Evidence of habitat associations and distribution patterns of rockfish in Puget Sound from archival data (1974-1977)

Hilary F. Browning

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Marine Affairs

University of Washington
2013

Committee:
Terrie Klinger
Ben Stewart-Koster

Program Authorized to Offer Degree:
School of Marine and Environmental Affairs

University of Washington
Graduate School

This is to certify that I have examined this copy of a master's thesis by

Hilary F. Browning

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

____
Terrie Klinger

____
Ben Stewart-Koster

Date: ______________________________

Signature: ______________________________

Date: ________________________________

ACKNOWLEDGMENTS

I would like to first give thanks to my outstanding thesis committee: committee chair Terrie Klinger and committee member Ben Stewart-Koster. I would like to give special thanks to Dan Tonnes for recruiting me to this project and for providing project guidance and development. Thank you to Dan Ito for the data upon which this analysis depends, and for review of my thesis. Thanks go to Miles Logsdon for assistance with ArcGIS for extracting environmental data, and to Mary Ramirez for the lovely sampling location map that I could not have created myself. Thank you also to The School of Marine and Environment Affairs and the UW Department of Biology for the financial support that allowed me to pursue my educational goals. Finally, sincere thanks go to my friends and family for their support.

INTRODUCTION

Pacific rockfish (*Sebastes* spp.) comprise an integral part of the Puget Sound groundfish assemblage. It has been estimated that there may be as many as twenty-eight species in Puget Sound (Miller and Borton, 1980), although only about half of these are commonly observed (Palsson et al., 2009). Rockfish serve important ecological functions as predators (Washington et al., 1978; see also review *in* Palsson et al., 2009) and prey (Mills et al., 2007), and are generally one of the most common and species-rich groups of bottom and mid-water fish along the Pacific coast of North America (Love et al., 2002). This group is characterized by unusually long life-spans (Munk, 2001), slow growth, and high fecundity (Haldorson and Love, 1991). These life history traits evolved as a strategy to persist over years or decades of unfavorable environmental conditions that reduce larval recruitment into the juvenile and adult populations, and therefore reproductive success (Ralston and Howard, 1995; Parker et al., 2000).

The life history traits characteristic of rockfish make them especially vulnerable to the effects of overfishing (Parker et al., 2000). Although native subsistence fishers have opportunistically caught rockfish in Puget Sound for hundreds of years or longer, and commercial fisheries have used rockfish as an off-season supplement to their income since the early 1900s, it appears that rockfish were seldom caught in significant numbers prior to the 1970s (Williams et al., 2010). Following a series of events in the mid-1970s that restricted opportunities for the Washington salmon fishery, the state opened new fisheries for Pacific cod and dogfish and expanded trawling opportunities for groundfish throughout Puget Sound (Palsson et al., 2009). Rockfish were publicized by both state and federal agencies as good recreational catch, and research was conducted on the best angling gear to use (Washington, 1977). As a result, the landings of rockfish rose from approximately 300,000 lbs per year in the mid-1970s to almost 900,000 lbs per year in 1980, and then declined precipitously (Palsson et al., 2009).

It was recognized in the mid-1980s that rockfish stocks might not be able to sustain such intensive fishing effort, and the first restrictive management measures were introduced in 1983. Despite increasing restrictions, rockfish populations continued to decline throughout the 1990s and 2000s (Palsson et al., 2009). Several petitions to list rockfish in Puget Sound under the Endangered Species Act (ESA) were submitted between 1999 and mid-2007; all of these were declined on the grounds that the data were insufficient to warrant protection under the ESA (NMFS, 2001; NMFS, 2007). Sparse data have often characterized the state of knowledge about rockfish populations and especially trends in abundance. Despite this, in 2010 populations of canary rockfish (*S. pinniger*) and yelloweye rockfish (*S. ruberrimus*) in Puget Sound were listed as threatened and bocaccio (*S. paucispinis*) were listed as endangered under the ESA (NMFS, 2010). Thirteen species of rockfish in Puget Sound are now listed as species of concern by the Washington Department of Fish and Wildlife (WDFW, 2011b).

The absence of data concerning rockfish has motivated a recent interest in examination of the historical record because information regarding rockfish in Puget Sound prior to their intense exploitation could be useful for guiding future management decisions. In general, there has been increasing interest among scientists in using historical data to detect change over time, as evidenced by the proliferation of papers regarding the establishment of reference conditions (e.g., Fulé et al., 1997; Bennion et al., 2004; Stoddard et al., 2006). Historical data, when used appropriately, can reveal insights into patterns of species' interactions and spatial distributions (Torres et al., 2013). Even incomplete records have a demonstrated potential to provide robust predictive power if the correct analytical methods are used (Elith et al., 2006; Elith and

Leathwick, 2007), which is vital given that it is usually difficult to collect comprehensive data about an exploited species' historical attributes or range. Most fisheries will lack the data necessary to determine long-term historical trends, so it may be necessary to mine older fisheries records or fishery-independent surveys in order to provide a complete picture.

Few rockfish surveys from the 1970s or earlier are suitable for analysis or comparison with contemporary data. Misidentification and poor record-keeping have reduced the utility of many records in determining the historical abundance, species' assemblages, and distribution patterns of rockfish in Puget Sound. I examined one of the few available archival data sets of rockfish catch from the 1970s. The data set, which comes from Washington et al. (1978) and relied exclusively on the use of recreational fishing gear, is the earliest known rockfish sampling survey in Puget Sound to accurately identify species. I analyzed this data to determine whether it had the potential to detect change in rockfish distribution and abundance over time, when compared to later studies. I used clustering and ordination to evaluate rockfish catch composition across sites and to detect associations between catch composition and environmental variables known to be important to rockfish. I predicted that the unique characteristics of this data set would make it a valuable source of new information about the patterns of rockfish associations in the 1970s.

METHODS

Puget Sound is a complex fjord-like estuary in western Washington that encompasses approximately 2,330 km^2 and includes 3,700 km of shoreline. Puget Sound is commonly divided into five sub-basins: Northern Puget Sound, Whidbey Basin, Main Basin, Hood Canal and

Southern Puget Sound (Figure 1; NMFS, 2000). Each of these deep basins, with the exception of Northern Puget Sound, is partially separated from the others by submarine ridges, or sills, of glacial origin (Kruckeberg, 1995). The ichthyofauna of Puget Sound are diverse and comprise approximately 60 families, including several of special economic and cultural significance like Salmonidae, Gadidae and Sebastidae (Miller and Borton, 1980).

Historical data collection

Researchers from the National Marine Fisheries Service (NMFS) angled to capture rockfish throughout Puget Sound from 1973 until 1977. The study was intended to determine the most effective tackle for developing a recreational rockfish fishery and to gather information about diet, reproduction, and growth relationships of rockfish species. Rockfish surveys primarily focused on the Main Basin of Puget Sound (Washington et al., 1978). For the purposes of those surveys, the sampling region was divided into units of one square nautical mile (3.43 km^2). Sampling was not uniform or systematic among grids; instead, sampling was concentrated in grids near rocky shoreline or where researchers found suspected rockfish habitat based on a combination of kelp, bathymetry and depth, with the most intensive sampling focused on the area around Bainbridge Island. Of the 100 sampling sites in which rockfish were caught, 56 sites were sampled only once; 21 sites were sampled twice; and the remaining 23 sites were sampled between three and fifteen times. An unrecorded number of sites were fished with no encounters. Due to missing entries in number of anglers or hours spent fishing (i.e., CPUE), only 74 of these sites were ultimately retained for this analysis.

Anglers used a variety of methods and tackle, primarily drift fishing (mooching) with herring bait or hook and line (jigging) with artificial lures, and fished in 0 – 180 meters of water from a 24 ft Radon Craft outfitted with a Lowrance fish finder capable of reporting bottom profile and depth. Researchers left port from Seattle or Mukilteo, WA and headed for areas that had the characteristics of high quality rockfish habitat: complex bottom structure, kelp beds and areas of known rockfish abundance (D. Ito, personal commun.). Fishing began in the morning and generally proceeded until mid-afternoon or until the weather deteriorated. As a result, length of the fishing day ranged from 0.5 to nine hours; sampling periods of between three and five hour's duration were most common. Sampling took place across all seasons of the year and was unevenly distributed across months. Incorporating seasonality effects into the analysis risked introducing excess zero observations; therefore effort was averaged across all years and seasons.

Standard biological measurements were taken of all rockfish collected. A total of twenty-three additional species of groundfish, primarily of the families Gadidae (cods), Hexagrammidae (greenlings), Paralichthyidae (lefteye flounders) and Pleuronectidae (righteye flounders) were recorded as caught and processed; fish of many more species were caught and discarded (D. Ito, personal commun.). Total length (mm) was recorded for all fish retained.

CPUE and Environmental Data

For each species, I divided the number of fish caught by angler-hours to calculate raw or nominal catch per unit effort (CPUE) at each site. I removed entries that lacked data on the number of anglers or the total hours fished. Because effort was not uniform across the study area and because tackle combinations varied in an unsystematic manner, it was not possible to adjust the

CPUE to account for effects from the use of different combinations of gear, bait and lure, and depths at capture. Therefore, I rejected the preferred method of standardizing catch per unit effort (CPUE) using a generalized linear model (Maunder and Punt, 2004) and instead used nominal CPUE in this analysis. The practice of using nominal CPUE has precedence in data-poor situations, particularly those involving the catch of tropical tunas (Lan et al., 2011).

The original data set formed a matrix of biological, environmental and administrative variables linked by the catch of a particular organism. Given the spatial focus of my study, I excluded all original variables aside from site, species, number of anglers, and hours spent fishing from this analysis. I further excluded data from 1973 because they were missing from the data set. It was desirable to include environmental characteristics for use in constrained ordination; however the environmental data from the original study were sporadically recorded and the data collection methods were not described. Consequently, to test for associations between rockfish CPUE and environmental data, I used the average magnitude of bottom currents obtained from the Puget Sound Hydrodynamic and Transport model created by researchers at the Pacific Northwest National Laboratory (Yang and Khangaonkar, 2007). Average magnitude of bottom current was assumed to be a proxy for kelp-appropriate abiotic habitat, e.g., rocky, high-energy areas (Springer et al., 2006). I calculated mean depth for each 1 NM^2 cell from the 250-m Cascadia Digital Elevation Model (Haugerud, 1999) using the "mean" function provided by the ArcGIS Spatial Analyst Zonal Statistics. I calculated the mean depth variation for each grid cell at the highest resolution of the data by subtracting each cell value from the average depth of the adjacent 3x3 neighborhood. I averaged this focal mean over a larger 7x7 neighborhood which closely approximated the 1NM targeted size of analysis. In this way the resulting grid cell value represented the mean fine scale variation of depth within a

$1NM^2$ neighborhood. I applied this same methodology to obtain slope and aspect variation. Together, I assumed that these measures would provide a deconstructed version of the variables that describe “roughness” of the seafloor.

To test associations between rockfish CPUE and kelp habitat, I retrieved data on kelp through the Washington State ShoreZone Inventory (Berry et al., 2001). The ShoreZone Inventory combines canopy forming kelps (*Macrocystis* and *Nereocystis*) as "floating kelp" and prostrate or stipulate kelps (*Laminaria* spp., *Hedophyllum*, *Egregia menzesii*, etc.) as "nonfloating kelp". Although there are biologically meaningful differences in rockfish use among the various types of kelp (Hayden-Spear, 2006), there was no straightforward way to incorporate these differences given the needs of the analysis; consequently, I combined floating and stipulate kelps in this analysis. I coded proximity to kelp measured from the centroid of each sampling cell as a binary variable (within 1 km of kelp = 1, not within 1 km of kelp = 0). I used one kilometer in this analysis based on the findings of Haldorson et al. (1994) that indicated that adults of many rockfish species moved less than 1 km during tagging studies.

Cluster Analysis

I used hierarchical clustering with average linkage (UPGMA) to group the 74 sites into a more manageable set of related objects and to explore the relationship among geographic locations. I chose UPGMA because this data set failed to meet the assumptions of equal sampling probabilities required for alternative methods such as Ward’s minimum variance (Ward, 1963). I used Bray-Curtis distance because this association coefficient has many properties that uniquely assist the ecological researcher: *independence of joint absences*, often otherwise known as asymmetry; *localization*, in which the inclusion of additional samples does not affect the resemblance calculated for previous samples; and *complementarity*, in which sites that have no species in common are assigned the maximum distance (Clarke et al., 2006). Bray-Curtis distance assigns lower weight to unobserved taxa than do other distance measures common in community ecology. I used the cophenetic correlation coefficient to assess the ability of the dendrogram to accurately depict these Bray-Curtis distances. I used a scree plot to visually inspect the number of stable clusters.

Nonmetric Multidimensional Scaling

I employed nonmetric multidimensional scaling (NMDS) with Bray-Curtis distance to assess differences in nominal CPUE of all rockfish species and across sites. NMDS is robust to the presence of rare species (present at less than <5% of sites) because it does not assume linear or modal relationships among variables. All species data were log transformed (ln x+1) prior to analysis. To reduce the risk of the ordination settling upon local minima, I performed 100 random starts and selected the lowest stress value from among these. Due to high beta diversity (i.e., many sites with no species in common) I applied a flexible shortest path adjustment to allow the solution to converge (Williamson, 1978; Bradfield and Kenkel, 1987). I accepted the three-dimensional solution because inspection of a scree plot suggested that this solution provided the best balance between complexity and ordination stress.

I used species' loadings to visually estimate associations between different species' catch and to assess the statistical significance of the relationship between species and geographic locations. Loadings are calculated by a linear correlation analysis between each object (e.g., sampling sites) and the original descriptors (e.g., species). These vectors are scaled by their correlation; longer vectors indicate a stronger correlation and better predictive power. I determined statistical significance for each vector using a permutation test of the environmental variables with a fixed a fixed number of permutations (n=1000).

Canonical Correspondence Analysis

I assessed the relationship between rockfish catch composition and environmental characteristics at each site using a canonical correspondence analysis (CCA) with biplot scaling by species. CCA is the constrained version of correspondence analysis (CA) and like CA is appropriate when the response of the community to environmental gradients is likely to be unimodal rather than linear. This assumption was verified by the length of the first axis of a detrended correspondence analysis (DCA axis > 2). Only species reported from >5% of the sites (copper rockfish (*S. caurinus*), black rockfish (*S. melanops*), brown rockfish (*S. auriculatus*), and quillback rockfishes (*S. maliger*)) were included in this ordination because the chi-squared distance upon which CCA relies tends to weight the contribution of rare species much more heavily than common species. Three sites defined exclusively by rare species were therefore excluded, which reduced the number of sites from 74 to 71 for this analysis.

I used Monte Carlo permutation tests to evaluate the significance of the ordination in its entirety as well as the significance of each CCA axis and environmental variable. The number of permutations for tests on the ordination and axes were controlled by the Type I and Type II error rates ($\alpha = 0.05$, $\beta = 0.01$). I used a fixed number (n=1000) of permutations for tests on each environmental constraint.

All statistical analyses were performed using R software (R Core Team, 2012) with the *vegan* (Oksanen et al., 2012*),* and *cluster* (Maechler et al., 2012) packages and the BIOSTATS (McGarigal, 2011) collection of functions.

RESULTS

Catch data

Examination of the catch data revealed large differences in CPUE across species (Table 1). For instance, over four years of sampling, researchers captured only a small number of bocaccio (21), canary rockfish (11) and yelloweye rockfish (30), all three of which are now listed under the ESA. In contrast, the four most commonly captured species (black rockfish, brown rockfish, copper rockfish, and quillback rockfish) were represented by catches an order of magnitude higher than this. It is likely that this result was influenced by sampling methodology, rather than differential abundance of these species, given that average sampling depth in the original survey was shallower than the listed species' preferred depths (50 – 500 m; Palsson et al., 2009).

Catch was very low for five other species, which is consistent with observations from other surveys (Miller and Borton, 1980). Rougheye rockfish (*S. aleutianus*) and widow rockfish (*S. entomelas*) are captured very rarely in Puget Sound, and those that are may be members of the oceanic stock. Likewise, although yellowtail rockfish (*S. flavidus*) are caught in Puget Sound on a semi-regular basis, it is unclear whether they come from an undiscovered self-sustaining Puget Sound stock or if they are immigrants from the Pacific Ocean or Strait of Georgia. Finally, both greenstriped rockfish (*S. elongatus*) and redstripe rockfish (*Sebastes proriger*) are deepwater species that are infrequently caught in the contemporary recreational fishery (Palsson et al., 2009).

Geographic representation (cluster analysis)

Inspection of the scree plot (not shown) indicated that grouping the sites into eight clusters yielded the largest degree of within-group similarity and the greatest dissimilarity to other groups (Figure 2). The cophenetic correlation coefficient of 0.80 indicated that the dendrogram accurately represented the original data without distortion. Generally, correlations above 0.75 are considered acceptable (McGarigal et al., 2000). However, the eight clusters generated allowed only a weak geographic interpretation (Figure 3). Cluster 5 grouped together sites near south Bainbridge Island and north Vashon Island; cluster 7 grouped some sites surrounding the perimeter of Bainbridge Island and the shoreline of Seattle (e.g., Golden Gardens); cluster 8 included many areas just south of Whidbey Island and to the west of Alki Beach and cluster 6 was homogenously distributed throughout the sampling area. The remaining clusters were small and most likely defined by the presence of one or two rarer species.

Species catch composition across sites (NMDS)

The NMDS ordination of all rockfish species catch demonstrated that there were detectable differences in species' distributions across sampling sites at the time that the original data were collected. The ultimate 3-dimensional NMDS solution had an associated stress of 10.75, indicating a solution with useful interpretative ability. The goodness of fit plot indicated a strong correlation between the fitted values and the ordination distances (linear fit $R^2 = 0.937$). Although the three-dimensional solution was selected due to its lower stress, examination of the first two dimensions proved sufficient in this case for exploring the relationships among the variables (Figure 4).

According to the species' vectors produced from the NMDS solution, there was very little overlap between areas where copper rockfish and brown rockfish were likely to be caught. A weaker, gradient-like relationship in the distribution of catch was revealed for black rockfish, yelloweye rockfish, greenstriped rockfish, and quillback rockfish. Catch of copper rockfish was very strongly associated with cluster 5, while catch of brown rockfish was strongly associated with cluster 7. Black rockfish and yelloweye rockfish were significantly but weakly associated with both clusters 3 and 6. Greenstriped rockfish and quillback rockfish showed a significant but weak associations with cluster 8 (Figure 4). The remaining six rockfish species contributed to the orientation of objects in ordination space but were not plotted as vectors because their relationship of catch to site was found to be insignificant ($p > 0.05$).

Species catch composition and the environment (CCA)

Approximately 19.8% of the total variation in catch of the four most common species of rockfish was explained by the constrained axes, i.e., environmental factors. An abridged summary of these results are reported in Table 2. The results of the CCA indicated that rockfish catch distribution in part can be explained by proximity to kelp and average bottom current at sampling sites. Proximity to kelp was significant at $\alpha = 0.01$ and average bottom current was significant at

$\alpha = 0.05$. None of the other environmental constraints (average depth, variation in aspect, variation in slope and variation in depth) had significant explanatory power in the model.

Black rockfish and brown rockfish exhibited strong negative and positive associations with kelp, respectively. Quillback rockfish were weakly negatively associated with kelp and there was no detectable relationship between copper rockfish and kelp. Both black rockfish and brown rockfish showed significant, positive associations with bottom current (i.e., faster bottom currents resulted in a higher catch of both species). There was no apparent relationship to bottom current for either quillback rockfish or copper rockfish. These relationships are visually represented in Figure 5.

Results from the Monte Carlo permutation tests indicated that axes CCA1 and CCA2 were significant while CCA3 was not. Combined, these first two constrained axes accounted for 17.79% of the variability in the data. The three non-canonical axes, which accounted for 80.19% of the total inertia, describe the distribution of the four species' catch across the sites. These results are functionally similar to those from the NMDS ordination and are not presented here. However, it is worth noting that there was much higher redundancy in the ordination of site objects for the CCA than the NMDS. This is most likely because there are fewer possible combinations of catch with four species than with twelve. In order to provide a clearer visual depiction, the objects in Figure 5 were jittered at a factor of 100.

DISCUSSION

Analysis of historical records has proven to be a useful tool for evaluation of long-term ecological change. For example, archival data, including museum collections and commercial logbooks, have helped investigators reconstruct historical distributions of species (Torres et al., 2013), detect population declines (Shaffer et al., 1998), and predict likely future distributions (Elith and Leathwick, 2007). Data collected for a specific purpose have been successfully used to develop time series for detection of a range of phenomena, including climate change induced alterations in migration, community structure, abundance and breeding phenology (reviewed in Hawkins et al., 2013). The goal of this study was to determine whether a repurposed archival data set could provide useful insights into historical distributions and abundances of rockfish species in Puget Sound. Several of these rockfish are of conservation concern, and historical data for these species are limited. I found that while statistical analysis could be used to elucidate some historical spatial relationships, mismatches in scale of inquiry and sampling design between historical and contemporary investigations limited the utility of this archival data set.

Differences in geographic distribution among rockfish species were detectable in the analysis, and the resultant patterns were clear enough to interpret in the context of present-day environmental factors. Comparison of catch across sites demonstrated that copper rockfish and brown rockfish tended to be caught in different locations. This finding was unexpected given that Palsson et al. (2009) reported that the two species express similar habitat preferences, and that copper rockfish and brown rockfish had both been caught in large numbers around Bainbridge Island (Washington, 1977). Close examination of the distribution maps provided by Washington (1977) and Palsson et al. (2009), however, confirmed that copper rockfish are more commonly found around Vashon Island than are brown rockfish. Furthermore, inspection of the environmental attributes of sites characterized by copper rockfish or brown rockfish catch indicated that copper rockfish may prefer bottom habitats with higher variation in depth than do brown rockfish. This spatial difference and its associated environmental characteristic most likely drove the distinction in the NMDS ordination (Figure 4).

Catches of black rockfish, yelloweye rockfish, greenstriped rockfish and quillback rockfish varied along a continuum of latitude, longitude or environmental characteristics (Figure 4). The existence of such a gradient could provide support for the assemblage management scheme used for rockfish in Puget Sound (WDFW, 2011a). Black rockfish belong to the pelagic assemblage, yelloweye rockfish and greenstriped rockfish to the deepwater assemblage, and quillback rockfish to the nearshore sedentary assemblage (Palsson et al., 2009). The species distribution gradient detected in this study could reflect a range of catch locations that move progressively from the center of basins towards the shorelines of Puget Sound. More generally, the species-specific spatial distributions detected in this analysis are similar to distributions reported in the 1970s and more recently (Palsson et al., 2009), potentially indicative of areas where rockfish populations have persisted through time. Such sites could be candidates for protective designations such as Essential Fish Habitat (EFH; MSFCMA, 2007) or marine reserves.

Relationships between rockfish catch and various environmental characteristics varied in sensitivity to the resolution of data collected. The CCA was able to describe significant relationships between rockfish distribution and two environmental variables (kelp and magnitude of bottom current), yet was unable to detect any relationship between distribution and bathymetric characteristics despite the known ecological importance of these variables (e.g., Yoklavich, 2000, Young et al., 2010, Wigand, 2012). This result was obtained despite the fact that the spatial resolution of all environmental variables was similarly coarse. This suggests that, for a given archival data set, some patterns may be robust to limitations inherent in the data set, even if other patterns are obscured.

While proximity to kelp was a significant predictor of rockfish catch, it did not explain catch for all species nor did predictions vary in the directions expected. For instance, proximity to kelp was a strong negative predictor for black rockfish, a weak negative predictor for quillback rockfish, and an ineffective predictor for copper rockfish (Figure 5; Table 1). These results are not consistent with findings from other rockfish surveys. Palsson et al. (2009) reported copper rockfish, quillback rockfish, and brown rockfish as the primary species in Puget Sound for which kelp is important for juvenile recruitment, while studies in other regions have indicated a possible relationship between juvenile black rockfish and kelp habitats (Love et al., 1991). Kelp also provides habitat for adult copper rockfish (Johansson et al. 2008). The unexpected associations demonstrated here are likely artifacts of using contemporary kelp data to describe historical conditions, and suggests that the association between presence of kelp and local adult rockfish abundance may be sensitive to fine-scale variation in kelp abundance and distribution.

Average magnitude of bottom currents was a significant positive predictor of distribution for black rockfish and brown rockfish. This association could reflect a positive relationship between rockfish catch and high average bottom current and by extension the rocky, high-energy habitats appropriate for kelp growth. However, the prominent arch effect present in the CCA (Figure 5) suggests that this relationship be interpreted with caution. The arch indicates a single long gradient along which sites were linearly ordered. Therefore, the influence that the average magnitude of bottom currents has upon the analysis is due in part to its dominance of the second axis. It is unknown how large this impact likely was (and the interpretation of the arch effect remains controversial; Jackson and Somers (1991)), although average magnitude of bottom currents analyzed in isolation continued to be a significant predictor.

Variation in aspect, slope and depth, and average depth derived from the Cascadia Digital Elevation Model failed to be good predictors of rockfish catch distribution. Other studies have found aspect and slope to be strong predictors of rockfish distribution (Young et al., 2010; Wigand, 2012) and that increasing bottom complexity is positively related to the abundance of many species of rockfish (Yoklavich, 2000). Furthermore, it is widely accepted that depth is one of the most important factors influencing rockfish distribution (Williams and Ralston, 2002; Anderson and Yoklavich, 2007). This result may be influenced by the methods and finer spatial scales used in other studies of rockfish, which differed greatly from what I was able to employ. Given the large spatial scale of the original data (1 NM^2 grid), I found it most appropriate to use a similarly large digital elevation model (250 m). I then "averaged" this resolution over seven pixels in order to scale up to 1 NM^2. It is likely that the spatial scale at which the data were originally collected does not match the scale at which rockfish are distributed among micro-habitats. The home ranges of copper rockfish and quillback rockfish range from approximately 1500 – 2500 m^2 (Tolimieri et al., 2009) to as small as 10 m^2 in high relief habitat (Matthews, 1990). Areas subject to disproportionately high use compared to the rest of a home range (core areas) are even smaller at <500 m^2 (Tolimieri et al., 2009). These smaller, localized patches of distinct habitat may better represent the scale at which factors affect rockfish distribution, but they are not captured in the archival data set that I used.

In general, the data proved to be unsuitable as a comparison point for the purposes of detecting change over time due to haphazard sampling design, coarse spatial resolution, and mismatches in scale. The sampling design used in the original study was *ad hoc*: tackle combinations were varied unsystematically, sites were sampled non-uniformly, and sampling was uneven across seasons and across 1 NM^2 grid cells. Variation in the use of fishing tackle prevented standardization of CPUE, which is an accepted practice in fisheries science. Because the original data set did not include environmental variables, these had to be estimated from more recent measurements that did not necessarily accurately reflect conditions at the time the data were collected, nor was it possible to determine whether they were scaled appropriately to the original survey data. The process of scaling up or down may have resulted in critical loss of resolution.

CONCLUSIONS

Investigators will continue to turn to historical data to enhance their understanding of past conditions in ways that can inform contemporary management and conservation decisions. My study demonstrates that even challenging data sets can offer insights that are of practical management relevance. Given that it is not uncommon for historical or archival data, particularly those repurposed from earlier studies, to suffer from data limitations similar to those described here (Swetnam et al., 1999; Zeller et al., 2005), the key may lie in combining archival and modern data sets to piece together information about the historical landscape. Other studies have confirmed that reconstructions of environmental history are improved with the use of a variety of complementary sources (Swetnam et al., 1999; Bieler and Mikkelsen, 2004; Olson and Rauzon, 2011). The work reported here represents one of the first attempts at a reconstruction of rockfish distributions in Puget Sound prior to their intense exploitation and sharp decline. Future historical analyses that build upon this work may provide a more complete picture and facilitate effective management strategies.

FIGURES

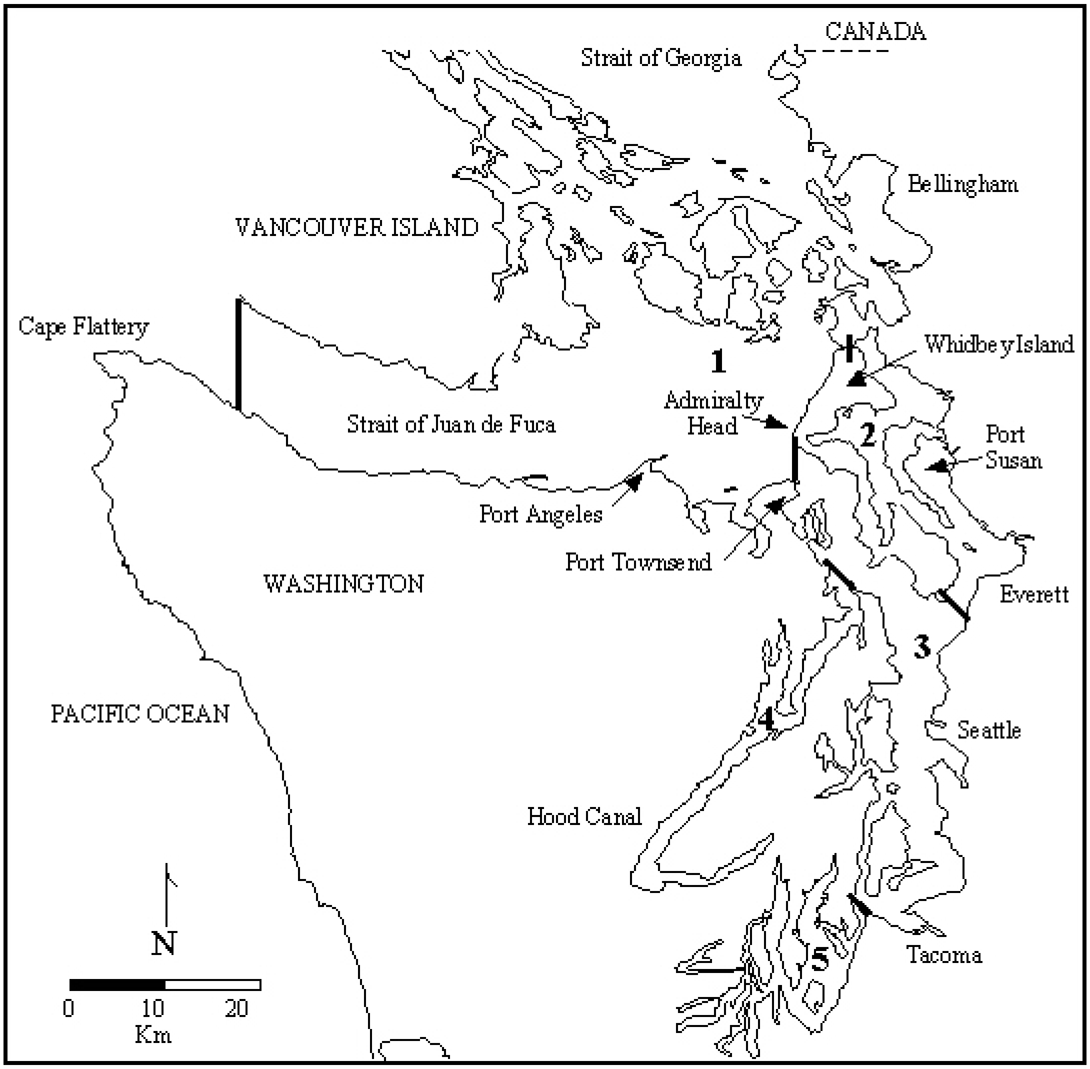

Figure 1. Regional sub-basins of Puget Sound: 1) Northern Puget Sound, 2) Whidbey Basin, 3.) Main Basin, 4.) Hood Canal, and 5) Southern Puget Sound. Adapted from NMFS (2000).

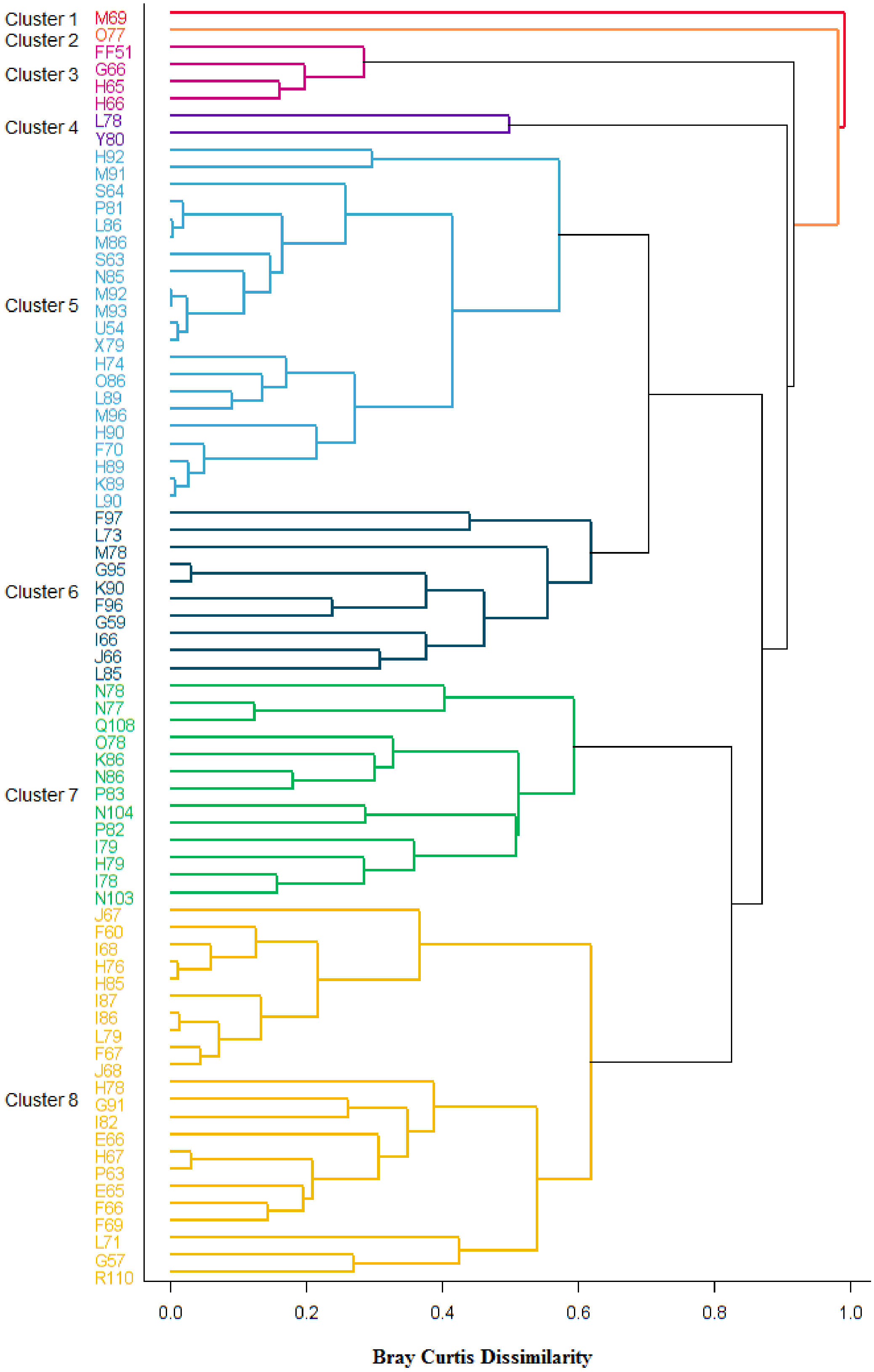

Figure 2. Cluster analysis with average linkage and Bray-Curtis distances based upon nominal CPUE.

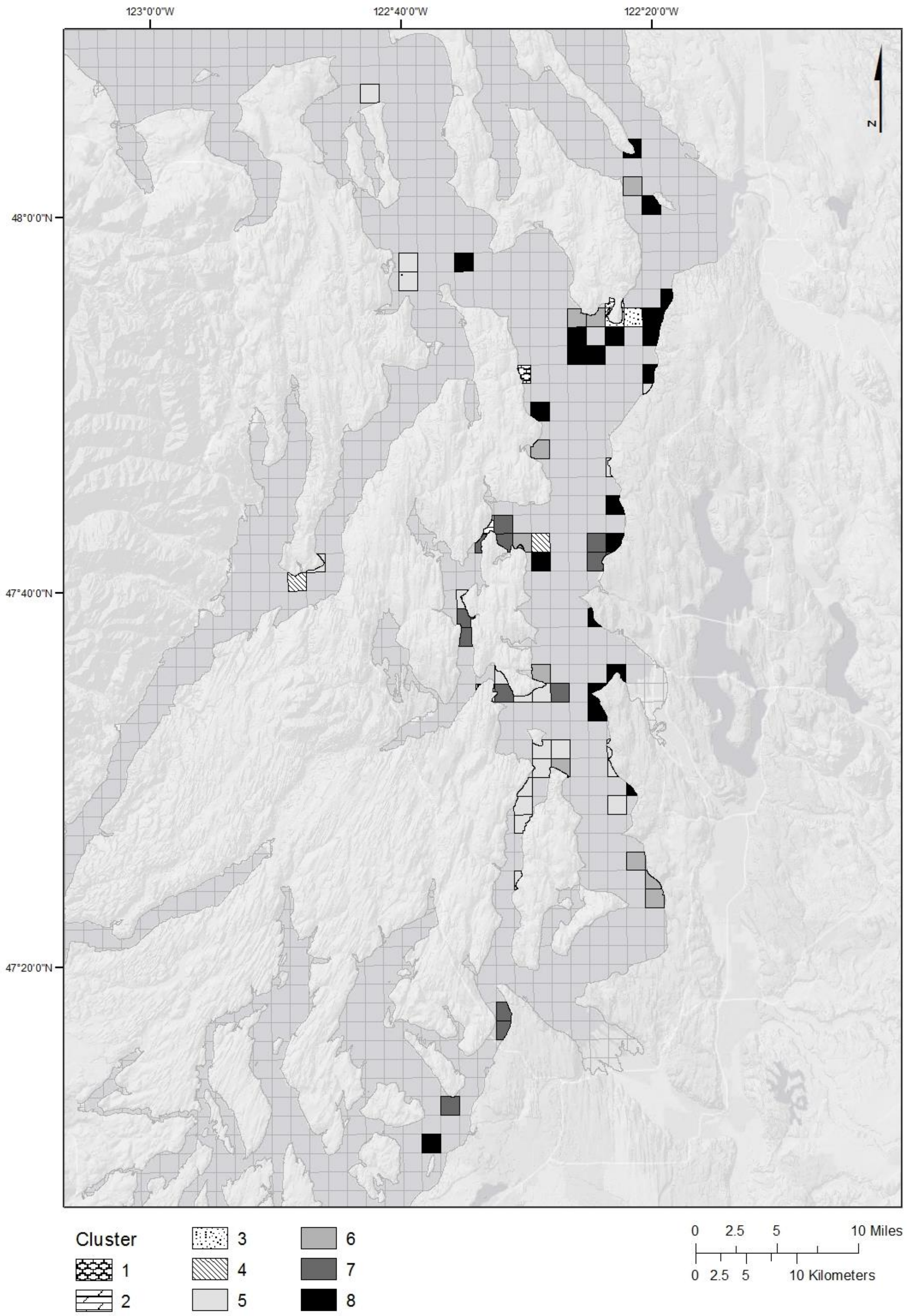

Figure 3. Puget Sound with sampling sites used in the analyses. Clusters correspond to results from the cluster analysis.

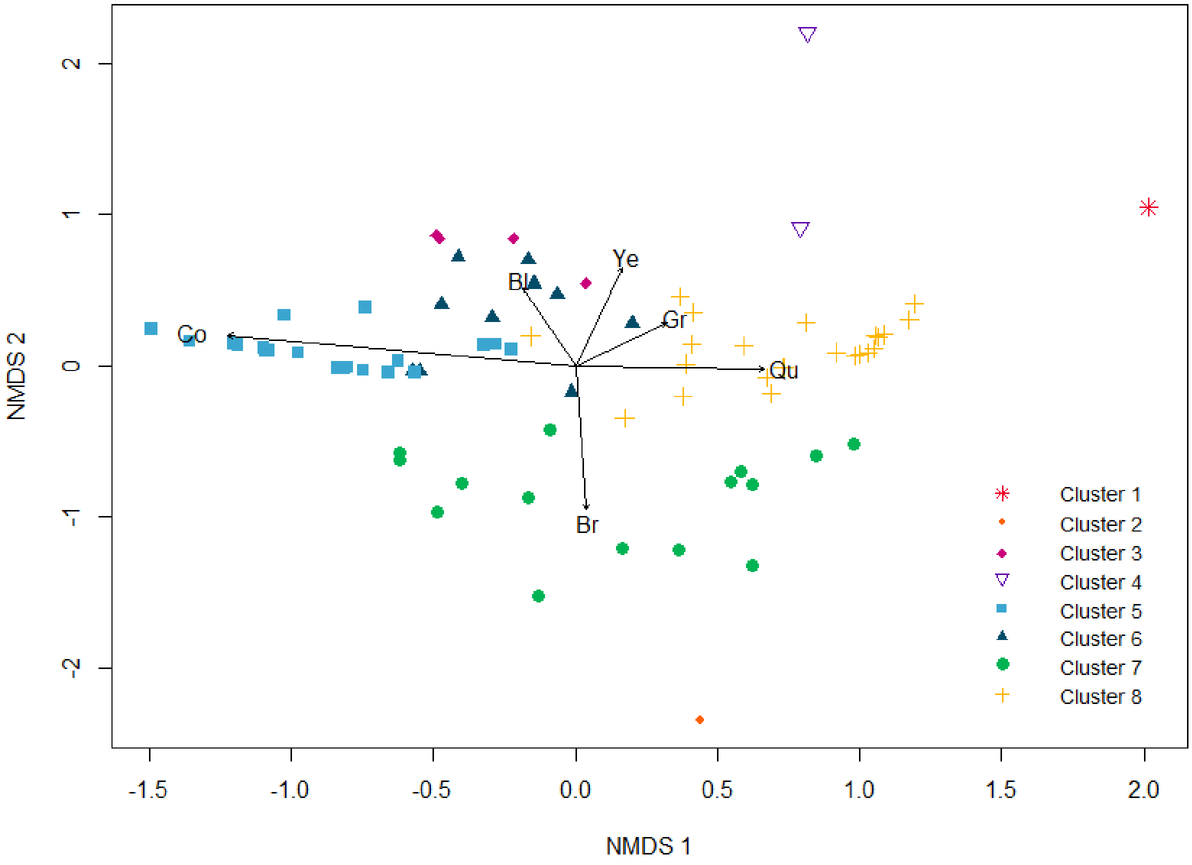

Figure 4. Three-dimensional NMDS ordination solution showing the first two axes. Distinct groups derived from cluster analysis are color-coded for comparison. Species vectors indicate significant relationships ($p < 0.05$). Bl = black rockfish; Br = brown rockfish; Co = copper rockfish; Gr = greenstriped rockfish; Qu = quillback rockfish; Ye = yelloweye rockfish.

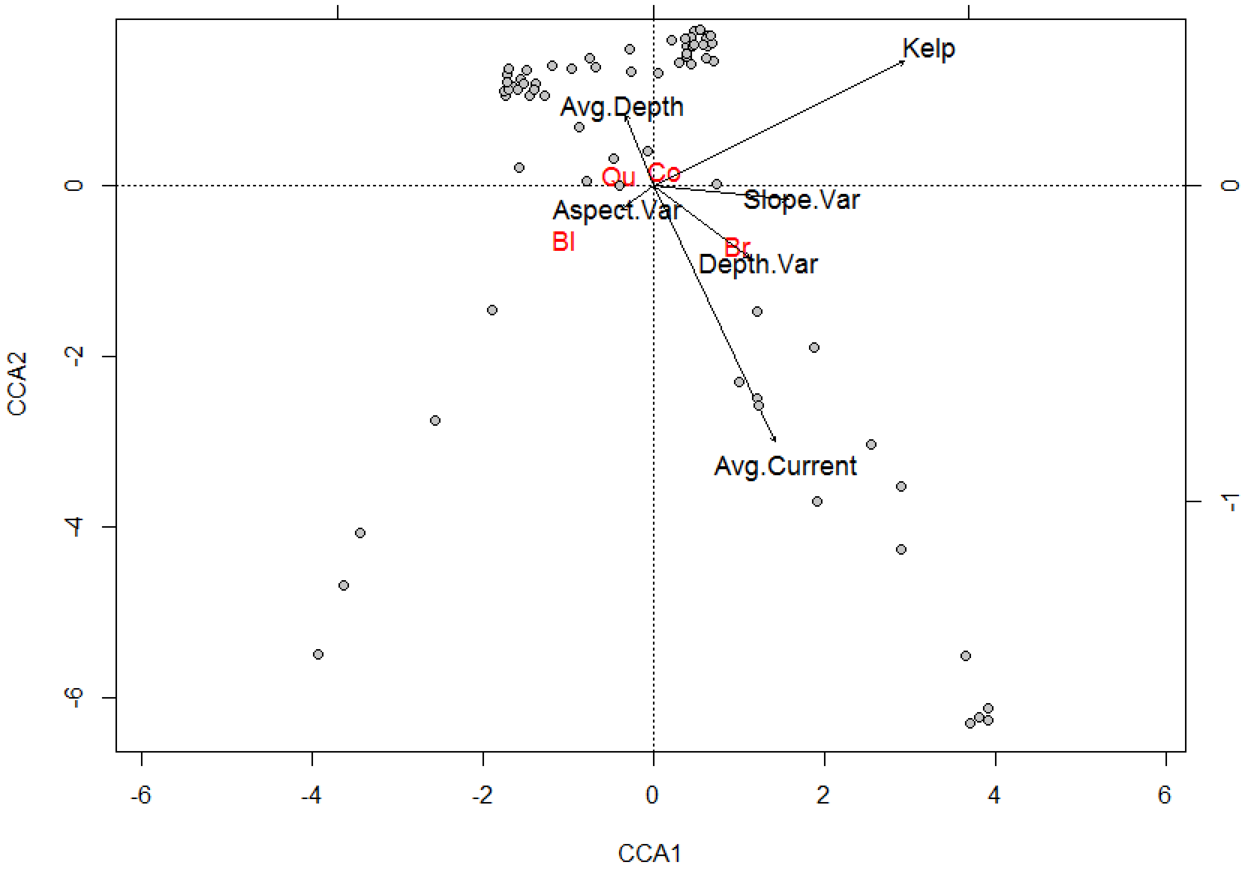

Figure 5. Canonical correspondence analysis showing relationship of four rockfish species to environmental characteristics (CCA model: p = 0.0497). Bl = black rockfish; Br = brown rockfish; Co = copper rockfish; Qu = quillback rockfish. Note that site objects were jittered in ordination space to avoid excessive overlap.

TABLES

Table 1. Tabulation of all records available and those used or excluded from analysis. Note that rare species were included in NMDS ordination but that only the four most abundant species were included in the CCA.

Species	Total Number in Data Set	Number Used in Analysis	Number Excluded*
Black rockfish	270	270	0
Bocaccio	21	21	0
Brown rockfish	232	144	88
Canary rockfish	11	10	1
Copper rockfish	519	488	31

Greenstriped rockfish	4	4	0
Quillback rockfish	350	301	49
Redstripe rockfish	8	4	4
Rougheye rockfish	1	1	0
Widow rockfish	1	1	0
Yelloweye rockfish	30	28	2
Yellowtail rockfish	40	40	0

* Reasons for exclusion in analysis include: missing sampling location, missing effort information (either number of anglers fishing or hours fished) or capture from otter trawling rather than recreational methods

Table 2. Abridged summary of results from CCA. After Legendre and Legendre (2012).

	Canonical axes			**Non-canonical axes**		
	I	II	III	I	II	III
Eigenvalues	0.2531	0.10912	0.04120	0.7057	0.5219	0.4054
Proportion explained	0.1243	0.05359	0.02023	0.3465	0.2563	0.1991
Cumulative proportion	0.1243	0.17786	0.19809	0.5446	0.8009	1.0000
Eigenvectors (“species scores”, scaling 2)						
Black rockfish	-1.0418	-0.6202	-0.2203	0.3707	-1.9858	-0.7094
Brown Rockfish	0.9851	-0.6875	0.1593	-1.2369	-0.6181	1.5441
Copper Rockfish	0.1458	0.1784	-0.1148	0.5939	0.2973	0.1032
Quillback Rockfish	-0.3966	0.1306	0.3535	-1.2552	0.4164	-0.7107
Correlations of environmental variables with site scores						
Avg bottom current*	0.38781	-0.81199	0.35236			
Kelp*	0.79743	-0.03307	-0.03307			
Avg depth	-0.08596	0.19725	0.19725			
Aspect variation	-0.10157	-0.35608	-0.35608			
Slope variation	0.42762	-0.58134	-0.58134			
Depth variation	0.30476	-0.47691	-0.47691			

* = $p < 0.05$

REFERENCES

Anderson, T. J. & Yoklavich, M. M. Multiscale habitat associations of deepwater demersal fishes off central California. *Fishery Bulletin* **105**, 168–179 (2007).

Bennion, H., Fluin, J. & Simpson, G. L. Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. *Journal of Applied Ecology* **41,** 124–138 (2004).

Berry, H.D., J.R. Harper, T.F. Mumford, Jr., B.E. Bookheim, A.T. Sewell, and L.J. Tamayo. The Washington State ShoreZone Inventory User's Manual. Nearshore Habitat Program, Washington State Department of Natural Resources, Olympia, WA (2001).

Bieler, R. & Mikkelsen, P. M. Marine bivalves of the Florida Keys: a qualitative faunal analysis based on original collections, museum holdings and literature data. *Malacologia* **46,** 503–545 (2004).

Bradfield, G. E. & Kenkel, N. C. Nonlinear ordination using flexible shortest path adjustment of ecological distances. *Ecology* 750–753 (1987).

Clarke, K. R., Somerfield, P. J. & Chapman, M. G. On resemblance measures for ecological studies, including taxonomic dissimilarities and a zero-adjusted Bray–Curtis coefficient for denuded assemblages. *Journal of Experimental Marine Biology and Ecology* **330**, 55–80 (2006).

Elith, J., Graham, C. H., Anderson, R. P., Dudı´k, M., Ferrier, S., Guisan, A., Hijmans, R. J., Huettmann, F., Leathwick, J. R., Lehmann, A., Li, J., Lohmann, L. G., Loiselle, B. A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J. McC., Peterson, A. T., Phillips, S. J., Richardson, K. S., ScachettiPereira, R., Schapire, R. E., Sobero´n, J., Williams, S., Wisz, M. S. & Zimmermann, N. E. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* **29**, 129–151 (2006).

Elith, J. & Leathwick, J. Predicting species distributions from museum and herbarium records using multiresponse models fitted with multivariate adaptive regression splines. *Diversity and Distributions* **13**, 265–275 (2007).

Fulé, P. Z., Covington, W. W. & Moore, M. M. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications* **7,** 895–908 (1997).

Haldorson, L. & Love, M. Maturity and fecundity in the rockfishes, Sebastes spp., a review. *Marine Fisheries Review* **53,** 25–31 (1991).

Haldorson, L., Stanley, R. D., Leaman, B. M. & O'Connell, V. M. Movements of tagged adult yellowtail rockfish, *Sebastes flavidus*, off the west coast of North America. *Fishery Bulletin* **92,** 655–663 (1994).

Haugerud, R. A. Digital elevation model (DEM) of Cascadia, latitude 39N–53N, longitude 116W–133W. *U.S. Geological Survey Open-file Report*, 99–369 (1999).

Hawkins, S. J., Firth, L. B., McHugh, M., Poloczanska, E. S., Herbert, R. J. H., Burrows, M. T., Kendall, M. A., Moore, P. J., Thompson, R. C. & Jenkins, S. R. Data rescue and re-use: Recycling old information to address new policy concerns. *Marine Policy* **42,** 91–98 (2013).

Hayden-Spear, J. Nearshore habitat associations of young-of-year copper (*Sebastes caurinus*) and quillback (*S. maliger*) rockfish in the San Juan Channel, Washington. MS thesis, University of Washington (2006).

Jackson, D. A. & Somers, K. M. Putting things in order: the ups and downs of detrended correspondence analysis. *The American Naturalist* **137,**704–712 (1991).

Johansson, M. L., Banks, M. A., Glunt, K. D., Hassel-Finnegan, H. M. & Buonaccorsi, V. P. Influence of habitat discontinuity, geographical distance, and oceanography on fine-scale population genetic structure of copper rockfish (Sebastes caurinus). *Molecular Ecology* **17,** 3051–3061 (2008).

Kruckeberg, A. R. *The natural history of Puget Sound country*, 2nd ed. University of Washington Press, Seattle, WA. (1991).

Lan, K. W., Lee, M. A., Lu, H. J., Shieh, W. J., Lin, W. K. & Kao, S. C. Ocean variations associated with fishing conditions for yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic Ocean. *ICES Journal of Marine Science: Journal du Conseil* **68,** 1063–1071 (2011).

Legendre, P. & Legendre, L. *Numerical Ecology*. Elsevier, Amsterdam. (2012).

Love, M. S., Carr, M. H. & Haldorson, L. J. The ecology of substrate-associated juveniles of the genus Sebastes. *Environmental Biology of Fishes* **30**, 225-243 (1991).

Love, M. S., Yoklavich, M. & Thorsteinson, L. *The Rockfishes of the Northeast Pacific*. University of California Press, Berkeley, CA (2002).

Maechler, M., Rousseeuw, P., Struyf, A., Hubert, M. & Hornik, K. (2012). cluster: Cluster Analysis Basics and Extensions. R package version 1.14.3.

Matthews, K. R. A telemetric study of the home ranges and homing routes of copper and quillback rockfishes on shallow rocky reefs. *Canadian Journal of Zoology* **68,** 2243–2250 (1990).

Maunder, M. N. & Punt, A. E. Standardizing catch and effort data: a review of recent approaches. *Fisheries Research* **70**, 141–159 (2004).

McGarigal, K. BIOSTATS Documentation. (2011). [Available from http://www.umass.edu/landeco/teaching/ecodata/labs/biostats.pdf].

McGarigal, K., Cushman, S. & Stafford, S. *Multivariate Statistics for Wildlife and Ecology Research*. Springer Science+Business Media, Inc., New York (2000).

Miller, B.S. & Borton, S. F. Geographical distribution of Puget Sound fishes: Maps and data source sheets. University of Washington Fisheries Research Institute, 3 vols (1980).

Mills, K. L., Laidig, T., Ralston, S. & Sydeman, W. J. Diets of top predators indicate pelagic juvenile rockfish (Sebastes spp.) abundance in the California Current System. *Fisheries Oceanography* **16,** 273–283 (2007).

MSFCMA (Magnuson-Stevens Fishery Conservation and Management Act). As amended through January 12, 2007. May 2007. Second Printing. U.S. Department of Commerce.

Munk, K. M. Maximum ages of groundfishes in waters off Alaska and British Columbia and considerations of age determination. *Alaska Fishery Research Bulletin* **8,** 12–21 (2001).

NMFS (National Marine Fisheries Service). Status review of Pacific Hake, Pacific Cod, and Walleye Pollock from Puget Sound, Washington. NOAA Tech. Memo. NMFS-NWFSC-44, 275 p (2000).

NMFS (National Marine Fisheries Service). Endangered and threatened species: Puget Sound populations of copper rockfish, quillback rockfish, brown rockfish, and Pacific herring. *Federal Register* (Docket No. 010312061–1061–01; 3 April 2001) 66(64): 17659-17668 (2001).

NMFS (National Marine Fisheries Service). Listing endangered and threatened species and designating critical habitat: Petition to list five rockfish species in Puget Sound (Washington) as endangered or threatened species under the Endangered Species Act. *Federal Register* (Docket No. 070924535–7536–01; 5 October 2007) 72(193): 56986-56990 (2007).

NMFS (National Marine Fisheries Service). Endangered and threatened wildlife and plants: Threatened status for the Puget Sound/Georgia Basin distinct population segments of yelloweye and canary rockfish and endangered status for the Puget Sound/Georgia Basin distinct population segment of bocaccio rockfish (Final Rule). *Federal Register* (Docket No. 080229341–0108–03; 28 April 2010) 75(81): 22276 – 22290 (2010).

Oksanen, J., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Henry, M., Stevens, H. & Wagner, H. vegan: Community Ecology Package. R package version 2.0-5. (2012). [Available from http://CRAN.R-project.org/package=vegan].

Olson, S. L. & Rauzon, M. J. The extinct Wake Island Rail *Gallirallus wakensis*: A comprehensive species account based on museum specimens and archival records. *The Wilson Journal of Ornithology* **123,**663–689 (2011).

Palsson, W. A., Tsou, T-S., Bargmann, G. G., Buckley, R. M., West, J. E., Mills, M. L., Cheng, Y. W. & Pacunski, R. E. *The biology and assessment of rockfishes in Puget Sound*. Washington Department of Fish and Wildlife, Fish Management Division, Olympia, WA, 208 p (2009).

Parker, S. J., Berkeley, S. A., Golden, J. T., Gunderson, D. R., Heifetz, J., Hixon, M. A., Larson, R., Leaman, B. M., Love, M. S. & Musick, J. A. Management of Pacific rockfish. *Fisheries* **25,** 22–30 (2000).

Ralston, S. & Howard, D. F. On the development of year-class strength and cohort variability in two northern California rockfishes. *Fishery Bulletin* **93**, 710-720 (1995).

R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. (2012). [Available from http://www.R-project.org/]

Shaffer, H. B., Fisher, R. N. & Davidson, C. The role of natural history collections in documenting species declines. *Trends in Ecology & Evolution* **13,** 27–30 (1998).

Springer, Y., Hays, C., Carr, M., Mackey, M. & Bloeser, J. Ecology and management of the bull kelp *Nereocystis luetkeana*: a synthesis with recommendations for future research. A report to the Lenfest Ocean Program at the Pew Charitable Trusts. 45 pg (2006).

Stoddard, J. L., Larsen, D. P., Hawkins, C. P., Johnson, R. K. & Norris, R. H. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* **16,** 1267–1276 (2006).

Swetnam, T. W., Allen, C. D. & Betancourt, J. L. Applied historical ecology: using the past to manage for the future. *Ecological applications* **9,** 1189–1206 (1999).

Tolimieri, N., Andrews, K., Williams, G., Katz, S. & Levin, P. S. Home range size and patterns of space use by lingcod, copper rockfish and quillback rockfish in relation to diel and tidal cycles. *Marine Ecology Progress Series* **380,** 229–243 (2009).

Torres, L. G., Smith, T. D., Sutton, P., MacDiarmid, A., Bannister, J. & Miyashita, T. From exploitation to conservation: habitat models using whaling data predict distribution patterns and threat exposure of an endangered whale. *Diversity and Distributions* **doi: 10.1111/ddi.12069** (2013).

WDFW (Washington Department of Fish and Wildlife). *Final Puget Sound Rockfish Conservation Plan: Policies, Strategies and Actions*. Olympia, Washington. (2011a).

WDFW (Washington Department of Fish and Wildlife). Washington State species of concern lists. (2011b). [Available from http://wdfw.wa.gov/conservation/endangered/lists/search.php?searchby=simple&search=rockfish&orderby=AnimalType%2CCommonName].

Washington, P.M. Recreationally important marine fishes of Puget Sound, Washington. NOAA/NMFS Northwest and Alaska Fisheries Center Processed Report, 131 p (1977).

Washington, P. M., Gowan, R. & Ito, D. H. A biological report on eight species of rockfish (Sebastes spp.) from Puget Sound, Washington. NOAA National Marine Fisheries Service Northwest and Alaska Fisheries Science Center Processed Report, 50 p (1978).

Ward Jr, J. H. Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association* **58**, 236–244 (1963).

Wigand, L. A. Spatial pattern in the Eastern Bering Sea: An application of spatial analysis to groundfish abundance along the Bering Sea outer continental margin. MMA Thesis, University of Washington (2012).

Williams, E. H. & Ralston, S. Distribution and co-occurrence of rockfishes (family: Sebastidae) over trawlable shelf and slope habitats of California and southern Oregon. *Fishery Bulletin* **100**, 836–855 (2002).

Williams, G. D., Levin, P. S. & Palsson, W. A. Rockfish in Puget Sound: An ecological history of exploitation. *Marine Policy* **34,** 1010–1020 (2010).

Williamson, M. H. The Ordination of Incidence Data. *Journal of Ecology* **66,**911–920 (1978).

Yang, Z. & Khangaonkar, T.P. Development of a hydrodynamic model of Puget Sound and Northwest Straits. Pacific Northwest National Laboratory. (2007). [Available from http://www.pnl.gov/main/publications/external/technical_reports/PNNL-17161.pdf].

Yoklavich, M. M. Habitat associations of deep-water rockfishes in a submarine canyon: an example of a natural refuge. *Fishery Bulletin* **98**, 625–641 (2000).

Young, M. A., Iampietro, P. J., Kvitek, R. G. & Garza, C. D. Multivariate bathymetry-derived generalized linear model accurately predicts rockfish distribution on Cordell Bank, California, USA. *Marine Ecology Progress Series* **415,** 247–261 (2010).

Zeller, D., Froese, R. & Pauly, D. On losing and recovering fisheries and marine science data. *Marine Policy* **29**, 69–73 (2005).

APPENDIX: SUPPLEMENTARY INFORMATION

The following figures and tables were used during preliminary data exploration. These early forays into analysis focused upon three species categories of interest: the four most commonly captured species in Puget Sound (black rockfish, brown rockfish, copper rockfish, and quillback rockfish); the three ESA listed species (bocaccio, canary rockfish, and yelloweye rockfish); and Pacific cod. At the early stages of analysis, it was unclear whether or not the data would be sufficient to draw conclusions about the status of the ESA listed species from the time that the data had been collected (1974 – 1977). Pacific cod were also considered for analysis early on due to the large number of specimens collected during the survey and the declining status of this species in Puget Sound. Pacific cod were ultimately removed from analysis because of the ecological dissimilarities between members of Sebastidae and Gadidae.

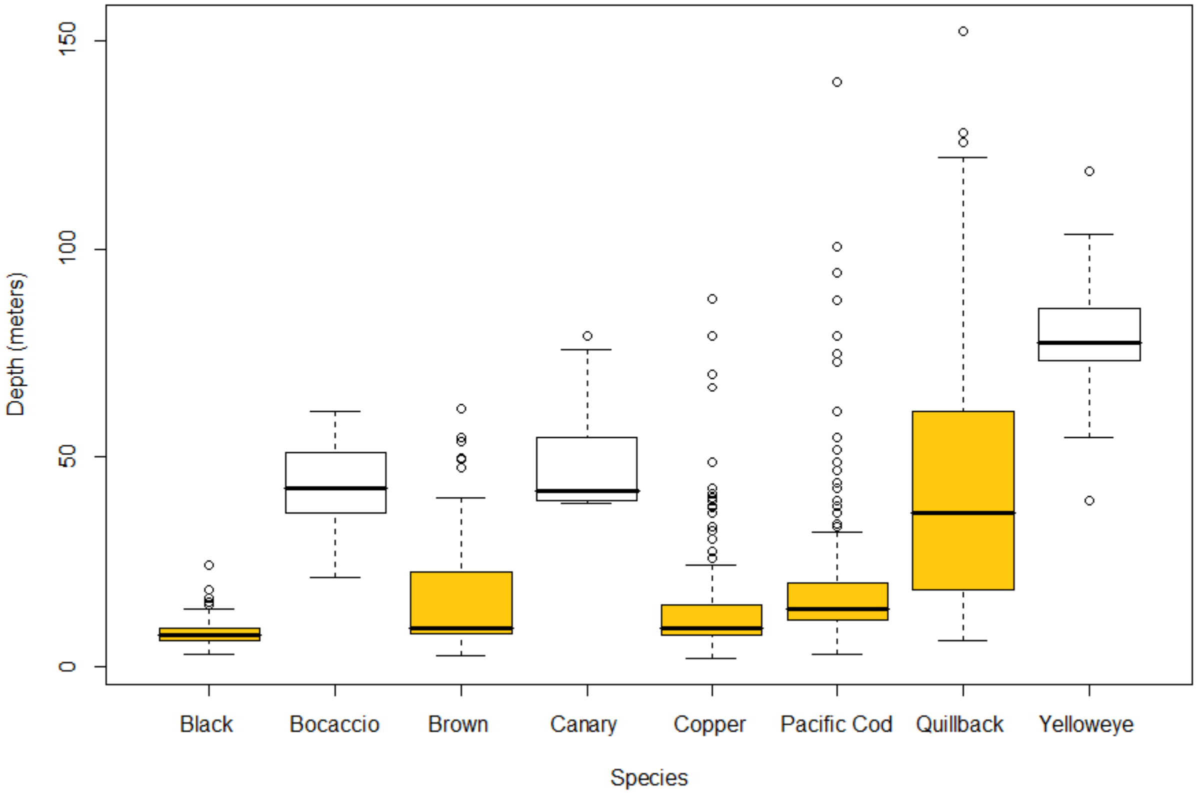

Figure A1. Recorded depths at capture for Pacific cod, as well as the four most commonly captured species of rockfish and the ESA listed species of rockfish. Listed species are distinguished by white boxes.

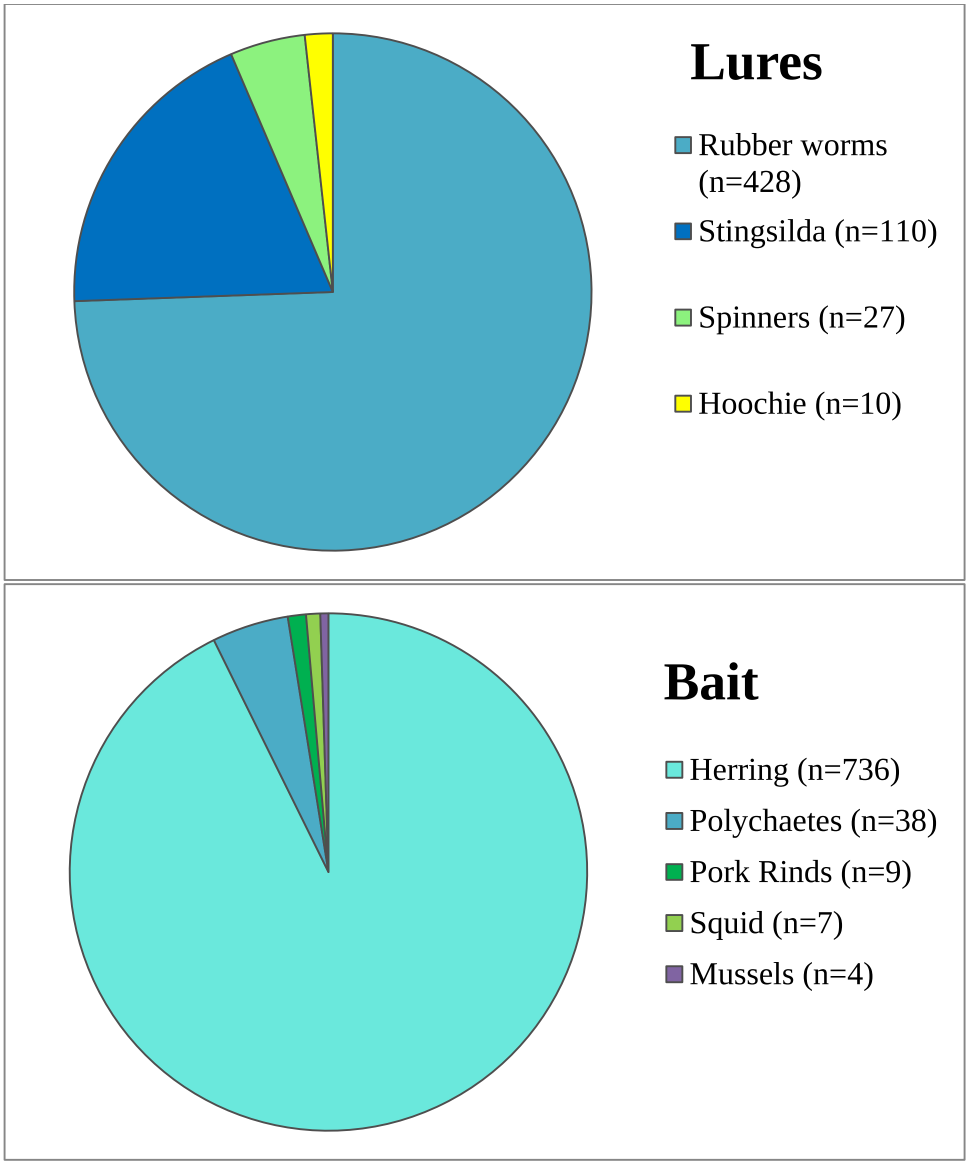

Figure A2. Break-down of lures and baits used in sampling across all three years. Different tackle types were used together in a variety of combinations.

Species	**Fish per angler-day**	**Angler-days needed to catch one fish**
Copper rockfish	1.209	0.83
Quillback rockfish	0.808	1.24
Black rockfish	0.636	1.57
Brown rockfish	0.353	2.83
Yellowtail rockfish	0.094	10.61
Yelloweye rockfish*	0.071	14.14
Bocaccio*	0.049	20.21
Canary rockfish*	0.026	38.58
Pacific cod	0.820	1.22

* designates ESA listed species

Table A1. Nominal catch per unit effort (CPUE) for Pacific Cod, as well as the four most commonly captured species of rockfish and the ESA listed species of rockfish averaged across all sampling sites and years. Note that angler-days needed to catch one fish is the reciprocal of fish per angler-day.