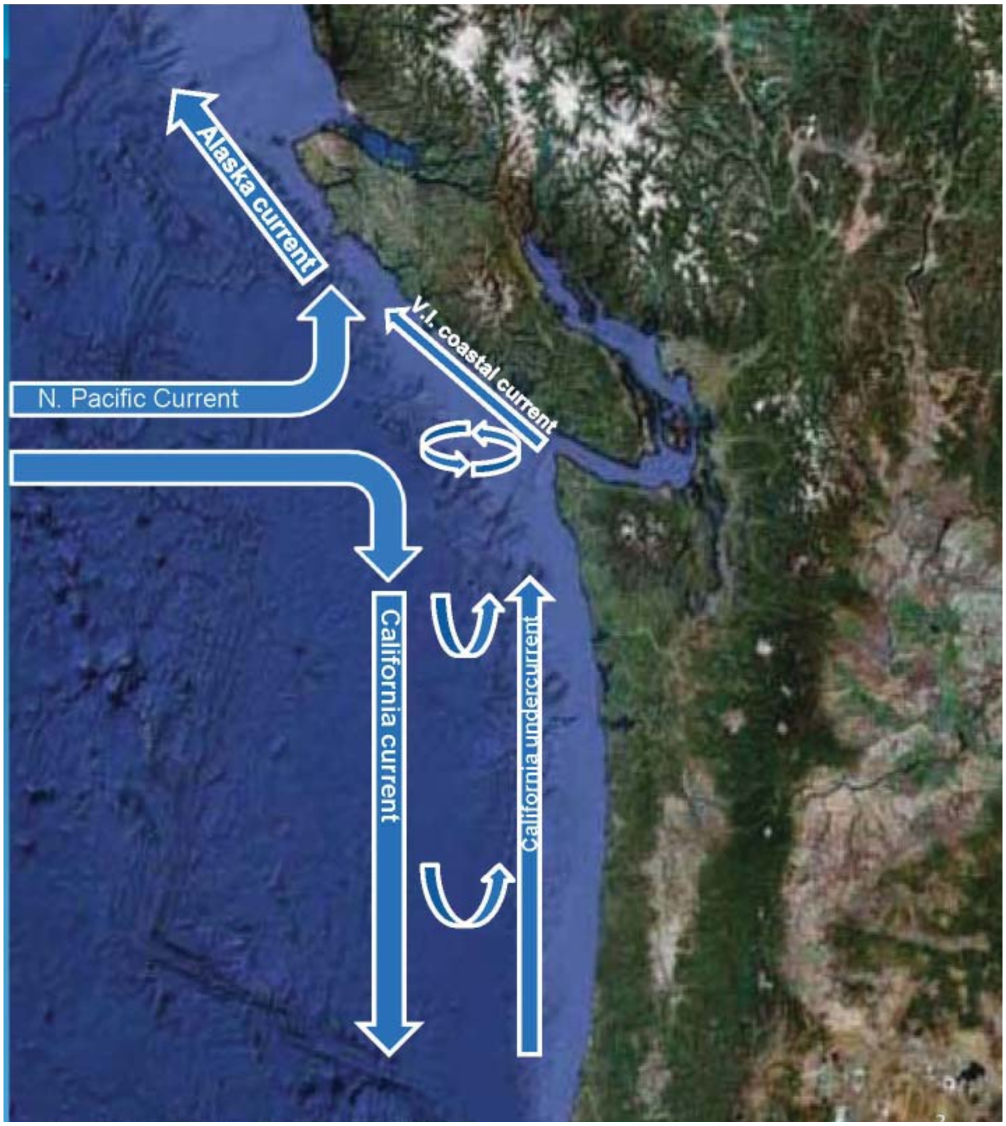


Figure 2.1. Major ocean currents off the coasts of Oregon, Washington, and southern British Columbia include the North Pacific Current from the west which splits into the Alaska current to the north and the California Current to the south. There is also seasonal upwelling, an eddy feature and countercurrents.

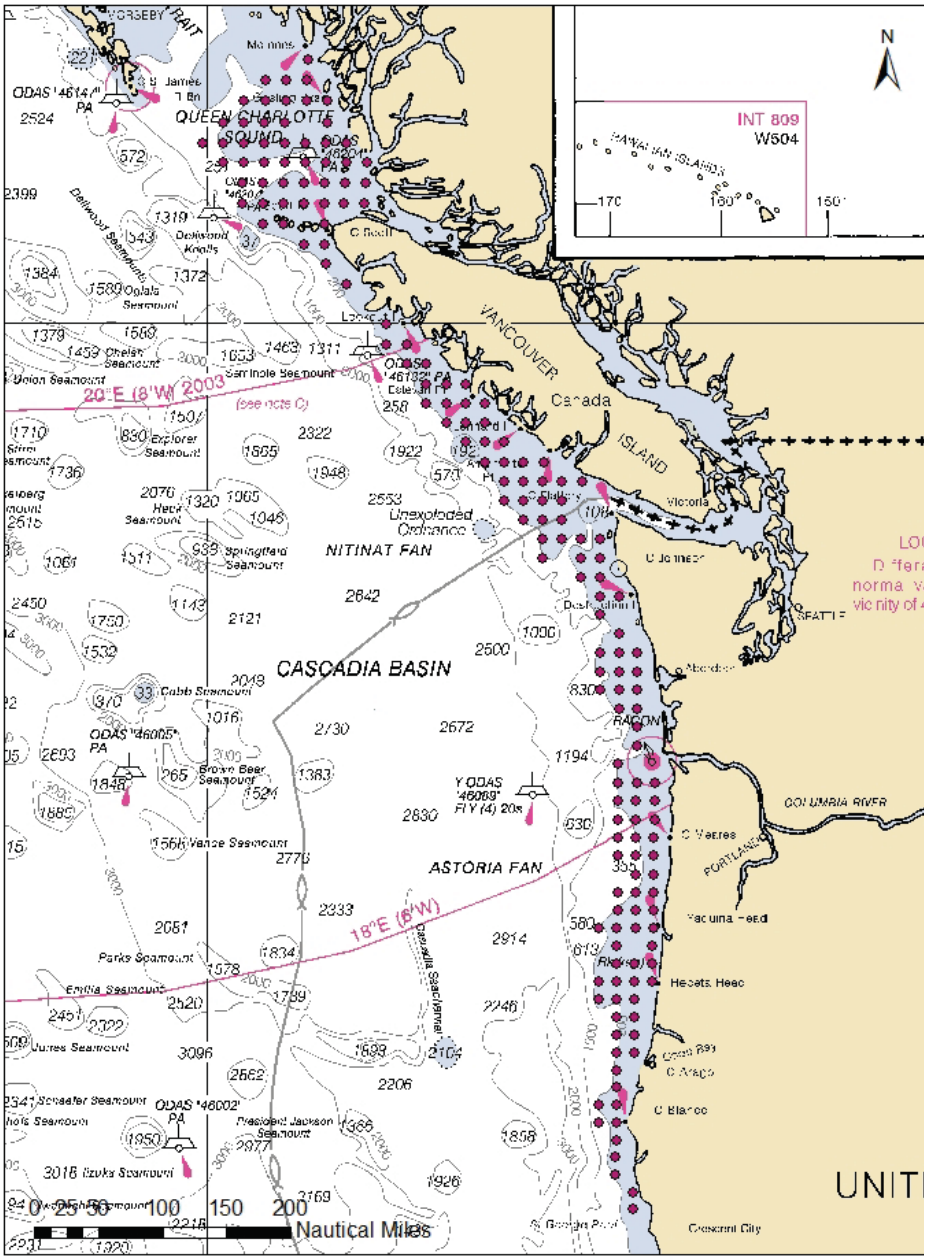


Figure 2.2. Approximate station locations for data collection are situated on a 10x10 nmi grid. Inshore of the 200-m depth contour is highlighted in blue.

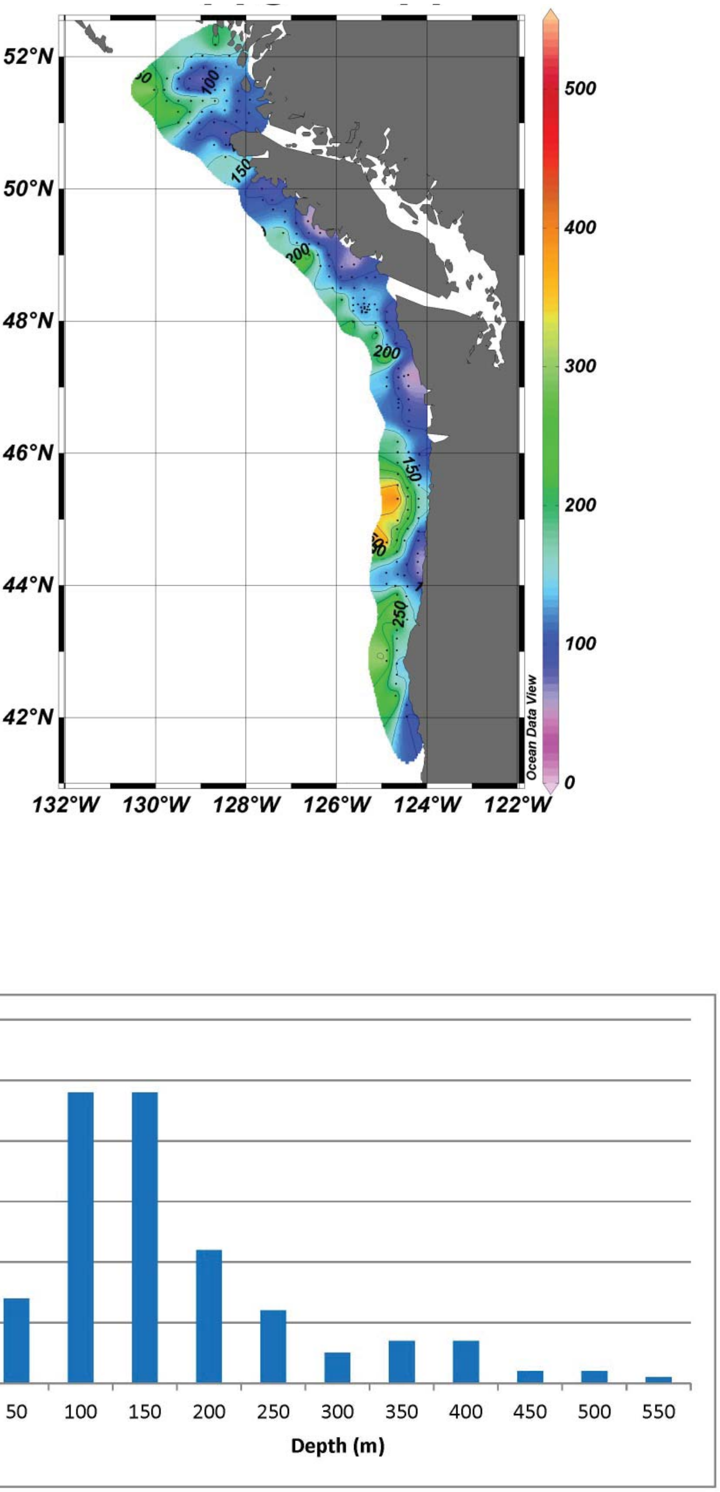


Figure 2.3. Depth profile of the study area. The top panel (a) shows an isosurface map based on depths experienced at each station. Iso-surface map generated using Ocean Data View software (Schlitzer 2010). The bottom panel (b) shows the distribution of stations by 50 m category.

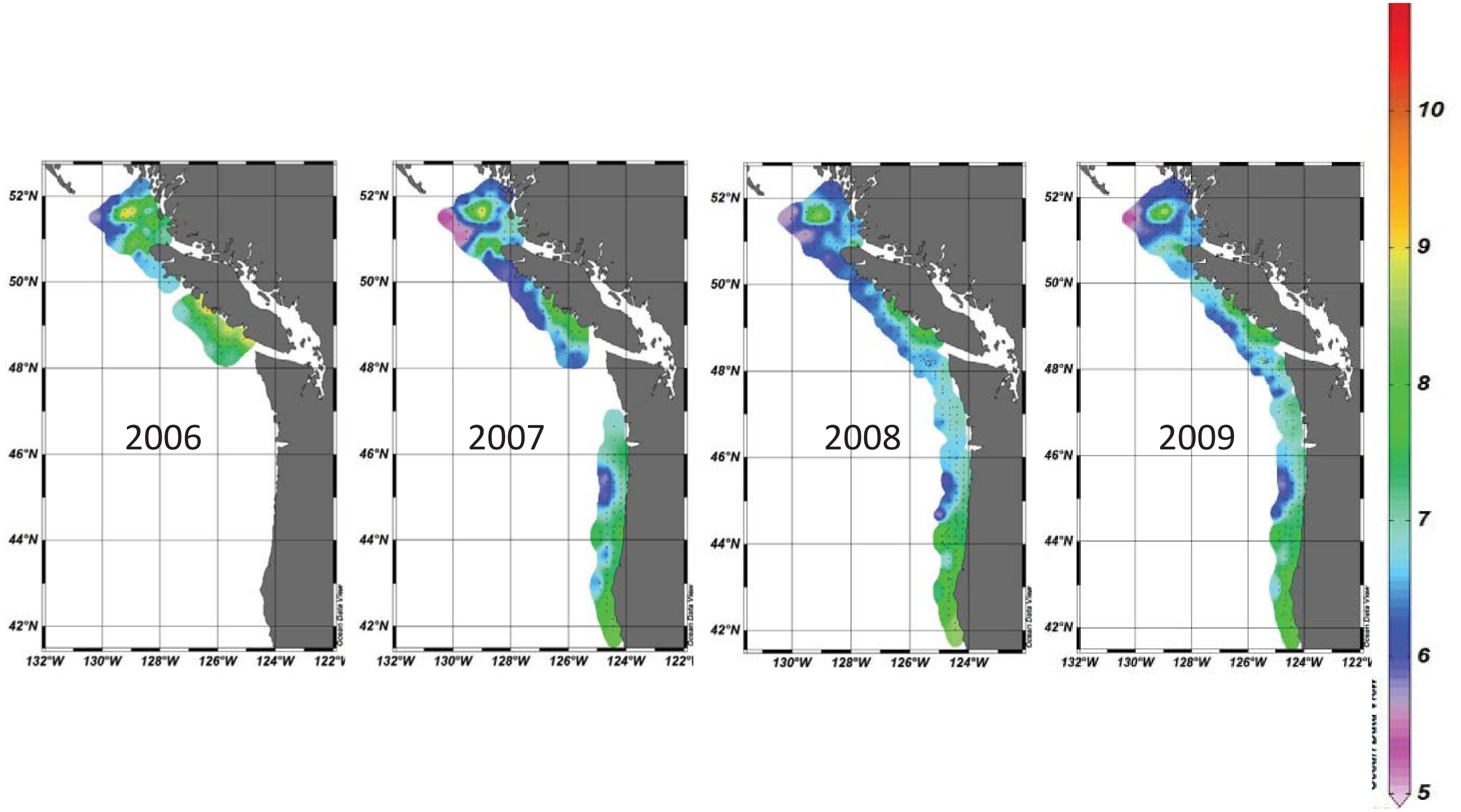


Figure 2.4a. Iso-surface maps of near-bottom temperature (°C) for the years 2006-2009 (from left to right). The isosurface is based on data gathered on a 10x10 nautical mile grid over the study area, then interpolated between points to make the solid surface. The color key is shown on the right and uses the same units as the variable. Note that in 2006, oceanographic data were collected only in the northern part of the study area and in 2007, waters off Washington were not sampled. Maps generated using Ocean Data View software (Schlitzer 2010).

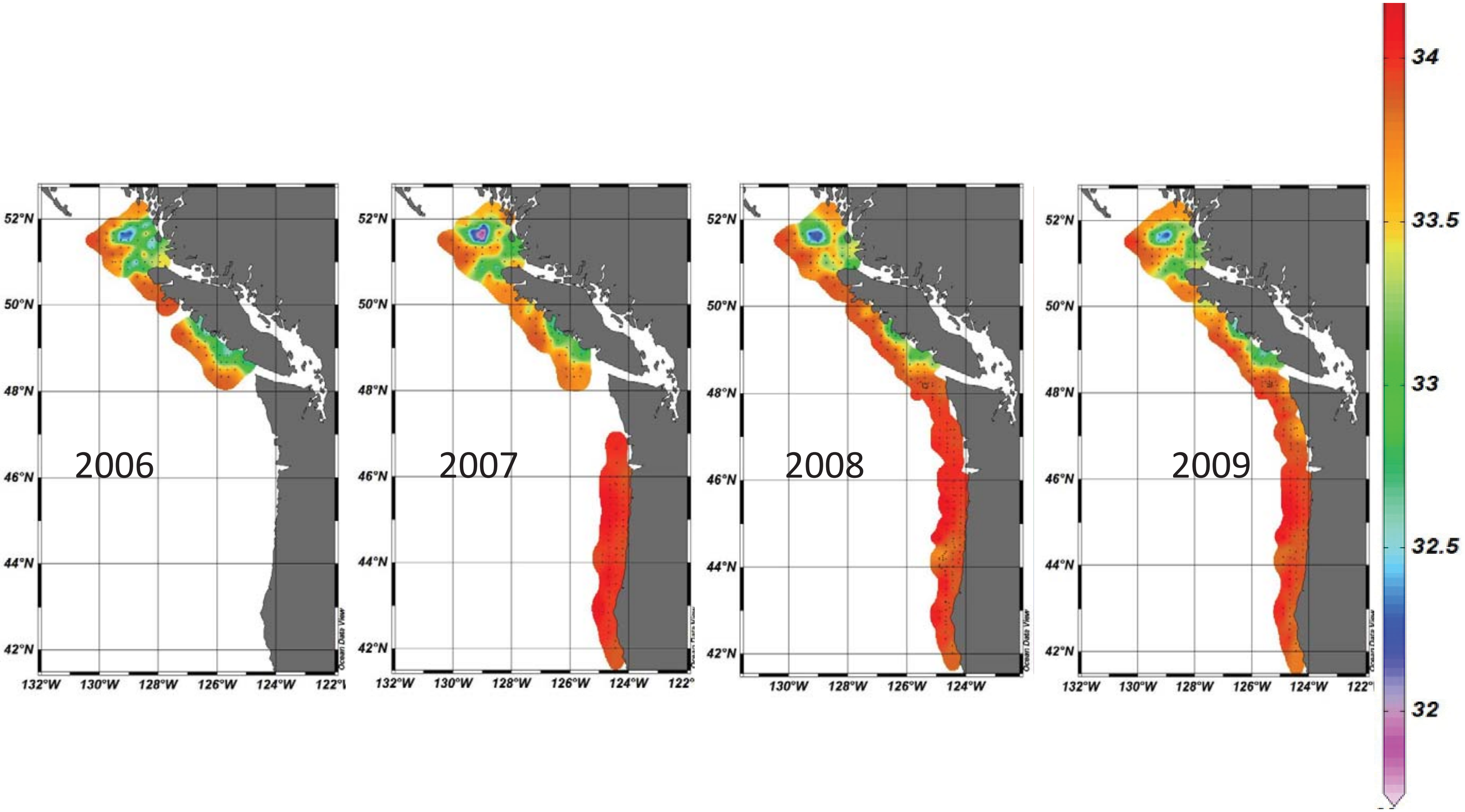


Figure 2.4b. Iso-surface maps of near-bottom salinity (psu) for the years 2006-2009 (from left to right). The isosurface is based on data gathered on a 10x10 nautical mile grid over the study area, then interpolated between points to make the solid surface. The color key is shown on the right and uses the same units as the variable. Note that in 2006, oceanographic data were collected only in the northern part of the study area and in 2007, waters off Washington were not sampled. Maps generated using Ocean Data View software (Schlitzer 2010).

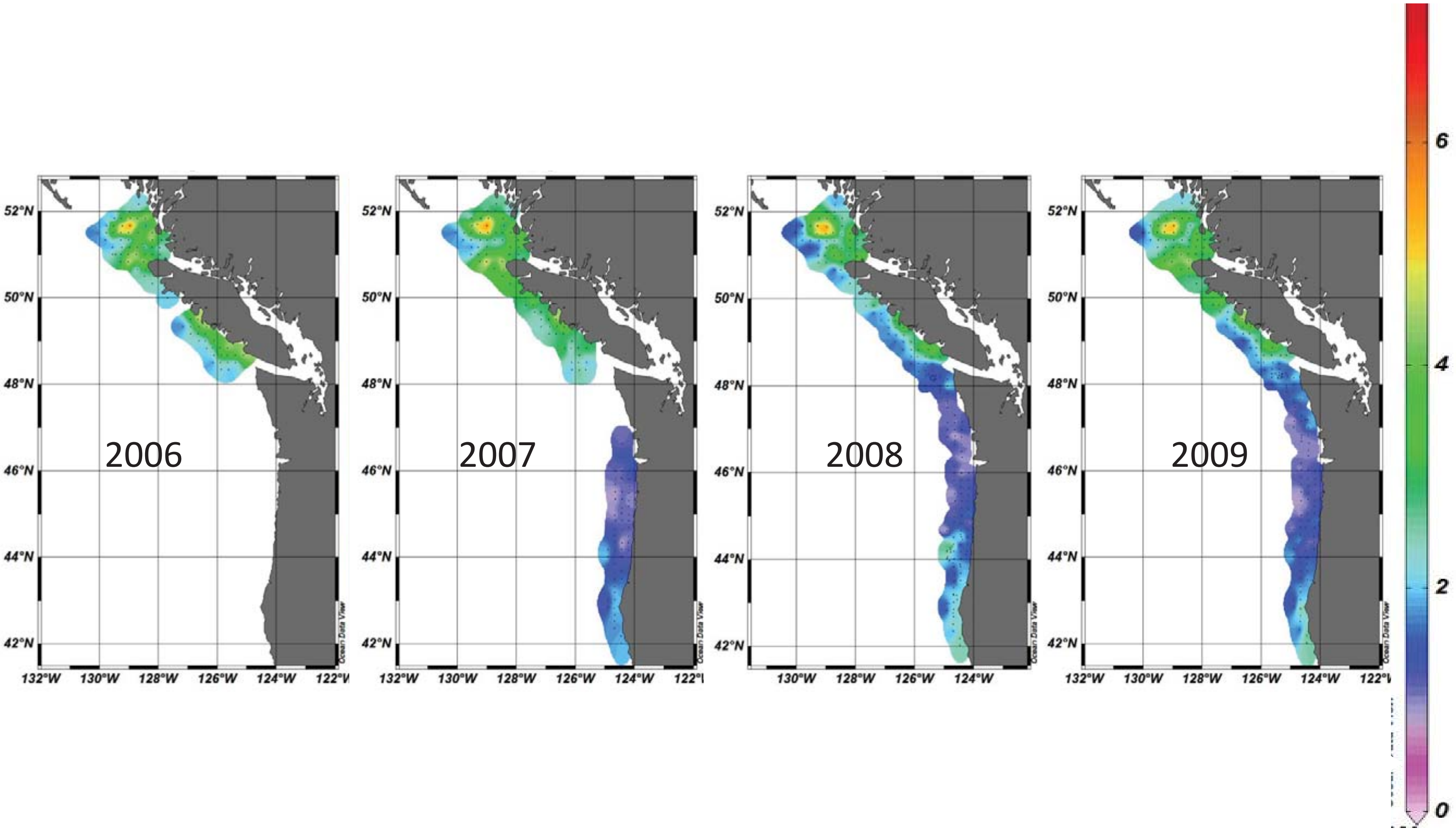


Figure 2.4c. Iso-surface maps of near-bottom dissolved oxygen (ml/L) for the years 2006-2009 (from left to right). The isosurface is based on data gathered on a 10x10 nautical mile grid over the study area, then interpolated between points to make the solid surface. The color key is shown on the right and uses the same units as the variable. Note that in 2006, oceanographic data were collected only in the northern part of the study area and in 2007, waters off Washington were not sampled. Maps generated using Ocean Data View software (Schlitzer 2010).

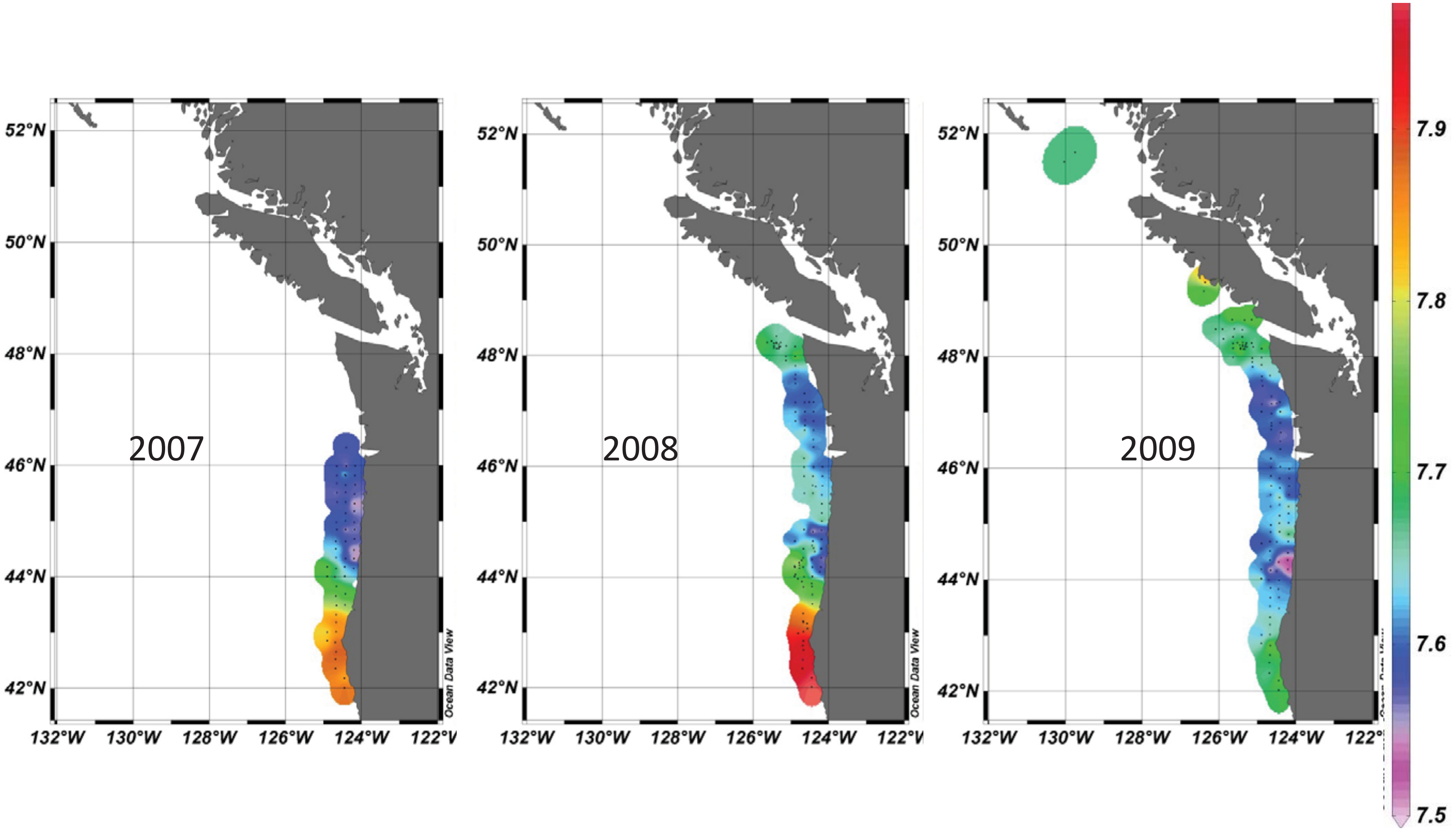


Figure 2.4d. Iso-surface maps of near-bottom pH for the years 2007-2009 (from left to right). The isosurface is based on data gathered on a 10x10 nautical mile grid over the study area, then interpolated between points to make the solid surface. The color key is shown on the right and uses the same units as the variable. There were no pH data collected in 2006, and pH data were not complete in other years due to sensor malfunction. Maps generated using Ocean Data View software (Schlitzer 2010).

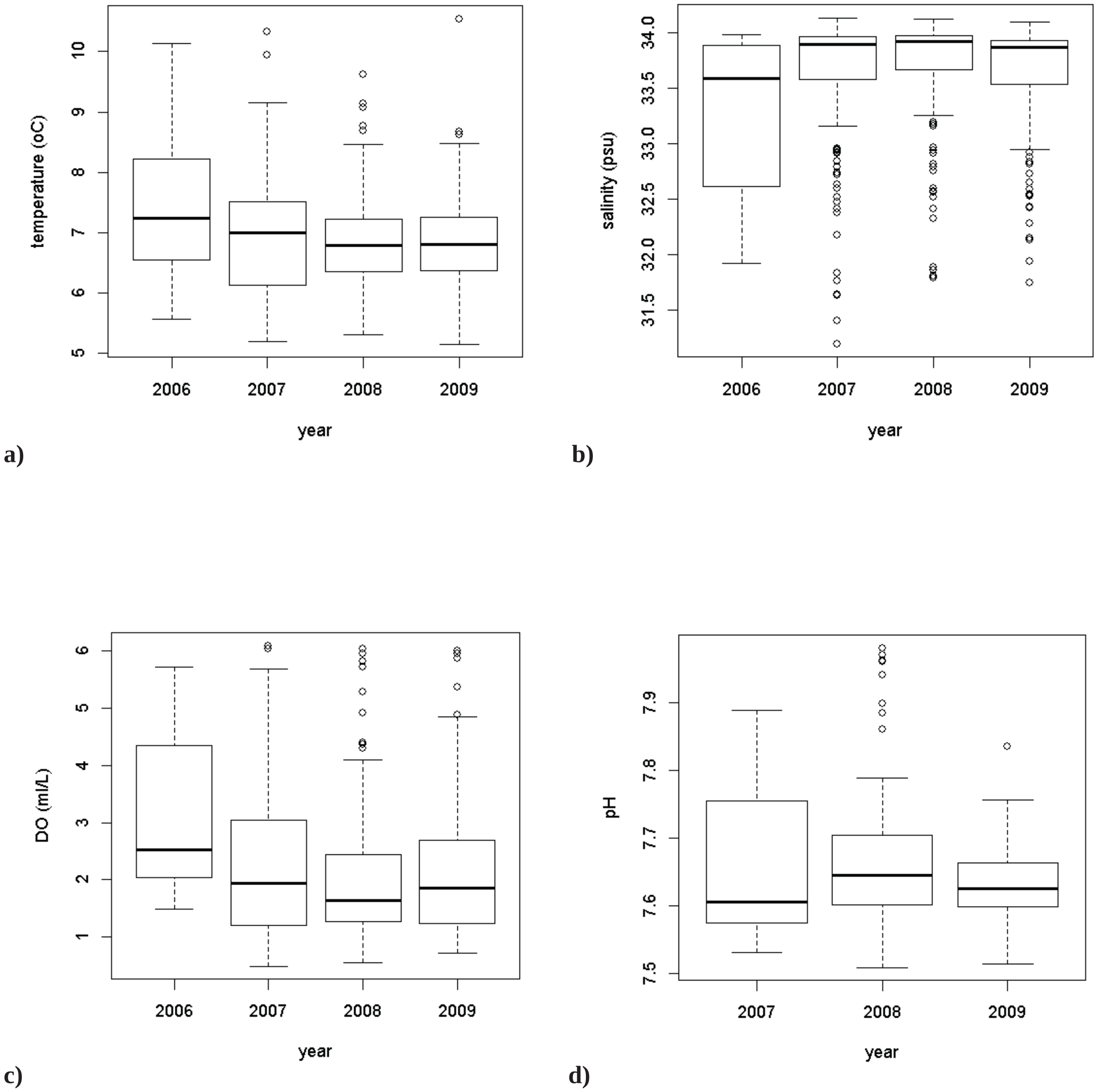
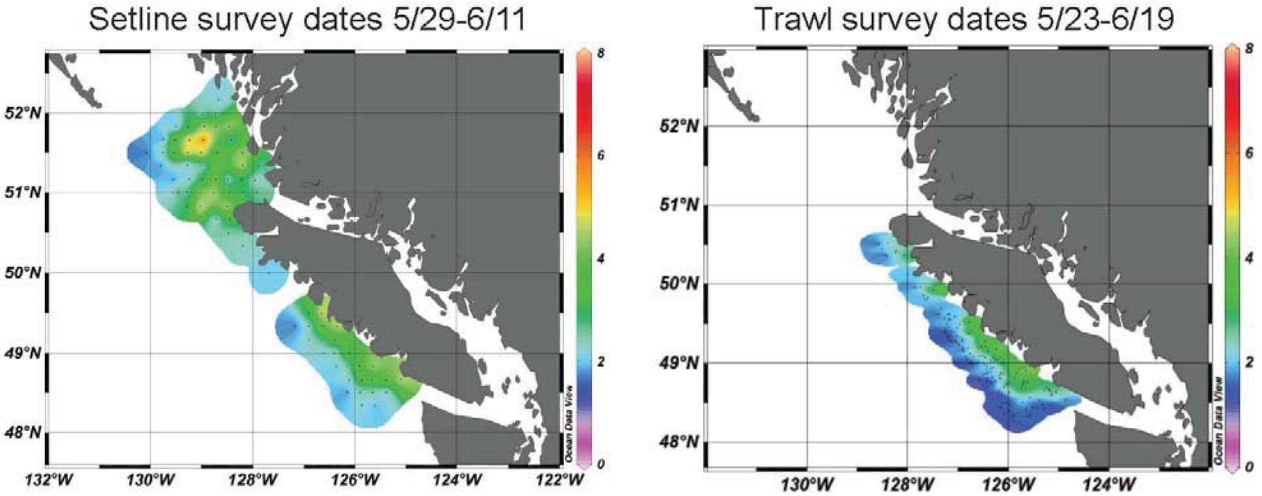
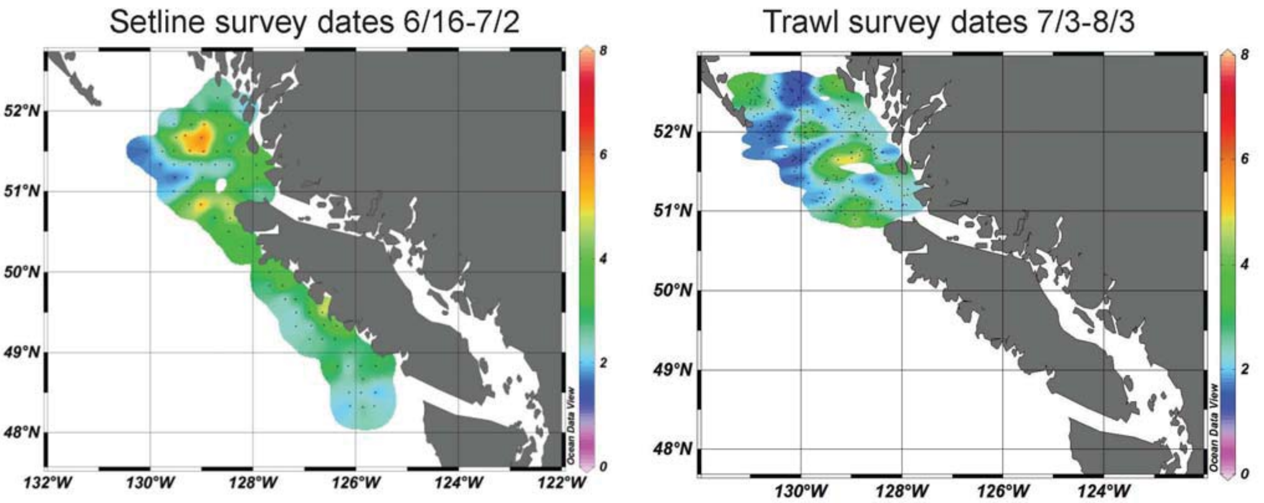


Figure 2.5. Box and whisker plots of environmental data for each study year. The plots highlight the within-year variability as well as the relative consistency among years.


Setline survey dates 5/29-6/11

Trawl survey dates 5/23-6/19

Figure 2.6a. IPHC setline (left) and DFO trawl (right) survey results for near-bottom DO observations in 2006 along with survey dates. Iso-surface plots generated using Ocean Data View software (Schlitzer 2010).


Setline survey dates 6/16-7/2

Trawl survey dates 7/3-8/3

Figure 2.6b. IPHC setline (left) and DFO trawl (right) survey results for near-bottom DO observations in 2007 along with survey dates. Iso-surface plots generated using Ocean Data View software (Schlitzer 2010).

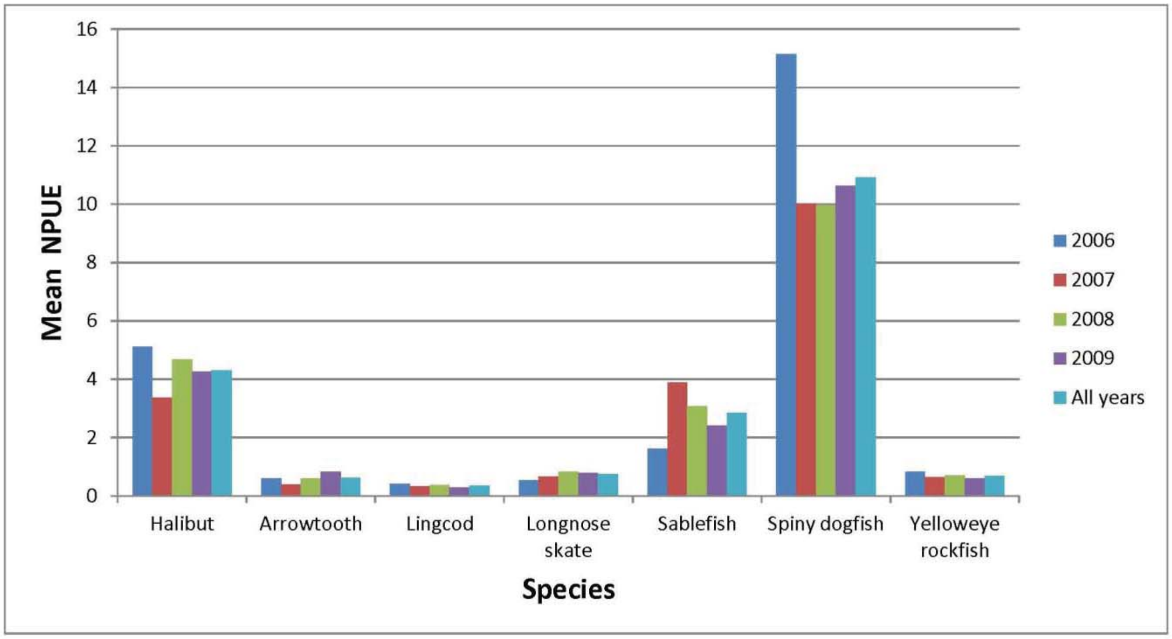


Figure 2.7. Mean number per unit effort (NPUE) over the entire study area for each species and year. Note that 2006 includes stations to the north of Washington only. Spiny dogfish were clearly the most abundant species followed by Pacific halibut and sablefish, respectively.

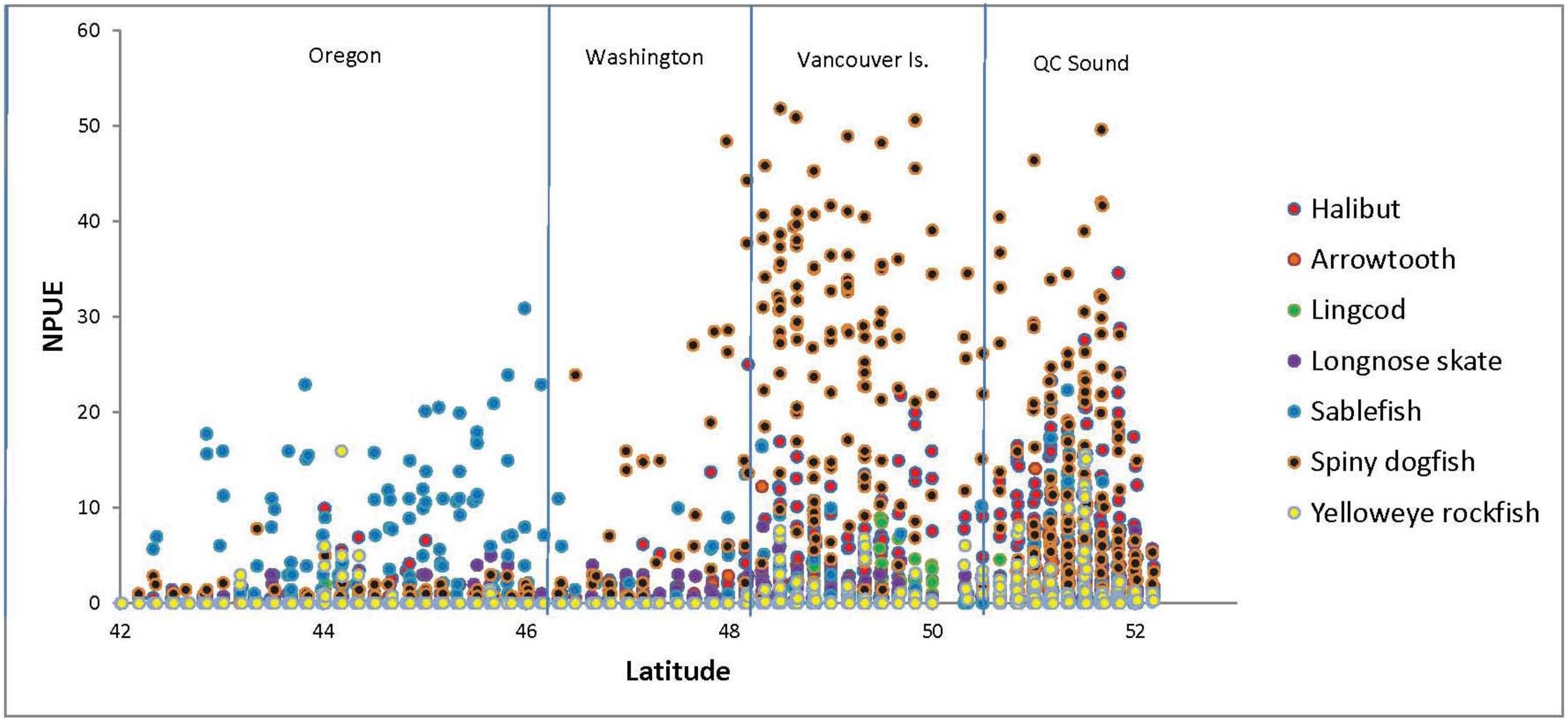


Figure 2.8. Number per unit effort (NPUE) for each of the study areas by latitude. NPUE for most species is clearly higher in the northern regions than further south, except for sablefish which is found in comparable numbers throughout the study area.

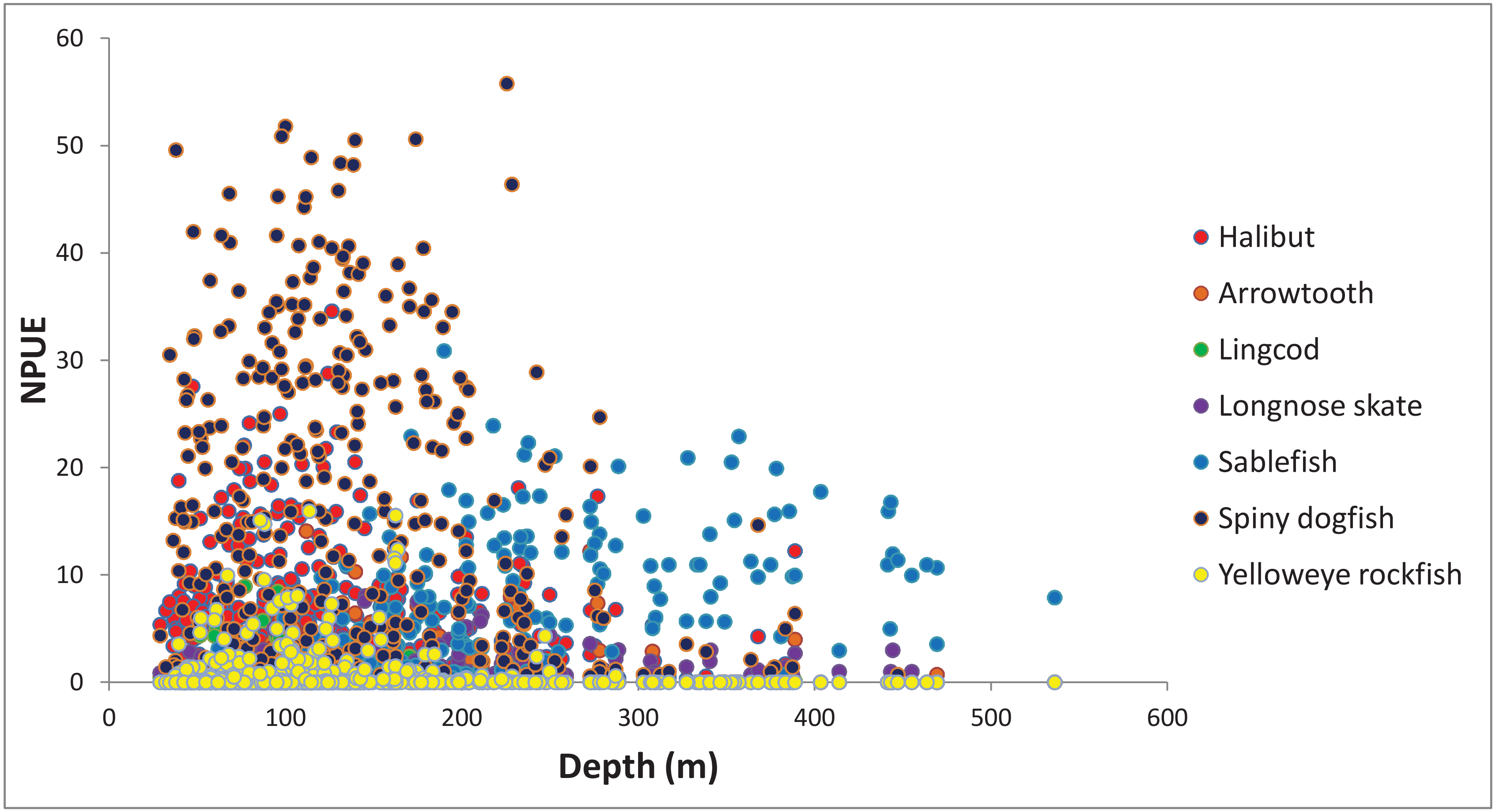


Figure 2.9. Number per unit effort (NPUE) of study species by depth (m). The majority of species are found primarily in depths <300 m, except for sablefish which were found at the deepest stations.

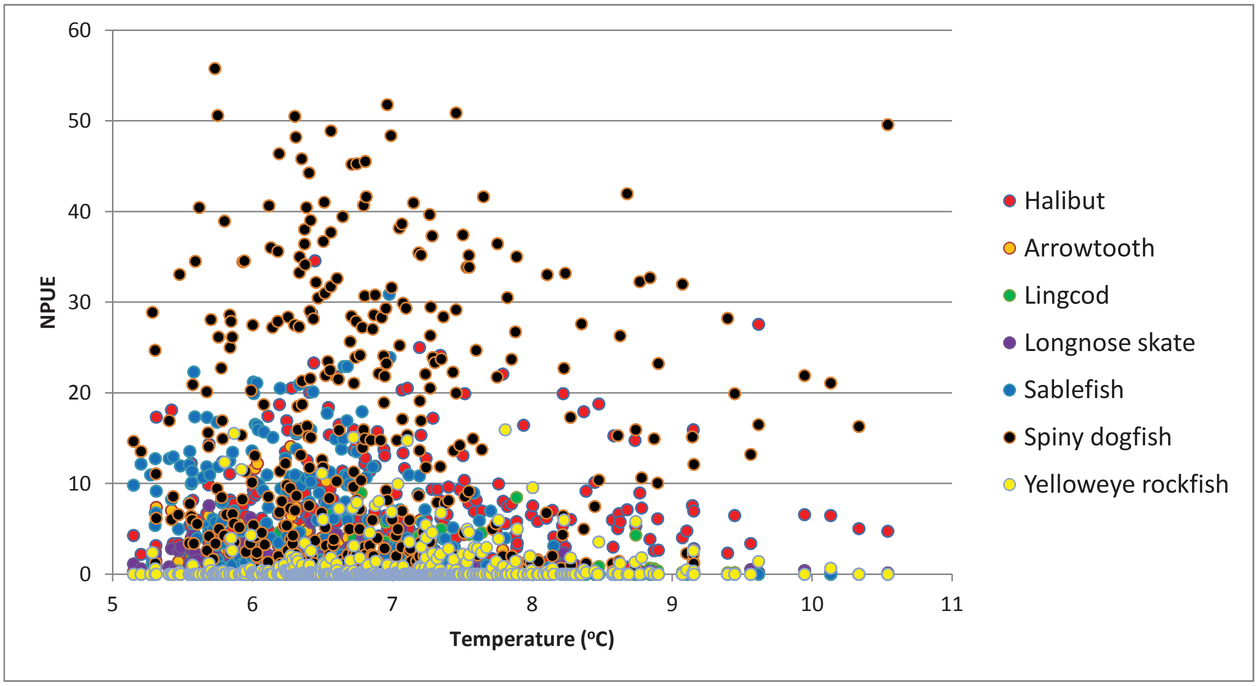


Figure 2.10a. NPUE plotted against temperature as observed during the study. Clearly, some of the species appear more sensitive to temperatures than others.

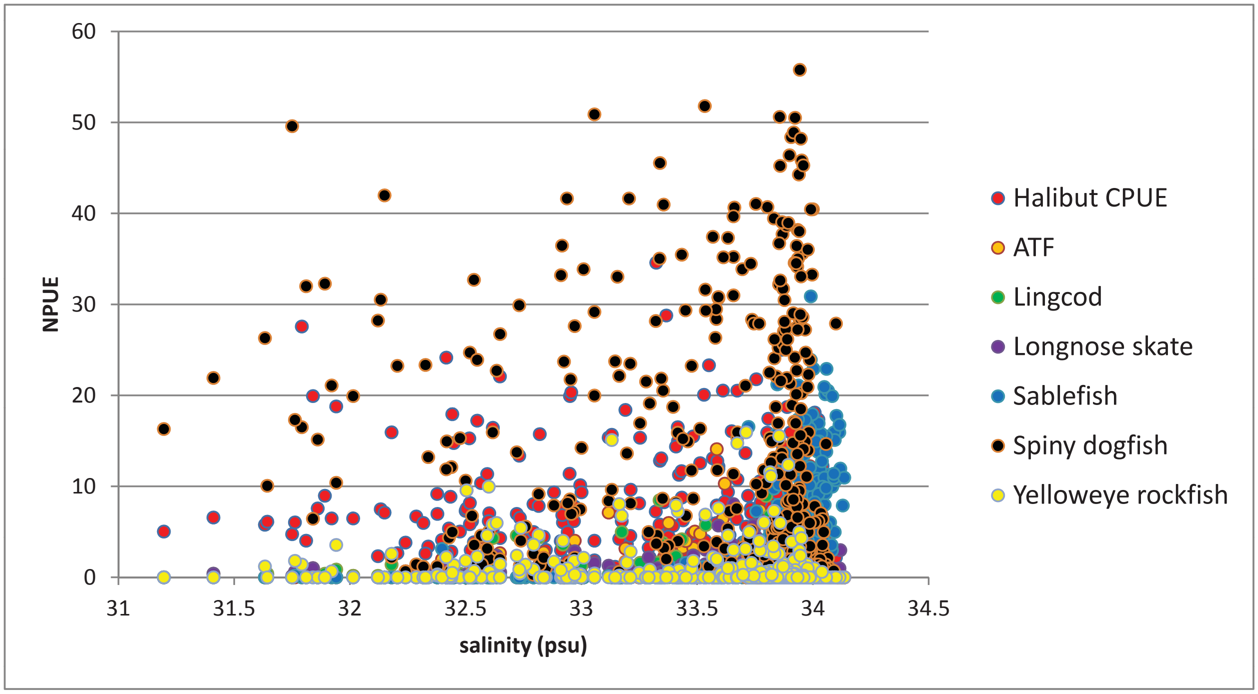


Figure 2.10b. NPUE plotted against salinity as observed during the study.

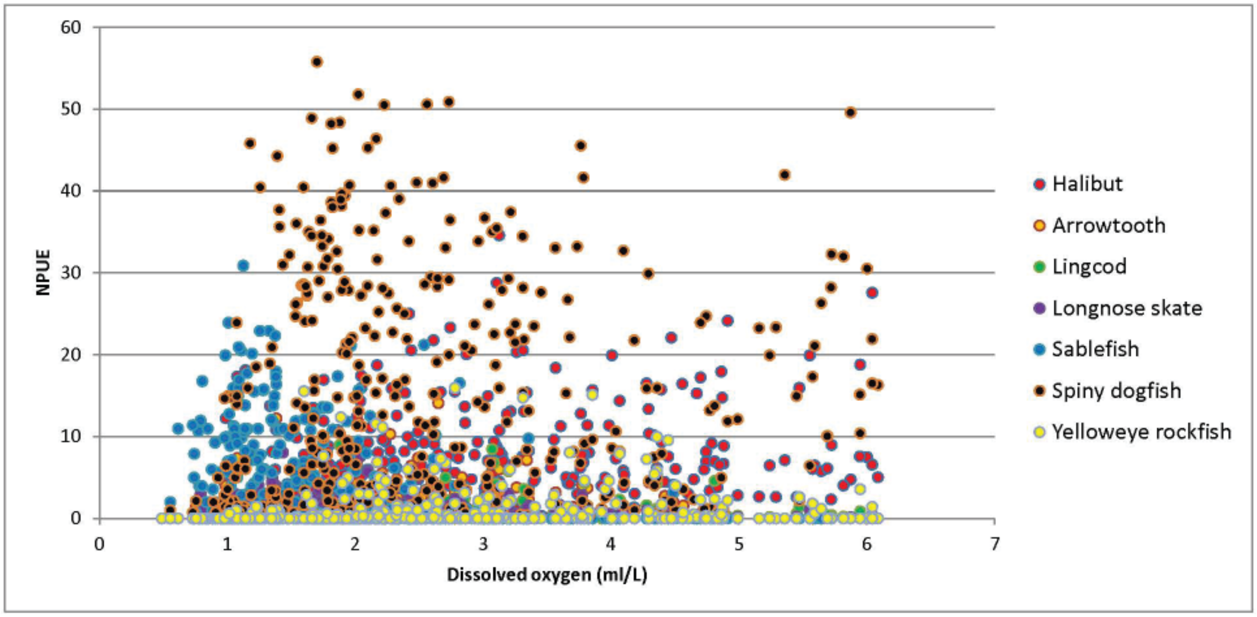


Figure 2.10c. NPUE plotted against DO as observed during the study.

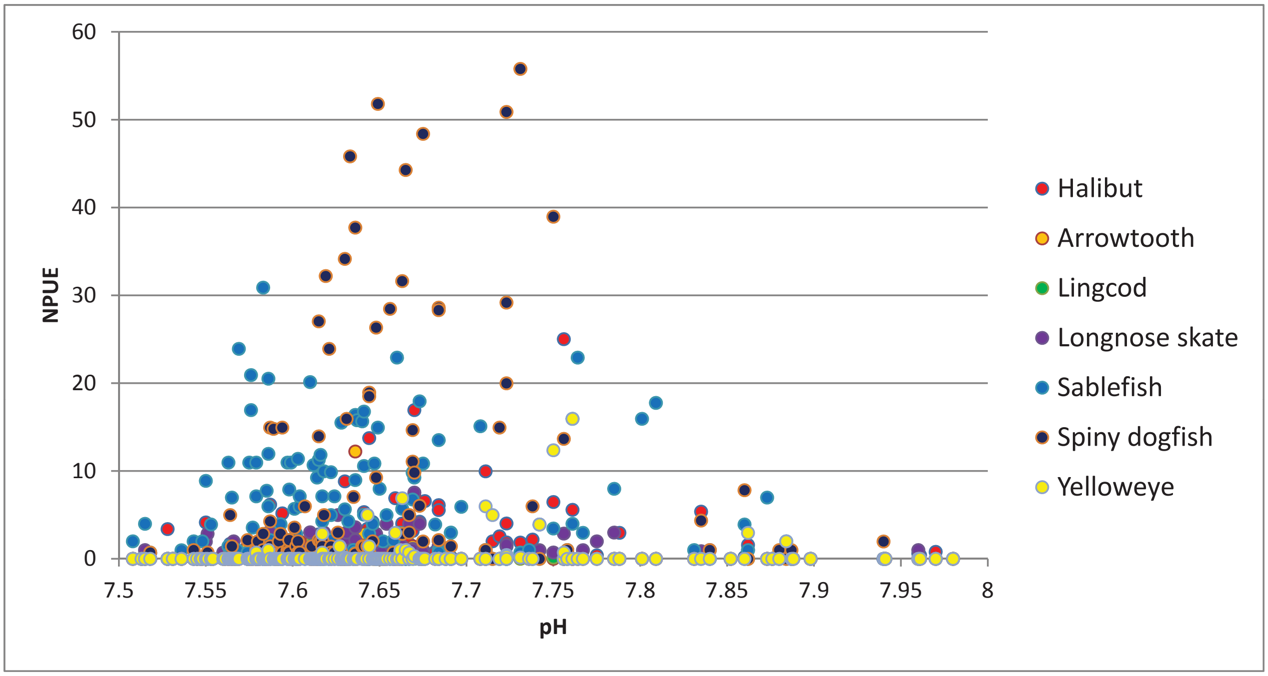


Figure 2.10d. NPUE plotted against pH as observed during the study. Note that only about half of the stations where data were collected over the four year period resulted in useable pH data.

Chapter 3. Habitat use for seven frequently caught species in the IPHC's longline surveys in the NE Pacific Ocean

Introduction

Fish habitats are likely a confluence of many factors including physical and chemical water properties like horizontal currents, temperature, dissolved oxygen (DO), pH, water clarity, and light levels; community factors such as availability of prey, proximity of predators and competitors; and physical characteristics such as substrate type and depth. It has been shown through various studies (e.g. Hurst 2007 and Prince et al. 2010) that a change in one or more of these factors could result in a behavioral/distributional change in the organism. When examining these factors and attempting to build predictive models, it is important to examine the environmental variables for spatial correlation as well as regional variation (i.e. where processes differ across the study area, in this case geographically) which may help provide answers to additional underlying processes or conditions affecting the populations and the stock monitoring methods.

Projected increases in global temperature have inspired studies looking into the effects of climate change on species complexes especially where commercial fisheries exist. Hurst (2007) found that juvenile walleye pollock had increasing swim speeds with decreasing temperature as well as increased group cohesion with lower temperatures. Several studies have looked at effects of environmental factors on fish distributions over the long term. For example, Perry et al. (2005) found that in the North Sea, over a period of 25 years, 60% of species studied showed a change in latitude or depth or both in response to rising temperatures. Sabates et al. (2006) found that a small sardine species native to the Mediterranean expanded its range progressively further north coincident with rising water temperatures over a 20-year period. Mueter and Litzow (2008) showed that fish communities in the Bering Sea altered their range in concert with changes in sea ice cover and the extent of the cold pool.

DO concentration is a factor that has gained increasing global attention in recent years as the number and expanse of low oxygen (hypoxic) zones has increased (Diaz and Rosenberg 2008). Seasonal hypoxic conditions (< 1.4 ml/L) off the coast of Washington State have been occurring for some time on the mid to outer shelf and occasionally the inner shelf, according to Connolly et al. (2010) who studied historical observations from 1950-1986. They reported that historical levels were comparable to those observed in the 2000s, with the exception of 2006 when hypoxic conditions were of a greater magnitude and spanned a broader range than seen previously. Off the Oregon coast, regularly-occurring seasonal hypoxia is thought to be a relatively new development on the inner-shelf region, having been detected annually since 2002 to varying degrees (Chan et al. 2008, Gewin 2010, OSU Unpub).

The study of fish response to low DO is of increasing concern as hypoxic zones that were once primarily features for the deep ocean are shoaling and expanding onto the continental shelves (Keeling et al. 2010). Different fish species likely have different tolerance thresholds for DO, and demersal fishes, especially those found in deeper water (and naturally lower oxygen) of the continental shelf, may be more tolerant of low levels than their pelagic and more shallow counterparts.

Many recent studies have looked at the effect of hypoxia on various organisms concluding notable displacement of mobile organisms and mortality or density reduction of sessile organisms. For example, Rabalais et al. (2001a, 2001b) found that locations where hypoxic conditions form annually near the mouth of the Mississippi River in the Gulf of Mexico, mobile fish species in the area are forced outward and closer to the surface in the presence of hypoxia. During the particularly intense hypoxic event off Oregon and Washington in 2006, Chan et al. (2008) used a remote submersible and found massive kills of stationary and slow moving organisms, and a complete absence of mobile fishes (both dead and alive), suggesting that mobile fish were able to move to locations with more tolerable DO levels. Likewise, Prince et al. (2010) found that the Atlantic billfish in the tropical Atlantic experienced habitat changes when they were forced outward and closer to the surface in order to find higher DO concentrations. Keller et al. (2010) described differences in biomass levels of trawl caught species off the U.S. West Coast based on DO concentration and found that eight fish species showed a significant decrease in biomass with lower DO while another seven showed no significant difference. It is unclear whether the fish simply moved out of the hypoxic zone or actually suffered mortality as a result of DO stress. Essington and Paulsen (2010) looked at the impacts of hypoxic events in Hood Canal, Washington and found reduced densities of immobile organisms during these events.

Ocean acidification, i.e. decreasing pH in the global ocean due to seawater reacting with increasing atmospheric CO_2 concentrations, is now a widely accepted fact (Caldeira and Wickett 2005). However, not all seawater has the same chemical properties. Deep water that is upwelled, for example, is typically already naturally low in pH and can be under-saturated with respect to aragonite. The areal/spatial extent of these corrosive waters can expand as upwelled seawater comes in contact with acidified surface water (Feely et al. 2008).

Studies on the effects of acidification on biological processes thus far have shown a multitude of effects. Marine calcifying organisms such as various species of plankton, corals, and molluscs experience decreased ability to form shells as the pH of the seawater decreases (Doney et al. 2009). A synthesis by Fabry et al. (2008) reported that in fishes, acidification resulted most often in metabolic suppression which in turn affects feeding, growth, and reproduction. While metabolic suppression may be an effective coping mechanism in the shorter term, longer term exposure to acidified water may have detrimental effects. Recent research (Hoffman and Schellnhuber 2009) has also shown that ocean acidification does not exist independently of other environmental factors such as oxygen, but is in fact a part of a complex system where acidification triggers or contributes to the expansion of marine hypoxic zones. Hauri et al. (2009) describes the mechanism for this trigger whereby acidification reduces the production of mineral ballast by calcifying organisms which limits the transport of organic matter to deep ocean layers, and leads to re-mineralization of organic matter in shallow waters, leading to higher demand of DO in the upper ocean and a resulting DO decrease.

Animals may prefer certain bottom types over others thus affecting distribution. For example, structured bottom may act as refuge from predators, sandy bottom may allow for burrowing, and each bottom type likely hosts a unique set of prey species for the same reasons. Wieland et al. (2009) reported that in a study conducted in the North Sea, catch rates were significantly different depending on bottom type.

This chapter explores environmental variables in relation to the distribution of seven demersal fish species found off the coasts of Oregon, Washington, and southern British Columbia that were captured during the IPHC longline survey in 2006-2009.

Data and methods

Seven macrofauna species found commonly off the U.S. West Coast were selected for analysis. The criteria for selecting the study subset was as follows:

1) Organisms were present in all study regions.

2) Total counts exceeded 200 animals.

3) Any organisms that may have been snagged (i.e. not actively caught) on the gear such as sea stars or other invertebrates were excluded.

The seven species included: Pacific halibut (*Hippoglossus stenolepis*), arrowtooth flounder (*Atheresthes stomias*), spiny dogfish (*Squalus suckleyi*), longnose skate (*Raja rhina*), sablefish (*Anoplopoma fimbria*), yelloweye rockfish (*Sebastes ruberrimus*), and lingcod (*Ophiodon elongates*). The selected species comprised 92% of the animals caught during the survey. Basic life history characteristics (age of maturity, maximum age, size at maturity, and fecundity characteristics) are summarized in Table 3.1.

The full dataset includes number per unit effort (NPUE) data for the seven species described above that were collected during the IPHC's summertime long-line surveys (procedure described in IPHC (Unpub.)) along with coincident environmental information collected at each survey station using Seabird™ water column profiling units. The survey sampling stations were positioned on a 10x10 nmi grid laid across the continental shelf from about 30-500 m depth. Data were collected from 2006-2009, and all regions were fished in those years, however environmental data were collected over the entire region in 2008 and 2009, in the entire region except the Washington coast in 2007, and only in the northern regions (north of Washington state) for 2006. The environmental variables collected during the IPHC surveys and evaluated in this study include pressure (depth), temperature, pH, and DO. Malfunction of the pH sensor during portions of the data collection resulted in fewer pH observations than stations profiled, so pH was used in a qualitative way, and in the tree models, but was not used as an explanatory variable in the linear regression models.

Bottom type was not collected during the survey, but was added as a variable using data from USGS (2012) and DFO (2012). Ultimately, each station was assigned one of three conditions: mud/silt, sand, and pebbles/hard bottom.

Untransformed data for all years were combined for exploratory purposes to examine the relationships between NPUE and environmental factors using scatterplots and loess smoothed least squares regression lines. Simple scatterplots help to identify patterns in the data including threshold levels and NPUE trends. Additionally, understanding how or if explanatory variables are correlated to one another is essential to fully understanding these relationships, both in the simple as well as the more complex models. To that end, a Kendall's tau test was performed on each variable pairing.

Three different types of models were used to examine species NPUE in relation to multiple environmental variables: 1) Multiple regression models were used to characterize which factors were most influential on the distribution of each of these animals, the nature of the relationship between the animal and the significant factors, and to explore to what degree NPUE's can be predicted by a linear model with the suite of variables available; 2) Spatial analysis was used to study clustering of model residuals and regional variability (also called non-stationarity), i.e. the validity of the linear regression models across the study area (study area is shown in Fig. 3.1); and 3) tree regression analysis was used to examine which variables most influence NPUE both on a area-wide and local level. Each of these models contributes to the overall understanding of the species/environmental relationships and each has its strengths.

The NPUE data for all species were highly skewed with large numbers of zero stations. A number of traditional transformations were tried in order to normalize the NPUE data and its variance without satisfactory results. Ultimately, the data were transformed using a family of power transformations called the Boxcox Transformation (Box and Cox 1964). Osborne (2010) concluded that the Box-Cox transformation improves on the traditional methods for this type of data and Olivier (2011) concluded that Box-Cox was simpler to apply than other methods. As a result of a consultation with a biometrician at the IPHC (R. Webster, pers. comm., 2320 W Commodore Way, Seattle, WA 98199), a power transformation of 0.4 was ultimately selected.

$$\text{Boxcox}(y) = (y^{0.4} - 1)(0.4) \qquad \text{Equation 1}$$

Multiple linear regression (Equation 2) was conducted on the two full years of data combined (2008 and 2009) using a backward elimination process to select explanatory variables where significance was determined by a p-value of ≤ 0.05. The regression equation is:

$$Y_s = \beta_{0,s} + \beta_{1,s}x_1 + \beta_{2,s}x_2 + \ldots\ \beta_{n,s}x_n + \varepsilon_s \qquad \text{Equation 2}$$

where y = NPUE, $\beta_{n,s}$ = regression coefficients, n is an index for each predictor used, s is an index for each species, and x_n the predictor variables. A k-fold cross validation method was used to test the robustness of the model and the validity of the explanatory variables. In this process, the data were divided randomly into three folds and two of the folds were used as training data and the third was held out as validation data. Each combination of subsets was run resulting in three runs for each species model. ANOVA was then performed to test whether the model variables were considered significant under the subset conditions.

Spatial analysis was conducted on the 2009 data using ArcGIS software v.9.3.1. This software allowed the examination of model results geographically which helped inform about spatial structure of the data that may be missed with other methods. As a first step, ordinary least squares (OLS) linear regression was used to confirm that the significant variables found in the initial multiple regression analysis were valid for the single year model used here. Residuals were mapped geographically and several more tests were performed to also examine residuals including Moran's I (Moran 1950), QQ plots, and histograms.

Using only environmental data, in many cases residuals were not normally distributed and Moran's I confirmed a high level of residual clustering. The data were examined by geographically mapping NPUE as well as the residuals from the base model. Upon examination, it was clear that several of the species displayed residual aggregations which were not explained by the environmental variables alone. A new variable was added to account for this, termed *A* or the *aggregating variable*. This new weighting variable was developed by accounting for relative numbers of the same species of fish (NPUE) at survey stations directly adjacent to and, in most cases, within 10 nautical miles (Fig. 3.1) of the data point being evaluated. The only exception was a station off of north Vancouver Island where the nearest station was ~14 nmi away and so that station was used. Ruppert et al. (2009) did something similar by applying a site fidelity correction (previous year's CPUE) when looking at Atlantic cod distributions in relation to environment. The following formula was used to calculate *A* for each data point:

$$A_a = \text{Mean}(\text{NPUE}_{\text{adjacent stations}})/\sum \text{NPUE}_{\text{all stations}} \qquad \text{Equation 3}$$

where a = the station being evaluated. Therefore, *A* was always less than one, larger for stations with higher adjacent NPUEs, and smaller for lower adjacent NPUEs.

The addition of the aggregating variable stabilized the multiple regression models in most cases and drastically improved the model in some. The variables ultimately available for all of the regression models included pressure (depth), temperature, salinity, oxygen, substrate (bottom) type, and aggregating, although salinity was removed for reasons previously discussed. Model diagnostics such as Joint Wald, Joint F, and the Koenker statistic were used to ensure the model was valid. The best model fit was selected using R^2_{adj} and Akaike's Information Criterion (AIC) values.

Even given the addition of the aggregating variable, an examination of standardized residuals continued to indicate mild clustering (regional variation) in some cases. Geographically Weighted Regression (GWR), developed by Fotheringham et al. (1997, 1998) and available as an application in ArcGIS software, was used to address this problem. In a review of species distribution models, Elith and Leathwick (2009) named GWR as an effective method of dealing with non-stationarity (regional variation). Specifically, GWR develops regression coefficients and intercepts for each data point, working from the base assumption that these may not be the same throughout the study area (Brunsdon et al. 1998). Exploration of the kernel bandwidth parameter led to the ultimate use of a fixed kernel (i.e. allowing the program to choose the optimal distance) as opposed to an adaptive kernel where the number of neighbors (i.e. stations) is defined. In several cases, GWR improved the model fit over OLS (based on R^2_{adj} and AIC values), but in some cases number of variables used had to be reduced to avoid severe model problems related to redundancy. Collinearity problems were identified using condition numbers generated with GWR for each data point, i.e. condition > 30 indicated a local collinearity problem. In those cases, different combinations of explanatory variables were explored until the model stabilized. The final variable combination with the highest R^2_{adj} was ultimately chosen. As with OLS, standardized residuals were examined using histograms, normal QQ plots, and Moran's I.

A univariate-response tree regression (Breiman et al. 1984) was undertaken with single species abundances plotted against the six environmental variables for all years combined; the environmental variables were pressure, temperature, DO, pH, and bottom type. This approach, a form of clustering, builds a tree structure that is designed to split into branches where the dissimilarity of sites within clusters is minimized (i.e. each split minimizes the total sums of squares within the two nodes and maximizes between nodes) (De'ath 2002). The structure is such that splits at the top of the tree reflect variables that operate at larger, area-wide, spatial scales, and subsequent splits reflect finer scale (local) variability (Moore et al. 1991; Ruppert et al. 2009). This model type yields interpretable results even when variables are collinear (Loh 2006), when there is missing data (such is the case with pH data in this study), and in the face of non-linear and interactive relationships between variables (De'ath and Fabricius 2000). Franklin (1998) and Vayssieres et al. (2000) compared tree regression analysis with generalized linear models and generalized additive models and found that tree models yielded better predictions. For this analysis, rows containing "NA" values for pH were omitted resulting in 221 useable rows of data.

A pseudo R^2 was calculated as follows:

$$1- (\text{model deviance}/\text{null deviance}).$$

Each tree was examined to see if "pruning" was needed using the cross-validation method where deviance was examined for each split to detect where the tree had the smallest predicted mean square error (described in Breiman et al. 1984). Ultimately, it was determined that the R-cran *tree* package default of a 1% threshold for terminal nodes was sufficient (i.e. where the mean square error was 1% or below and no splits were made beyond that).

The next step was to construct univariate response trees for 2009 only, to enable a comparison of model results to the OLS and GWR models. Latitude was included as an explanatory variable here but the aggregating variable was not since this variable was constructed mainly to stabilize the residuals in the linear models and was not needed here. There were also some missing values for pH which, in this statistical package, results in station/rows being dropped from the analysis. Therefore, the tree models were run with and without pH and the best fitting model was selected for comparison.

The *R* statistical package was used for all tree analyses in this section (https://cran.r-project.org). Major supplemental libraries included: *vegan* (Oksanen et ak, 2012), *MASS* (Ripley 2012), and *tree* (Ripley 2012).

Results

There were both similarities and differences among species in terms of descriptor variables and model fits. The Kendall's Tau test revealed that the majority of explanatory variables were indeed correlated in various ways (Table 3.2). Knowing how they relate to one another increases the overall understanding of the system and its complexity, and illustrates the need to consider all of the correlated variables together.

Scatterplot observations

Halibut were found in all depths of the survey (from ~20 to approximately 400 meters) which is well within the known summer depth distribution described in IPHC (1998). Temperatures above ~ 8.5^{o}C yielded no zero halibut stations while temperatures below 8.5^{o}C yielded both zero and non-zero halibut stations. However, there were no thresholds experienced during the survey as temperatures were within the known range for halibut (IPHC 1998). There does appear to be a relationship between halibut and low levels of DO, i.e. halibut appear able to tolerate DO concentrations to about 0.9 ml/L, but not below this level, presented in the data as absent from the catch. A closer examination of the relationship (Fig. 3.2a) reveals that very small numbers of halibut are present at levels below this, and there is also a tendency for increasing NPUE up to a DO concentration of ~3 ml/L.

In arrowtooth flounder, occupation of more shallow depths was evident although they were also found in deeper water in smaller concentrations. While no minimum temperature stood out in these data, Spencer et al. (2011) found evidence that arrowtooth may redistribute in order to avoid temperatures <3°C (not encountered during the study). Temperatures under about 8.5°C yielded higher concentrations than warmer temperatures. It also appears that this species can tolerate a wide range of DO levels with a minimum DO similar to halibut at ~0.75 ml/L but a less clear signal at higher DO concentrations (Fig. 3.2b).

Spiny dogfish tended to inhabit more shallow water (less than 200 m) with a maximum depth of about 400 m, although some were found deeper. Varying concentrations of dogfish were seen over the range of temperatures experienced with no obvious temperature signal. While it appears that dogfish can tolerate a wide range of DO concentrations, a similar minimum to halibut of 0.9 ml/L is apparent with a few animals located in levels below. There appears to be a steep increase in NPUE up to approximately 1.8 ml/L before leveling off (Fig. 3.2c).

Longnose skate were found in all but the deepest stations showing neither a distinct minimum nor maximum depth tolerance. Longnose inhabited the cooler temperatures with animals present to the lowest temperatures encountered and there was a clear decline in animal encounters above 8.5°C. It appears that these animals can tolerate a wide range of DO concentrations but showed a distinct minimum at approximately 0.8 ml/l where no skates were caught in waters below this level. (Fig. 3.2d).

Depth was the most distinct factor relating to sablefish NPUE. NPUE rose with increasing depth, and sablefish were caught in only very small numbers at depths <100 m. As noted previously, sablefish are found as deep as 700 m and the longline survey does not cover this entire depth range. Temperature appears to have a strong effect on distribution with the absence of sablefish in waters just over 8°C and above. Sablefish were also caught at locations with DO as low as 0.55 ml/L, well below levels considered to be hypoxic for many other marine fishes (Fig. 3.2e). Kimura

(1998) discussed sablefish migrations from Alaska to the West Coast and rejected the idea that sablefish follow the continental slope because low oxygen zones would be encountered in the deep water thus making the route impassable. However, the findings here suggest that sablefish have a high tolerance for low DO concentrations, even if only for short periods of time.

Lingcod catches were primarily at depths to about 250 m during the study. They were found over a range of temperatures, with the highest NPUEs existing between 6-9^{o}C. Lingcod NPUE showed sensitivity to low DO with a tolerance minimum of 1 ml/L, a concentration slightly higher than that for most of the other species in this study (Fig. 3.2f).

Yelloweye rockfish were caught in relatively shallow depths during the surveys with a maximum depth of catches at about 300 m. Love et al. (2002) documented yelloweye at depths to 549 m, but also reported that adults preferred more shallow depths, with variations occurring with latitude. There were no obvious patterns between yelloweye NPUE and temperature. Yelloweye occurred at DO concentrations >1 ml/L. Palsson et al. (2008) found that rockfish in the Puget Sound were sensitive to low DO which was further confirmed here (Fig. 3.2g).

OLS and GWR regression models

The OLS and GWR regression models illustrated the similarities and differences among species. Overall, the variables used to best describe NPUE and the resulting coefficients were unique to each species, but there were commonalities. Temperature was a significant variable for all species with the exception of sablefish where pressure (depth) was the only significant variable. Pressure was significant for five of the seven species in the study. Salinity looked to be significant for just one species, lingcod, but significance did not hold up under cross validation. A K-fold cross validation test, randomly dividing the data into three test groups where two groups were used to predict the third, was used to test the significance of all of the variables in the OLS models (Fig. 3.3). The final OLS and GWR model results for each species are shown in Table 3.3 and are discussed in detail below.

Multiple regression modeling for halibut showed that multiple variables play a role in NPUE, yielding significant values for all variables except salinity and bottom type. Coefficients indicated a negative relationship to pressure and temperature, and a positive relationship to DO. Halibut also indicated a strong positive relationship to aggregating. The R^2_{adj} for the combined regression model was 0.57 (Table 3.3a). When examined for regional variation using spatial analysis, the full GWR model indicated severe model problems having to do with spatial correlation. When pressure (depth) was excluded, the model was able to run properly. Ultimately the GWR model improved the fit considerably over OLS with an R^2_{adj} of 0.72 and the variable combination of DO and aggregation. Figure 3.4 shows a geographic mapping of the model residuals for both OLS and GWR. Residuals are clearly more random in both models to the north and more clustered to the south, but the GWR model shows less clustering than OLS, especially in the mid-latitudes of the study area, thus providing a better fit. Figure 3.5 illustrates the observed NPUE and predicted NPUE based on the GWR model. The model predictions show less variability in NPUE among stations north of Washington than the observed, but the general patterns are captured.

Regression modeling resulted in two highly significant coefficients: temperature and aggregation for arrowtooth flounder, and resulted in an $R^2_{adj} = 0.33$. The GWR method improved the fit to the 2009 data compared to the OLS model ($R^2_{adj} = 0.42$ for the 2009 OLS), yielding an R^2_{adj} of 0.49 (Table 3.3b). However, neither model produced particularly impressive fits.

For spiny dogfish, the OLS regression analysis yielded a highly significant and strong positive relationship between NPUE and the aggregating variable. This is not surprising given that the species has strong documented schooling behavior (Bester 2011b). There was also a positive relationship to DO and a negative relationship to depth and temperature, yielding an R^2_{adj} of 0.64 for the 2009-only model (Table 3.3c). For GWR, pressure was dropped due to multi-collinearity issues. The final model included temperature, DO, and aggregating, and ultimately was not an improvement over the OLS model with an $R^2_{adj} = 0.58$.

Longnose skate NPUE showed a negative relationship to temperature and a positive relationship to aggregating, but otherwise, no other variables were significant in explaining distribution (Table 3.3d). The combined OLS regression model yielded an R^2_{adj} of 0.21, and 0.27 for the 2009-only data. Notably, this is the only species where bottom type approached significance in some model combinations, yielding a p-value between 0.5 and 1.0. GWR providing a slightly improved fit over OLS with an R^2_{adj} of 0.36 for the 2009 data.

When building the regression model for sablefish, pressure, aggregating, and DO were significant variables in the combined-year model. However, the K-fold cross validation test indicated that DO was not significant so that variable was dropped. For the 2009-only data, aggregating was not a significant variable in the OLS model so it was dropped and the 2009 models were run with pressure as the only explanatory variable ($R^2_{adj} = 0.58$; Table 3.3e). As stated previously, the aggregating variable was used to stabilize the models, i.e. render randomized residuals. A Moran's I test was used in each case to ensure that clustering and over dispersion had been dealt with properly. With the elimination of the aggregating variable, Moran's I showed slight clustering, but it was not significant (Moran's I p-value = 0.084). GWR yielded an R^2_{adj} value of 0.59 and an AIC score very close to the OLS so the GWR was not considered an improvement.

The two-year regression model for lingcod showed all explanatory variables in this study to be significant with the exception of bottom type, yielding an R^2_{adj} of 0.28 and confirmed by the K-fold cross validation test. The 2009 OLS regression model included pressure, temperature, DO, and aggregating like the combined model, and yielded an R^2_{adj} of 0.45. The GWR model was not an improved fit with an R^2_{adj} of 0.44 (Table 3.3f).

Combined-year regression modeling for yelloweye rockfish indicated that all variables were significant in different combinations except bottom type, but k-fold cross validation showed that temperature was not. In fact, the backward elimination process did not yield any satisfactory models where Moran's I indicated non-clustered residuals, and the inclusion of the aggregating variable was not sufficient to stabilize the model in this case. However, the one constant was that DO was highly significant in every combination. Palsson et al. (2009) reported that rockfish in the Puget Sound are often found aggregating in rockfish assemblages, but not necessarily with like species so a multi-species aggregating variable in this study may improve the fit.

Tree regression models

The tree models using 2009 data, yielded pseudo-R^2 values ranging from 0.35 for yellow-eye rockfish to 0.73 for sablefish (Table 3.4). Specific model results for each species follow.

Latitude was the primary splitting factor for the 2009-only Pacific halibut model (Table 3.4) which yielded a pseudo-R^2 of 0.65. In that model, the lowest mean NPUE of 0.34 was found at lower latitudes which included southern Washington and Oregon. The highest mean NPUE of 16.6 was at latitudes north of southern Washington, where DO was > 2.3 ml/L, temperature was between 6.5-7.2^{o}C and depth was > 92 m (Fig. 3.6).

Temperature and latitude were the first two splitting variables in the 2009-only model for arrowtooth flounder (Table 3.4), which had a pseudo-R^2 of 0.46, close to the GWR model. The lowest mean NPUE of 0.071 was found at temperatures < 6.7^{o}C, and lower latitudes, the area from central Washington southward. The highest mean NPUE of 5.9 was at temperatures < 6.6^{o}C, latitudes north of central Washington (> 47.5), and in depths less than 112.8 m (Fig. 3.7). Technically, the GWR was the best fitting model although all 2009 models had R^2 values that were not vastly different.

Latitude followed by latitude again were the primary splitting factors for spiny dogfish. (Table 3.4). The lowest mean NPUE of 1.3 was at latitudes which included the area from central Washington southward. The highest mean NPUE of 32.0 was in the area northward of central Washington to northern Vancouver Island in depths from 67-148 m. The tree regression model yielded a pseudo-R^2 of 0.64, making it a better fit than the GWR model and comparable to the OLS model (Fig. 3.8).

The tree model for longnose skate had primary and secondary splits of latitude and DO. The lowest NPUE of 0.21 was found at the lower latitudes, southward of southern Washington. The highest mean NPUE of 4.0 was found northward of southern Washington, in DO levels less than 2.6 ml/L, temperatures between 5.8-6.6^{o}C, and depths from 169-212 m. The tree model was the best 2009 model fit for this species yielding a pseudo-R^2 of 0.58 (Table 3.4; Fig. 3.9).

Pressure and pH were the first two splitting variables for the sablefish tree model, respectively (Table 3.4) which also was considered the best fitting model with a pseudo-R^2 of 0.73 (Fig. 3.10). The lowest mean NPUE of 0.52 was in depths less than 159 m. The highest mean NPUE of 12.00 was in depths greater than 159 m, in pH between 7.60-7.64, and DO > 1.2 ml/L.

DO was the primary splitting variable for lingcod, followed by latitude. The lowest mean NPUE of 0.002 was found in DO less than 2.6 ml/L and in the area southward of Vancouver Island. The highest mean NPUE of 2.4 was found at DO greater than 2.6 ml/L, off Vancouver Island (latitudes 48.5-50.5), and depths greater than 72 m. The tree model yielded a pseudo-R^2 of 0.49, making it the best fitting 2009 model of the three types (Fig. 3.11).

For yelloweye rockfish, DO was both the primary and secondary splitting variable. (Table 3.4) yielding a pseudo-R^2 of 0.35. The lowest mean NPUE of 0.1 was found in DO less than 1.9 ml/L and the highest mean NPUE of 6.4 was found in DO from 3.8-4.1 ml/L. The tree model was the best fit for the 2009 data by default since satisfactory OLS or GWR models could not be found (Fig. 3.12).

Discussion

In this analysis, the model that produced the best results was used as an inidcator of the overlying processes in each particular species. For example, the GWR model specifically addressed geographic non-stationarity and was the best fit of the three for Pacific hailbut. The tree model allowed for correlated predictor variables, which provided the best fit for most of the species in this study. Spatial correlation and geographic non-stationarity complicated the analysis, but also informed how the animals interact with their environment and what might still be missing from an environmental predictive model.

Perhaps not surprisingly, no single variable stood out as a primary NPUE predictor across the board. Instead, the best NPUE predictions tended to be produced by combinations of variables unique for each species. In several cases, environmental thresholds were identified, especially for DO, which will be useful in considering how animals may redistribute under seasonal or long-term DO variability. In cases where one or two fish were found below apparent threshold levels, one explanation may be that they may have been actively moving from the site when caught or were perhaps captured at some other point in the water column (during setting or retrieval of the gear) where DO levels were higher. It may also be inferred from the decreasing NPUEs that halibut are sensitive to DO < 3 ml/L and begin to move from the area even though levels are not at the 0.9 ml/L threshold.

When considering highly dynamic variables such as DO, it is necessary to consider the ability of an animal to redistribute quickly when faced with conditions that may be outside of the normal range and more difficult to tolerate. All of the species studied here are mobile and are able to seek out suitable environmental conditions provided their physiology enables detection, and if species-specific behavioral norms enable them to do so. IPHC (1998) and Webster et al. (In prep.) report that Pacific halibut are highly migratory as juveniles, traveling a thousand miles in some cases, and although the frequency of along-shelf movement lessens as they reach adulthood, it continues on a smaller scale along with significant seasonal cross-shelf movement. According to NOAA (2012), sablefish, arrowtooth flounder, and spiny dogfish all undertake large scale migrations. Lingcod (DFO 2011) migrate as juveniles then become essentially non-migratory as adults but continue to undertake short seasonal migrations to more shallow waters for spawning. Yelloweye rockfish (ADF&G 2012) tend to become essentially site specific once reaching adulthood. The migratory habits of longnose skate are largely unknown.

Several studies have described how low DO can initiate distributional shifts of mobile fish from normal habitats (e.g. Rabalais et al. 2002, Pihl et al. 1991, and Gray et al. 2002). This study suggests that several of the species included here also have DO thresholds that have the potential to exclude them from an area for a period of time in the event that hypoxic conditions reach these threshold levels. Both lingcod and yelloweye rockfish inhabit more shallow water and had relatively high, lower-end DO thresholds which suggests these animals may be particularly susceptible to negative impacts associated with habitat displacement in the event of inner shelf hypoxia, i.e. they may have nowhere to go but towards the surface water where DO concentrations are presumably higher, but where they may not have access to the kind of substrate they require. In the case of yelloweye the non-migratory behavior once reaching adulthood may also exacerbate their susceptibility to low DO conditions. On the other hand, Pacific halibut, arrowtooth flounder, spiny dogfish, and longnose skate displayed lower DO thresholds, and they are also known to inhabit a wider depth range (which was also confirmed in this analysis of longline survey data). This suggests that these animals may be more likely to leave an area that becomes hypoxic below their threshold, but are better able to alter their depth to compensate, and thus have more choices of alternate habitat.

How animals redistribute when forced from an area of low DO is unclear. For example, it has been shown that halibut appear to have the ability to leave or avoid a hypoxic area. Given that halibut tend towards aggregating behavior, it follows that uncharacteristically high concentrations of halibut may be found immediately outside a hypoxic zone as has been demonstrated to be the case in other animals (e.g. Rabalais 2001a). This behavior may make them more vulnerable to predation or fishing pressure, and also make it more difficult for managers to assess their distributions and abundance through periods of varying DO concentrations where distributions are thought to be more dispersed. Alternatively, if prey species (smaller fishes for example) are exhibiting a similar response to low DO, then feeding may be temporarily enhanced. Future tagging studies could help to answer the question of fish proximity to threshold environmental conditions.

Temperature has been shown to alter species range spatially in other areas and species (e.g. Perry et al. 2005 and Sabates et al. 2006). In this study, sablefish clearly inhabited locations with relatively cooler temperatures. Again, looking at the bigger picture and collinear nature of the environmental variables is important because sablefish have a known depth range which exceeds the depths sampled in this study so either or both may be the driving force in NPUE variations in this case. For the other species, it is most likely that the sampling area does not currently include either upper or lower temperature thresholds for these species. Still, as long-term changes in climate persist, the temperature profile for the area may change and potentially present thresholds that are not there at the present time.

The multiple regression models for NPUE performed best for species with the highest overall numbers (e.g. halibut, sablefish, and spiny dogfish) and were weakest for species with lower NPUEs (e.g. lingcod, longnose skate, arrowtooth flounder, and yelloweye rockfish). The persistence of clustered residuals in the OLS models led to an investigation into causes for model misspecification, leading to the conclusion that the spatial structure of the animals was not adequately explained by the included environmental variables alone in most cases. However, by accounting for relative catch at adjacent stations, the residuals were stabilized. This variable likely accounts for not only aggregating of the species as the name suggests, but a combination of factors (as yet unidentified) influencing distribution. An example of these variables may include such things as primary production, sea surface temperature, predator/prey interactions, or multi-species assemblage structures of the animals.

Once the models were properly specified, spatial analysis revealed that minor clustering (although non-significant) was still a factor in some cases, suggesting collinearity of variables or regional variation. If regional variation is the source of the clustering, then the use of a spatial-based smoother like GWR modeling will improve results, which it did in the case of both flatfishes.

The fact that a geographic smoother designed to deal with regional variation provided improved results over other models for halibut, suggests that there are factors to consider in addition to changes in abundance. One consideration is the method of data collection in terms of uniformity of catchability. Since the gear used in this survey is passive in nature, i.e. requiring animals to become attracted to and ultimately consume the bait, regional variation may be reflecting behavioral differences related to environmental variables. The longline survey operates over a wide range of variables so understanding the changes in catchability over this range is imperative to the halibut stock assessment and full understanding of all of the animals encountered on the gear. Within the study area, catches in the southern half were generally much lower overall, and clustered compared to the northern half which were higher and more evenly dispersed. The southern areas also experienced threshold levels of DO during the study period for many species, while the northern areas did not. It may be that catchability is not greatly affected within “normal” ranges of environmental variables, but is in “threshold” environments. Further investigation may be accomplished by expanding the analysis over additional years and to other survey areas to the north and east where other environmental thresholds do and do not exist, for comparison.

The collinear nature of many of the explanatory variables and their relationship to the animals in this study, was highlighted in the fact that the tree models, which allow for correlated variables, were the best fitting model for the majority of species. A multivariate approach that further defines the nature of the patterns of co-variation among species and habitat variables in addition to a look at species aggregations is a natural next step in the analysis and is considered in the next chapter.

Figures

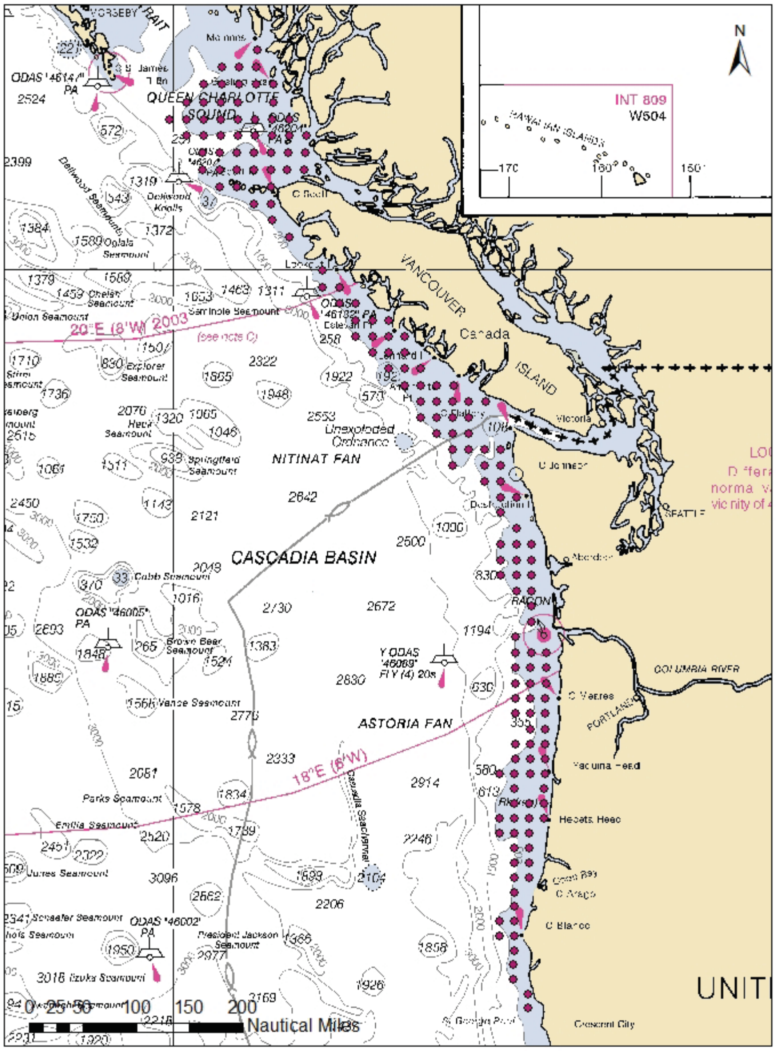


Figure 3.1. The study area extends from southern Oregon to Queen Charlotte Sound, B.C. Both catch and oceanographic data were collected on a 10x10 nmi grid depicted on this map as dots for each sampling station. Inshore of the 200-m depth contour is highlighted in blue.

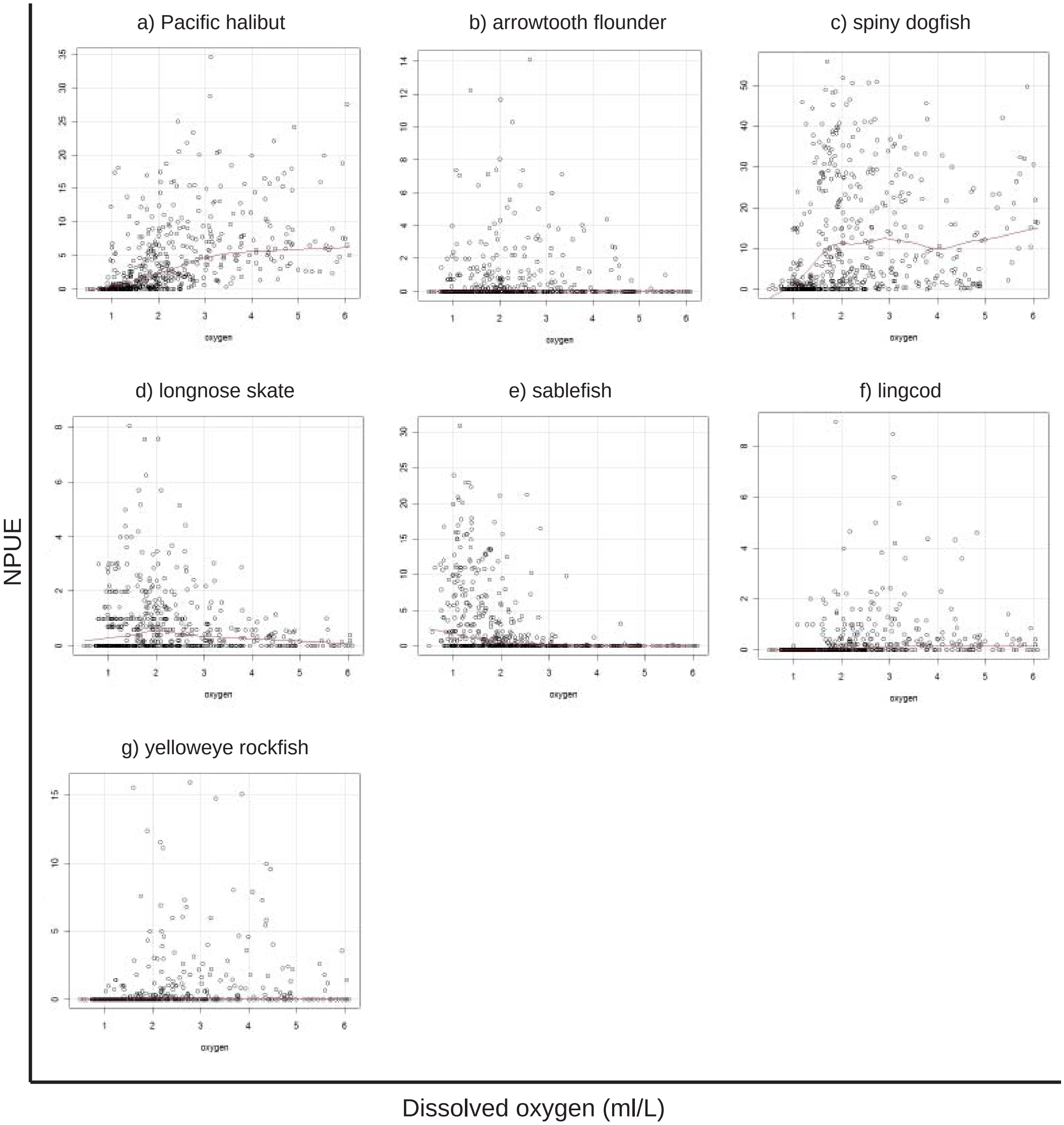


Figure 3.2. Scatterplots of dissolved oxygen (ml/L) plotted against number per unit effort (NPUE) for each species: a) Pacific halibut, b) arrowtooth flounder, c) spiny dogfish, d) longnose skate, e) sablefish, f) lingcod, g) yelloweye rockfish. A loess smoothed regression line is included.

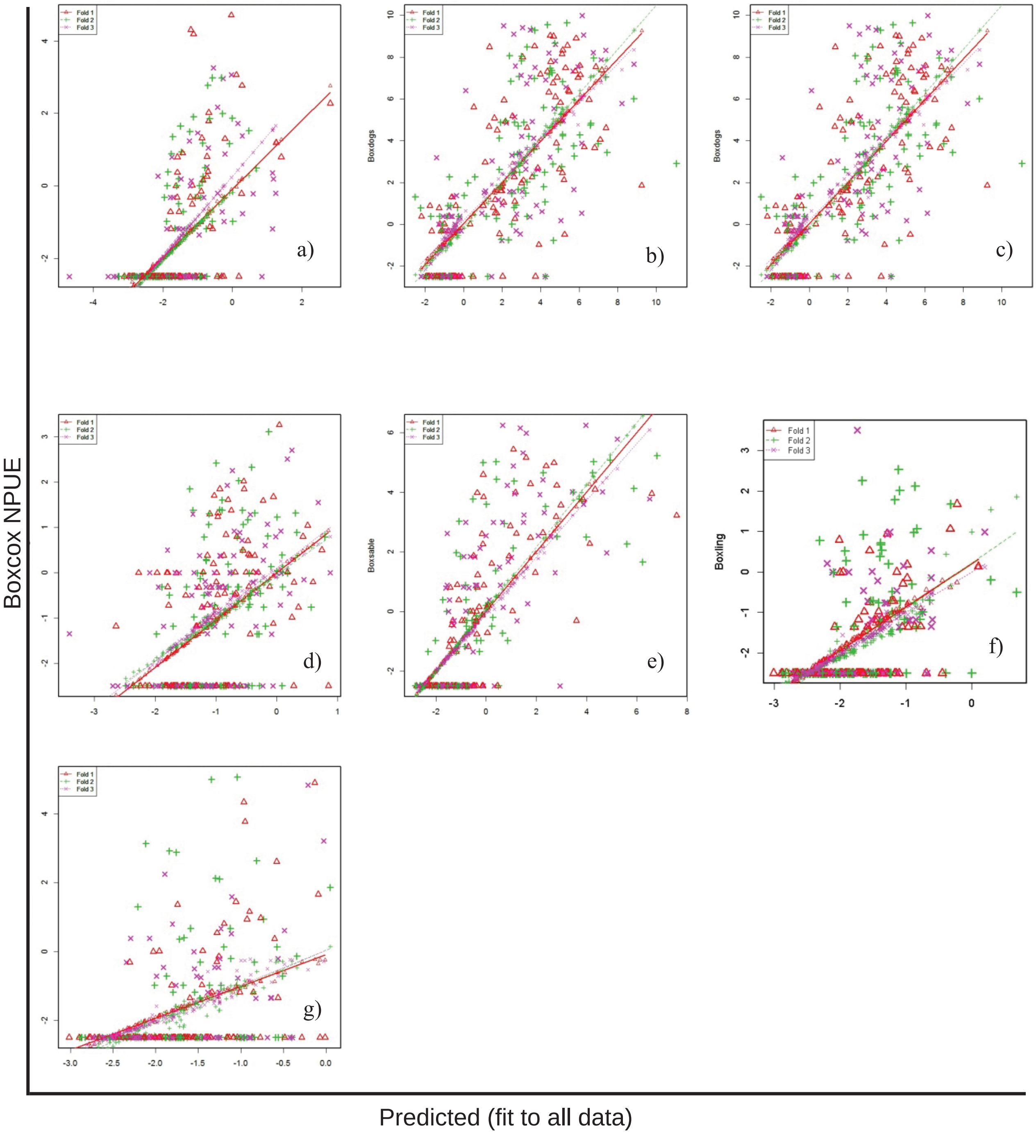


Figure 3.3. K-fold cross validation results for the multiple linear regression models for the years 2008-2009 combined. NPUE data were Boxcox transformed (Box and Cox 1964). Data were randomly placed in three subsets with two sets then randomly chosen to predict the third. The panels refer to a) Pacific halibut, b) arrowtooth flounder, c) spiny dogfish, d) longnose skate, e) sablefish, f) lingcod, and g) yelloweye rockfish.

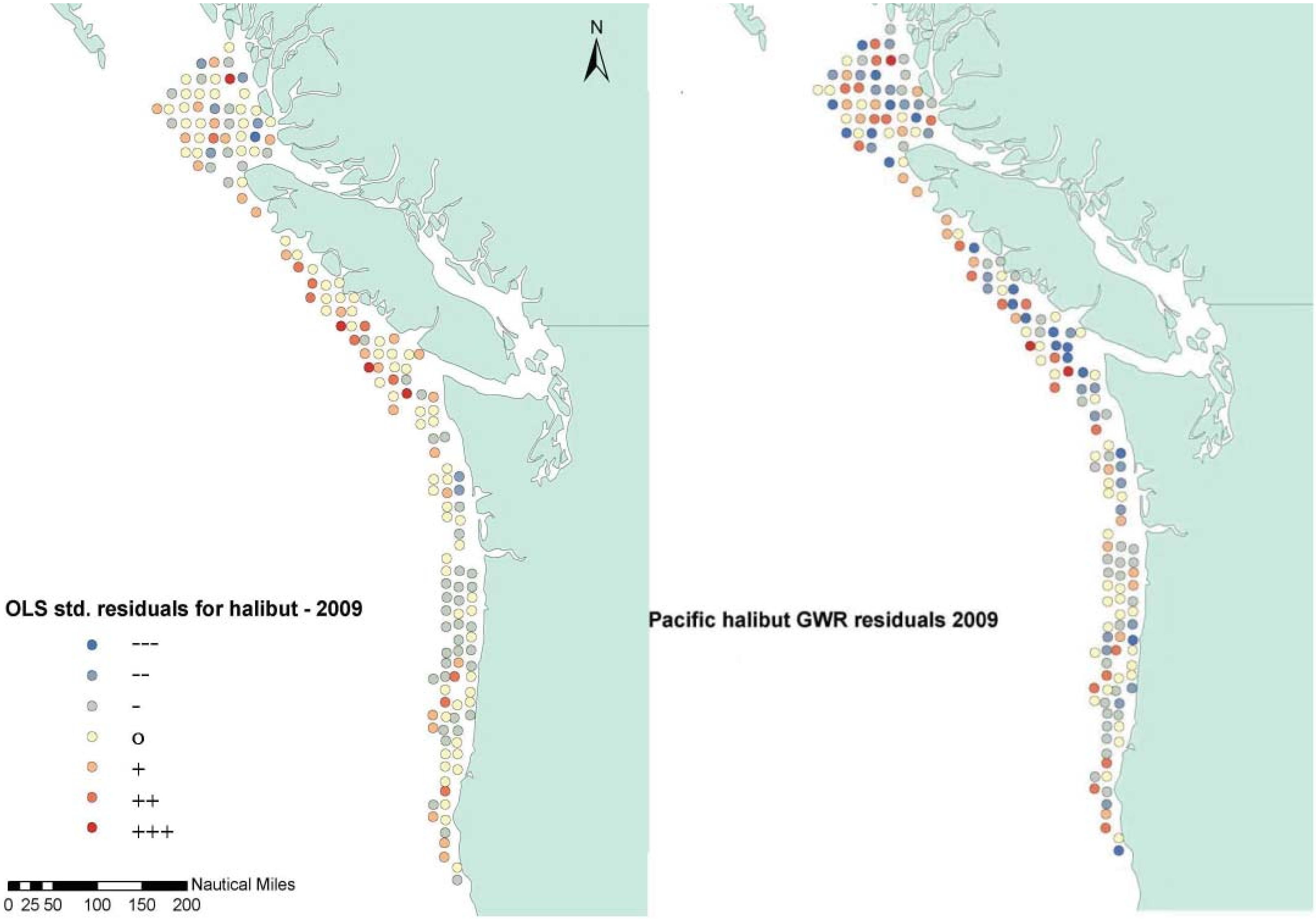


Figure 3.4. Standardized residuals for both the final Pacific halibut OLS model (left) and the final GWR model (right) are mapped geographically. The residuals clearly appear more random in the GWR model, especially in the northern portion of the study area, signifying a better fit than the OLS model.

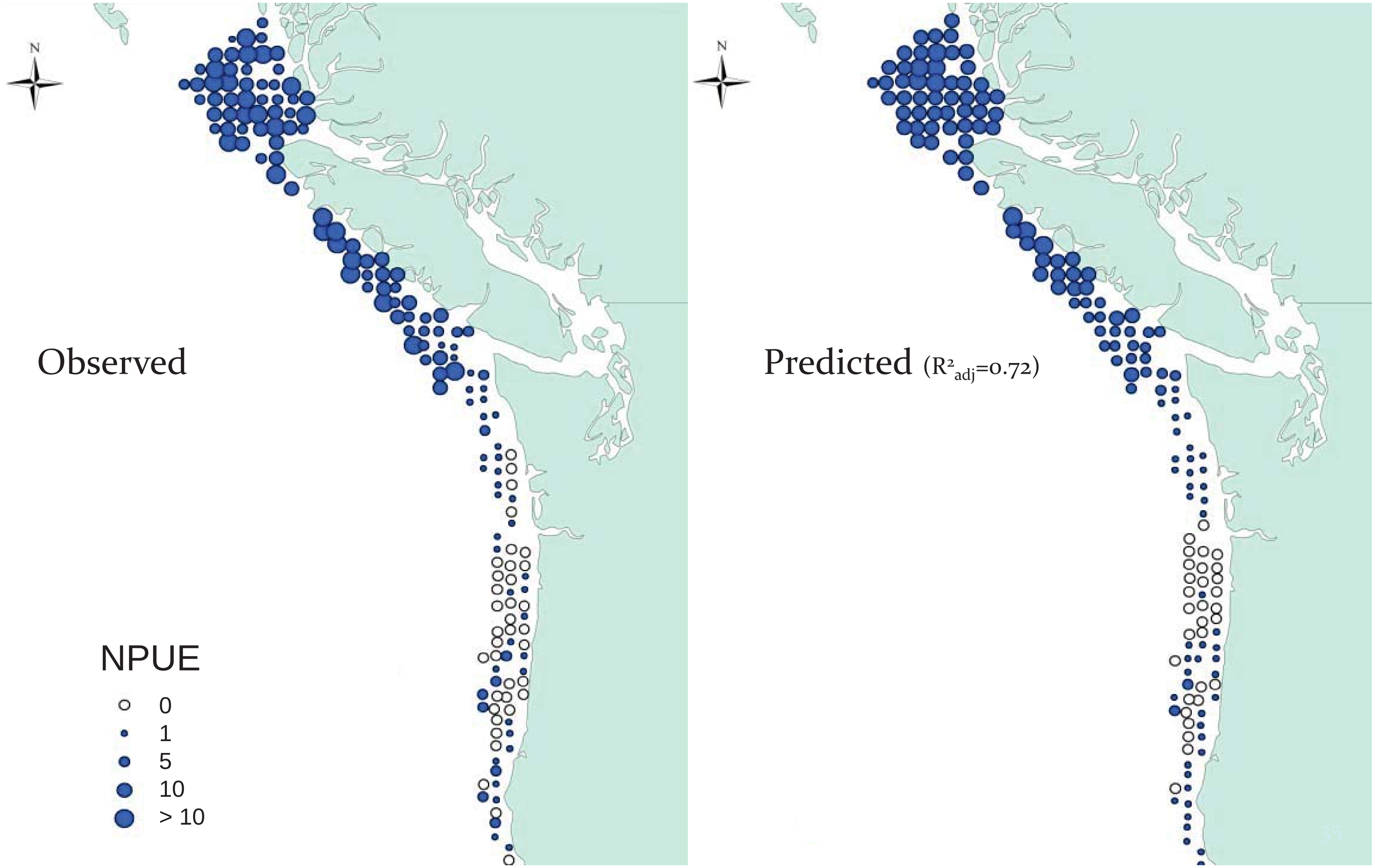
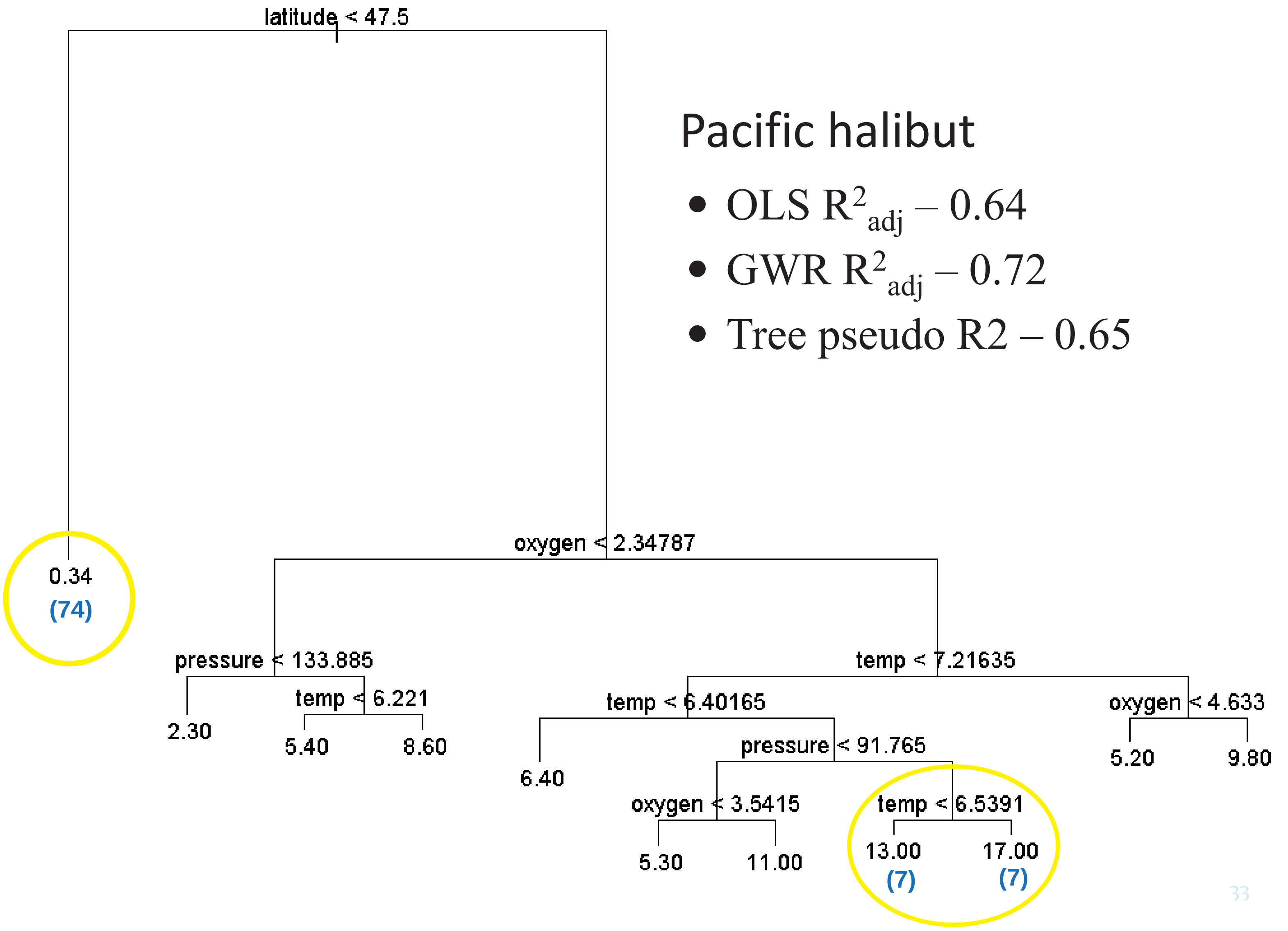


Figure 3.5. “Best” 2009 model results for Pacific halibut were produced by the GWR model with an R2adj = 0.72. Observed NPUE is shown in the left panel and the predicted NPUE based on back transformed model results is shown on the right.



Pacific halibut

- OLS R^2_{adj} – 0.64
- GWR R^2_{adj} – 0.72
- Tree pseudo R2 – 0.65

Figure 3.6. Tree regression model result for Pacific halibut using 2009 data, and compared with other models using R^2 values. Terminal nodes show mean NPUE for each cluster. Minimum and maximum mean NPUEs are circled and indicate number of sampling stations in that cluster (number in parenthesis).

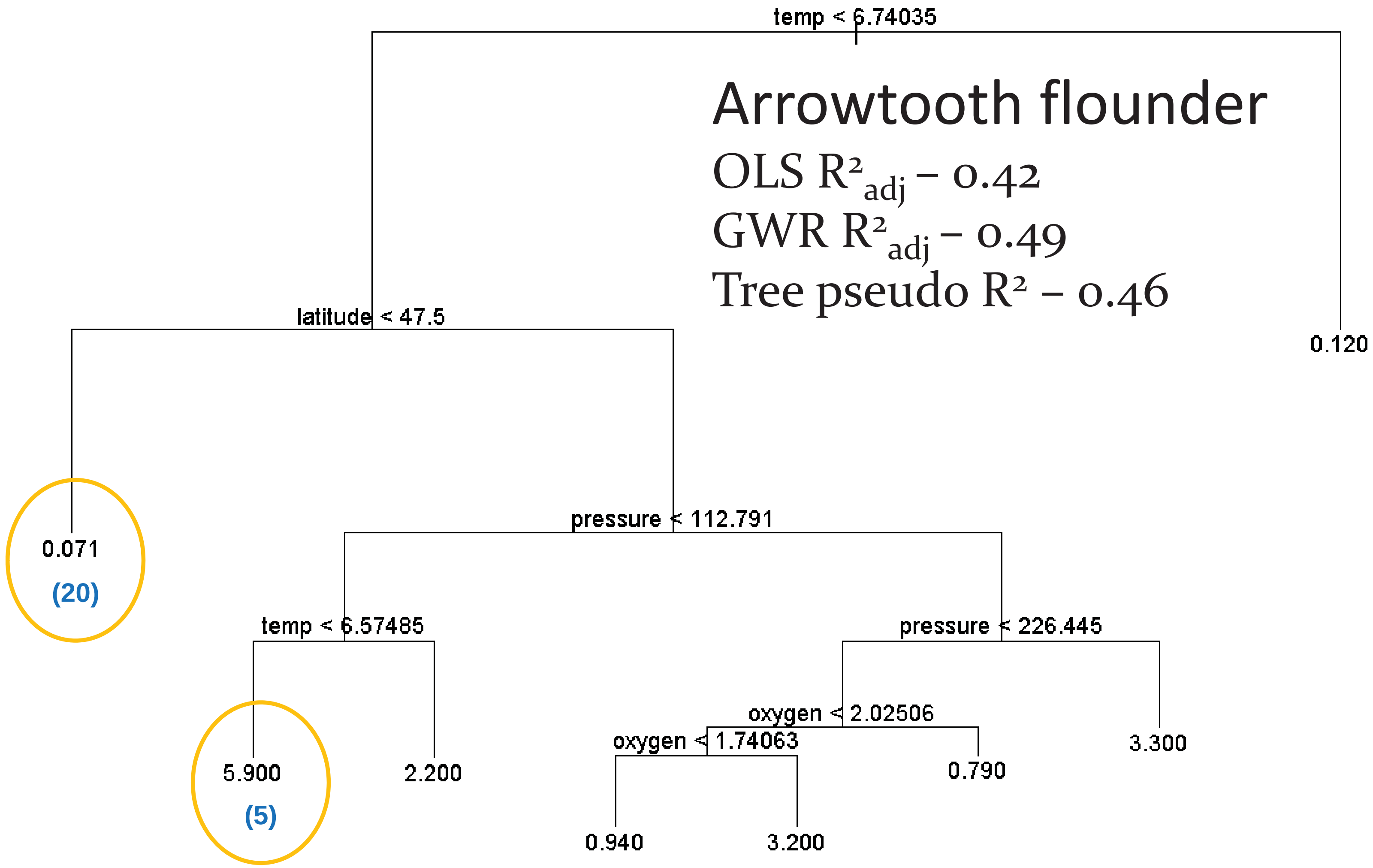
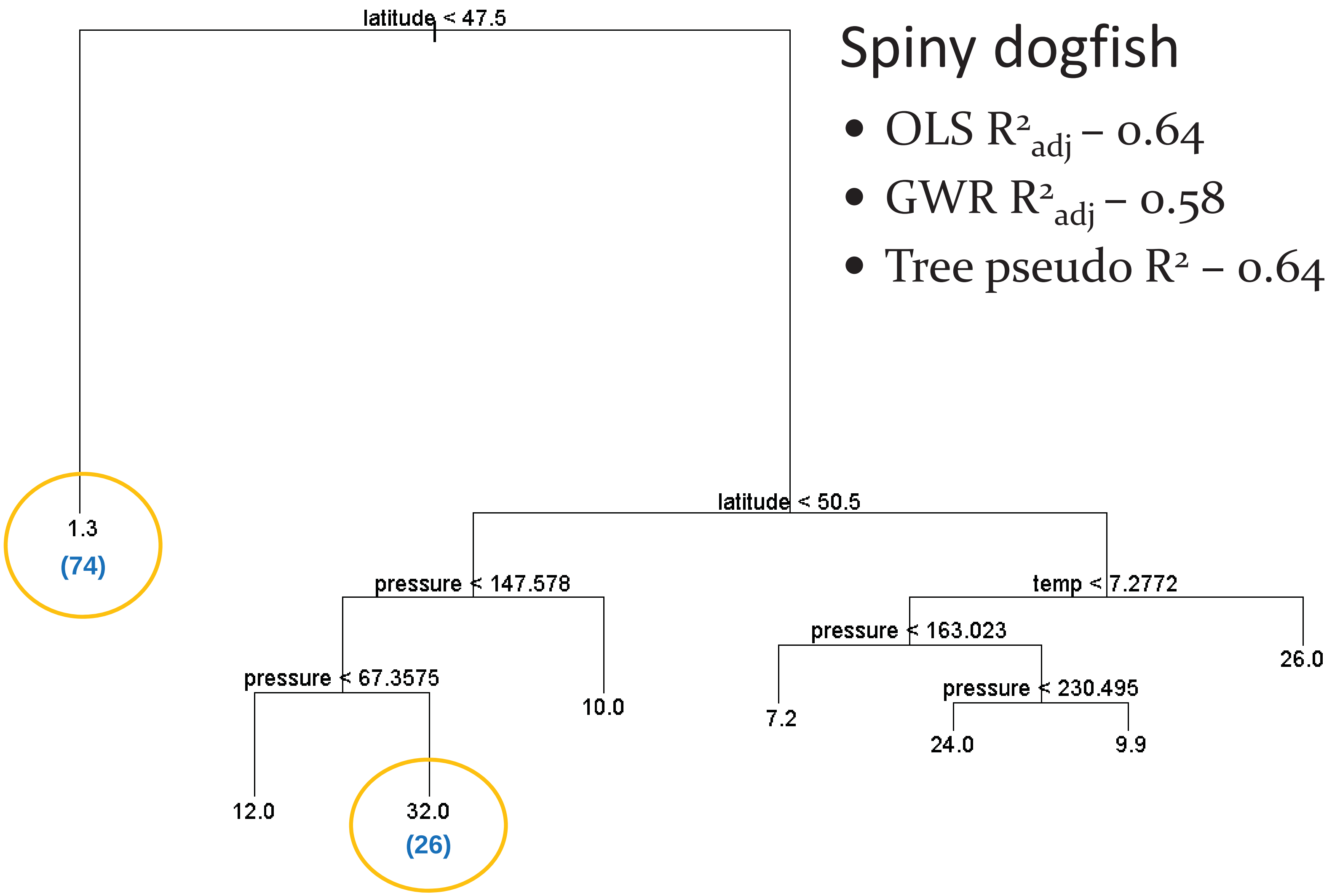


Figure 3.7. Tree regression model result for arrowtooth flounder using 2009 data, and compared with other models using R^2 values. Terminal nodes show mean NPUE for each cluster. Minimum and maximum mean NPUEs are circled and indicate number of sampling stations in that cluster (number in parenthesis).



Spiny dogfish

- OLS R^2_{adj} – 0.64
- GWR R^2_{adj} – 0.58
- Tree pseudo R^2 – 0.64

Figure 3.8. Tree regression model result for spiny dogfish using 2009 data, and compared with other models using R^2 values. Terminal nodes show mean NPUE for each cluster. Minimum and maximum mean NPUEs are circled and indicate number of sampling stations in that cluster (number in parenthesis).

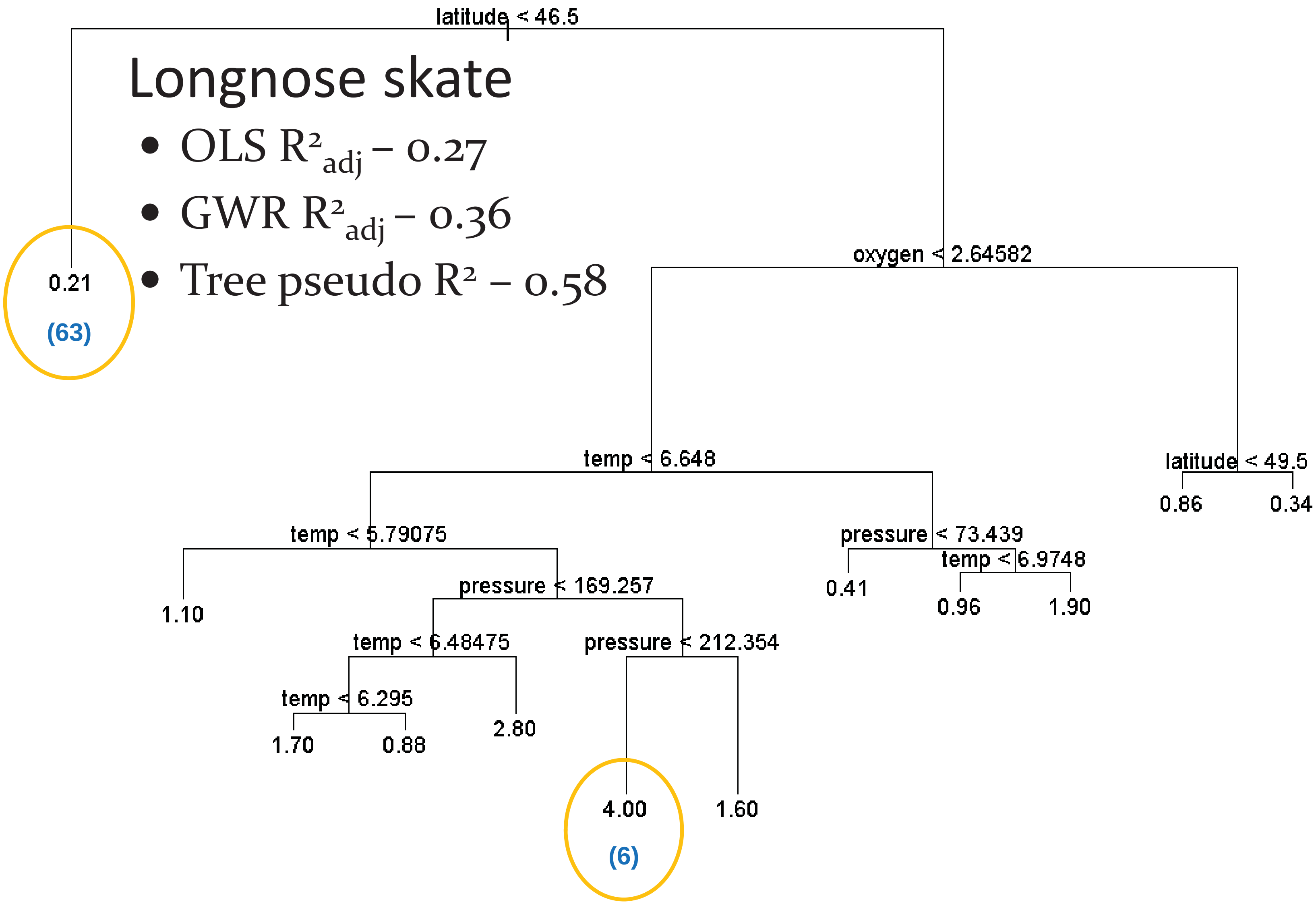
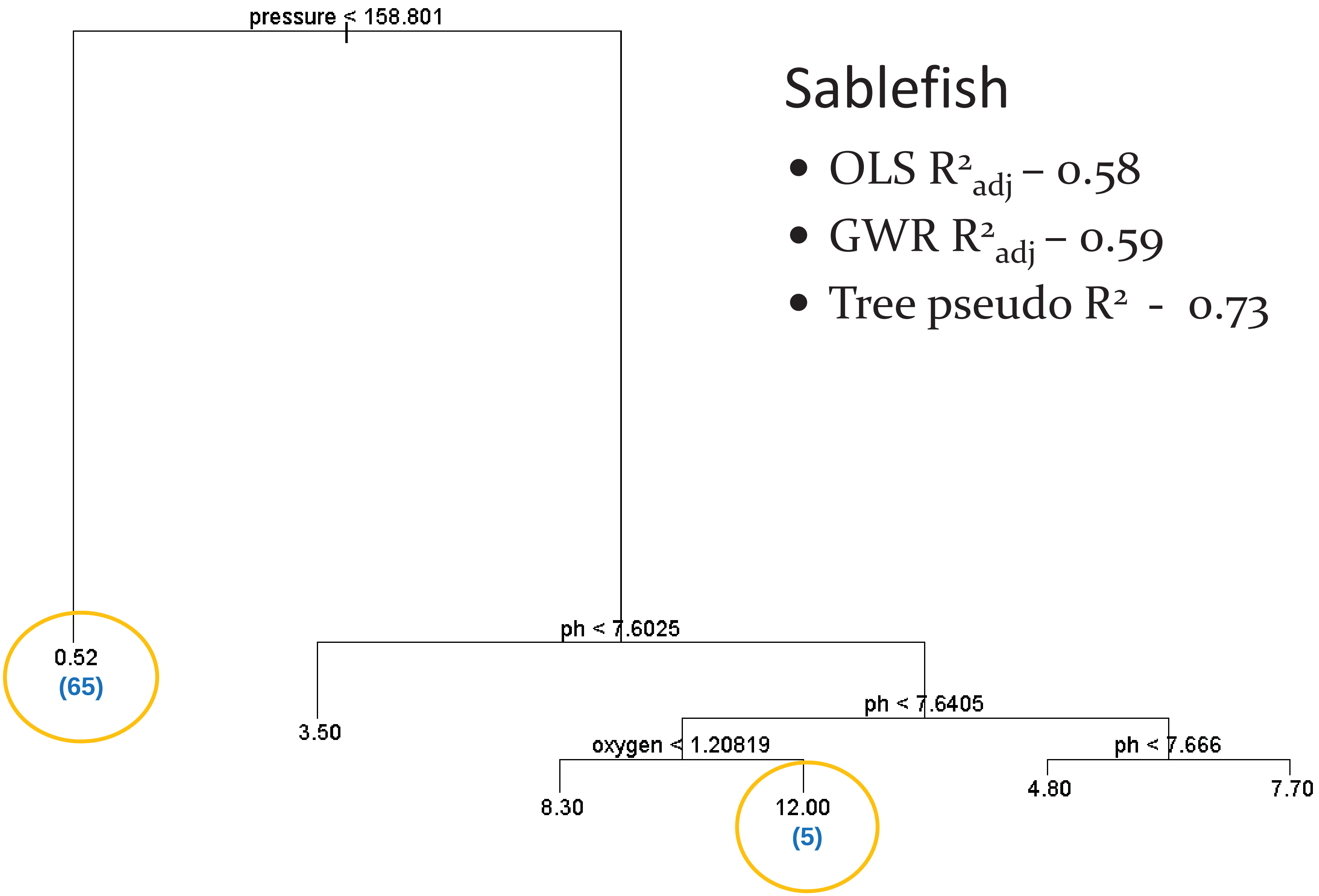


Figure 3.9. Tree regression model result for longnose skate using 2009 data, and compared with other models using R^2 values. Terminal nodes show mean NPUE for each cluster. Minimum and maximum mean NPUEs are circled and indicate number of sampling stations in that cluster (number in parenthesis).



Sablefish

- OLS R^2_{adj} – 0.58
- GWR R^2_{adj} – 0.59
- Tree pseudo R^2 - 0.73

Figure 3.10. Tree regression model result for sablefish using 2009 data, and compared with other models using R^2 values. Terminal nodes show mean NPUE for each cluster. Minimum and maximum mean NPUEs are circled and indicate number of sampling stations in that cluster (number in parenthesis).

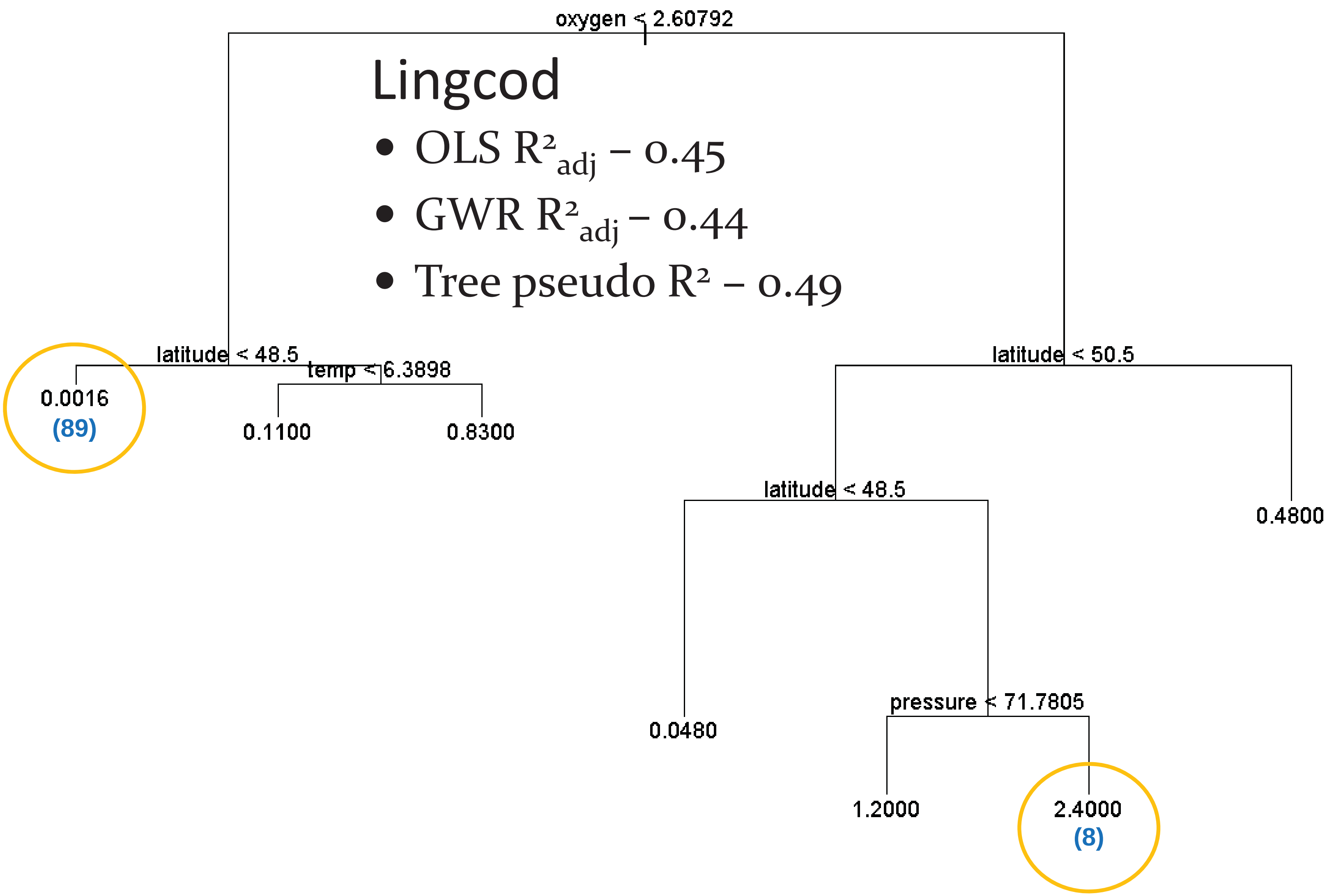
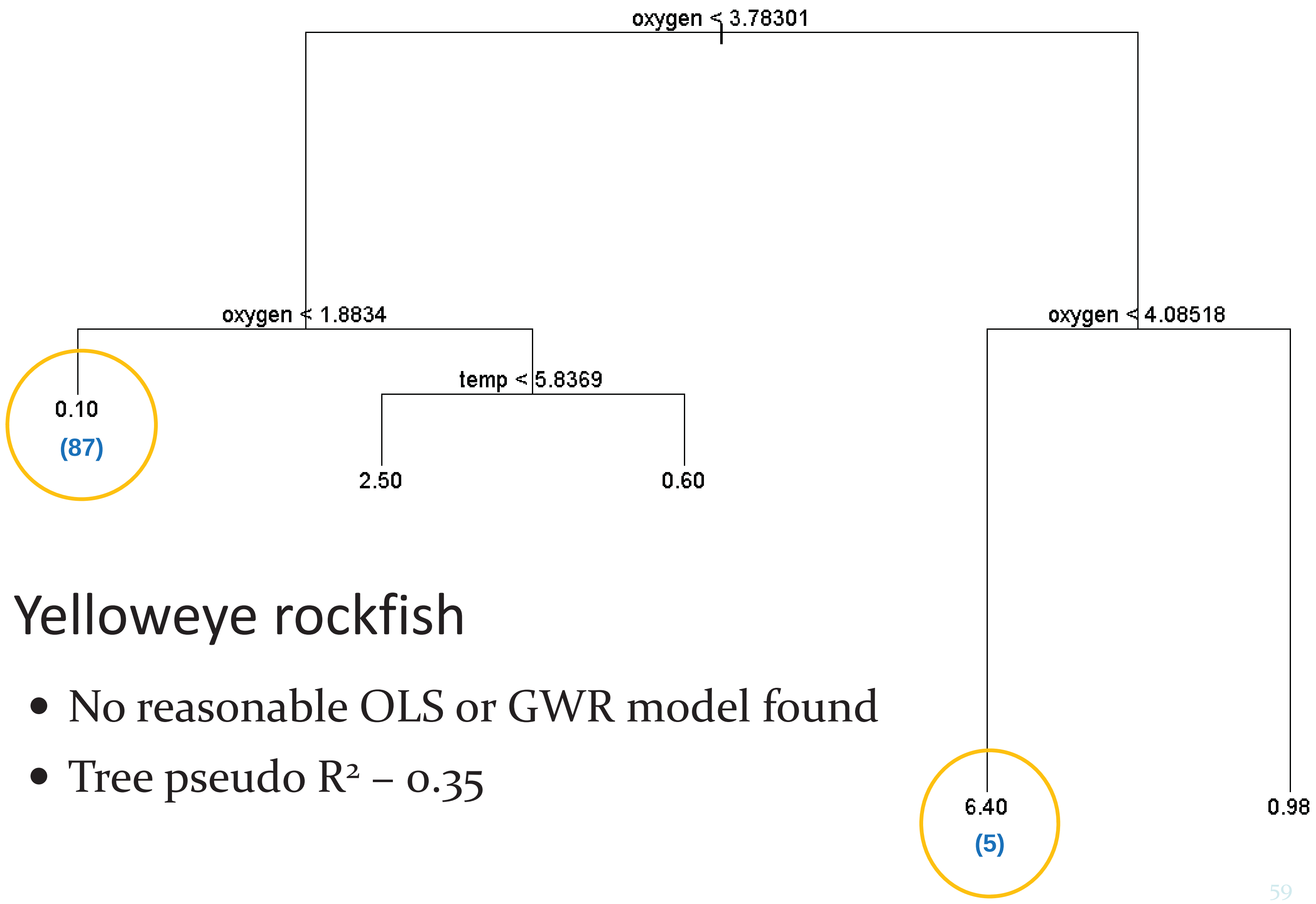


Figure 3.11. Tree regression model for lingcod using 2009 data, and compared with other models using R^2 values. Terminal nodes show mean NPUE for each cluster. Minimum and maximum mean NPUEs are circled and indicate number of sampling stations in that cluster (number in parenthesis).



Yelloweye rockfish

- No reasonable OLS or GWR model found
- Tree pseudo R^2 – 0.35

Figure 3.12. Tree regression model result for yelloweye rockfish using 2009 data, and compared with other models using R^2 values. Terminal nodes show mean NPUE for each cluster. Minimum and maximum mean NPUEs are circled and indicate number of sampling stations in that cluster (number in parenthesis).

Tables

Table 3.1. A summary of life history traits for species included in this study.

Species	Avg. F age at 50% maturity (years)	Avg. F length at 50% maturity (cm)	Reproduction	Maximum age (years)	Source[1]
Pacific halibut	12	105	Spawner/winter	55	IPHC
Arrowtooth flounder	8	48	Spawner/winter	*	NOAA, Stark (2012)
Spiny dogfish	34	*	Live birth/2 year cycle	100	NOAA, Tribuzio et al. (2008)
Longnose skate	17	100	Egg purse/season*	22	NOAA, McFarlane et al. (2010)
Sablefish	3-5	55	Spawner/winter	113	DFO
Lingcod	3-5	68	Spawner/winter	20(F), 14(M)	DFO
Yelloweye rockfish	19	46	Spawner/November	118	DFO, Love et al. (2002)

* No information found.

[1] Agency listings indicate that information was retrieved from general information available on the webpages in 2011.

Table 3.2. Results of a Kendall's Tau (τ) correlation test on the environmental variables collected for this study. Note that virtually all combinations of variables yielded a statistically significant result indicating that they are not independent of one another and should be considered together in the analysis.

Variables	Z-score	p-value	Tau (t)	Correlation
pressure:temperature	-18.07	<2.2e-16	-0.527	-
pressure:oxygen	-13.67	<2.2e-16	-0.398	-
pressure:salinity	18.97	<2.2e-16	0.553	+
pressure:ph	1.90	0.05739	0.086	0
pressure:latitude	-2.24	0.02515	-0.069	-
temperature:oxygen	8.96	<2.2e-16	0.261	+
temperature:salinity	-11.90	<2.2e-16	-0.347	-
temperature:ph	3.67	0.00024	0.166	+
temperature:latitude	-7.60	2.75e-14	-0.236	-
oxygen:salinity	-24.28	<2.2e-16	-0.708	-
oxygen:ph	11.51	<2.2e-16	0.521	+
oxygen:latitude	13.52	<2.2e-16	0.419	+
salinity:ph	-1.67	0.09526	-0.076	0
salinity:latitude	-13.078	<2.2e-16	-0.405	-
ph:latitude	-3.14	0.00169	-0.152	-

Table 3.3. Final regression model results for the species in this study with the exception of yelloweye rockfish because no reasonable model was found. The 2008-2009 combined data (left side) were used to determine significant explanatory variables and to test the robustness of the model with a K-fold cross validation test. The 2009 data (right side) were used as sample data for spatial analysis in order to compare across models and examine stationarity. Note: OLS refers to ordinary least squares regression and GWR refers to geographically weighted regression.

a) Pacific halibut

	2008-2009 combined				2009					
					OLS			GWR		
Variable	Coefficient	SE	p-value	K-fold cross validation p-value	Coefficient	SE	p-value	Variables Included		
Intercept	9.056	1.368	1.5e-10	-	7.467	1.865	0.0001	-	Bandwidth	146732
pressure	-0.006	0.001	4.7e-06	3.6e-13	-0.003	0.002	0.0454	-	Res. Squares	261.05
temperature	-1.547	0.193	2.3e-14	<2e-16	-1.414	0.259	0.0000	-	Eff. Number	24.69
oxygen	1.274	0.132	<2.0e-16	<2e-16	1.342	0.171	0.0000	X	Sigma	1.35
aggregating	99.773	21.381	4.5e-06	4.5e-06	100.640	28.414	0.0005	X		
AIC					625			595		
R^2	0.59				0.65			0.76		
R^2_{adj}	**0.57**				**0.64**			**0.72**		

b) Arrowtooth flounder

	2008-2009 combined				2009					
					OLS			GWR		
Variable	Coefficient	SE	p-value	K-fold cross validation p-value	Coefficient	SE	p-value	Variables Included		
Intercept	3.342	0.691	2.1e-06	-	3.524	1.067	0.0002	-	Bandwidth	312179
temperature	-0.762	0.099	1.7e-13	<2e-16	-0.786	0.147	0.0000	X	Res. Squares	226.52
aggregating	52.973	6.585	1.7e-14	1.7e-14	75.419	14.20	0.0000	X	Eff. Number	11.26
									Sigma	1.21
AIC					560			546		
R^2	0.33				0.43			0.52		
R^2_{adj}	**0.33**				**0.42**			**0.49**		

Table 3.3. continued

c) Spiny dogfish										
	2008-2009 combined				2009					
					OLS			GWR		
Variable	Coefficient	SE	p-value	K-fold cross validation p-value	Coefficient	SE	p-value	Variables Included		
Intercept	10.408	1.884	6.9e-08	-	8.285	3.210	0.0012	-	Bandwidth	1396754
pressure	-0.007	0.002	0.0002	1e-06	-0.007	0.003	0.0099	-	Res. Squares	945.35
temperature	-1.578	0.255	1.9e-09	<2e-16	-1.266	0.413	0.0002	X	Eff. Number	5.02
oxygen	0.736	0.158	4.6e-06	<2e-16	0.651	0.179	0.0012	X	Sigma	2.42
aggregating	316.189	22.696	<2e-16	<2e-16	360.323	36.227	0.0000	X		
AIC					625			775		
R^2	0.54				0.65			0.59		
R^2_{adj}	**0.54**				**0.64**			**0.58**		

d) Longnose skate										
	2008-2009 combined				2009					
					OLS			GWR		
Variable	Coefficient	SE	p-value	K-fold cross validation p-value	Coefficient	SE	p-value	Variables Included		
Intercept	2.367	0.710	0.0010	-	2.434	0.928	0.0096	-	Bandwidth	367809
temperature	-0.559	0.101	5.6e-08	1.3e-11	-0.581	0.131	0.0000	X	Res. Squares	215.63
aggregating	73.122	11.676	1.2e-09	1.2e-09	91.447	16.26	0.0000	X	Eff. Number	10.83
									Sigma	1.18
AIC					552			537		
R^2	0.22				0.28			0.40		
R^2_{adj}	**0.21**				**0.27**			**0.36**		

Table 3.3. continued

e) Sablefish										
	2008-2009 combined				2009					
					OLS			GWR		
Variable	Coefficient	SE	p-value	K-fold CV p-value	Coefficient	SE	p-value	Variables Included		
Intercept	-3.342	0.176	<2e-16		-3.216	0.196	0.0000		Bandwidth	351676
pressure	0.018	0.001	<2e-16	<2e-16	0.019	0.001	0.0000	X	Res. Squares	380.38
aggregating	52.293	14.842	0.0005	0.0005	-		-	-	Eff. Number	8.21
									Sigma	1.55
AIC					629			627		
R^2	0.57				0.58			0.61		
R^2_{adj}	**0.57**				**0.58**			**0.59**		

f) Lingcod										
	2008-2009 combined				2009					
					OLS			GWR		
Variable	Coefficient	SE	p-value	K-fold CV p-value	Coefficient	SE	p-value	Variables Included		
Intercept	-21.920	10.800	0.0439		0.105	0.855	0.9021		Bandwidth	18311437
pressure	-0.002	0.001	0.0011	6.7e-08	-0.001	0.000	0.0136		Res. Squares	114.10
temperature	-0.388	0.096	6.27e-05	0.0014	-0.417	0.114	0.0003	X	Eff. Number	4.01
oxygen	0.632	0.131	2.07e-06	2.5e-09	0.414	0.078	0.0000	X	Sigma	0.84
salinity	0.643	0.311	0.0393	4.7e-08	-	-	-	-		
aggregating	20.140	4.130	1.74e-06	1.7e-06	31.108	9.401	0.00116	X		
AIC					418			420		
R^2	0.29				0.46			0.45		
R^2_{adj}	**0.28**				**0.45**			**0.44**		

Table 3.4. Univariate-response tree regression model results for 2009. Values in parenthesis indicate the variable value at the split.

Response variable	1st split	2nd split	3rd split	Tree Pseudo R^2	OLS/GWR R^2_{adj}
Pacific halibut	latitude (47.5)	DO (2.35)	pres (133.9); temp (7.22)	0.65	0.72
Arrowtooth flounder	temp (6.74)	latitude (47.5)	pres (112.8)	0.46	0.49
Lingcod	DO (2.61)	latitude (48.5); latitude (50.5)	temp (6.34)	0.49	0.45
Longnose skate	latitude (46.5)	DO (2.65)	temp (6.65); latitude (49.5)	0.58	0.36
Sablefish	pres (158.8)	pH (7.60)	pH (7.64)	0.73	0.59
Spiny dogfish	latitude (47.5)	latitude (50.5)	pres (147.6); temp (7.28)	0.64	0.59
Yelloweye rockfish	DO (3.78)	DO (1.88); DO (4.09)	temp (5.84)	0.35	n/a

Chapter 4. A multivariate analysis of environmental factors and catch records for seven frequently caught species in the IPHC's longline surveys in the NE Pacific Ocean

Introduction

Characterizing relationships between environmental variables and species distributions is a necessary step in defining habitat and predicting how number per unit effort (NPUE) is affected by changes in the environment. It is also necessary to examine regional variation of environmental/ NPUE relationships and assess whether current data collection methods adequately capture spatial structure of the animal populations. In Chapter 3, multiple linear regression, spatial analysis, and tree regression models were used to examine relationships between environmental factors and NPUE for seven frequently caught species in the International Pacific Halibut Commission (IPHC) longline surveys. In that analysis, the addition of the aggregating variable to stabilize the residuals was a necessary step in order to model the relationship of NPUE to environment. However, what defines that variable remains unclear. Spatial correlation among the environmental variables used as NPUE predictors posed challenges to the linear modeling process, making a multivariate NPUE-environment modeling approach a logical next step.

Multivariate approaches can help explore non-linear relationships that may exist and also further inform about the collinear nature of predictor variables. For example, Bennett et al. (2005) used principle component analysis (PCA) to identify dominant patterns of rockfish catch per unit effort (CPUE) over time and then related those CPUE patterns to major ocean climate cycles such as El Niño. Their analysis uses both PCA and principle coordinate analysis (PCoA) in an attempt to parse out dominant features of both the environmental and species complexes. Cluster analysis was used by Lee and Sampson (2000) to look at species groupings in the Oregon groundfish trawl fishery and by Mueter et al. (2007) to identify groups of Pacific salmon stocks in the northeast Pacific that responded similarly to climate variations. Regression and classification tree models were employed by Ruppert et al. (2009) to examine Atlantic cod distributions in relation to environmental variability.

Single species/single factor linear regression models can be informative, but they ignore possible multispecies assemblages and also limit how we view the environmental variables given that many are covarying and should be considered together. In a global sense, the animals are all demersal and occupy similar geographic ranges, thus the reason they were caught on the longline survey gear during this study. However, relationships among and between habitat preferences for these seven species and environmental sensitivities remain unclear. For example, the aggregating variable, although originally added as an attempt to stabilize residuals, was also informative in identifying which species tended more strongly towards that behavior, (e.g. spiny dogfish, known for their tendency to tightly aggregate, yielded a very high positive aggregating coefficient with a highly significant p-value) but there was no mechanism introduced to account for interactions among different species. Multivariate approaches may help to further explain site/occupancy relationships.

Research on multi-species complexes in the north Pacific in relation to environment are few, likely due to the fact that environmental and species catch data have not been typically collected coincident to one another until recently. With an interest in fisheries management to move toward ecosystem-based models, recent studies have attempted to define habitat of groundfish for further use in these models. Both Jose' et al. (2009) and Tolimieri and Levin (2006) found strong correlations to groundfish assemblages based on latitude and depth, and Jose' et al. (2009) also found associations with individual oceanographic factors such as chlorophyll, salinity, and temperature. Keller et al. (2010) found a positive relationship between DO, and both species CPUE and species diversity in a study conducted off of Oregon during a hypoxic event, but did not look at assemblages specifically.

Methods

The dataset for this study includes number per unit effort (NPUE) data for the seven species described above that were collected during the IPHC's summertime long-line surveys (procedure described in IPHC (Unpub.)) along with coincident environmental information collected at each survey station using Seabird™ water column profiling units. The survey sampling stations were positioned on a 10x10 nmi grid laid across the continental shelf from about 30-500 m depth (Fig. 4.1). Data were collected from 2006-2009, and all regions were fished in those years, however environmental data were collected over the entire region in 2008 and 2009 only and only in the northern regions for 2006 and 2007. The environmental variables collected during the IPHC surveys and evaluated in this study include pressure (depth), temperature, pH, and DO. Malfunction of the pH sensor during portions of the survey resulted in fewer pH observations than stations profiled, so pH was used in a qualitative way but not as an explanatory variable in the regression models. Bottom type data were obtained from the USGS (USGS 2012) for the area off of Oregon and Washington and from DFO (DFO 2012) for the west coast of British Columbia. The DFO data included three designations and the USGS included seven. Therefore, all the data were put into three categories which included mud/silt/clay (M), sand (S), and gravel/hard bottom (H), and each station was given a bottom type designation. The bottom type data for Oregon and Washington were point data, so a station was assigned a bottom type based on the closest sampled bottom type stations. DFO data were presented as a surface map so the stations for this study were overlaid and assigned the corresponding bottom type.

Multivariate-response regression tree modeling (Breiman et al. 1984) was used to evaluate relationships between multi-species complex NPUEs in relation to environmental variables. This approach, a form of clustering, builds a tree structure that is designed to split into branches where the dissimilarity of sites within clusters is minimized (i.e. each split minimizes the total sums of squares within the two nodes and maximizes between nodes) (De'ath 2002). The structure is such that splits at the top of the tree reflect variables that operate at larger, more global, spatial scales, and subsequent splits reflect finer scale (local) variability (Moore et al. 1991; Ruppert et al. 2009). This model type yields interpretable results even when variables are collinear (Loh 2006), when there is missing data (such is the case with pH data in this study), and in the face of non-linear and interactive relationships between variables (Ripley 1996, De'ath and Fabricius 2000). Franklin (1998) and Vayssieres et al. (2000) compared tree regression analysis with generalized linear models and generalized additive models and found that tree models yielded better predictions. The *R* statistical package was used for all analysis in this section (https://cran.r-project.org). Major supplemental libraries used in this analysis included: *vegan* (Okanen 2012), *MASS* (Ripley 2012), and *mvpart* (De'ath et al. 2012).

Species abundance

Principle coordinate analysis

One of the first steps of this analysis was to look at relationships among the seven species and among stations. A review of various ordination approaches led to the selection of Principle Coordinate Analysis (PCoA; Gower 1966), using the Bray-Curtis dissimilarity coefficient (Bray and Curtis, 1957) which compares sites based on the minimum abundance (in this case minimum NPUE) of each species.

Species data were organized into site rows so that the sum of each row yielded the sum of all NPUEs found at that station. All rows that summed to zero were removed for this analysis resulting in 500 total rows. Data were then log transformed. The PCoA was run and the resulting eigenvalues and eigenvectors were calculated.

Environmental data

Principal component analysis

The data matrix consisted of 527 rows (station/year) and five environmental columns (pressure, temperature, salinity, dissolved oxygen, and latitude). PCA assumes linear relationships, and is also sensitive to variables that are measured on different scales. Data were considered linear and were untransformed for this analysis, but were row standardized to a mean of zero and standard deviation of one. Structural coefficients (loadings or eigenvectors) were derived for each of the environmental variables for each of the leading principal components to allow for interpretation of each empirical mode.

Linking species NPUE to environmental variables

A number of multivariate strategies were tried in an effort to explain species assemblages using environmental variables. Constrained ordination models were initially selected to examine this question but did not yield a satisfactory model. Tree regression models were ultimately selected.

Finally, a multivariate response regression tree was constructed for each year and for all years combined to look at overall and inter-annual variability in environmental variables that affected the species complex studied here. To better illustrate the dominant species at each station species NPUE data were standardized to a sum of 1 for each row. The pH data contained “NA” values which were simply ignored and no rows were excluded. However, a side effect of “NA” values is that they can elevate the importance of the variable because only the non-missing values are used to compute the impurity and thus it is easier to “purify” the node by splitting on a variable with fewer (more missing) values (Loh 2008). Tree regression is a form of cluster analysis where variability is maximized between clusters and minimized within.

Results

The PCoA on species abundance data yielded five principle coordinates. The percent of variation explained by each coordinate is as follows:

Principle Component	1	2	3	4	5
% variation explained	49.94	16.99	13.97	10.28	8.86

Regression analysis between coordinate scores and log-transformed species abundance data yielded the component values for each species (Table 4.1). All species in this study were shown to have statistically significant loadings on each of the first two coordinates (which explained 67% of the variability). Sablefish had a positive loading on Dim 1 whereas the other five species had negative loadings, perhaps reflecting depth effects (Fig. 4.2). The second coordinate had positive loadings for Longnose skate, sablefish, and spiny dogfish, and negative loadings for halibut, arrowtooth flounder, lingcod, and yelloweye rockfish.

The PCA of environmental variables yielded five principle components (Table 4.2) with PC1 explaining 62% of the variance and PC2 explaining 25%. PC eigenvalues versus broken stick null model distribution values showed that PC1 was statistically significant and PC2 was borderline significant. To look at these components more closely, a randomization test was run on the eigenvalues for each PC and both PC1 and PC2 were found to be statistically significant (Table 4.2). While not statistically significant, the general pattern within the other PCs, specifically PC3, is still valid.

Table 4.3 shows the contribution of each variable for each of the first two PCs. All five environmental variables were significant in PC1 with pressure and salinity having positive loadings while oxygen, temperature, and latitude had negative loading. PC2 had a strong positive coefficient for latitude and a strong negative coefficient for temperature. Pressure was the most significant contributor to PC3 which may suggest that at least part of the pressure data varies independently from the other input variables. The right side of Table 4.3 gives the loadings squared values which represent the percentage of variance in each original variable that is accounted for by each PC. Clearly, the bulk of the variance for each variable is captured in the first two PCs ranging from 62% for pressure to 96% for latitude. Figure 4.3 illustrates how the variables relate to one another in ordination space.

Tree regression models do not require variables to be independent or normally distributed, but knowing how one explanatory variable is correlated to another is useful information in interpreting results from the tree splits and comparing among years. Results from the Kendall's Tau correlation test (Table 4.4) were used to help describe results.

The multivariate tree regression model was generated for each year of data (2006-2009; Figs. 4.4 - 4.7, respectively). Salinity was not used since it is closely correlated with other variables and is well within the ranges tolerated by ocean-going species. Not all areas were surveyed in all years, so the results are not directly comparable spatially. In 2006, only the area north of Washington was surveyed and dogfish were clearly dominant in the southern part of this survey, while halibut and dogfish were prominent in the north. This pattern was present in each of the years off of Vancouver Island and in Queen Charlotte Sound. To the south, sablefish tended to dominate the stations. Relative error (RE), a measure of predictive accuracy based on impurity of the nodes or variability explained, ranged from 20% in 2006 to 60% in 2007. De'ath (2002) noted that RE can provide an over optimistic view of model fit and suggested the cross-validated relative error (CVRE) be used. The CVRE ranged from 17% in 2006 and 2009 to 46% in 2007 (Table 4.5).

For all years combined (Fig. 4.8), latitude was the primary splitting factor. South of 46.5°N the species complex was further split by pressure with all species represented in the more shallow depth cluster and clearly dominated by sablefish at the deeper stations. At mid-latitudes (46.5°N to 50.5°N) spiny dogfish were the dominant species and at the highest latitudes (>50.5°N) halibut and dogfish tended to dominate the shallower stations (down to 156 meters depth) while sablefish and dogfish dominated the deeper stations. Arrowtooth flounder tended towards the higher latitude stations, lingcod tended towards the mid to lower latitude stations, and yelloweye and longnose skate were more prevalent at more shallow depths. The RE and CVRE were 36% and 33%, respectively (Table 4.5).

Conclusions

Multivariate approaches provided a means to look at environmental variable and species distribution patterns in relation to one another. It is important to keep in mind the collinear nature of these variables when interpreting the various models because it is more likely that species are reacting to a variety of factors concurrently and habitat considerations should include all of these variables. The PCA of environmental variables showed that there were gradients with PC1 capturing primarily depth affects and PC2 capturing latitudinal affects.

While constrained analyses models were tried and found statistically significant, the amount of variation explained was very low and not very informative. The species compositions were better explained with the multivariate regression tree approach. With salinity excluded, latitude and pressure were the most common splitting variables with DO and temperature less common. Part of the original criteria for selecting the species in the study was their presence overall years and regions so it makes sense that these animals were found to have significant crossover in terms of explanatory variables. However, the trees clearly identifed those conditions where one or more species dominated the catch or where catches were lower.

Ultimately, halibut and dogfish were found in all study conditions with dogfish inhabiting all latitudes, but were especially present at mid-latitudes. DO and temperature were prominent in many of the single species regression trees presented in the previous chapter, but were much less common in the multivariate trees. The exception was in the 2007 data where DO was the primary splitting variable. Ultimately, it appears that variables other than latitude and pressure do less to define species compositions at particular sites, than in defining habitat for individual species. Expanding this type of analysis further north where environmental variables are not near threshold levels for these fishes, could help to piece out what variables or combination of variables are truly being represented given their collinear nature.

There is little doubt left that environmental variables play a role in how demersal animals are distributed on the fishing grounds. It is also clear that each organism responds in unique ways and to a variety of factors concurrently. The fact that many of the environmental variables are correlated to one another tends to complicate interpretation but also informs on how changes in any one of these variables, for example, in temperature or DO, may also correspond with changes in depth distributions.

Understanding how animals distribute in relation to current environmental scenarios is necessary in order to make broad predictions of how climate variability in the future will affect overall range and distribution patterns. It is also necessary to consider how or if environmentally driven distribution changes could affect survey sampling results. For example, DO can change abruptly over space, time, and through the water column, and certainly from one sampling station to another. Knowing the DO level at depth along with tolerance thresholds and resulting behavior, will help inform scientists regarding changes in distributions and species assemblages from year to year and translating that information into stock assessment models. Archival tagging studies have enabled scientists to gather detailed information of a fish's movement over time (e.g. Loher and Seitz 2006; Seitz et al. 2011) and similar tagging conducted early in the season within the study area could help to answer the question of movement of the animals when faced with threshold DO conditions and better consider species assemblage changes. If, for example, a species is found in a certain area one year when DO is slightly higher, but is absent at those same stations in the next year when DO is below the identified threshold, scientists can make informed decisions regarding whether the results may show a true decrease in biomass, a change in distribution (i.e. captured

Figures

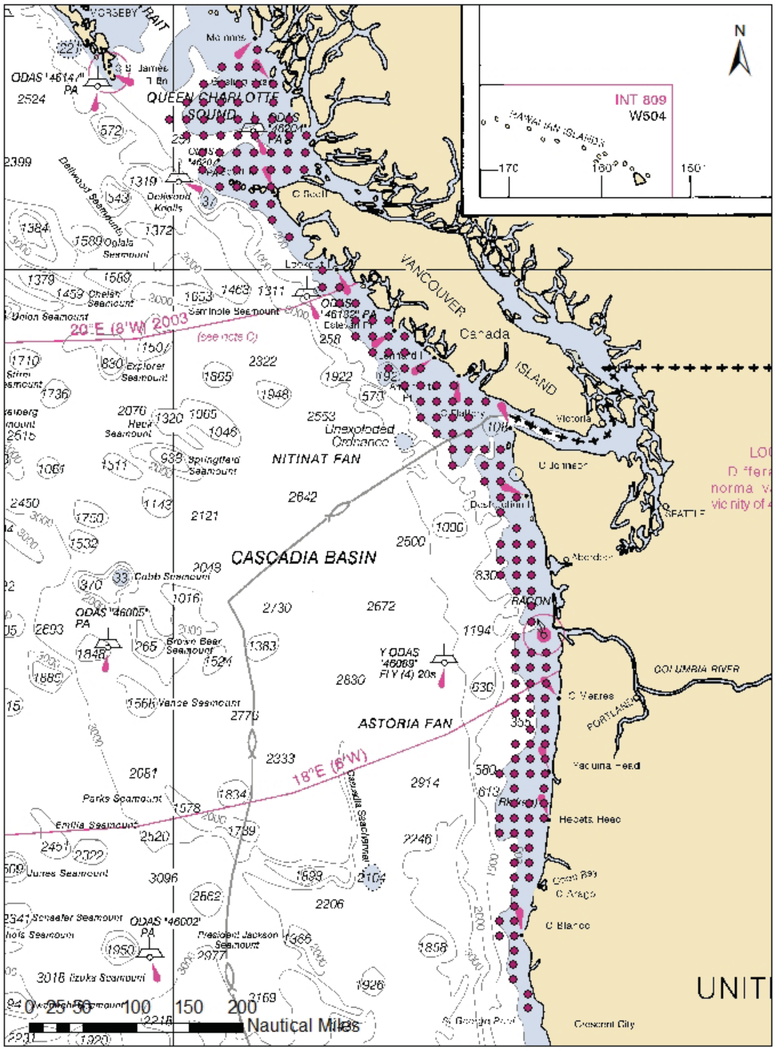


Figure 4.1. The study area extends from southern Oregon to Queen Charlotte Sound, B.C.. Both catch and oceanographic data were collected on a 10x10 nmi grid depicted on this map as dots for each sampling station. Inshore of the 200-m depth contour is highlighted in blue.

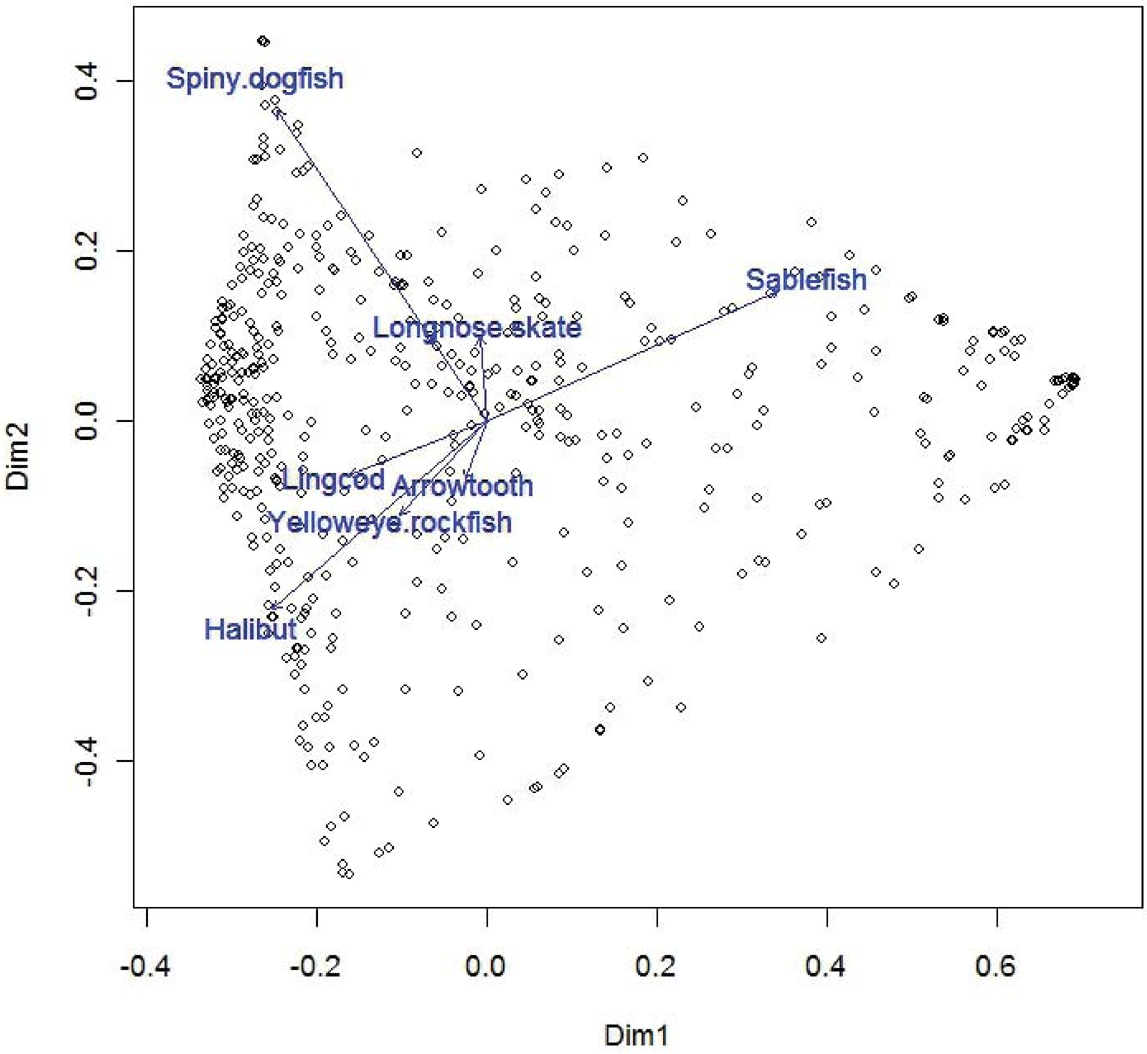


Figure 4.2. Principle coordinate analysis ordination plot with first two dimensions shown, which explained 67% of the species variability. All species were shown to have statistically significant loadings on the first two coordinates.

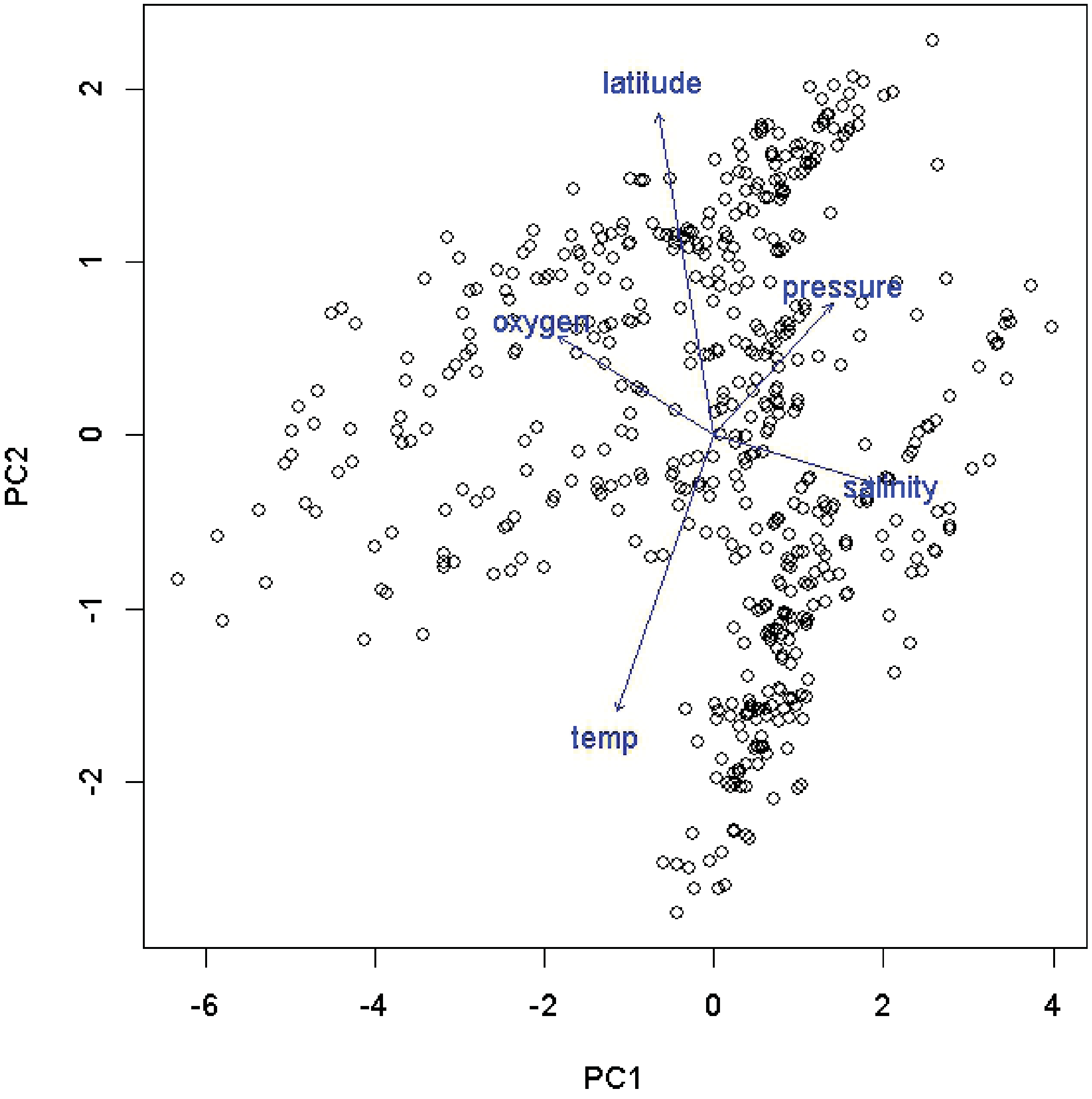


Figure 4.3. Principle component ordination plot for environmental data. PC1 (x-axis) appears to explain primarily depth effects while PC2 (y-axis) explains primarily latitudinal effects. A comparison to the broken stick null model showed that PC1 was significant and PC2 was borderline. A randomization of eigenvalues test showed that both PCs were significant.

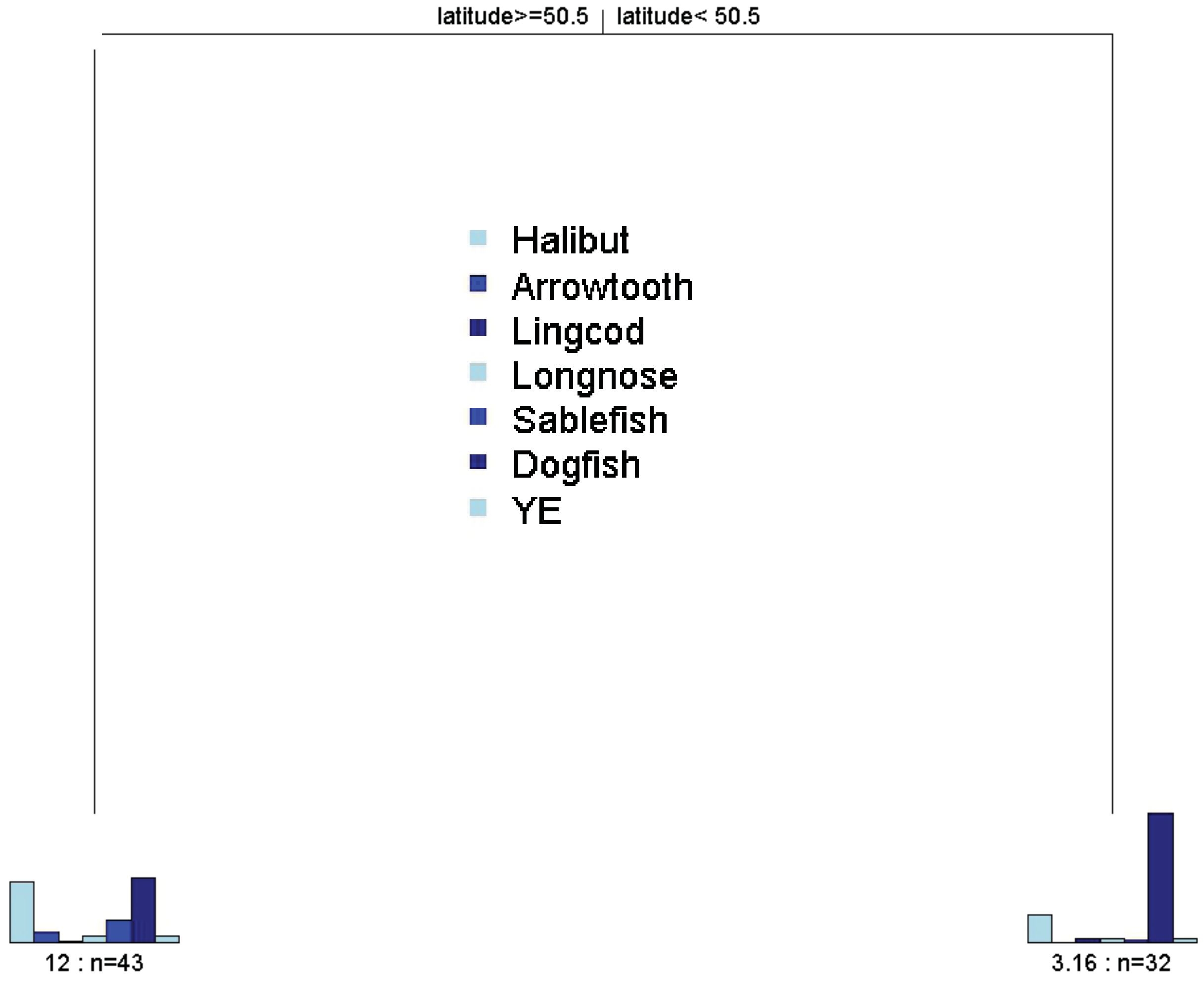


Figure 4.4. Multivariate tree regression model result for 2006. The bar graphs at each terminal node show the mean proportion of hooks occupied by each species relative to the others in that cluster of stations. Also at each terminal node is the deviance for that node along with the number of stations included (n). Latitude (^{o}N) was the only splitting variable with spiny dogfish clearly the dominant species. Note that 2006 included the area north of Washington only.

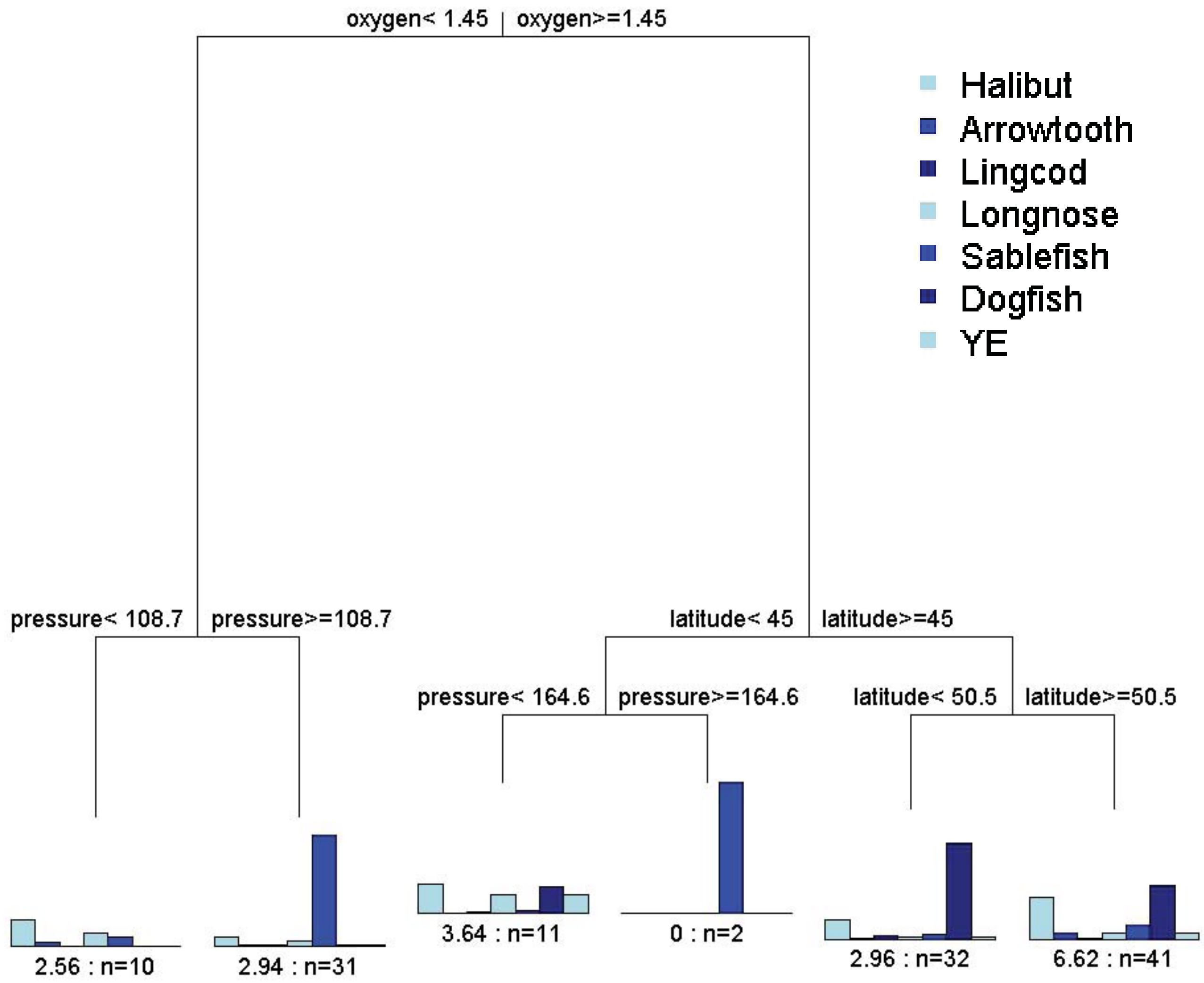


Figure 4.5. Multivariate tree regression model result for 2007. The bar graphs at each terminal node represent the mean proportion of hooks occupied by each species relative to the others in that cluster of stations. Also at each terminal node is the deviance for that node along with the number of stations included (n).DO (ml/L), along with pressure (comparable to depth in meters), and latitude (^{o}N) were the splitting variables. Sablefish were clearly dominant in the southern part of the study area, while spiny dogfish were dominant in the north.

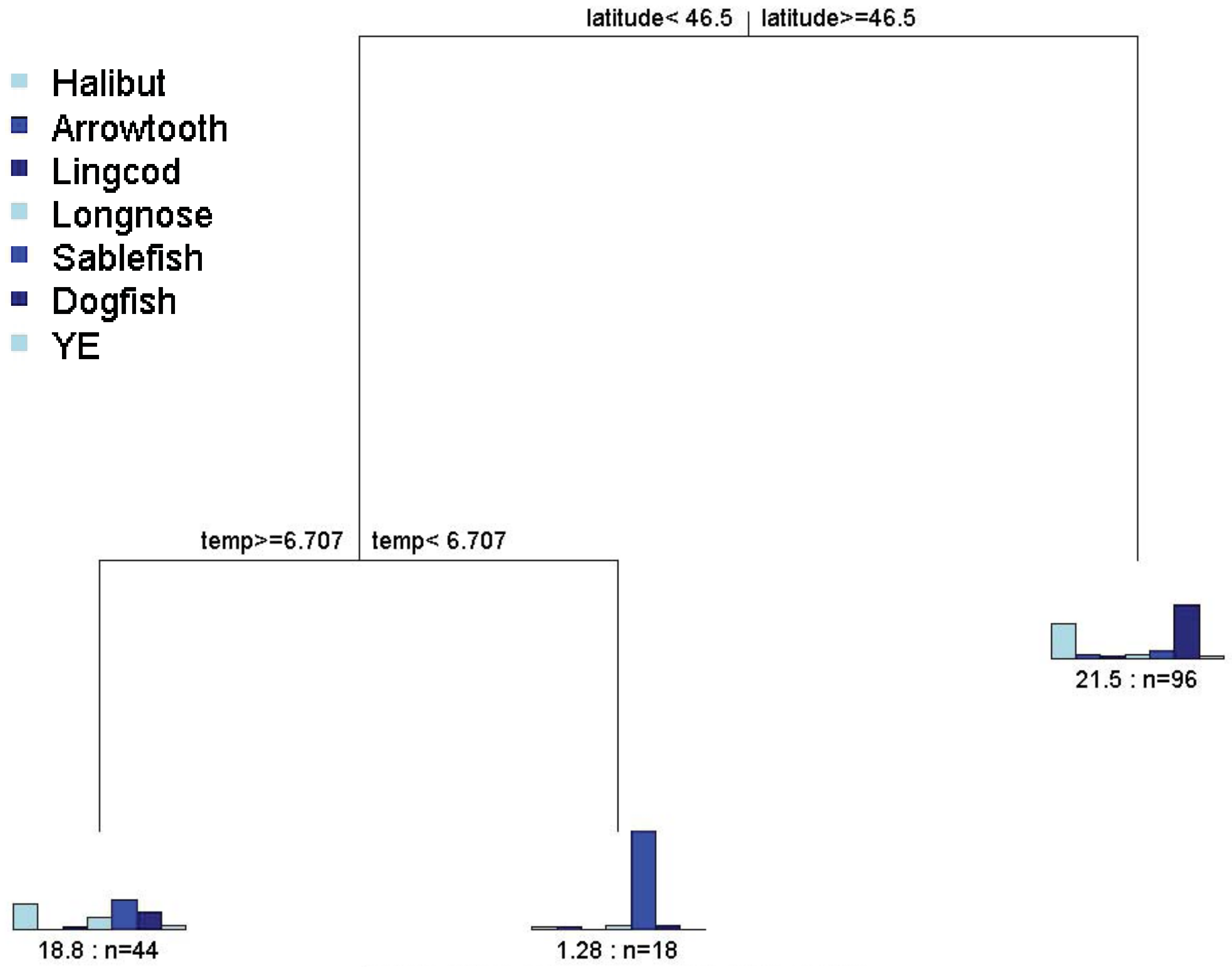


Figure 4.6. Multivariate tree regression model result for 2008. The bar graphs at each terminal node represent the mean proportion of hooks occupied by each species relative to the others in that cluster of stations. Also at each terminal node is the deviance for that node along with the number of stations included (n). Latitude (°N) and temperature (°C) were the splitting variables. Sablefish were dominant to the south, Pacific halibut and spiny dogfish to the north.

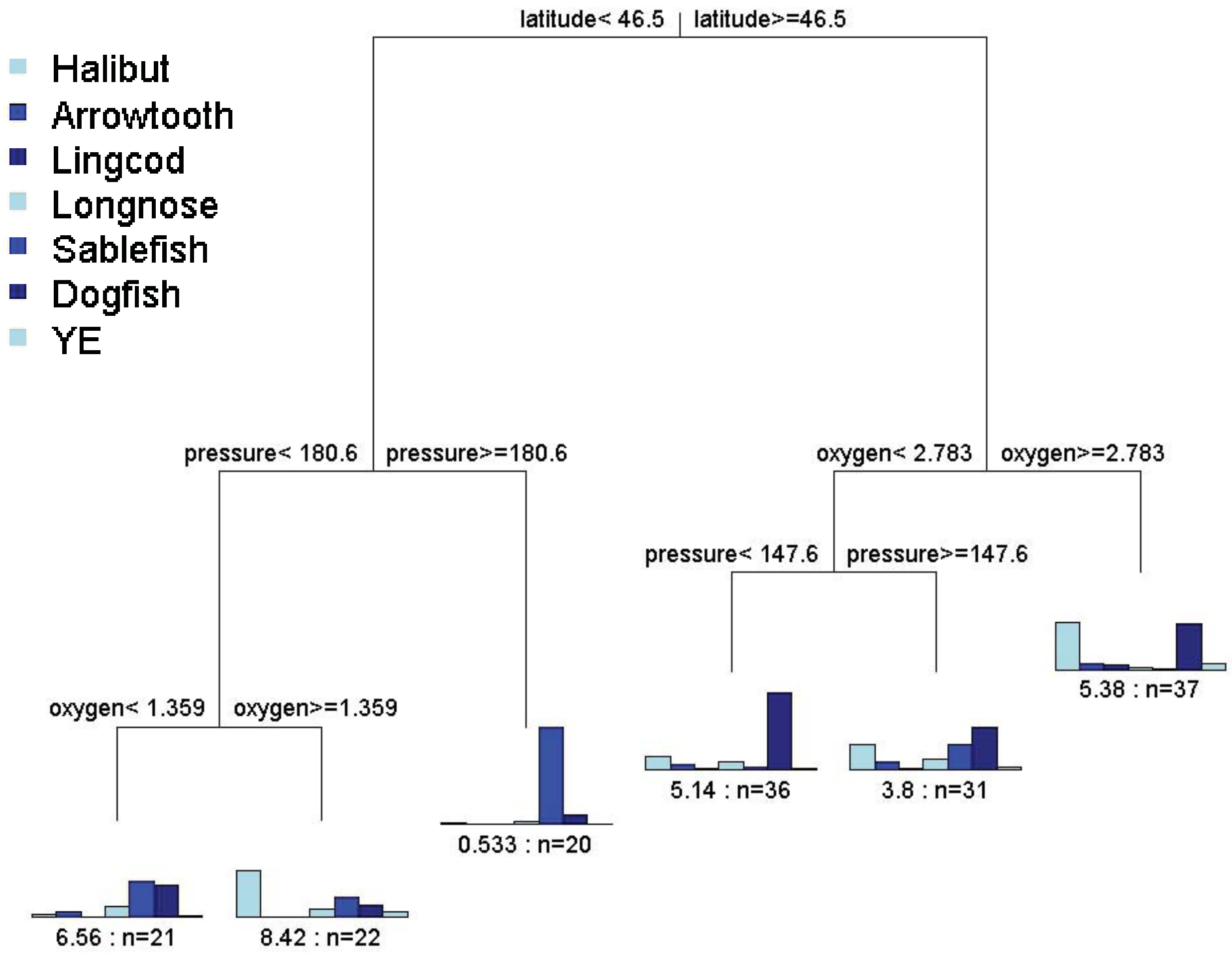


Figure 4.7. Multivariate tree regression model result for 2009. The bar graphs at each terminal node represent the mean proportion of hooks occupied by each species relative to the others in that cluster of stations. Also at each terminal node is the deviance for that node along with the number of stations included (n). Latitude (ºN), followed by pressure (comparable to depth in meters) and DO (ml/L).

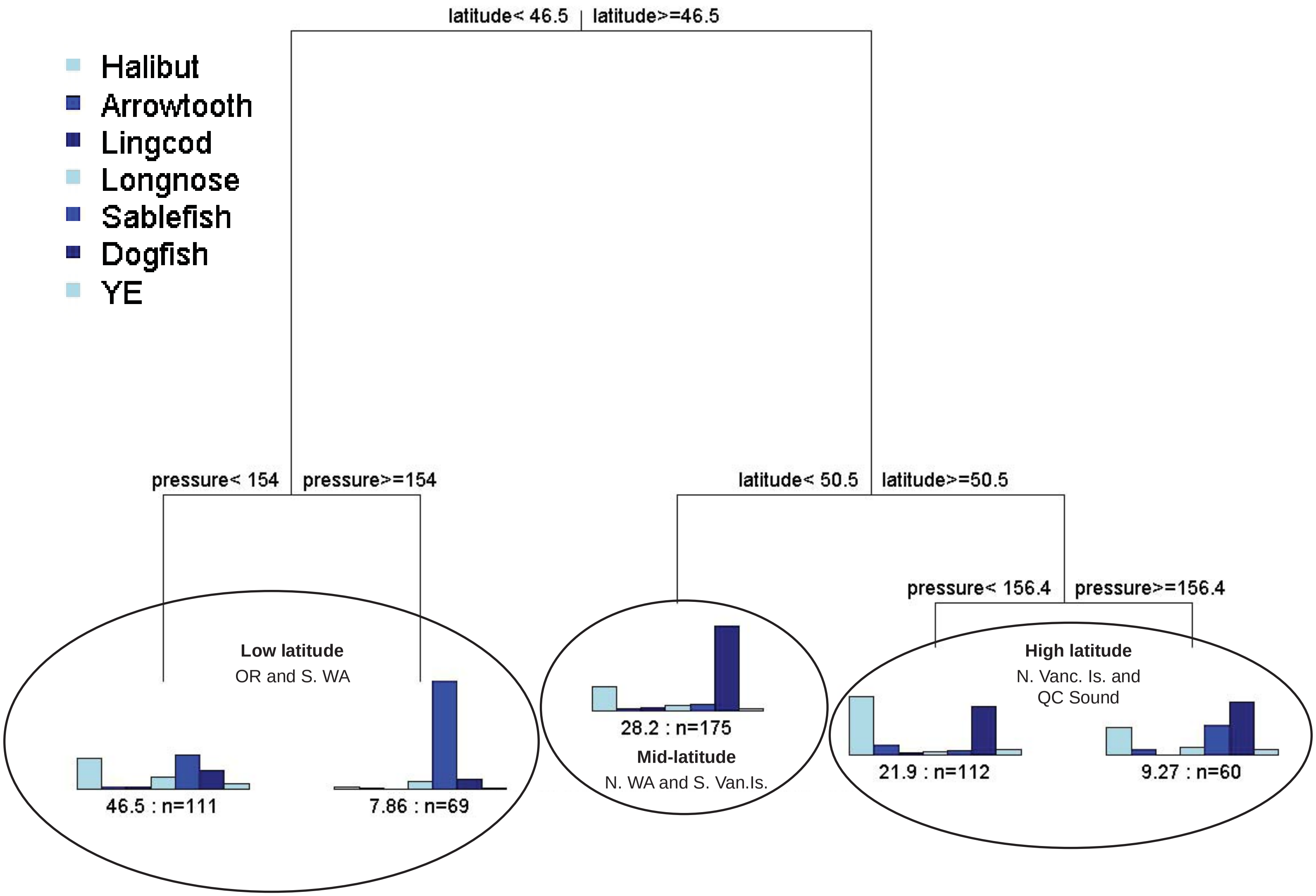


Figure 4.8. Multivariate tree regression model result for all years combined. The bar graphs at each terminal node represent the mean proportion of hooks occupied by each species relative to the others in that cluster of stations. Latitude (°N) was the primary splitting variable for species assemblages, and pressure (comparable to depth in meters) was also a factor.

Tables

Table 4.1. Results of regression analysis using principle coordinate analysis (PCoA). A Bray-Curtis dissimilarity coefficient (Bray and Curtis, 1957) was used and species data were log transformed.

PCoA results	Dim1	Dim2	r^2	Pr(>r)	
Pacific halibut	-0.75	-0.66	0.51	0.0010	***
Arrowtooth flounder	-0.35	-0.94	0.02	0.0030	**
Lingcod	-0.93	-0.37	0.14	0.0010	***
Longnose skate	-0.08	1.00	0.05	0.0010	***
Sablefish	0.91	0.41	0.64	0.0010	***
Spiny dogfish	-0.56	0.83	0.88	0.0010	***
Yelloweye rockfish	-0.68	-0.73	0.10	0.0010	***
Variance					
Pacific halibut	0.57	0.43			
Arrowtooth flounder	0.12	0.88			
Lingcod	0.87	0.13			
Longnose skate	0.01	0.99			
Sablefish	0.83	0.17			
Spiny dogfish	0.31	0.69			
Yelloweye rockfish	0.46	0.54			

Table 4.2. Principle component (PC) scores of the environmental data. To test significance, the values were compared to the broken stick null distribution model and a randomization test of eigenvalues with 1000 permutations. The broken stick comparison showed that PC1 was significant, but PC2 was borderline. However, the randomization test showed that both PC1 and PC2 were significant.

PC results	PC1	PC2	PC3	PC4	PC5
Variance(eigenvalue)	3.08	1.26	0.53	0.08	0.06
Proportion of Variance	0.62	0.25	0.11	0.02	0.01
Cumulative Proportion	0.62	0.87	0.97	0.99	1.00
Broken-stick value	2.28	1.28	0.78	0.45	0.20
Randomization test of eigenvalues					
P-value	0.0000	0.0000	1.0000	1.0000	1.0000

Table 4.3. Structural loadings for PC1 and PC2. Squared, these coefficients explain the percentage of variance in each original variable accounted for by each PC. Note that the rows of variance do not sum to one because only the statistically significant principle components (PC1 and PC2) are included.

	Structural loadings		Variance	
	PC1	PC2	PC1	PC2
Pressure	0.742	0.259	0.551	0.067
Temp	-0.731	-0.645	0.534	0.416
Salinity	0.948	-0.088	0.899	0.008
Oxygen	-0.936	0.187	0.876	0.035
Latitude	-0.474	0.855	0.225	0.731

Table 4.4. Results of a Kendall's Tau (τ) correlation test on environmental variables. Note that most combinations are significantly correlated.

Variables	Z-score	p-value	Tau (t)	Correlation
pressure:temperature	-18.07	<2.2e-16	-0.527	-
pressure:oxygen	-13.67	<2.2e-16	-0.398	-
pressure:salinity	18.97	<2.2e-16	0.553	+
pressure:ph	1.90	0.05739	0.086	0
pressure:latitude	-2.24	0.02515	-0.069	-
temperature:oxygen	8.96	<2.2e-16	0.261	+
temperature:salinity	-11.90	<2.2e-16	-0.347	-
temperature:ph	3.67	0.00024	0.166	+
temperature:latitude	-7.60	2.75e-14	-0.236	-
oxygen:salinity	-24.28	<2.2e-16	-0.708	-
oxygen:ph	11.51	<2.2e-16	0.521	+
oxygen:latitude	13.52	<2.2e-16	0.419	+
salinity:ph	-1.67	0.09526	-0.076	0
salinity:latitude	-13.078	<2.2e-16	-0.405	-
ph:latitude	-3.14	0.00169	-0.152	-

Table 4.5. Multivariate tree regression model results for the years 2006-2009 and all years combined including the cross validated relative error for each. Values in parenthesis indicate the variable value at the split.

Year	1st split	2nd split	3rd split	RE	CVRE
2006	latitude (50.5)	-	-	20%	17%
2007	DO (1.45)	Pres (108.7); latitude (45)	Pres (164.6); lat (50.5)	60%	46%
2008	Latitude (46.5)	Temp (6.7)	-	28%	19%
2009	Latitude (46.5)	Pres (180.6); DO (2.78)	Pres (147.6)	44%	17%
All	latitude (46.5)	Pres (154.0); latitude (50.5)	pressure (156.4)	35%	32%

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