Multispecies Management and Assessment in the US West Coast Groundfish Fishery

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2018

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Program Authorized to Offer Degree:

School of Aquatic and Fishery Sciences

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Abstract

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Multispecies fisheries are complex and present tradeoffs between ecological, economic, and social goals. Multispecies trawl fisheries, in which trawl gear is not easily able to select one species while avoiding others, pose additional management challenges. For example, managers might reduce catch limits to rebuild overfished populations, but this reduction might then limit catches of valuable species. Catch shares are a management strategy that may allow fishers flexibility to better catch target species while avoiding overfished species. Under catch shares, individual entities are allocated transferable shares of quota for managed species. Some portion of the fleet might decide they are better off leasing or selling the quota resulting in a smaller, more efficient fleet. The US West Coast Groundfish fishery shifted to catch shares in 2011 in order to improve fleetwide economic efficiency and accounting of managed species.

In this dissertation, I evaluate the implications and effects of catch shares in the US West Coast Groundfish fishery. Many of the West Coast species live in rocky reef habitats that can be difficult to monitor, resulting in inaccurately informed catch limits that can constrain economic outcomes without ecological benefit. In Chapter 1, I conducted a simulation study evaluating the ability of hook-and-line surveys to detect changes in population size. All simulations displayed hyperstability, in which catch-per-unit-effort declines more slowly than population size, although preferentially sampling in sites with higher fish densities were better able to detect changes in population size. In Chapter 2, I focused on the ability of catch shares to improve catch-quota balancing (the ratio of catch to total allowable catch) in the West Coast Groundfish fishery. Catch-quota balancing declined in the West Coast from 0.41 to 0.29 in the four years before and four years after catch shares. The similar BC fishery had a decrease from 0.70 to 0.62 in the four years before and after catch share implementation. Chapter 3 focuses on the fleet dynamics of the West Coast Groundfish fishery in response to catch shares. The numbers of vessels and tows both declined about 40% after catch shares. Additionally, results from a random utility model of tow-level data show that distance, expected revenue, and individual vessel habits are important factors in fishing behavior before and after catch shares. Catch shares have not been a panacea in the West Coast Groundfish fishery, perhaps due to the need to rebuild many overfished populations. This work highlights the consequences of particular design aspects of catch shares to inform future catch share programs in multispecies trawl fisheries.

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ACKNOWLEDGEMENTS

I am indebted to a large group of people without whom I would not have been able to do this work. First, thanks to my advisor Trevor Branch. He has been instrumental in my development as a scientist, and I thank him for all the opportunities and support throughout graduate school. He has always been the biggest advocate of my labmates and me.

Thanks to my committee members for their guidance and feedback. Their diverse backgrounds and skills broadened by fisheries perspectives. I thank Allan Hicks and Dan Holland for the generosity and patience. Much of this research would not have been possible without their expertise in stock assessment and fisheries economics. Thanks to Tim Essington for his comments that broadened the scope of my research.

I thank many people for their stock assessment guidance and expertise. Thanks to Kotaro Ono for sitting with me as I fumbled through Stock Synthesis. Thanks to Ian Taylor, Melissa Haltuch, and Owen Hamel for lending much technical expertise. Thanks to John Harms for sharing bringing me into the hook-and-line survey world and for inviting me on a survey.

I am grateful to have been a part of the SAFS community and to have shared a lab with Cole Monnahan, Melissa Muradian, John Trochta, Merrill Rudd, Sean Anderson, Lewis Barnett, and Caitlin Allen Akselrud. It is rare to connect with people both personally and professionally, and I feel very fortunate to have made friendships that will last a lifetime.

I thank Jono Wilson, Sarah Valencia, and Matt Kay for mentoring me as an undergraduate at UCSB. Having gone through graduate school, I’m amazed that they helped me so much given their personal and professional commitments. I never imagined moving away from the beach and was not even going to apply to UW. They provided research opportunities

that surely helped me get in and prodded me to consider that there is more to life than surfing (I remain skeptical). I would have never come to UW without them. Things couldn’t have worked out better.

Finally, I am very grateful to my funding sources that allowed me to complete my dissertation: NOAA funding as part of the QUEST program, a Regional Social Science grant from Sea Grant, the Gordon & Betty Moore Foundation, and the NOAA and Sea Grant Population Dynamics Fellowship.

DEDICATION

To my family. My grandparents are examples of endurance and patience through extreme hardship. My parents are role models of work ethic, sacrifice, and integrity. They have always supported and fostered my curiosities. My sister is one of my best friends and without her I would have no idea what kids these days are into. No thanks could ever be enough.

Introduction

Overfishing and overcapitalization have been prominent challenges in the West Coast Groundfish fishery as managers strive to maintain a viable, profitable, and efficient groundfish fishery (Pacific Fishery Management Council and NMFS 2010). The fishery spans the coasts of California, Oregon, and Washington and includes about 90 species, many of which are long-lived, slow-growing, and late-to-mature. Management is complicated by multiple species living in the same areas, so that reducing catch limits of one species will indirectly limit catches of another species. Selectively targeting a species is particularly difficult with trawl gear. Taken together, these factors pose challenges to managers who strive to prevent overfishing of all species and reduce excess fishing capacity while maintaining an economically viable fishery.

Overfishing occurred throughout much of the fishery's history due to harvest targets that were set too high, further exacerbated by the short data series available for analysis and assessment following the rapid build up in many of these fisheries, relative to life histories of many rockfish (*Sebastes* spp.) that can live for many decades (Love *et al.* 1987; Cailliet *et al.* 2001). At that time, rockfish were thought to be shorter lived and more productive than they are in reality, and as a result, fishing mortality rates were set at unsustainable levels. Assessments in the mid-1990s found that some stocks were below 20% of unfished biomass (Ralston 2011), far below the target levels which were based on spawning potential ratios below 35% (Clark 1991) and then updated to 40% (Clark 1993). Target harvest rates were reduced, and landings declined to the point that the fishery was declared an economic disaster in 2000 (Shaw and Conway 2007; Hilborn *et al.* 2012). In 2002, the PFMC specified rebuilding plans for overfished species and greatly reduced target fishing mortality rates to as low as 0.8% for Pacific ocean perch (Pacific

Fishery Management Council 2014). Rebuilding plans have been effective for most species, and seven of ten stocks have been declared rebuilt.

Overcapitalization, which is still an issue today, can be attributed to federal programs designed to build up the domestic American fleet. In the years following the passage of the Magnuson-Stevens Fishery Conservation and Management Act in 1976, the federal government offered loans and tax credits through the Farm Credit Act, Production Credit Associations, the Capital Construction Fund, and the Fishing Vessel Obligation Guarantee Program (Mansfield 2001) to develop sufficient capacity to keep foreign fleets from the USSR, Japan, and Korea out of American waters. In 1994, the PFMC implemented a limited entry system to prevent additional vessels from entering the fishery. Permits were awarded to 629 vessels, of which 384 were endorsed for trawl gear and 245 were endorsed for fixed gear (SSC 2000). Despite this cap on the number of participating vessels, overcapitalization remained an issue, the harvesting capacity of the fleet remained high, and stock status and allowable catches declined. In March of 2000, a council document stated:

> *Overcapitalization is the single most serious problem facing the West Coast groundfish fishery. The effectiveness of traditional management measures (e.g., landings limits, seasons) in ensuring that discards are minimized and that a reasonable economic livelihood can be made from the groundfish fishery has been seriously eroded in recent years.*

The fleet experienced high landings through much of the 1980s and 1990s (SSC 2000). However, in the years leading up to the Disaster declaration in 2000, the composition of the landings changed greatly and rockfish landings declined significantly. Throughout the 1980s, about 40% of the landings were made up of high-value rockfish species, but by the late 1990s, rockfish declined to less than 20% of landings, while 60-70% of the landings came from comparatively low-value Pacific whiting (*Merluccius productus*).

Throughout the 1980s and 1990s, the fishery was managed with individual trip limits, which restricted landing amounts for a single trip. The goals were to distribute catch throughout a fishing season to ensure a consistent flow of fish to processors, and limit catches to ensure rebuilding of overfished species. Trip limits eventually morphed into individual cumulative limits over two or three-month periods. Because discarded fish did not count towards trip limits, fishers had little incentive to fish more selectively to avoid catching overfished species. Management was ineffective at rebuilding stocks, as fishers would discard fish that exceeded their trip limits (Pikitch *et al.* 1988). As a result, reductions in allowable catches, and resulting reductions in trip limits, lead to an increase in discarding rather than a reduction in fishing mortality (Bellman and Heery 2013).

By 2003, the Council concluded that only 27-41% of the limited entry fleet was needed to fully catch the sablefish and Groundfish allocations (TNC 2008), and implemented a buyback program to reduce the number of vessels in the fishery. The buyback program purchased 92 of the remaining 284 limited entry permits in the fishery, and the fishers that remained are still paying for the buybacks today, since the buyback was implemented as a loan to be paid by the remaining fishers. Despite the reductions, the fleet was still overcapitalized, and in 2004 the PFMC began planning a catch share program (individual fishing quotas, or IFQs) to further address overcapitalization. The intent of the catch share program, which was implemented in 2011, was to increase net economic benefits, create individual economic stability, and provide for full utilization of trawl sector allocation, while still considering environmental impacts, and achieving individual accountability of catch and bycatch (Pacific Fishery Management Council and NMFS 2010). As an integral part of the program, the PFMC expanded the observer program to cover 100% of fishing trips and counted both discards and landings towards fishery-wide harvest limits. Under catch shares, when catches exceeded quota for any species, the boat would need to stop fishing until sufficient quota could be leased from others to cover their overage. This system provides incentives to avoid or target particular species, because quota for those species that are constraining will be expensive to lease.

The theory behind catch shares suggests that the PFMC's goal of rescuing overcapitalization should be achievable. Catch shares eliminate the race to fish (Hilborn *et al.* 2005; Costello *et al.* 2008) by granting fishers exclusive access to shares of total quotas. This should provide fishers the flexibility to fish at a less competitive rate, fish in different locations, and time fishing activity in order to fetch optimal market prices (Grafton 1996a; Beddington *et al.* 2007). Catch shares provide a market-based method for profitable fishers to buy quota from those operating at a loss, which should reduce fleet size and in turn overcapitalization (Arnason 2005). Catch shares grant fishers the ability to lease quota if catches exceed individual quota holdings of particular species or lease out quota of catches are less than their holdings (Copes 1986). Taken together, these aspects should increase net economic benefits in the fishery and allow fishers to better utilize total allocations.

Catch shares are implemented all over the world and much research is dedicated to empirically evaluating their effects. Meta-analyses found that catch shares may prevent fisheries collapses (Costello *et al.* 2008), and will reduce variation in biomass, landings, and ratios of catch to total allowable catch (Essington 2010; Melnychuk *et al.* 2011), although the exact effects of catch shares will depend greatly on regional management differences (Melnychuk *et al.* 2014). At the fishery-wide scale, the development of quota markets in New Zealand increased fishery profitability (Newell *et al.* 2005). However, catch shares are not a panacea. For example, landings in an Icelandic multispecies fishery, which permits quota of one species to be converted to quota of another, have increased since catch share implementation, but catches have exceeded catch recommendations in 67% of cases (Woods *et al.* 2015). As a result, managers must adjust behavioral incentives to align fishing behavior with the desired economic, social, and ecological goals (Grafton *et al.* 2006; Branch *et al.* 2006a). The design of catch shares is crucial and should be tailored to local conditions in order to achieve desired economic, social, and ecological effects.

The theoretical benefits of catch shares are rooted in economics, but social and ecological effects are also important. Much of the social concern and debate is centered on access to fishing rights. While catch shares reduce overcapitalization (Grafton 1996a; Eythorsson 2000), concentration of quota among a few entities may lead to the collapse of local fishing communities (Bromley 2009; Pinkerton and Edwards 2010). Armchair fishing, in which quota owners profit from leasing quota to others without fishing themselves, may prevent new fishers from entering the fishery due to high leasing costs, raising issues of equity (Pinkerton and Edwards 2009). Ecological sustainability is central to the economic and social sustainability of catch shares (and really any fisheries management strategy). Thus an “arms-length” stock assessment and monitoring program is proposed as a requirement to all catch share systems (Sumaila 2010) in order to set accurate and well-informed harvest guidelines. In summary, while catch shares may increase profits and economic efficiency, there are social issues that are problematic, and all aspects of a catch share fishery need to be tailored to address problems that are specific to each fishery.

Multispecies fisheries often have stocks with a wide range of productivities and can be managed to different outcomes. Maximizing yield across multiple species will lead to overfishing of the least productive or least abundance stocks, termed weak stocks or choke stocks (Paulik *et al.* 1967; Hilborn 1976; Worm *et al.* 2009). In the United States, overfishing of commercial species is prohibited, and preventing overfishing of weak stocks requires forgoing catch of other species. In the West Coast Groundfish fishery, weak stock allowable catches are so low that if there was no change in fishing behavior, preventing all overfishing would require fishers to leave substantial potential yield in the water (Hilborn *et al.* 2012). Stocks like canary rockfish (*Sebastes pinniger*), yelloweye rockfish (*Sebastes ruberrimus*), and cowcod (*Sebastes levis*) were among the most overfished species, and were expected to constrain overall catches. Subsequently, canary rockfish has been declared rebuilt and yelloweye rockfish and cowcod will likely be rebuilt within the next five years.

The history and complexity of the West Coast Groundfish fishery raise important questions about assessment and management addressed in this dissertation. Large commercial fisheries in regions like North America and Europe typically conduct trawl surveys, incorporating the data into stock assessments that ultimately inform management. The statistical properties of the trawl survey data are relatively well studied. However, overfished species in the West Coast fishery live in untrawlable habitats and inaccurate catch limits can impose economic constraints without ecological benefits. In Chapter 1, I evaluate the potential of hook-and-line surveys to improve species monitoring in untrawlable habitats. Simulations explored the ability of hook-and-line survey design aspects to minimize bias and imprecision in indices of abundance. Simulated aspects included the numbers of sampled sites, numbers of hooks deployed, and method of site selection.

Catch shares grant fishers flexibility to fish when and where they want, which should result in improved catch-quota balancing (i.e. catches should be close to the total allowable catch for each stock). In Chapter 2, I quantify the extent of catch-quota balancing in the West Coast fishery and compare the results to a similar catch share fishery in British Columbia, Canada. West Coast fishers had decreases in catch-quota balancing for nearly all species, and those that saw improvements were species that could be well selected through gear switching or seasonal targeting (Kuriyama *et al.* 2016). In British Columbia, there was no significant change in catch-quota balancing.

In Chapter 3, I measure the spatial shifts in effort and evaluate the importance of factors like distance, revenue, and habits on fishers' location choices. Effort might shift in response to a number of factors. The spatial footprint might expand if fishers begin to explore new areas, or it might contract if there are a limited number of known profitable locations. I found that effort declined and contracted rather than expanding after catch shares. Fishers in the biggest ports showed a shift towards more collaborative fishing and their fishing behavior was not significantly affect by bycatch. Although bycatch of weak stock species was incorporated as a cost in the model, there was no statistical evidence that fishers account for expected bycatch in deciding where to fish.

Overall, my dissertation answers questions regarding multispecies assessment and fleet responses to catch shares. Catch shares directly address many ecological and economic challenges but are not a panacea for fisheries management. There are many design aspects and fishery characteristics that can constrain responses. As a result, this dissertation identifies constraints that limit the performance of the West Coast fishery and generate empirical predictions of fleet responses to the implementation of catch share systems in multispecies fisheries.

Chapter 1. Investigating major sources of bias in hook-and-line surveys

1.1 ABSTRACT

Hook-and-line surveys can be used to estimate trends in the many fish species where more conventional methods such as trawl, acoustic, visual, or pot surveys cannot be applied. Hook-and-line surveys allow the collection of biological information including length, weight, age, and sexual maturity, but there are concerns about hook saturation, survey design, and the impact of competition among species on survey abundance estimates. We designed simulations to address these concerns and found hyperstability across all scenarios: catch per unit effort (CPUE) declined more slowly than population size. Despite hyperstability, the surveys still had statistical power to detect changes in abundance. Preferentially selecting sites with the most fish for survey sampling resulted in 45% stronger hyperstability but also a greater ability to detect changes in population size. When fish are distributed patchily, resulting in the most hyperstability, a decrease in relative abundance from 50% to 10% resulted in median CPUE values declining 28-35% when sampling preferentially and 11-12% when sampling randomly. Interspecies competition for hooks resulted in biased survey results when one species was more aggressive than another. Taken together, hook-and-line surveys offer a promising technique for species unsuited for other survey types.

1.2 INTRODUCTION

Biased and imprecise surveys lead to inaccurate population estimates that can impose large costs on fisheries. Standardization of survey data accounts for changes in factors unrelated to fishing abundance and should result in reduced bias (Maunder and Punt 2004). However, bias will remain if survey methods are unable to fully cover all fish habitat. Population estimates that are biased high result in overfishing (Worm *et al.* 2009), while those that are biased low result in underutilization of allowable catches (Hilborn *et al.* 2012).

In the search for precise fishery-independent population estimates, a wide variety of survey methods have been developed in addition to hook-and-line surveys (the topic of this paper), including trawl, acoustic, trap, and visual surveys. Each survey method has different tradeoffs. Most large commercial fisheries rely on trawl survey data, which collect indices of abundance for many species together with age, length, and weight information, all of which are used as inputs in statistical catch-at-age stock assessments (Methot and Wetzel 2013). However, trawl surveys are less effective at sampling rocky areas, and trawling gear causes more harm to habitat and non-target species than other survey methods. Acoustic surveys are best used on densely schooling, abundant species like Pacific hake (*Merluccius productus*; (Berger *et al.* 2017). Species identification requires additional biological sampling or visual verification and acoustic surveys cannot easily track fish near the ocean floor (Foote 1987). Trap surveys are most useful for crabs and lobsters that are commercially caught in the same gear, but are affected by trap saturation (Fogarty and Addison 1997; Bacheler *et al.* 2013a,b). Visual survey methods, including divers, and underwater vehicles, are non-lethal and can collect both habitat information and species information(Yoklavich *et al.* 2000; 2007). However, age, sex, length, and weight information are difficult to collect, and behavioral responses to observers and vehicles might bias survey results (Stoner *et al.* 2008; Laidig *et al.* 2013).

Rocky reef habitats pose unique survey challenges, that might be addressed by hook-and-line methods. Trawling is usually prohibited in rocky, because of damage to trawl gear and because fragile reef species may be damaged by trawling, thus precluding collection of age, length, weight, and maturity information. Acoustic surveys are also not viable since they cannot distinguish among species, while visual surveys are not able to collect biological information without ancillary biological sampling. Hook-and-line surveys overcome some of these disadvantages because they allow sampling in untrawlable habitats and collect length, weight, age, and other biological information. Hook-and-line surveys have been used to study growth (Zhao *et al.* 1997), survey fish communities (Chester *et al.* 1984), estimate size selectivity (Ralston 1990), and assess population status (Collins and Sedberry 1991).

In this paper, we examine the ability of hook-and-line survey characteristics to reduce bias in abundance estimates. Concerns about hook-and-line surveys include hook saturation in areas of high density, and sampling protocols that could include random sampling or preferential sampling in high density areas, both of which may lead to non-linear relations between abundance and catch-per-unit-effort (CPUE) (Cadigan 2012). A particular concern is that hook saturation may lead to hyperstability (Harley et al. 2001) which is when CPUE declines more slowly than abundance. To test these concerns, we designed a simulation framework to identify general sources of bias and imprecision in hook-and-line survey estimates of abundance. The simulations were designed to test the effect of different protocols for sample site selection, sampling intensity, distribution of fish, relative abundance of fish, and competition for bait among species. We applied our general simulation framework to a case study, the Southern California Shelf Rockfish Hook and Line Survey (hereafter, "California hook-and-line survey").

1.3 METHODS

We examined a suite of factors that will affect all hook-and-line surveys: fish densities, how fish are allocated among sites, site selection methods, number of sites surveyed, and competition among species for bait on hooks.

1.3.1 Survey simulations

Each simulated survey had three components: initial fish distribution, a method of site selection for surveys, and the number of sample sites. Our simulations occurred over a survey area with 900 sites.

Fish distribution refers to the distribution of numbers of fish across the 900 sites. We used four forms of a beta distribution (which has two parameters, α and β) to initially distribute fish: left skew ($\alpha = 10$, $\beta = 1$; Figure 1.1a), symmetric (5, 5; Figure 1.1b); uniform (1, 1; Figure 1.1c), and patchy (0.1, 10; Figure 1.1d). The descriptions refer to the beta distribution form, thus a uniform distribution means that there is an equal probability of a small number of fish or a large number of fish at a given site, while a symmetric distribution implies most sites will have an intermediate number of fish and few will have large or small numbers of fish. Fish were distributed by sampling 900 values (one for each site) from the corresponding beta distribution, standardizing the values to sum to one, and multiplying the standardized values by the total number of fish in the entire survey area. We generated simulations with either one species or two species. Two-species simulations tested the effect of species competition and survey results. Initial numbers of fish ranged from 0 to 200,000 in increments of 20,000 (Table 1.1). For simulations with two species, we multiplied the standardized beta distribution samples by the initial numbers of fish for species one and species two, assuming that both species have the same site preferences. This ensured that simulations could test the hook competition effect of one species on another independent of possible habitat preferences.

Survey site selection was either random or preferential. For random sampling, a selection of sites was picked at random from all sites. For preferential sampling, sites were sampled with probabilities proportional to the numbers of fish in each site, ensuring that sampling was more likely to be in sites with more fish. In reality information for preferential sampling could come from fisher knowledge or information about habitats preferred by the target species, such as rocky reefs.

The precision of the survey estimates was modelled by simulating different number of sampling sites: 5, 20, 50, or 100, which were randomly or preferentially selected from among the 900 sites. In each site, a fixed number of hooks was deployed (in this case, 75 hooks, to match our case study).

1.3.2 Sampling probabilities

The probability of catching a fish was based on the number of fish of all species, together with species-specific catchabilities (probability of being caught given a fish encounters a hook). Species *s* out of *m* total fish species had a relative catchability of q_s, which was 0.01 in the base model. Under the assumption that fish randomly encounter hooks, the probability of catching a fish of species *s* in isolation (p_s) increases asymptotically towards one as the number of fish (n_s) and q_s increase:

$$p_s = 1 - exp(-n_s q_s) \tag{1.1}$$

For *m* species, the probability of one hook catching a fish (*h*) is:

$$h = 1 - \prod_{s=1}^{m} (1 - p_s) \tag{1.2}$$

For the simulations, in the simplest case where only one species is simulated, for each hook, one Bernoulli trial B(P = $h = p_s$) determined if the hook caught a fish. If a hook caught a fish then n_s was reduced by one, and Equations 1.1 and 1.2 updated the *h* value. We assumed that each hook had an equal probability of catching fish, and did not explore interactions between hook probabilities as there might be in reality for hooks at different depths on a single line.

If a hook caught a fish in multispecies simulations, the probability of catching species *s* (c_s) was calculated from the species-specific abundances n_s and catchabilities q_s:

$$c_s = \frac{n_s q_s}{\sum_{s=1}^{m} n_s q_s} \tag{1.3}$$

A single draw from a multinomial distribution M(1, P = $c_1, c_2, \ldots, c_m$) determined the caught species.

Competition between species was controlled by the initially specified catchabilities, with three scenarios simulated whether species 1 was either less than (q_1=0.003, q_2=0.007), equal to (q_1=0.005, q_2=0.005), or more aggressive (q_1=0.007, q_2=0.003) than species 2.

1.3.3 Scenarios

For the single-species scenarios, we conducted each simulation for a range of relative abundances by setting the total number of fish summed over all sites from 0 to 200,000 in increments of 20,000 (Table 1.1), where the highest simulated abundance (200,000) was considered to have a relative abundance of 1.0. To control for recruitment, mortality, movement, and local depletion, each simulation was conducted independently for one time period, thus avoiding the need to model those factors. For each combination of survey type (random or preferential), fish distribution (left skew, symmetric, uniform, and patchy) and relative abundance, we distributed fish among the 900 sites once and then repeatedly sampled 1000 sets of 5, 20, 50, or 100 sites to simulate 1000 surveys. For the two-species simulations, we simulated a reduced set of scenarios, looking only at surveys with sampling at 50 survey sites, with initial fish distributions that were patchy or symmetric, and with random or preferential sampling.

1.3.4 Summary values

Site-specific catch-per-unit-effort (CPUE) is the number of fish caught divided by the number of hooks. Survey CPUE was the average of site-specific CPUE values, and was reported as a median and 95th percentiles across 1000 sets of surveys.

To estimate the degree of hyperstability between abundance and CPUE, we fit the power curve equation

$$CPUE = q_{CPUE} N^{\beta} \tag{1.4}$$

to individual abundance (N) and survey CPUE values using linear regression to estimate survey catchability (q_{CPUE}) and shape (β). When the shape parameter is $0 < \beta < 1$, this indicates hyperstability: when CPUE declining more slowly than biomass; when $\beta > 1$, this indicateshyperdepletion, where CPUE declines faster than biomass; and when $\beta = 1$ there is neither hyperstability nor hyperdepletion and instead a linear relationship between CPUE and abundance (Harley *et al.* 2001).

1.3.5 Power Analysis

To test the power of the surveys to detect declines in abundance, we conducted a resampling analysis. In each case we repeatedly sampled 1000 pairs of survey CPUEs with different relative abundance levels, for example comparing 1.0 (unfished) to a lower abundance level (e.g. 0.9), recording what proportion of these differences are increases or declines. This process was used to estimate the power to detect declines from a relative abundance of 1.0 to relative abundances from 0.1 to 0.9, and to detect changes from a relative abundance of 0.5 to values from 0.1 to 0.9.

1.3.6 Case study: California Hook-and-Line Survey

For our case study, we looked at the US West Coast, where rockfish (*Sebastes* spp.) play a particularly prominent role in management: they are long lived, slow growing, late to mature, and slow to recover from sustained overfishing (Punt and Ralston 2007; Clark 2011). Highly restrictive catch limits for overfished rockfish have constrained catches for many co-occurring species in this region for decades under both trip limit and catch share management (Kuriyama *et al.* 2016). There are more than 60 species of rockfish on the US West Coast, most of which are associated with rocky untrawlable habitats (Rooper *et al.* 2010; Jones *et al.* 2012). The California hook-and-line survey is intended to address this gap in surveys, and has been conducted in untrawlable habitat in southern California by the Northwest Fisheries Science Center since 2004 (Harms *et al.* 2010). Data from the survey were used in the recent bocaccio (*S. paucispinis*) stock assessment (He *et al.* 2015) and have been used to spatially account for density dependence in rockfish abundance estimation (Thorson *et al.* 2015). As in our simulations, the California hook-and-line survey (Harms *et al.* 2010) surveys about 100 sites annually. Survey designers worked with recreational fishing captains and fishery managers to select survey sites with high fish densities, similar to preferential site selection in the simulations. Operationally, each vessel has three anglers positioned at the bow, middle, and stern of the boat, and each angler has a line with five hooks. In each of five "drops" from the survey vessel, the anglers drop lines for a maximum of 15 minutes, totally 75 hooks per site.

For comparison with the simulation results, we examined the results of the California hook-and-line survey, focusing on the two most caught species: bocaccio (*Sebastes paucispinis*) and vermilion rockfish (*S. miniatus*). We present site-specific CPUE (number of fish/75 hooks at each site) and CPUE for bocaccio and vermilion rockfish (the average of site-specific CPUEs in each year). To quantify species aggression we calculated the average time to first bite for bocaccio and vermilion rockfish for drops where lines caught only one species. Finally, we calculated length frequencies for the two species in each year to show cohorts moving through the population, highlighting the ability of hook-and-line surveys to capture biological information.

1.4 RESULTS

1.4.1 Single Species:

Surveys with patchy initial distributions have the highest degree of hyperstability, evidenced by β values closer to zero than to one (Table 1.2). For patchy initial distributions, hyperstability is more marked with preferential site selection (median β = 0.14-0.22; Table 1.2) than for random site selection (median β = 0.39-0.49; Table 1.2). Surveys with left-skew, symmetric, and uniform initial distributions have much lower hyperstability (median β = 0.55-0.67; Table 1.2) and display less difference between preferential and random site selection (Figure 1.2a-l). Generally, preferential site selection results in greater hyperstability (Table 1.2). Surveys with hyperstability are biased because they deviate from a linear relationship between relative abundance and CPUE.

In our simulations, preferential sampling is nearly always more precise than random sampling, but is prone to bias. This is particularly true with the simulations using patchy initial distributions and higher abundances. The range between 5th and 95th percentile CPUE values for surveys with patchy initial distributions and five survey sites is 0.17-0.42 with preferential sampling and 0.29-0.59 with random sampling (Figure 1.2m; Table 1.3). These ranges decrease when sampling in more site, for example when 100 sites are sampled they are 0.05-0.07 for preferential sampling and 0.06-0.12 for random sampling (Figure 1.2p; Table 1.3). Surveys of left-skew initial distributions (where the number of fish differs little among sites) have the smallest ranges, less than 0.1, for preferential and random site selection and at all numbers of survey sites (Figure 1.2a-d; Table 1.3).

Of greatest interest is the circumstances under which it is possible to detect significant changes in CPUE. Surveys with preferential site selection are better able to detect changes in CPUE than surveys with random site selection, because the increased precision of preferential selection outweighs the increased hyperstability (e.g. Figure 1.3m-p). Preferential sampling detects a decrease in 90% of the simulations at the same or smaller level of true depletion when compared to random sampling. For example, simulations with patchy initial distribution and 20 site samples show that preferential sampling significantly (90% confidence) detects a decrease from a relative abundance of 1.0 to 0.3, while random sampling can only detect a decrease from 1.0 to 0.1 (Figure 1.3n). Increasing sample size increases the ability to detect change in CPUE values. For the same case but 100 sites surveyed, decreases could be detected from a relative abundance of 1.0 to 0.6 with preferential site selection and from 1.0 to 0.3 with random site selection (Figure 1.3p). Overall, increasing sample sizes leads to a greater ability to detect change, and the improved ability is greatest with patchy initial distributions. However, because of hyperstability, even when a change is detected, the magnitude of change detected in CPUE is nearly always less than the true magnitude of change in abundance, and this bias increases as abundance declines (Figure 1.3).

Similar general patterns were found when detecting increases and decreases from a relative abundance of 0.5 (Figure 1.4). Again, preferential site selection results in a greater ability to detect changes, and this ability is improved with greater numbers of sites (Figure 1.4m-p). Notably, surveys are better able to detect decreases than increases in median CPUE values because with hyperstability, CPUE declines more for each unit of abundance change at lower abundance than CPUE increases for each unit of abundance increase at higher abundance. Indeed, at very low levels of abundance, it is possible for CPUE declines to be larger than abundance declines, especially for preferential sampling (e.g., the lowest two CPUE values in Figure 1.4n).

1.4.2 Two Species:

Indices of abundance for one species are affected by the relative abundance of both species. Species 1 CPUE can increase due to an increase in its own relative abundance (Figure 1.5) or a decrease in relative abundance of species 2, its competitor for baited hooks. This pattern is consistent for species distributions that are symmetric or patchy, and survey sampling that is random or preferential. The magnitude of the effect depends on the relative aggression (catchability) of the species: aggression increases the degree of positive bias (Figure 1.5; if unbiased the points would track the dotted lines). When species 1 is more aggressive, median CPUE (filled circles) increases more linearly than actual abundance (dashed black lines) (Figure 1.5). Additionally, surveys with patchy initial distributions have median CPUE values ranging from 0.04-0.93 with preferential site selection (Figure 1.6m-r) and 0.01-0.26 with random site selection (Figure 1.6s-x).

1.4.3 Applicability of simulation results to the California Hook-and-Line Survey

Results from the California hook-and-line survey suggest that fish are patchily distributed with CPUE most often less than 0.5 in the surveyed sited (Figure 1.7), which themselves are chosen preferentially. The two most-caught species in the survey, bocaccio and vermilion rockfish, account for 52% of fish caught in the survey from 2004-2014. Unstandardized CPUE shows bocaccio declining and then increasing (and indeed it has just been declared rebuilt); while vermilion rockfish shows a fairly consistent increasing trend over time (Figure 1.8). The survey also provides valuable information on relative aggression of the two species that could be used to correct for the impacts of interspecies competition on CPUE. In this survey, vermilion rockfish is somewhat more aggressive (higher catchability) than bocaccio, on average having a shorter time to first bite when comparing bite times for gangions that only caught a single species, although the ranges were large (Figure 1.9). The California hook-and-line survey also collects length-frequency data for many species from rocky habitats that would be difficult or impossible to collect using trawl, acoustic or visual methods (Figure 1.10), showing cohorts moving through the population for bocaccio and to a lesser extent vermilion rockfish.

1.5 DISCUSSION

Our simulations show that over a wide range of scenarios, hyperstability is expected to occur in hook-and-line surveys. Nevertheless, these surveys are able to detect changes in abundance, particularly declines. Although preferential sampling results in more hyperstability in CPUE, it is also more precise than random sampling, and hence has a greater ability to detect changes in populations. Both hyperstability and the effects of preferential sampling are magnified when fish are patchily distributed, which data from the California hook-and-line survey suggest is the case for rockfish along the US West Coast.

Our results suggest that hyperstability should be assumed by default when using CPUE indices from hook-and-line surveys. In these surveys, hyperstability arises from hook saturation: too few hooks, and too many fish. Note, these results are specific to the simulated survey design with 75 hooks and up to 100 sites. A hook-and-line survey with 1000 hooks per site would likely result in less hyperstability, and the conclusions might not be applicable to larger-scale hook-and-line surveys. Hyperstability is also common in many other fisheries, and can arise from targeting spawning aggregations (Erisman *et al.* 2011), from contractions in spatial survey/fishing grounds (Walters 2003), or in other types of gear that also might become saturated (e.g. traps, pots, and longlines). While hyperstability is most common (Harley *et al.* 2001), there are also fisheries where hyperdepletion might occur. Notably, hyperdepletion could occur in a preferential sampling design if localized depletion of small high-density sites occurred, but most fish were at lower densities in lightly fished areas (Hilborn and Walters 1992).

Hook saturation leading to hyperstability is not the only potential bias in hook-and-line surveys, since many factors can bias fish catchability, and in turn bias the relationship between CPUE and population size. Fish catchability is affected by factors at many scales, ranging from the state of an individual fish to a vessel captain's fishing style (Lennox *et al.* 2017). An individual fish must make a decision to bite a hook (Løkkeborg and Bjordal 1992), which depends partly on the internal state of a fish (Lennox *et al.* 2017) and environmental conditions like temperature and dissolved oxygen levels (Stoner 2004). Larger pieces of bait or different types of bait attract larger fish (Garner *et al.* 2016; Ingólfsson *et al.* 2017), and fishing gear selects for certain sizes or traits of fish (Ricker 1969; Götz *et al.* 2007). Additionally, more skilled anglers might catch more fish, successive surveys could lead to avoidance behavior, and vessels might have individual fishing styles that could bias results. In addition, there are multi-year sources of bias not addressed in our simulations, such as recruitment, environmental change, and fish movements. Each of these potential sources of bias suggest areas of future research to extend the scope of the current study.

The tradeoff between bias and precision is a key part of the design of fisheries-independent surveys. Obviously, increasing sample size always improves precision. In addition, as found in our simulations, randomly selected sites are less biased but result in less precision (Kimura and Somerton 2007), while preferential sampling with surveys generally are more biased and more precise when tracking population changes (Van der Meer 1997). For the cases that we simulated, preferential sampling is better at detecting abundance changes because the increase in precision outweighs the additional bias. Where preferential sampling is problematic to interpret, methods have been developed to account for this bias. For example, groundfish surveys in the Bering Sea (Alaska, USA) preferentially conduct trawl surveys in areas with fish aggregations that are identified with acoustic methods (Hanselman *et al.* 2012). In that case, simulations of the sampling process were used to correct for bias and improve precision in abundance indices (Spencer *et al.* 2012). Wildlife surveys are another arena where preferential sampling is common, and hierarchical models that account for fixed and random effects can reduce the associated bias (Conn *et al.*). Our simulation model could be used to inform the development of a mixed-effects model incorporating site, vessel, and angler effects, to reduce bias in a similar manner to these other studies.

Bias in CPUE can also result from competition between species. Our simulations show that with two species, even if the true abundance of one species is constant over time, CPUE will decline substantially as the abundance of a competitor species increases. Trends in CPUE are also affected by relative catchability between species: when one species is more aggressive than another, the CPUE of the less aggressive species will be lower when its competitor is abundant. Similar findings have been reported for other types of surveys where species competition can affect catch rates, notably for longlines (Godø *et al.* 1997; Rodgveller *et al.* 2008) and traps (Richards et al. 1983). Competition between species affects survey results but is difficult to quantify. Although relative catchability (aggressiveness) is generally hard to measure, the

California hook-and-line survey data did suggest that vermilion rockfish are more aggressive than bocaccio, in the analyses of time-to-first-bite data. Similar detailed data on the timing of catches in other types of surveys might also reveal relative catchability among species.

All of these aspects of survey design and bias are present in the specific case study we examined, the California hook-and-line survey (Harms *et al.* 2010). This survey provides information for many different species, including genetic data, otoliths for ageing, and lengths and weights to track cohorts and measure length-weight and age-length relationships. In addition, the survey CPUE is one of seven indices of abundance that have been used in recent assessments for bocaccio (He *et al.* 2015). The unstandardized CPUE indices we presented here for bocaccio have similar trends and comparable changes to the standardized CPUE indices used in recent stock assessments (He *et al.* 2015). In the actual survey, the data were standardized using a generalized linear model that incorporates explanatory variables like soak time, angler, vessel, and site (Harms *et al.* 2010). Our simulations point out several additional biases that also need to be accounted for: notably the non-linearity between CPUE and abundance (hyperstability), the impact of the preferential sampling design, and interactions between species.

Hook-and-line surveys can also be improved by coupling with additional survey methods, such as the video surveys conducted at a subset of the California hook-and-line survey sites that provide information on site-specific species compositions and abundances. Hook-and-line surveys sample a wide range of sizes (Millar and Fryer 1999; Starr *et al.* 2016), although for certain species, video surveys might observe both the smaller and larger fish than those captured using hook-and-line methods (Starr *et al.* 2016). Indeed, hook-and-line selectivity has been estimated to be dome-shaped (Garner *et al.* 2014), although this varies by species and hook size.

Our results investigate many of the potential biases in hook-and-line surveys, which are useful for tracking life histories and species in habitats that are not easily surveyed by trawl and acoustic methods. Surveys that miss primary habitats could result in biased population assessments and impose catch limits that constrain ecological, economic, and social outcomes in multispecies fisheries. Hook-and-line surveys offer considerable promise since they are able to detect declines in abundance, despite important biases such as hyperstability from hook saturation and multispecies competition.

1.6 TABLES

Table 1.1: Ranges (minimum–maximum) and median numbers of fish for each level of relative abundance and initial distribution type.

		Ranges				**Medians**			
Number of Fish	**Relative Abundance**	**Left Skew**	**Normal**	**Patchy**	**Uniform**	**Left Skew**	**Normal**	**Patchy**	**Uniform**
20,000	0.1	12–25	5–39	0–756	0–44	23	22	0	23
40,000	0.2	24–50	10–78	0–1512	0–88	46	44	0	46
60,000	0.3	36–73	15–117	0–2269	0–132	68	66	1	69
80,000	0.4	47–98	20–156	0–3025	0–176	91	88	1	92
100,000	0.5	59–122	25–195	0–3781	0–220	114	110	1	114
120,000	0.6	71–147	29–234	0–4537	0–264	137	131	1	137
140,000	0.7	83–171	34–273	0–5294	0–308	160	153	1	160
160,000	0.8	95–195	39–312	0–6050	0–352	183	175	1	183
180,000	0.9	107–220	44–351	0–6806	0–397	205	197	2	206
200,000	1.0	118–244	49–390	0–7562	0–441	228	219	2	229

Table 1.2: Shape estimates (*β*) from CPUE values for each initial distribution, sampling type, and number of sites. Shape estimates closer to 0 are more biased.

Initial Distribution	**Sampling Type**	**5**		**20**		**50**		**100**	
Left Skew	Preferential	**0.67**	(0.65–0.69)	**0.64**	(0.63–0.65)	**0.64**	(0.63–0.65)	**0.65**	(0.65–0.66)
Left Skew	Random	**0.67**	(0.65–0.70)	**0.65**	(0.64–0.66)	**0.64**	(0.63–0.65)	**0.66**	(0.65–0.66)
Symmetric	Preferential	**0.65**	(0.57–0.73)	**0.62**	(0.59–0.65)	**0.62**	(0.60–0.63)	**0.62**	(0.61–0.63)
Symmetric	Random	**0.67**	(0.60–0.77)	**0.64**	(0.60–0.67)	**0.64**	(0.62–0.66)	**0.64**	(0.63–0.66)
Patchy	Preferential	**0.14**	(0.05–0.29)	**0.16**	(0.11–0.22)	**0.18**	(0.15–0.22)	**0.22**	(0.20–0.24)
Patchy	Random	**0.49**	(0.12–1.00)	**0.40**	(0.23–0.64)	**0.39**	(0.30–0.51)	**0.39**	(0.32–0.47)
Uniform	Preferential	**0.56**	(0.49–0.67)	**0.55**	(0.51–0.59)	**0.55**	(0.53–0.57)	**0.55**	(0.54–0.57)
Uniform	Random	**0.61**	(0.52–0.75)	**0.60**	(0.55–0.66)	**0.59**	(0.57–0.63)	**0.60**	(0.58–0.62)

Table 1.3: Catchability (q_{CPUE}) estimates for each initial distribution, sampling type, and number of sites.

Initial Distribution	**Sampling Type**	**5**		**20**		**50**		**100**	
Left Skew	Preferential	**0.89**	(0.86–0.91)	**0.87**	(0.86–0.88)	**0.87**	(0.86–0.88)	**0.88**	(0.87–0.88)
Left Skew	Random	**0.89**	(0.86–0.91)	**0.87**	(0.85–0.88)	**0.87**	(0.85–0.87)	**0.87**	(0.87–0.88)
Symmetric	Preferential	**0.9**	(0.81–0.97)	**0.88**	(0.84–0.92)	**0.88**	(0.85–0.90)	**0.88**	(0.86–0.90)
Symmetric	Random	**0.87**	(0.75–0.95)	**0.85**	(0.80–0.89)	**0.84**	(0.81–0.87)	**0.85**	(0.82–0.87)
Patchy	Preferential	**1**	(0.86–1.00)	**1.00**	(0.93–1.00)	**0.99**	(0.95–1.00)	**0.97**	(0.94–1.00)
Patchy	Random	**0.26**	(0.02–0.63)	**0.28**	(0.14–0.43)	**0.28**	(0.19–0.37)	**0.28**	(0.22–0.35)
Uniform	Preferential	**0.94**	(0.78–1.03)	**0.93**	(0.86–0.98)	**0.92**	(0.88–0.95)	**0.92**	(0.89–0.95)
Uniform	Random	**0.78**	(0.54–0.98)	**0.77**	(0.66–0.87)	**0.76**	(0.69–0.83)	**0.76**	(0.72–0.81)

Table 1.4: Difference in CPUE between 95th and 5th quantiles for each initial distribution, sampling type, and number of sites.

			Relative Abundance Level									
Initial Distribution	**Sampling Type**	**Number of Sites**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
Left Skew	Preferential	5	0.02	0.03	0.04	0.07	0.08	0.05	0.05	0.04	0.05	0.05
		20	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.03
		50	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		100	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Random	5	0.02	0.03	0.04	0.08	0.08	0.06	0.05	0.04	0.05	0.05
		20	0.01	0.02	0.02	0.03	0.04	0.03	0.03	0.03	0.03	0.03
		50	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		100	0.00	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
Symmetric	Preferential	5	0.06	0.11	0.15	0.19	0.19	0.18	0.18	0.16	0.15	0.15
		20	0.03	0.05	0.08	0.09	0.09	0.08	0.08	0.08	0.08	0.07
		50	0.02	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.04
		100	0.01	0.02	0.03	0.04	0.04	0.04	0.04	0.04	0.03	0.03
	Random	5	0.07	0.12	0.16	0.21	0.22	0.21	0.21	0.20	0.19	0.18
		20	0.03	0.05	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.08
		50	0.02	0.03	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.05
		100	0.01	0.02	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Uniform	Preferential	5	0.10	0.16	0.23	0.25	0.27	0.27	0.26	0.24	0.22	0.21
		20	0.05	0.09	0.12	0.12	0.13	0.13	0.12	0.12	0.11	0.11
		50	0.03	0.05	0.06	0.07	0.07	0.08	0.08	0.07	0.07	0.07
		100	0.02	0.04	0.04	0.05	0.05	0.05	0.06	0.05	0.05	0.05
	Random	5	0.12	0.21	0.28	0.34	0.38	0.4	0.41	0.41	0.40	0.39
		20	0.06	0.10	0.14	0.16	0.17	0.19	0.19	0.19	0.19	0.19
		50	0.04	0.07	0.09	0.10	0.11	0.12	0.12	0.12	0.12	0.12
		100	0.03	0.05	0.06	0.07	0.08	0.08	0.09	0.09	0.09	0.09
Patchy	Preferential	5	0.42	0.39	0.34	0.29	0.24	0.21	0.19	0.18	0.17	0.17
		20	0.19	0.18	0.16	0.14	0.13	0.12	0.12	0.11	0.10	0.10
		50	0.11	0.11	0.10	0.10	0.09	0.08	0.08	0.07	0.07	0.06
		100	0.05	0.06	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05
	Random	5	0.29	0.38	0.42	0.47	0.51	0.54	0.56	0.57	0.58	0.59
		20	0.15	0.20	0.22	0.24	0.25	0.26	0.27	0.27	0.27	0.28
		50	0.09	0.12	0.14	0.15	0.16	0.17	0.17	0.17	0.18	0.17
		100	0.06	0.09	0.10	0.11	0.11	0.11	0.12	0.12	0.12	0.12

1.7 FIGURES

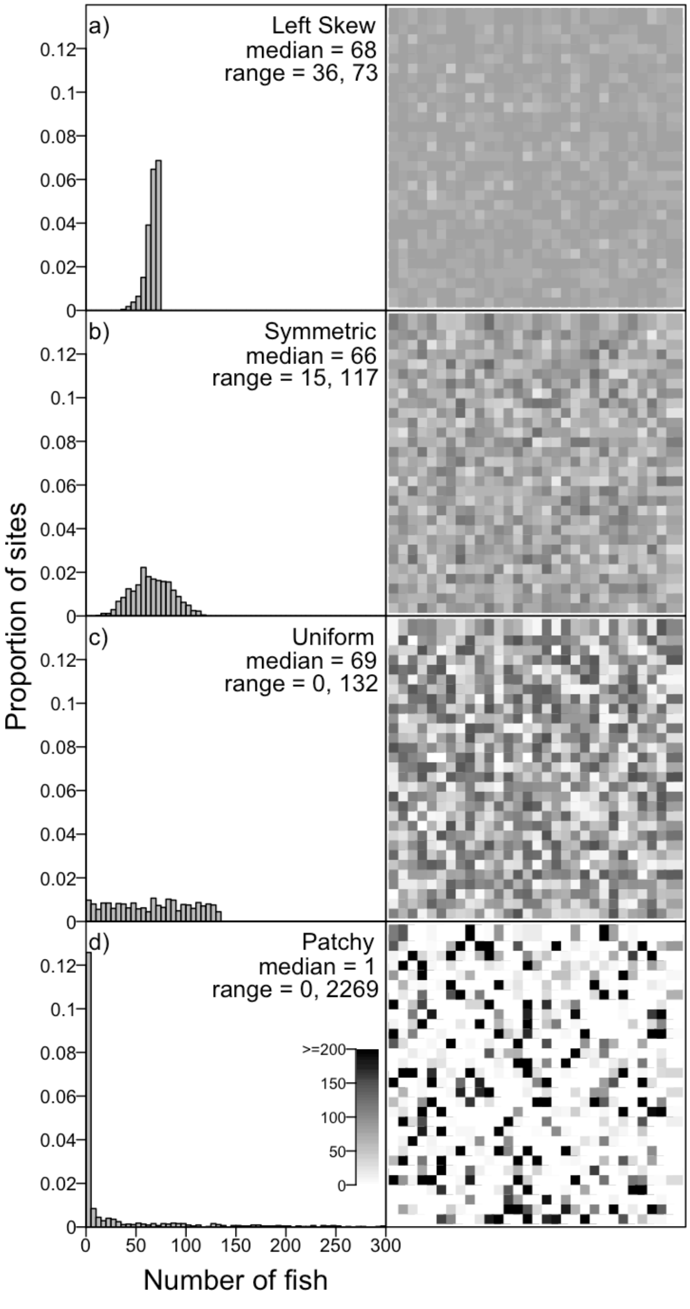

Figure 1.1: Histograms of the numbers of fish per site for the four initial distributions when 60,000 fish are distributed among 900 fishing sites. The median and range of numbers of fish in each site are shown in the top right of each panel. Plots in the right column show the numbers of fish (darker colors for higher numbers) in each site (squares) in the 900 fishing sites.

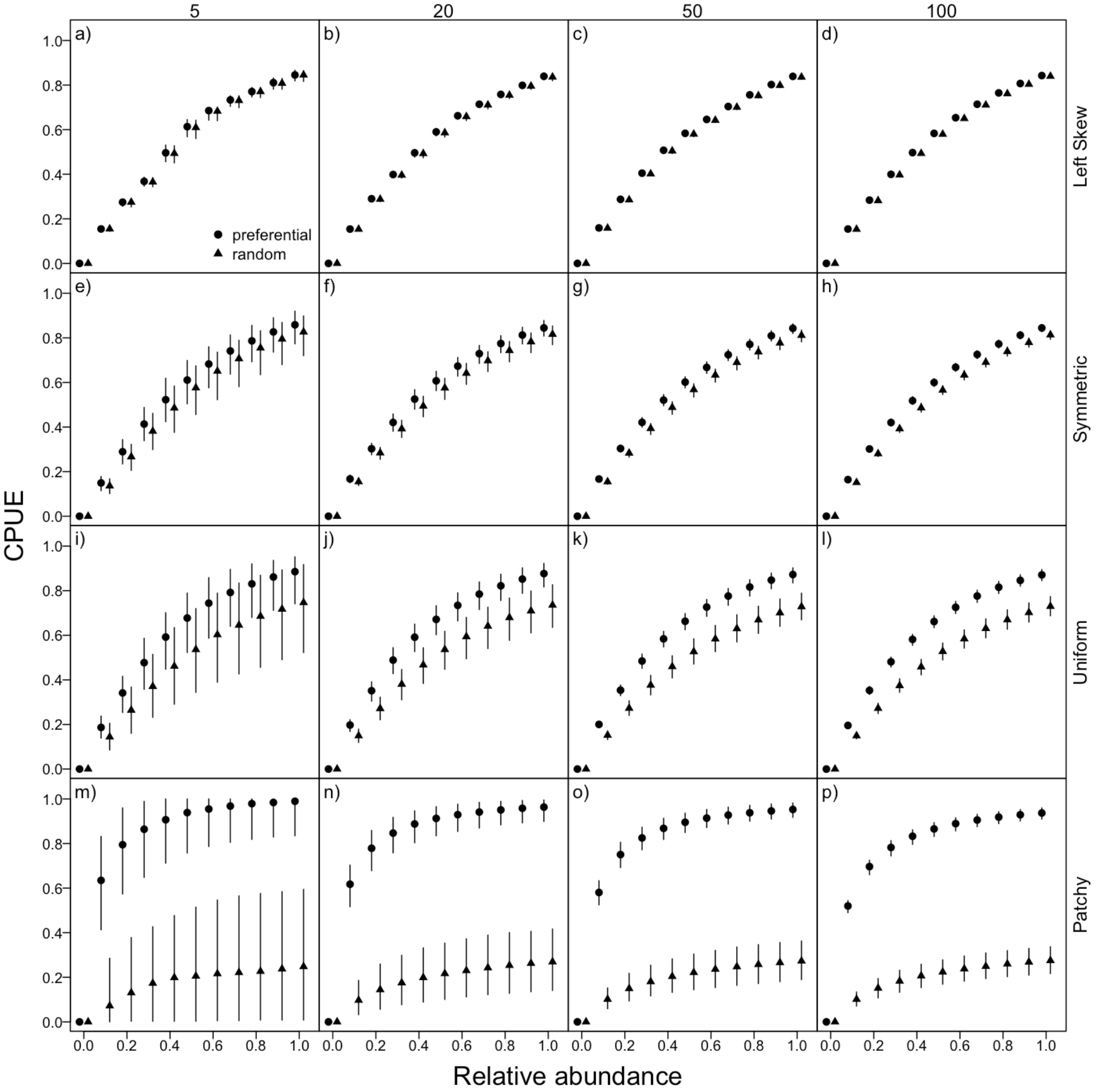

Figure 1.2: Catch per unit effort (CPUE) and relative abundance for each survey. CPUE is the number of fish caught per 75 hooks, averaged over all sites. Points indicate the median CPUE values for preferential sampling (circles) and random sampling (triangles), with 5th and 95th percentiles (lines) shown for 1000 replicates. Rows show initial distribution types and columns the number of survey sites.

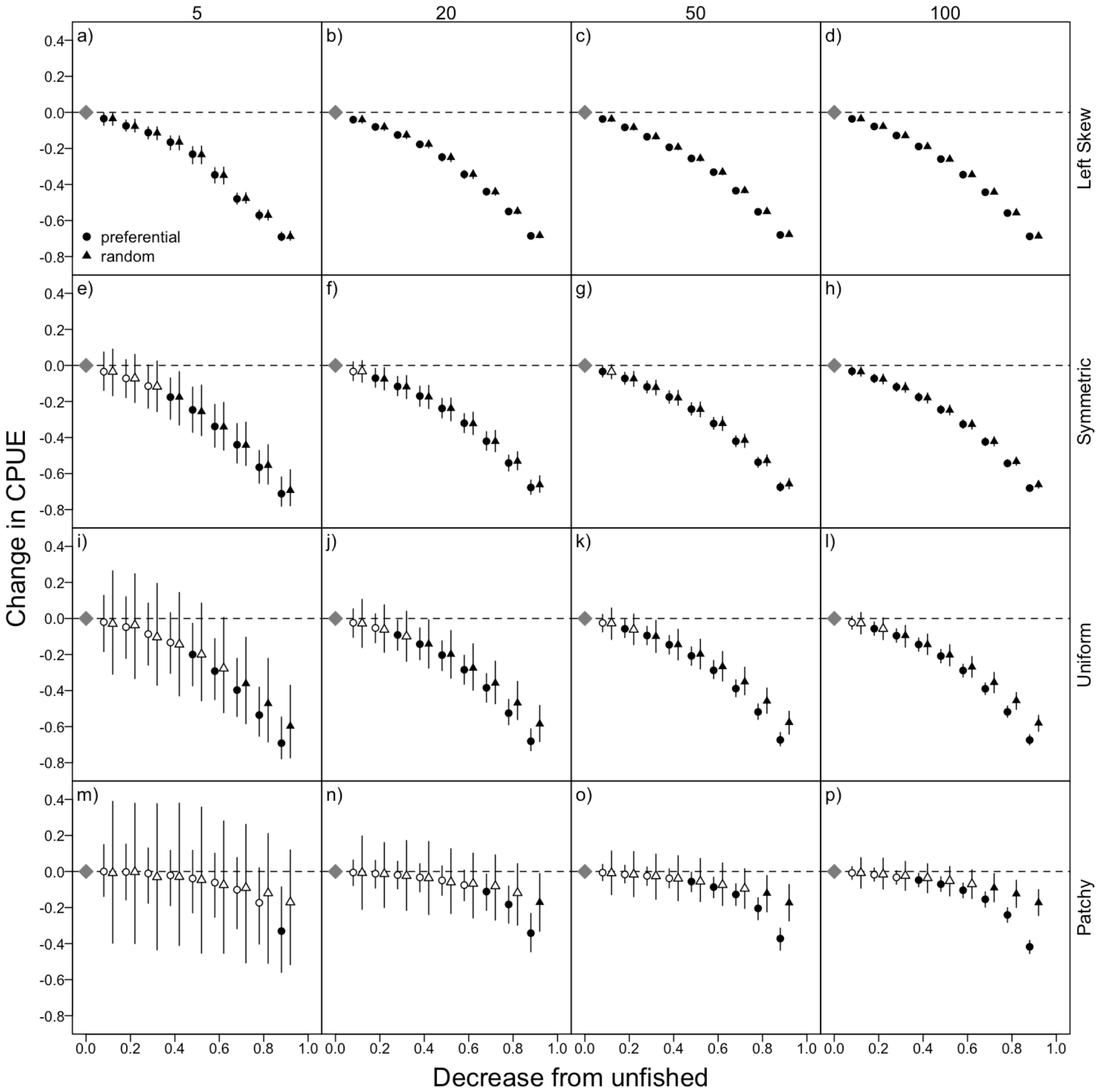

Figure 1.3: Change in estimated median catch per unit effort (CPUE) as populations decline from unfished levels (gray diamonds) given for preferential sampling (circles) and random sampling (triangles). Tails indicate the 5th and 95th percentiles of 1000 resampled differences from unfished relative abundance. Filled symbols are those that detected changes in CPUE more than 95% of the time Rows show initial pattern of distribution of fish, and columns the number of sites that were surveyed.

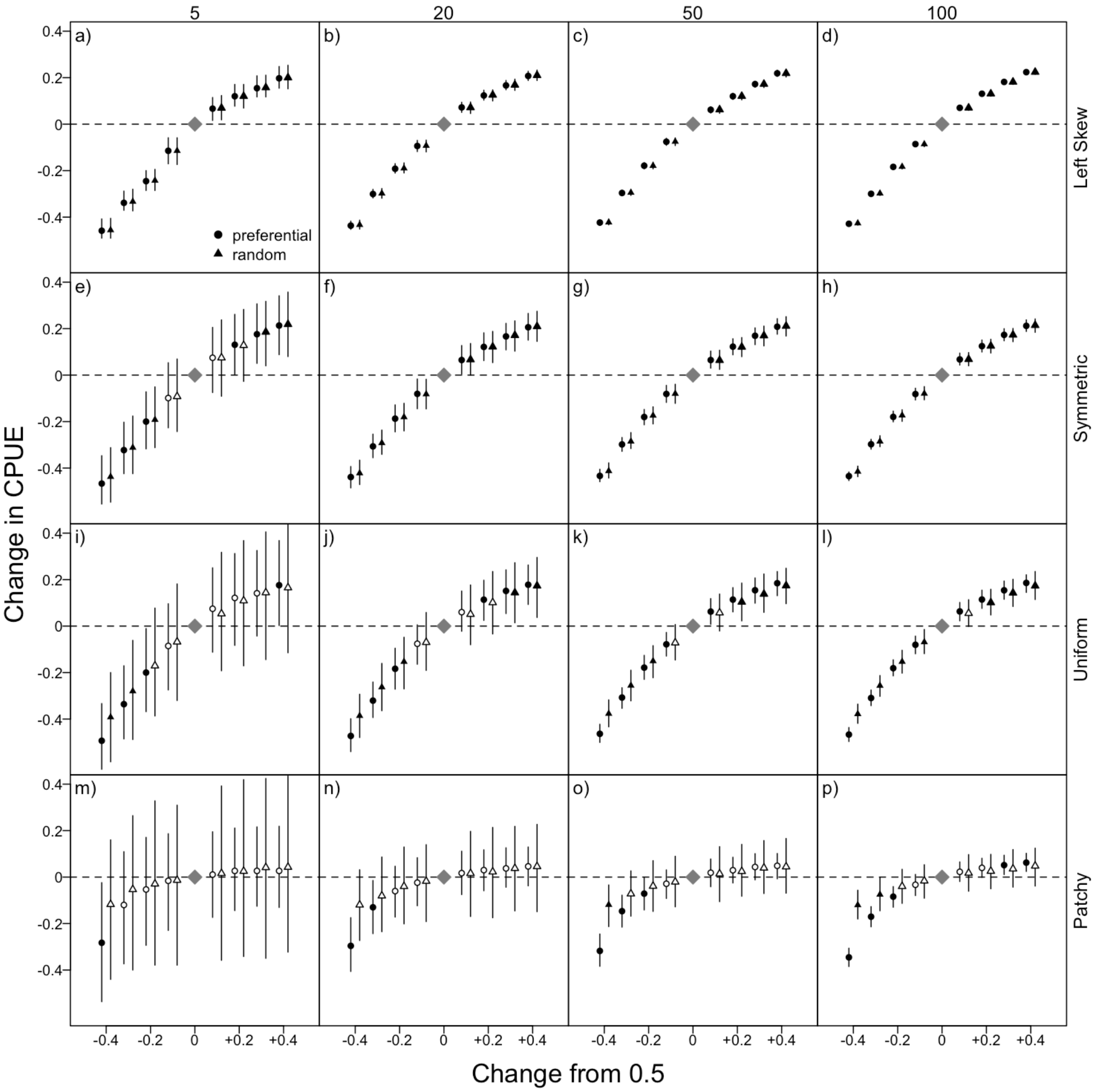

Figure 1.4: Change in estimated catch per unit effort (CPUE) versus change from a population at 50% of unfished abundance. Points indicate relative abundance of 0.5 (diamonds), median CPUE values for preferential sampling (circles) and random sampling (triangles). Tails indicate the 5th and 95th percentiles of 1000 resampled differences from relative abundance of 0.5. Points with tails that did not overlap 0 (filled points) detect significant changes in CPUE. Rows show initial distribution types and columns the number of survey sites.

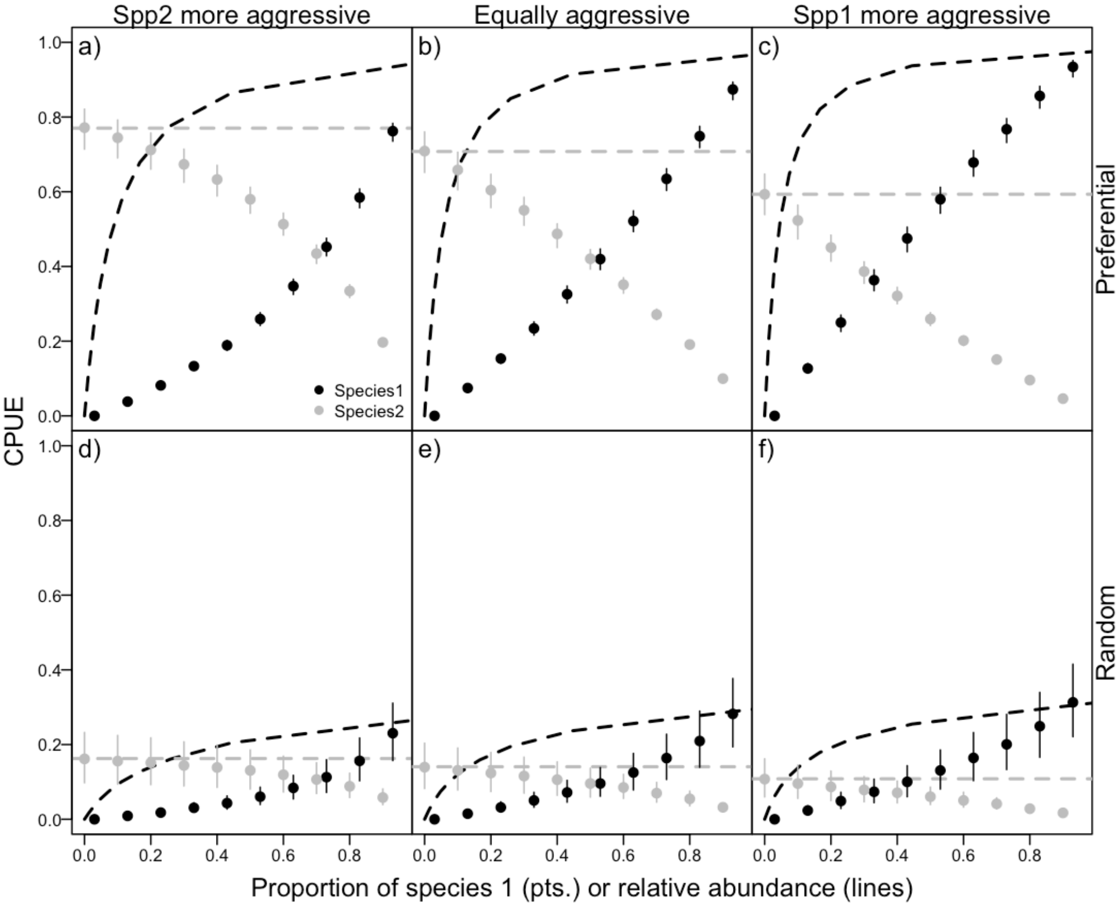

Figure 1.5: Proportion of species 1 vs. CPUE (points are median values; tails are 5th and 95th percentiles) for species 1 (black) and species 2 (gray). Relative abundance vs. CPUE (lines) are shown for species 1 in the absence of species 2 (black) and species 2 in the absence of species 1 (gray). Numbers of species 1 increase by ever-larger amounts from left to right in each panel (from 0 to 540,000), but numbers of species 2 remain constant at 60,000. The three competition scenarios (columns) are species 2 more aggressive than species 1, both species equally aggressive, and species 1 more aggressive than species 2. Rows indicate sampling type. Paired points are slightly offset to prevent overplotting.

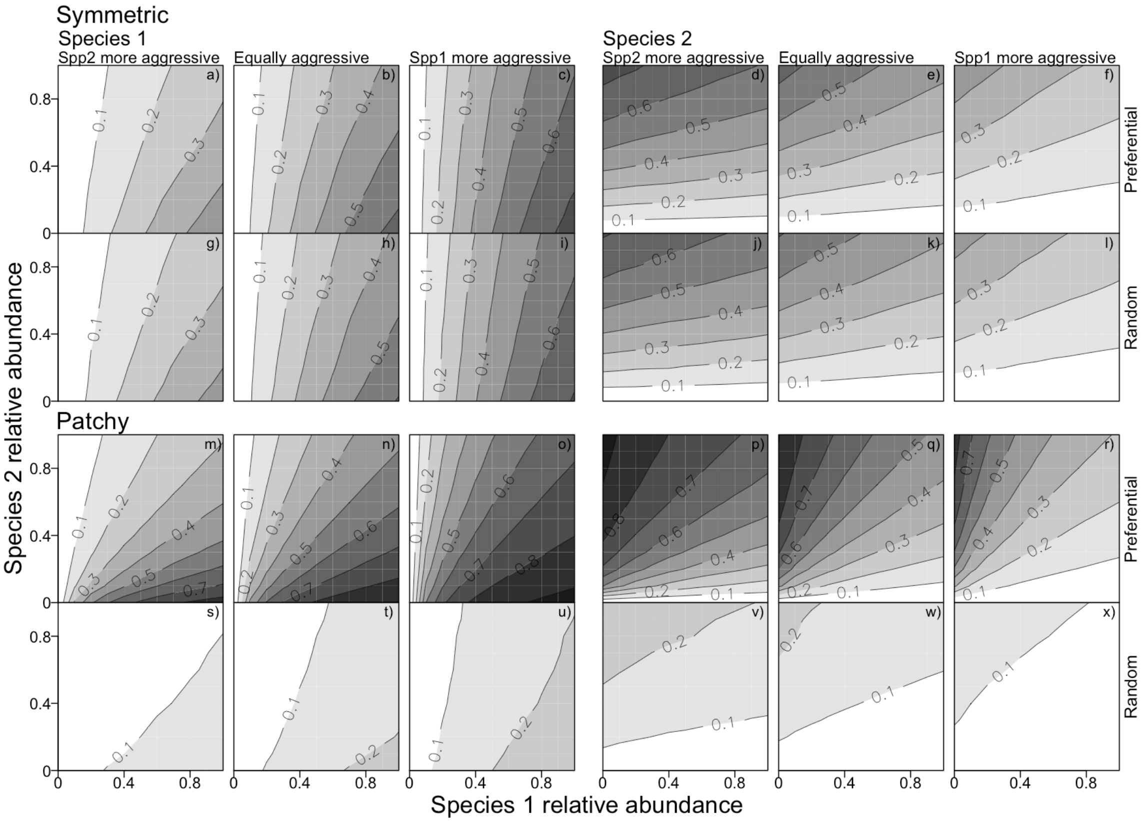

Figure 1.6: Contour plots of median CPUE values at relative levels of abundance for species 1 (x-axis) and species 2 (y-axis). Darker shades indicate higher CPUE values. Symmetric and patchy initial distribution results are shown here. Left skew and uniform initial distribution results look similar to those of the symmetric distribution. Columns 1-3 show species 1 results and columns 4-6 show species 2 results. The first and third rows show preferential site selection, and the second and fourth rows show random site selection.

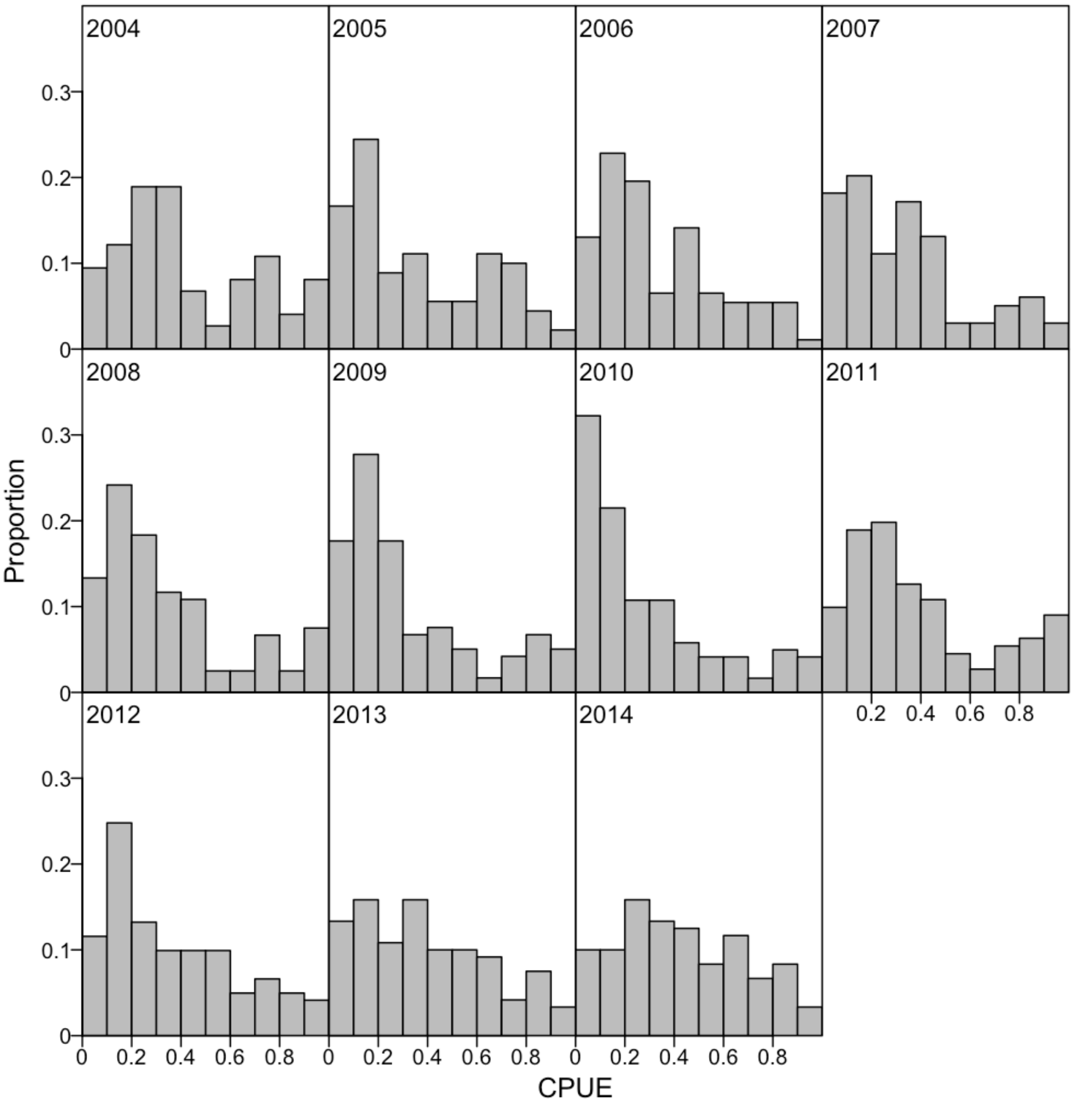

Figure 1.7: Histograms of site-specific catch per unit effort (CPUE; number of fish / 75 hooks) in each year.

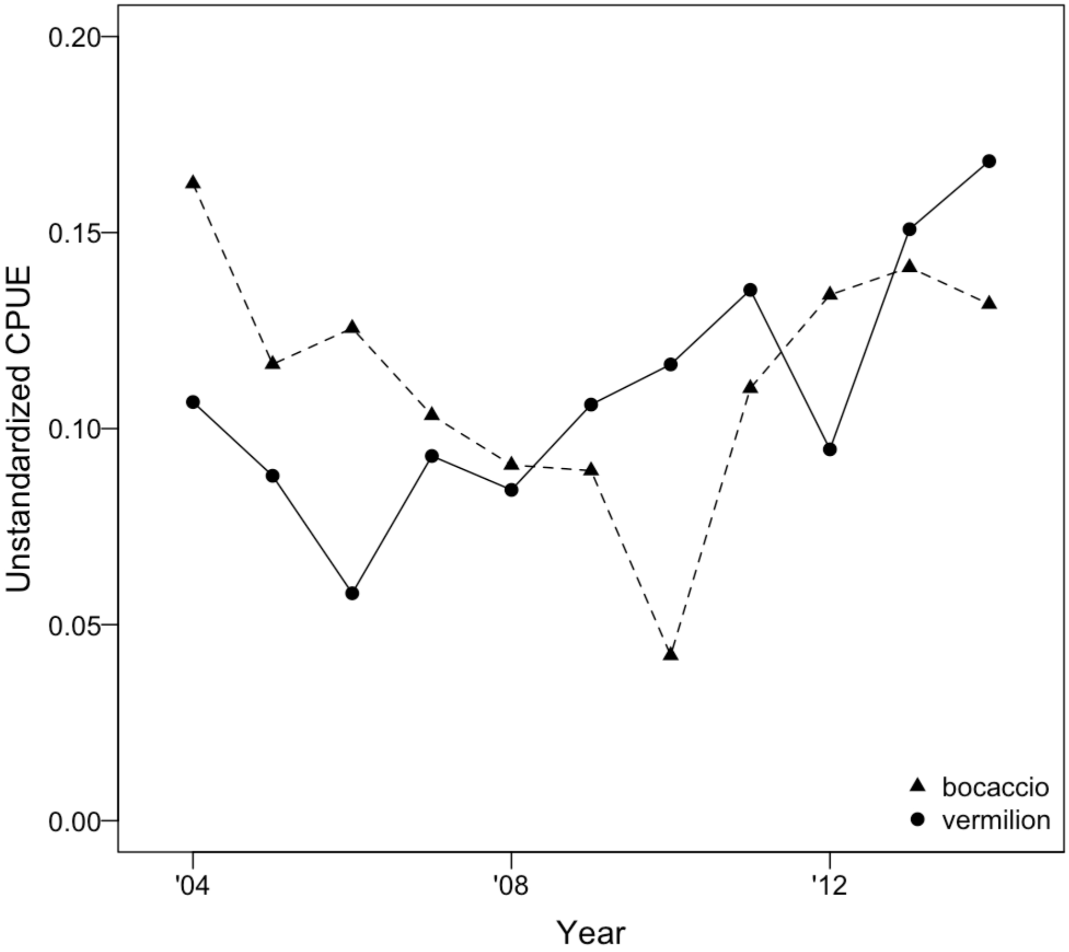

Figure 1.8: Unstandardized CPUE (average of site-specific CPUE in each year) for bocaccio and vermilion rockfish from 2004-2014.

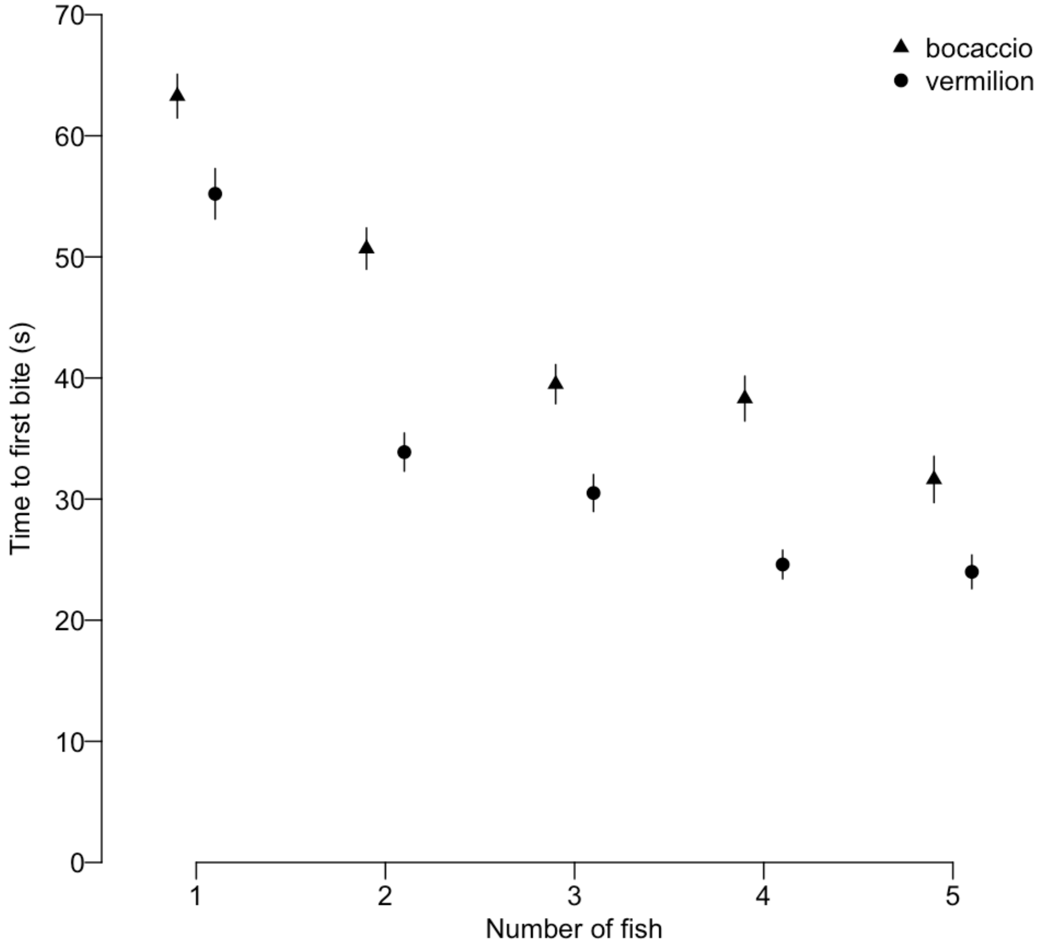

Figure 1.9: Mean (point) and standard error (tails) values of time to first bite (seconds). The values here come from gangions (lines with five hooks) with only bocaccio or only vermilion rockfish.

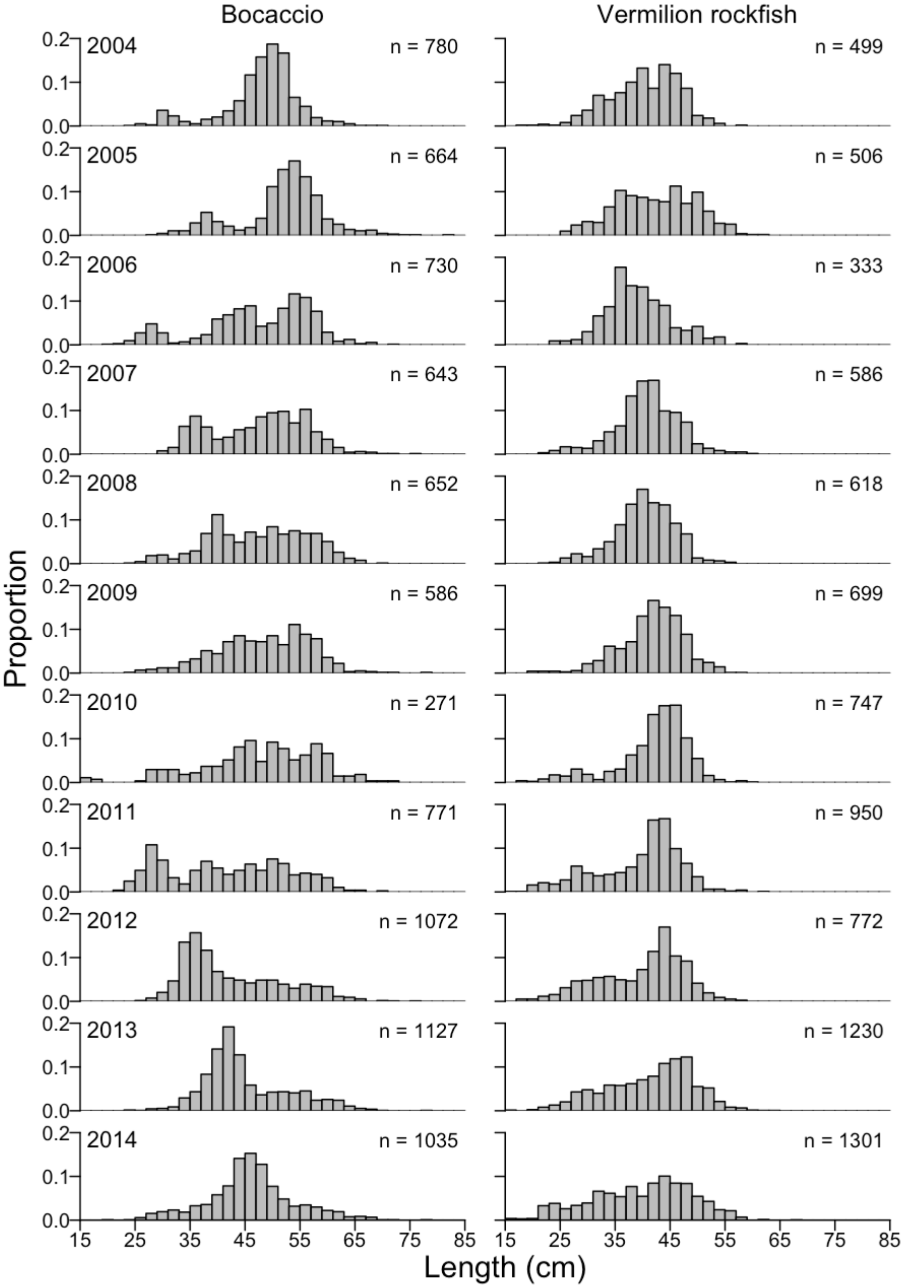

Figure 1.10: Length frequencies of bocaccio (*Sebastes paucispinis*) and vermilion rockfish (*Sebastes miniatus*) from 2004-2014 in the California hook-and-line survey. Values in the top right of each plot indicate the number of fish sampled.

Chapter 2. Catch shares have not led to catch-quota balancing in two North American multispecies trawl fisheries

2.1 ABSTRACT

Catch shares, where annual catch limits are divided among individuals, communities or cooperatives, are a commonly used fisheries management strategy to increase profits and reduce overcapitalization. Usually these quota shares can be sold or leased, which is theorized to allow for greater utilization of fleet-wide quota. However, this catch-quota balancing may not be achieved in multispecies trawl fisheries where it is difficult to selectively target valuable species while avoiding overfished species. Two similar catch-share-managed, multispecies trawl fisheries were compared to evaluate whether catch shares lead to catch-quota balancing. The U.S. West Coast Groundfish fishery has several species with low total allowable catches (TACs) while the Canadian British Columbia Trawl fishery has comparatively higher TACs. Results indicate that the West Coast fishery had a statistically significant decrease in catch-quota ratios from 0.41 in the three years before catch shares to 0.29 in the three years after catch shares. In contrast, the BC fishery had no change in fishery-wide average catch-quota ratios, which were 0.70 in the three years before and 0.62 in the three years after catch shares were implemented. In the West Coast fishery, the risk of exceeding quotas for some species may be so high that fishers are unable to achieve high degrees of catch-quota balancing and instead focus on species that can be well selected with changes in fishing behavior. Multispecies fisheries management has direct tradeoffs between maximizing yield and achieving conservation goals, and these results may highlight the tradeoff between rebuilding overfished species by reducing TACs, and the achievement of catch-quota balancing.

2.2 INTRODUCTION

Multispecies fisheries management confronts a trade-off between overfishing and optimum yield. That is, fisheries that achieve a maximum multispecies sustainable yield will overfish and collapse some stocks (Worm *et al.* 2009); while preventing overfishing across multiple species requires fishers to forego catch and revenue. For example, Hilborn et al. 2004 showed that preventing all overfishing would require fishers in the U.S. West Coast groundfish fishery to leave 90% of potential yield in the water (Hilborn *et al.* 2004). Setting and enforcing low total allowable catches (TACs) for overfished stocks will prevent overfishing but preclude fishers from matching catches to quotas. If overfished stocks have TACs that are orders of magnitude lower than TACs for target species, the risk of exceeding low TACs may constrain fishers' behavior. In these cases, actual catches of overfished stocks can be low relative to the TACs and fishers may have to forego catches of target species.

The constraints of low TACs in multispecies fisheries may be reduced under catch share management. Catch shares are an oft-used management strategy to align environmental and economic incentives to achieve sustainable fisheries (Costello *et al.* 2008). Under catch shares, participating fishers, cooperatives, or communities are granted a share of the TAC. The allocation of rights or privileges to a specified amount of fish ends the race to fish (Grafton 1996a), which can grant fishers the flexibility to time catch rates to market prices (Grafton 1996a; Scheld and Anderson 2014). Catch shares that permit quota transfers provide a market-based method for profitable fishers to buy quota from those operating at a loss. Transferability of quota should reduce fleet size and in turn overcapitalization (Arnason 2005). Additionally, catch shares with transferable quota offer additional flexibility: fishers can purchase or lease quota to legally land catches over their individual quota holdings, and sell or lease out quota if their catches are under their holdings (Copes 1986). The flexibility to transfer quota or cover quota overages allows fishers to better match catches with quotas (Sanchirico *et al.* 2006).

Taken together, these aspects of catch shares provide both the flexibility and the incentives for fishers to more fully catch TACs. These aspects of catch shares are particularly important in multispecies fisheries where fishers typically have allocations of a wide range of species and some ability to control catch composition by timing trips, fishing in specific locations, or changing gear type (Branch *et al.* 2005; Branch and Hilborn 2008; Worm *et al.* 2009). In practice, however, quotas may not be fully caught in multispecies fisheries for a variety of reasons (Squires *et al.* 1998; Costello *et al.* 2008). For example, there may be inefficient transfer markets where little quota is available for lease or sale; it may not be profitable to catch all species; and fishers may not be able to fully avoid species with very low TACs while targeting more abundant species. In New Zealand, to reduce the effect of these issues, fishers can pay fees in lieu of trading or leasing bycatch quota (Grafton 1996a; Holland and Herrera 2006; Beddington *et al.* 2007). The New Zealand system decreases the effect of constraining TACs on target catches but also increases the probability of exceeding TACs for constraining species (Arnason 2005; Holland and Herrera 2006). Allowing exchanges based on market prices between bycatch and target species may grant fishers flexibility when quota markets are imperfect, but the reality is that in most multispecies systems there is no solution to perfectly match catches to TACs (Copes 1986; Squires *et al.* 1998; Sanchirico *et al.* 2006).

Although catch shares offer mechanisms to better match catches to TACs, catch shares have mixed overall impacts on ecosystems and fisheries sustainability (Sanchirico *et al.* 2006; Branch 2009; Essington *et al.* 2012). Analyses of stock assessment data for catch share fisheries worldwide found no differences in population biomass and population trajectories after catch share implementation (Essington 2010; Essington *et al.* 2012). However, the variance of catch and of catch:TAC ratios are greatly reduced after catch share implementation (Essington 2010; Melnychuk *et al.* 2011; Essington *et al.* 2012; Melnychuk *et al.* 2014). Reduced variance in catch:TAC ratios may be beneficial for fishing companies when planning business operations. Costello *et al* (2008) found that landings in catch share fisheries were less likely to collapse, although landings data are not necessarily representative of stock status (Pauly *et al.* 2013).

2.2.1 The Two Fisheries

The U.S. West Coast Groundfish fishery (hereafter West Coast fishery) and British Columbia Trawl fishery (hereafter BC Fishery) are two similar fisheries that transitioned to catch share management. The two fisheries are comprised of vessels fishing for similar target species such as sablefish (*Anoplopoma fimbria*), petrale sole (*Eopsetta jordani*), thornyheads (*Sebastolobus* spp.), Dover sole (*Microstomus pacificus*), and a variety of rockfish (*Sebastes* spp.). Both fisheries are limited entry, have similar fleet sizes, mainly use trawl gear, and have comparable fishery-wide TACs (Branch *et al.* 2006b).

Both fisheries were previously managed under trip limits, in which fishery-wide landing limits for each species and area were set for weekly, monthly, or two-monthly periods. However, trip limits decreased as stock status deteriorated, which led to an increase in discarding as fishers were required to discard species with catches over the trip limits, but could continue fishing for other species, leading to little incentive to fish selectively. Before catch shares in the West Coast and BC fisheries, discarding was not penalized and was not observed reliably. The West Coast fishery had at-sea catch monitoring on only 20% of limited-entry sector trips prior to catch share implementation (Bellman *et al.* 2009), similar to pre-catch-share coverage rates in the BC fishery (Branch 2006). Discarding is wasteful, leads to lost income, and confounds estimates of fishing mortality for stock assessments (Acheson 2006; Branch *et al.* 2006b). Thus, trip limits proved ineffective as both fisheries were characterized by overfishing, high discards, and diminished profits. Under catch shares in both fisheries, observer coverage is 100% and discards count towards individual quotas.

One key difference between the fisheries is that the lowest TAC in the West Coast fishery is an order of magnitude lower than the lowest in the BC fishery. For example, in 2011 the lowest TAC in the West Coast fishery was 0.6 mt for yelloweye rockfish (*Sebastes ruberrimus*) compared to 5 mt for the complex consisting of quillback (*Sebastes maliger*), china (*Sebastes nebulosus*), copper (*Sebastes caurinus*), and tiger rockfish (*Sebastes nigrocinctus*) in the BC fishery. The next lowest TACs in 2011 were 1.8 mt for cowcod (*Sebastes levis*) and 50 mt for shortspine thornyhead (*Sebastolobus alascanus*) in the West Coast fishery, while the next lowest TACs in the BC fishery were 20 mt for canary rockfish and 61 mt for longnose skate (*Raja binoculata*).

The Pacific Fishery Management Council (Pacific Council) manages the West Coast fishery to prevent overfishing while maintaining an economically sustainable fishery. The low TACs occur because management was required by federal law to rebuild overfished species: bocaccio (*Sebastes paucispinis*), canary rockfish, cowcod, darkblotched rockfish (*Sebastes crameri*), Pacific ocean perch (*Sebastes alutus*), and yelloweye rockfish. Petrale sole (*Eopsetta jordani*) was a rebuilding species, but we consider it a target species, as it has now rebuilt, and is one of the most profitable species in the fishery. In the late 1990s, average biomass levels for rebuilding species were about 30% of the biomass that produces maximum sustainable yield (MSY; Figure 2.1). Many of these species can live longer than 50 years (Cailliet *et al.* 2001), and as a result, it may take many more decades to rebuild overfished stocks.

The Pacific Council has adopted a number of management policies to rebuild overfished stocks and reduce fishing capacity in the past 20 years. Trip limits were introduced in the early 1980s around the time the Pacific Council officially began managing the groundfish fishery. Trip limits, in which fishers are allowed to catch a fixed amount of fish per trip or time period, are designed to distribute fishing effort throughout the fishing season. Starting in the mid-1990s, the Pacific Council progressively reduced trip limits in order to rebuild stocks. Under trip limits, there were no penalties for discarding, and discard rates for rebuilding species increased as trip limits declined (Bellman and Heery 2013). In 2003, the Pacific Council addressed overcapitalization through a $46 million vessel buyback program to reduce the fleet from 263 to 171 vessels. In addition, as evidence of overfishing of multiple species grew, Groundfish Conservation Areas were declared in the early 2000s, which closed much of the most productive shelf region at depths of 180–450 m to fishing. In combination, these severe constraints on fishing led to greatly reduced profitability despite the rebuilding of widow rockfish (*Sebastes entomelas*), lingcod (*Ophiodon elongatus*), petrale sole, and darkblotched rockfish.

The final major change in West Coast fishery management was the transition from trip limits to catch shares in January 2011, with the explicit goals “to increase net economic benefits, create individual economic stability, provide for full utilization of trawl sector allocation, consider environmental impacts, and achieve individual accountability of catch and bycatch” (Pacific Fishery Management Council and NMFS 2010). From the start, it was recognized that the greatest impediment to full utilization of TACs would be low constraining quotas of overfished species. Yelloweye rockfish offers an extreme example where the TAC for the whole fishery was 0.6 t in 2011, resulting in 65% of the quota owners receiving fewer than 5 kg of quota for the entire year (Figure 2.2). For many fishers, the accidental catch of a single yelloweye rockfish would require a fisher to cease fishing until additional quota could be leased. More catastrophic scenarios included the possibility that a single tow could exceed the entire coastwide yelloweye rockfish TAC, and thereby close the entire groundfish fishery.

The Central California Risk Pool is one unique aspect of the West Coast fishery that began in 2011, at the same time as catch shares. Risk pools are arrangements in which fishers pool quota and make it available for other participants (Holland and Jannot 2012). The Nature Conservancy worked with fishers from Morro Bay, Fort Bragg, and Half Moon Bay to establish the Central California Risk Pool. Risk pool participants leased quota owned by The Nature Conservancy and collaboratively developed spatial fishing plans to avoid bycatch species habitats. Data from the risk pool were compiled from Fort-Bragg-Central Coast Risk Pool Annual Summary Reports. Risk pools and information sharing may improve the abilities of fishers to target valuable species and avoid bycatch species.

In the BC fishery, similar to the West Coast fishery, catch shares were also introduced at a crisis point in the fishery. The turning point was September 1995 when Fisheries and Oceans Canada closed the BC fishery for five months due to significant TAC overages (Turris and Shotton 2000). The fishing industry spent 14 months working with Fisheries and Oceans Canada to agree on the details of a new catch share program. During these discussions, in 1996, the fishery reopened with 100% at-sea observer coverage and 100% dockside monitoring of landed catches, but still governed by trip limits. The costs of the new programs were passed on to the fishing industry, including the $4.4 million cost of observer programs and increased vessel licensing fees (from $14 to $10,342); these fees further reduced the already small profits in the fishery. Subsequently, the fishery moved to catch shares in the form of individual transferable vessel quotas in April 1997. The main driver of catch share implementation was to maintain the economic viability of the fishery. In the BC fishery, vessel owners are allowed to transfer and trade quota to other participating vessels. Fisheries and Oceans Canada has also enforced a number of small closed areas, and fleet size has declined under catch shares although there was no vessel buyback program. Since catch-share implementation, the TACs have remained fairly constant for most species, in contrast to the sharp declines for some species in the 2000s in the West Coast fishery.

2.2.2 Responses to Catch Shares

The ability of catch shares to achieve catch-quota balancing were evaluated in two similar North American fisheries: The West Coast fishery and the BC fishery. Data from before and after catch share implementation in both fisheries were used to examine whether catch shares increased catch-quota balancing, as evidenced by catch:TAC ratios being closer to one. Several possible catch:TAC outcomes could occur assuming that both target and constraining species are unavoidably caught together. Constraining species are considered to be stocks for which the risk of exceeding the TACs is high. The analysis is framed around three hypotheses:

Hypothesis 1: Fishers will be able to more fully catch the TACs for target species under catch shares. This would arise if fishers can adjust fishing behavior to selectively target specific species and if quota transfers fluidly between fishers to balance overages and underages. Under this hypothesis, the average catch:TAC ratios for target species and the proportion of target species with high catch:TAC values should increase.

Hypothesis 2: Fishers will be unable to fully catch target species due to the high risk of exceeding low TACs of constraining species under catch shares. Under trip limits, fishers had the ability to discard excess landings so the risk of exceeding trip limits for constraining species was less of a factor. Whereas under catch shares, observers count both landings and discards against quota, so the risk of exceeding TACs for constraining species becomes a limitation on fishing activity. If the risk of exceeding TACs for constraining species is sufficiently high, catch:TAC ratios for target stocks should decrease, and catch:TAC ratios for constraining stocks should be unchanged or decrease under this hypothesis.

Hypothesis 3: Fishers will be unable to fully catch target species because of limited quota availability for constraining species. If the risk of exceeding TACs for constraining species is manageable, catch:TAC ratios for constraining species should be at or near one, and target species ratios will be unchanged or decrease. Note that throughout the text, constraining stocks are defined to be stocks for which the risk of exceeding quotas is high. However for this hypothesis, the definition of constraining stocks is relaxed as the risk of exceeding constraining stocks is low.

2.3 METHODS

2.3.1 Catch:TAC Ratios

Catch:TAC ratios were calculated to measure the abilities of fishers to meet management targets before and after catch shares. Landings and discard data were compiled for the West Coast fishery and summed to calculate total catches. For 2004-2010, landings and discard data specific to the trawl sector were obtained from the West Coast Groundfish Observer Program. On-board observers estimated discards for monitored vessels. Observer coverage was around 20% of vessels from 2002 to 2010 (Bellman *et al.* 2009) and 100% of vessels after catch share implementation in 2011. Total catch values, summed across all commercial and recreational sectors for each stock, were obtained from annual discard and total catch reports from 2004-2010 (http://www.nwfsc.noaa.gov/research/divisions/fram/observation/data_products/species_management.cfm) and used to calculate TACs specific to the trawl sector. For 2011-2013, total catch values (the sum of landings and discards) for the trawl sector were obtained from the Pacific Coast Groundfish Individual Fishing Quota database (https://www.webapps.nwfsc.noaa.gov/ifq/).

Total allowable catch values were compiled for the West Coast fishery, however the definition of the "TAC" differed through time. From 2004-2010, the trawl sector was managed with trip limits instead of quotas. Trip limits were set on a bimonthly basis but were not a hard cap on landings. As a result, TACs for 2004-2010 had to be calculated from coast-wide management values (including all commercial and recreational sectors) reported in annual discard and total catch reports. These coast-wide management values were taken to be those reported as optimum yields or those reported as allowable biological catches if optimum yield values were not listed. For 2011-2013, TACs were the allowable catch limits specific to the trawl sector reported in the Pacific Coast Groundfish Individual Fishing Quota database (https://www.webapps.nwfsc.noaa.gov/ifq/).

Total allowable catch values specific to the trawl sector from 2004-2010 were calculated based on the proportion of trawl catches in coastwide catches. Management limits (such as allowable biological catch or annual catch limits) were set by managers for both commercial and recreational sector. However, a trawl-sector-specific TAC value is necessary to keep catch:TAC ratios comparable before and after catch share implementation. The trawl-sector-specific TAC was calculated based on the proportions of trawl catches in total catches:

$$P_{x,t} = \frac{T_{x,t}}{F_{x,t}} \tag{2.1}$$

where $P_{x,t}$ is the proportion, $T_{x,t}$ is trawl catches, $F_{x,t}$ is total catches for species x in year t. Trawl TAC was calculated as:

$$TAC_{x,t} = PAvg_x MV_{x,t} \tag{2.2}$$

where $PAvg_x$ is the arithmetic mean of proportions $P_{x,t}$ from 2004 to 2010 for species x, $MV_{x,t}$ is the coast-wide management value (optimum yield or allowable biological catch) from Annual Groundfish Fishing Mortality reports for species x in year t. If catch:TAC ratios were calculated using $P_{x,t}$ rather than $PAvg_x$, both the numerator and denominator of catch:TAC calculations contain $T_{x,t}$ which subsequently cancels out [See Appendix A]. The Pacific Council set both trawl-specific and coastwide management values in 2011-2013, and calculations from this method are highly correlated with the actual trawl-specific TACs ($R^2 = 0.99$, Figure A1). Catches were calculated to be the sum of landings and discards from the trawl sector, because although discards did not count towards bimonthly trip limits from 2004-2010, regulations were based on total catches. Discards of lingcod and sablefish were assumed to have a 50% mortality rate, and catch calculations for these species were adjusted accordingly.

For the BC fishery, landings and catch data were obtained from observer data in Fisheries and Oceans Canada's PacHarvest database for 1994-1996 and from publicly available groundfish trawl summary documents for 1997-2013 released by Fisheries and Oceans Canada. TACs were obtained from the Groundfish Integrated Fisheries Management Plans reported annually by Fisheries and Oceans Canada for 1994-1996 and groundfish trawl summary documents for 1997-2013 (e.g. 2012-2013 Groundfish Trawl Summary of Catch vs Available Weight). Fishing seasons in BC are not based on calendar years and for most years start and end in February. For simplicity, we refer to fishing seasons by the predominant year e.g., the fishing season that starts 21 February 2011 and ends 20 February 2012 is labeled 2011.

Average catch:TAC ratios were calculated in the three years before and three years after catch share implementation (West Coast: 2008-2010 vs. 2011-2013; BC: 1994-1996 vs. 1997-1999) at the fishery-wide, group-wide (target, constraining, other), and individual stock scale.

Data for the BC fishery were unavailable prior to 1994, thus only the three years before and after could be analyzed. Fishery-wide catch:TAC averages used ratios from all stocks and group-wide averages used ratios from all stocks in each category. All averages were calculated with an unweighted arithmetic mean.

2.3.2 Target and Constraining Species

Fisheries scientists familiar with each of the fisheries were consulted to identify which species were targeted in each fishery. Based on these discussions, target species were assumed to be Dover sole, sablefish, and lingcod. Additionally, the West Coast fishery targets longspine thornyhead (*Sebastes altivelis*), petrale sole, and shortspine thornyhead, and the BC fishery targets yellowtail rockfish (*Sebastes flavidus*), Pacific ocean perch, yellowmouth rockfish (*Sebastes reedi*), petrale sole, widow rockfish, Pacific cod (*Gadus macrocephalus*), walleye pollock (*Theragra chalcogramma*), and silvergray rockfish (*Sebastes brevispinis*).

Constraining species were assumed to be those with rebuilding plans (West Coast fishery) or those listed as Endangered or Threatened by the Species At Risk Act (BC fishery) in Canada. For the West Coast fishery these species were canary rockfish, Pacific ocean perch, yelloweye rockfish, darkblotched rockfish, bocaccio, cowcod, and widow rockfish. For the BC fishery constraining species were canary rockfish, longspine thornyhead, rougheye rockfish (*Sebastes aleutianus*), yelloweye rockfish, and quillback rockfish. An additional constraining species in BC is bocaccio, which is listed by the Species At Risk Act but must be discarded as part of the BC catch share system.

Data for Pacific whiting (*Merluccius productus*) were excluded from analyses as the fishery is subject to different constraints. Whiting fishers typically use midwater trawls rather than bottom trawls and rarely encounter the species like yelloweye and canary rockfish (Taylor *et al.* 2014) which have the lowest TAC values.

2.3.3 Hypothesis Testing

Permutation tests were used to statistically evaluate the effects of catch shares at the fishery-wide scale and at the categorical scale (target, constraining, and other). Catch:TAC ratios for each stock were sampled without replacement from the six year time period under evaluation. Arithmetic means were calculated across the first three samples (“before”) and last three samples (“after”) across all stocks of interest. This process was repeated for 1000 iterations. P-values were assigned based on the proportion of iterations with before/after differences more extreme than the observed difference. The BC fishery had insufficient stock-specific data before catch share implementation to conduct this permutation test.

2.4 RESULTS

2.4.1 Hypothesis Testing

Permutation tests on catch:TAC ratios in the West Coast fishery showed statistically significant declines in catch-quota balancing for the whole fishery, constraining stocks, and other stocks. After catch share implementation, catch-quota balancing for the whole fishery had an observed change of -0.11 ($p = 0.001$). Constraining stocks had an observed change of -0.25 ($p = 0.001$), and other stocks had an observed change of -0.05 ($p = 0.02$). Target stocks had an observed change of -0.11 ($p = 0.07$). Decreases at all levels were most consistent with Hypothesis 2, suggesting that the risk of exceeding constraining species quotas is high.

Statistical analyses were not possible in the BC fishery as both target and constraining stocks were managed as mostly complexes prior to catch shares and single stocks after catch shares. Thus, the null hypothesis that catch shares had no effect on catch-quota balancing cannot be rejected. However, a number of descriptive results highlight the longer term trends seen in each fishery at different scales.

2.4.2 Descriptive Results

Average catch:TAC ratios at the fishery-wide level showed a decreasing trend in the West Coast fishery (Figure 2.3a) and remained generally constant in the BC fishery (Figure 2.3b). In the West Coast fishery, catches were low and TACs were high in the three years after catch shares (Figure 2.3c and e). In the BC fishery, both catches and TACs were relatively low and catch:TAC ratios were greater than 0.5 (Figure 2.3d and f). The averaged catch:TAC ratios, summed catches, and summed TACs are shown in Table 2.2.

Time series of average catch:TAC ratios at the category level show similar trends to the fishery-wide trends. In the West Coast fishery, target and constraining species have been generally declining since the beginning of the time series (Figure 2.4a and c). Maximum catch:TAC ratios for target and constraining species occurred in 2005 (Figure 2.4a and c). In the BC fishery, target and constraining species trends have been comparatively stationary (Figure 2.4b and d).

In the West Coast fishery, the proportion of target stocks with a catch:TAC ratio greater than 0.5 was 0.71 (n = 21) in the three years before catch shares and 0.40 (n = 25) in the three years after (Figure 2.5a-b). Sablefish, petrale sole, longspine thornyhead, and shortspine thornyhead had catch:TAC ratios that were over 0.5 in at least one year after catch shares (Figure 2.6). The proportion of constraining stocks with catch:TAC ratios less than 0.5 was 0.39 (n = 18) in the three years before catch shares and 0 (n = 18) in the three years after (Figure 2.5b-c).

Darkblotched rockfish, Pacific ocean perch, and canary rockfish had catch:TAC ratios greater than 0.5 in at least one year of the three years prior to catch share implementation (Figure 2.6).

In the BC fishery, the proportion of target stocks with catch:TAC ratios greater than 0.5 was 0.58 (n = 28) in the three years before catch shares and 0.75 (n = 84) in the three years after catch shares (Figure 2.7a-b). All target stocks had catch:TAC ratios greater than 0.5 at least once in the years after catch shares (Figure 2.8). The proportion of constraining stocks after catch shares was 100% (n = 16) in the three years after catch shares. Canary rockfish and rougheye rockfish had generally high catch:TAC ratios in the years after catch shares (Figure 2.8). Catch:TAC ratios in the risk pool in the West Coast fishery were similar to the values from the rest of the fishery. Petrale sole in 2012 was the only target species that had a lower catch:TAC ratio in the risk pool than in the fishery (Figure 2.6). Darkblotched rockfish and Pacific ocean perch in 2011 and 2012 were the only constraining species that had lower catch-quota balancing in the risk pool than in the fishery (Figure 2.6).

2.5 DISCUSSION

Catch shares did not improve catch-quota balancing in the West Coast and BC fisheries. The West Coast fishery had a statistically significant decline in fishery-wide-catch-quota balancing and a decline in constraining and other stock catch-quota balancing. Further, there was little evidence to support Hypothesis 1, that catch shares allow fishers to more fully catch TACs for target species, and little evidence to support Hypothesis 3 that the risk of catching constraining species is manageable. Results suggest that the risk of catching constraining species is high under catch shares, evidenced by the decline in catch:TAC ratios for constraining and target species. Limited data prior to catch shares in the BC fishery precluded statistical analyses, thus the null hypothesis that catch shares have no effect on catch-quota balancing is not rejected.

However, the numbers from the BC fishery show that catch-quota balancing under catch shares was comparatively higher than that of the West Coast fishery at the fishery-wide scale and for target and constraining stocks. It seems unlikely that the risk of catching constraining species has an effect on catch-quota balancing in the BC fishery.

The BC fishery had a higher degree of catch-quota balancing than the West Coast fishery—perhaps evidence that quota transfers in BC are quicker and more efficient than those in the West Coast fishery. Both Hypothesis 1 and Hypothesis 3 require quota to flow fluidly among fishers. The high catch-quota balancing, evidenced by catch:TAC ratios > 0.75, for both target and constraining stocks in the BC fishery indicates that fishers have developed methods of distributing quota to those in need. This result is consistent with a previous study that identified the movement of quota through barters rather than monetary transactions in the BC fishery (Holland 2013). Quota transfers may be less fluid in the West Coast fishery due to low constraining stock quotas. One reason for this is that the risk of exceeding quotas for constraining species is so high that fishers are likely to retain quota until the end of the season (J. Sullivan, pers. communication). Quota markets in New Zealand seem to be reasonably developed with traders having some sense of the value of different quotas (Newell *et al.* 2005). Barter markets in the BC fishery seems to transfer quota to those in need, although it seems unlikely for a economically efficient market to develop in the West Coast fishery due to fishers reluctance to give up constraining species quota.

Catch-quota balancing in the West Coast fishery appeared to be more affected by constraining stocks than in the BC fishery. In the West Coast fishery, the risk of exceeding constraining species quotas is so high that many fishers are fishing more conservatively or less overall (M. Burden, personal communication). This reduction in effort is seen here, as no constraining stocks had catch:TAC ratios greater than 0.5 in the West Coast fishery. Fishers in the BC fishery have demonstrated the ability to control catch compositions (Branch and Hilborn 2008), whereas the constraints in the West Coast fishery may preclude a similar degree of control. The few stocks with catch:TAC ratios near 1 could be selected by timing fishing or switching gear types. Petrale sole form spawning aggregations in winters (Haltuch *et al.* 2013), and sablefish quotas can be transferred to the fixed gear pot sector which is more selective than trawls. Fishers in the BC fishery may have higher degrees of regional specialization that would lead to high catch-quota balancing for both target and constraining stocks.

Policies such as carryover rules, deemed value systems, and species transformations are designed to grant fishers more flexibility. In these fisheries, carryover rules already grant fishers the ability to transfer unused quota to the following year. Carryovers of up to 10% a single-species TAC are permitted in the West Coast fishery, and in the BC fishery, carryovers of 30% for most species, 15% for lingcod, and 10% for dogfish are permitted. However, carryover rules were found to have little effect on catch-quota balancing in a meta-analysis of catch share fisheries (Melnychuk *et al.* 2014). Current carryovers of up to 10% have resulted in relatively low catch-quota balancing, and allowances may need to be much greater than 10% to have an effect on catch-quota balancing. Deemed value systems, in which fishers pay fees for landings in excess of quotas, are used in New Zealand to incentivize retention of bycatch and discourage fishers from targeting species without sufficient quota. Bioeconomic simulations of deemed value systems show that overexploitation of bycatch species was avoided when target and bycatch species had low spatial overlap (Holland and Herrera 2006). Allowable catches were exceeded in cases where species had more spatial overlap (Holland and Herrera 2006). These results are not applicable to the West Coast fishery as there is generally a great deal of overlap between target and constraining species, and TACs cannot be exceeded. Catch share fisheries in Iceland allow species transformations in which quota of one species can be converted to quota of another to improve catch-quota balancing. However, this system is similarly inapplicable to the West Coast fishery as the Icelandic system leads to frequent quota overages (Woods *et al.* 2015).

Risk pools may be the most promising means of improving catch-quota balancing in the West Coast fishery due to hard TACs. Risk pool fishers were effective at improving catch:TAC ratios for target species while avoiding constraining species. The Alaskan Amendment 80 fleet is also managed similar to a risk pool and had similar results (Abbott *et al.* 2015). However, applying risk pools at a larger scale may lead to economic free-riding (Evans and Weninger 2013) and reduce incentives to fish selectively and pool quota (Holland and Jannot 2012).

A number of factors that were not explicitly accounted for here may have affected the results. Conditions in the seafood market may alter the incentives to target certain species, and interactions between exclusivity and industry involvement were found to have the strongest effect on catch:TAC ratios (Melnychuk *et al.* 2014) but were not accounted for here. Price data were compiled from the NOAA Commercial Fisheries Statistics database (http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index) to gain some sense of market conditions from 2008-2013. Revenues and landings for species from the West Coast fishery were compiled, and price per kilogram for nearly all species remained relatively unchanged from 2008-2013 (Figure A2). Coastwide sablefish had a maximum value in 2011 (Figure A2), but sablefish north and south catch:TAC ratios were near one in 2011 and generally high throughout 2008-2013. Prices per kilogram are a rough proxy for market conditions, but there may have been strong incentives to target sablefish selectively in 2011.

Both fisheries have undergone a number of management changes. For example, prior to catch shares in the West Coast fishery, discards were not managed and there were no TACs specific to the trawl sector. The calculated TACs represent an approximation, and West Coast fishers were not managed with hard quotas. Changes in TACs would likely affect catch-quota balancing. In the West Coast fishery, TACs underwent decreases for sablefish, petrale sole, and canary rockfish (Fig. S3), but TACs in the BC fishery underwent less sharp declines (Fig. S3).

Assumptions about management may have affected the degrees of catch-quota balancing in each fishery. Fishers in the West Coast fishery and risk pool may have been adjusting to new management and additional restrictions from 2011-2013, so the data may not represent the limits of fishers' abilities. The distinction between target and constraining species in the BC fishery may not be well defined, which is perhaps one of the key differences between the two fisheries. The high degree of overall catch-quota balancing in the BC fishery is unaffected by species classifications.

2.6 CONCLUSION

In conclusion, it is clear from the results that catch shares will not result in perfect catch-quota balancing in multispecies fisheries, despite the increased fishing flexibility, incentives for information sharing and cooperation, and transfer of quota. Specifically, there may be few policies to increase catch-quota balancing as TACs for constraining species become more limiting.

2.7 ACKNOWLEDGEMENTS

Thanks to Merrick Burden, Jim Hastie, Brad Pettinger, Jim Seger, Joe Sullivan, and Bruce Turris for valuable insights into each of the fisheries. Thanks to Chris Grandin, Ian Taylor, and

Nathan Taylor for feedback on fish classifications. Thanks to Tim Essington, Dan Holland, and an anonymous reviewer for comments that improved the quality and clarity of the manuscript. PTK was supported by a Sea Grant/NOAA Fisheries Population Dynamics Fellowship, and PTK and TAB were supported by the Gordon and Betty Moore Foundation.

2.8 TABLES

Table 2.1: Constraining species quota from 2011. Coastwide TACs and area-specific TACs reported where applicable. Bolded TAC values are considered constraining.

Species	**BC TAC**	**WC TAC**
Bocaccio	-	**60**
Canary rockfish	**1004**	**26**
BC Area 3C/3D	**612**	-
BC Area 5A/5B	**268**	-
BC Area 5C/5D	**104**	-
BC Area 5E	**20**	-
Cowcod	-	**1.8**
Darkblotched rockfish	-	**251**
Pacific ocean perch (coastwide)	**6104**	**119**
BC Area 3C	**323**	-
BC Area 3D	**274**	-
BC Area 5A/5B	**2239**	-
BC Area 5C/5D	**2558**	-
BC Area 5E	**710**	-
Longspine Thornyheads	**522**	1966
Quillback, china, copper, tiger	**5**	-
Rougheye rockfish	**823**	-
Yelloweye rockfish	**7**	**0.6**

Table 2.2: Descriptive statistics from BC and West Coast fisheries

Fishery Wide	**3 Years Before**	**3 Years After**
WC Average catch:TAC	0.41	0.29
BC Average catch:TAC	0.7	0.62
WC Summed Catches (mt)	78,584	57,492
WC Summed TAC (mt)	161,178	199,225
BC Summed Catches (mt)	93,662	78,746
BC Summed TAC (mt)	157,020	127,795
Group Averages		
WC Targets avg. catch:TAC	0.62	0.49
WC constraining avg. catch:TAC	0.47	0.22
BC Targets avg. catch:TAC	0.65	0.67
BC constraining avg. catch:TAC	NA	0.78

2.9 FIGURES

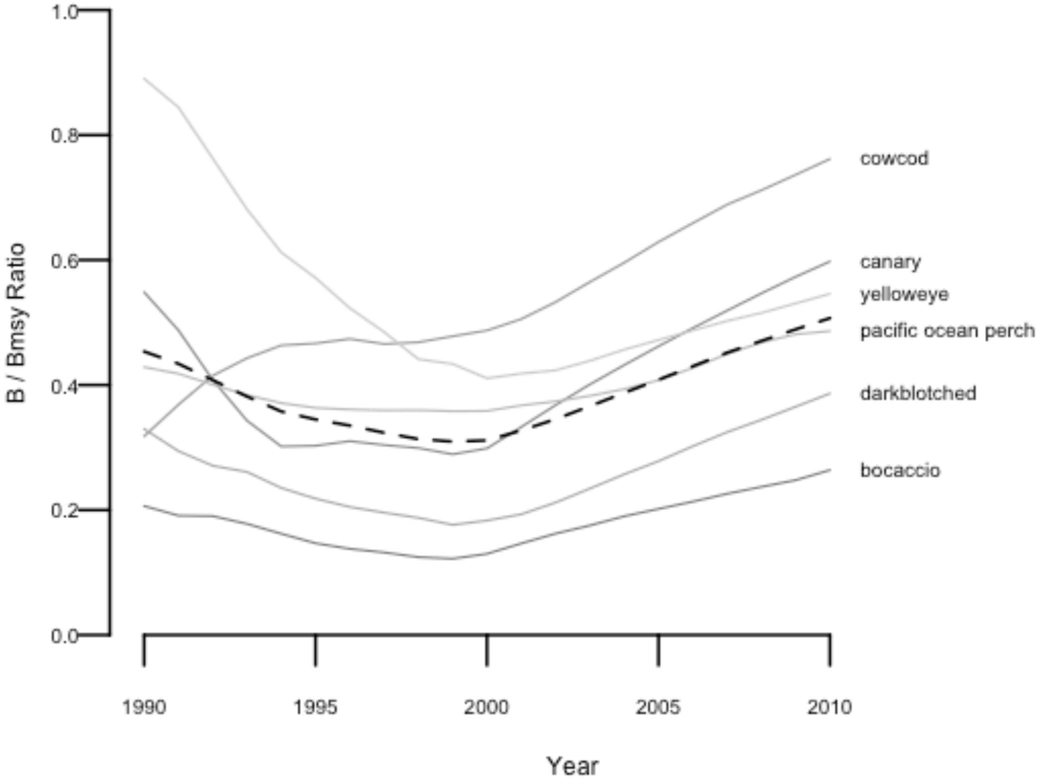

Figure 2.1: Trajectories of B / BMSY for constraining species in the West Coast fishery. The black dotted line indicates the average ratio across the Trajectories of B / B_{MSY} for constraining species in the West Coast fishery. The black dotted line indicates the average ratio across the six species. Values come from stock assessments for cowcod (Dick and MacCall 2014), canary rockfish (Wallace and Cope 2011), yelloweye rockfish (Taylor 2011), Pacific ocean perch (Hamel and Ono 2011), darkblotched rockfish (Gertseva and Thorson 2014), and bocaccio (Field 2013).

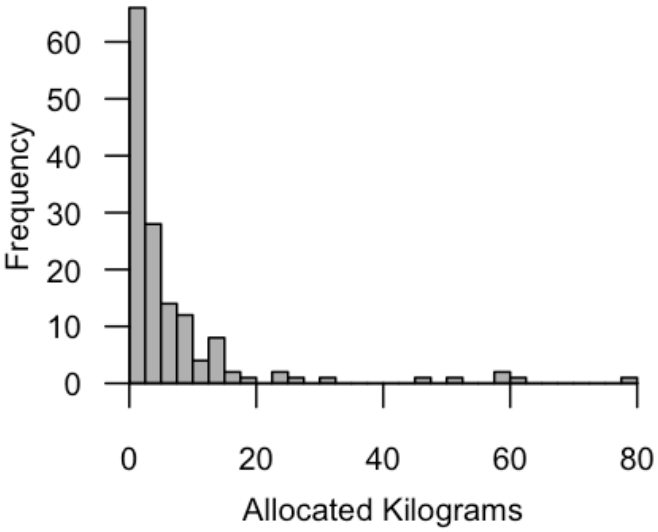

Figure 2.2: Histogram of individual quota allocations for yelloweye rockfish (*Sebastes ruberrimus*) in the 2011 West Coast fishery. Forty-six percent of quota owner (n = 145) receieved fewer than 2.3 kg of quota.

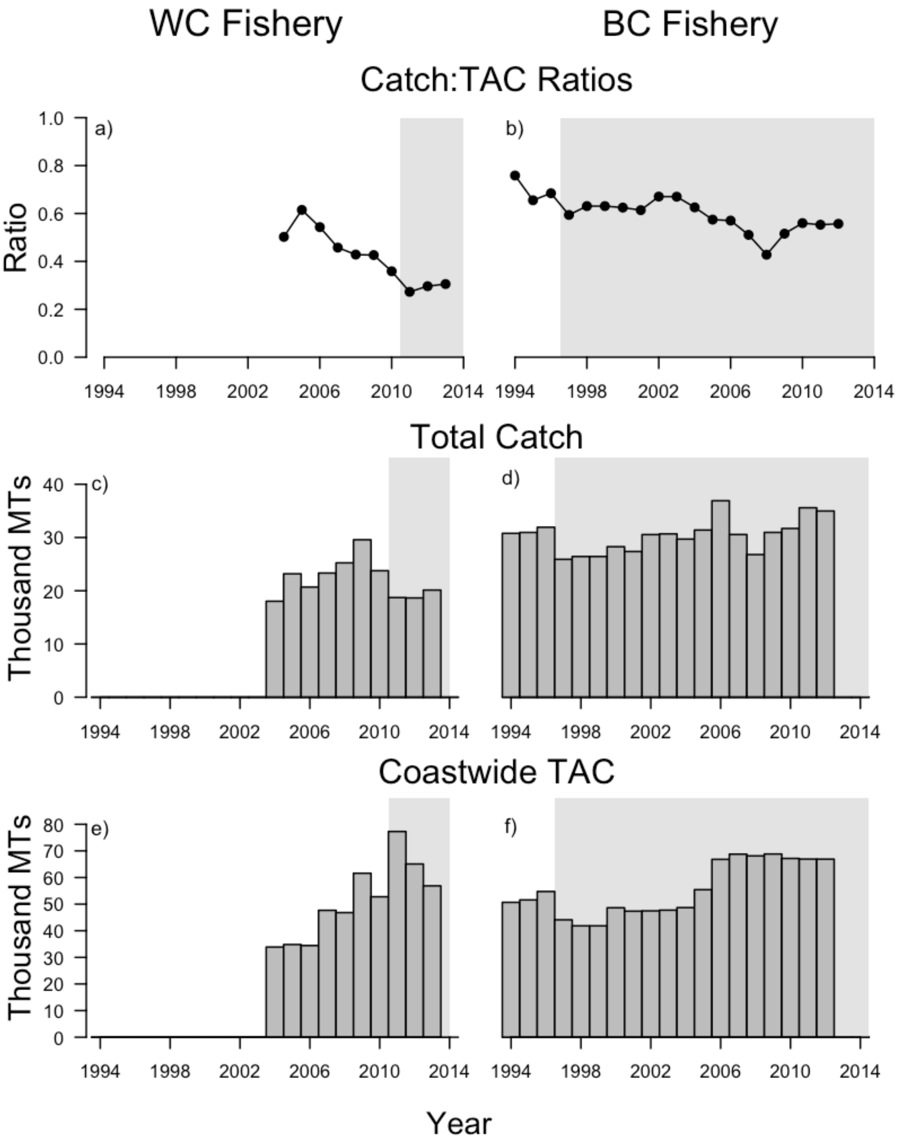

Figure 2.3: Fishery-wide catch:TAC ratios (a and b), total catch values (c and d), and TAC values for each fishery (e and f; excluding Pacific whiting).

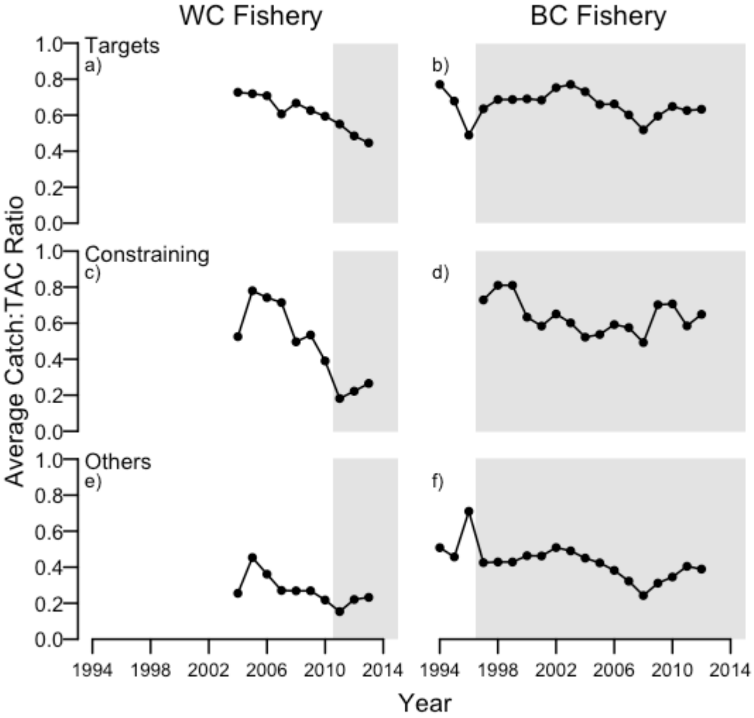

Figure 2.4: Plots of average catch:TAC ratio by year from 1996 to 2013 for target species (a), constraining species (b) , and other species (c). White bars indicate values from the BC fishery, and gray bars indicate values from the West Coast fishery. Years under catch share management (1997-2013 in BC and 2011-2013 in West Coast) are indicated by a light gray background color.

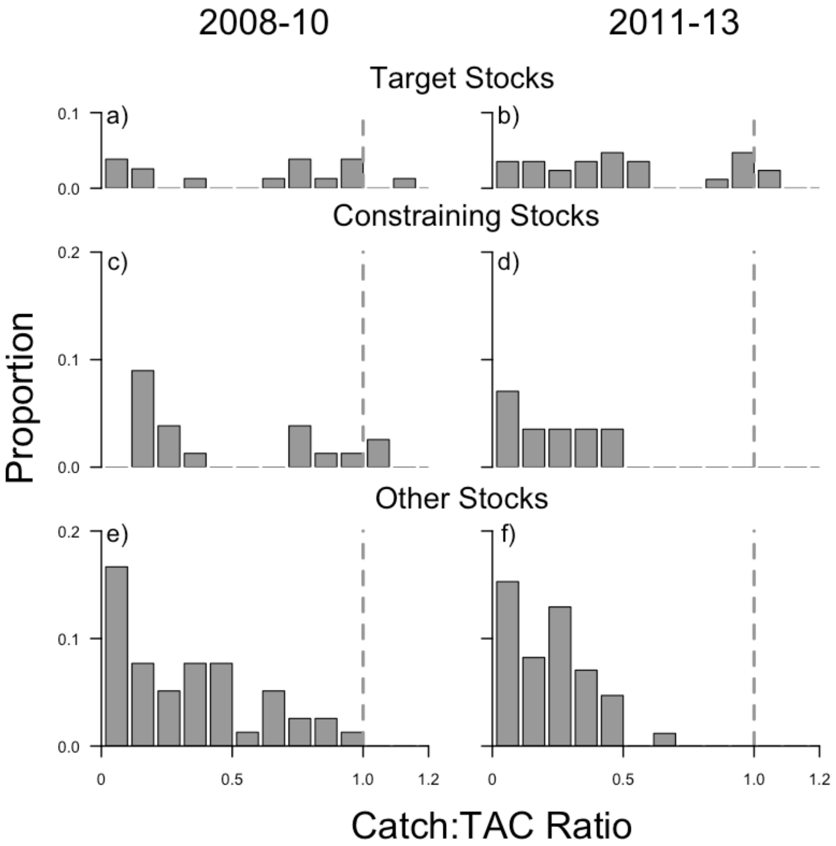

Figure 2.5: Histograms for catch:TAC ratios in the West Coast fishery. Shown are ratios for the three years before (a, c, e) and after (b, d, e) catch share implementation.

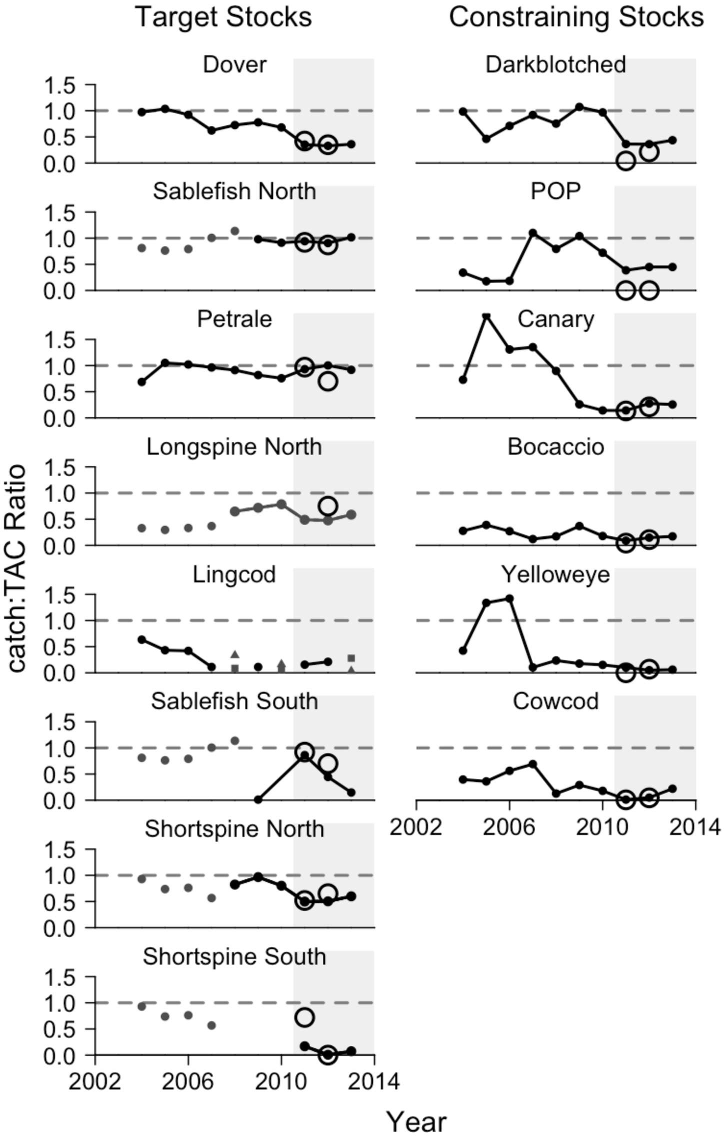

Figure 2.6: Time series of catch:TAC ratios for both target and constraining species in the West Coast fishery. Gray shading indicates years under catch share management. Squares in the sablefish north and sablefish south plots indicate years with the two stocks were managed as one stock. In 2008, 2010, and 2013, lingcod were managed as northern (squares) and southern (triangles) stocks. Circles in the shortspine panels indicate years in which the stock was managed on a coastwide basis. There were no TACs for southern shortspine thornyhead from 2007 to 2010. Open circles indicate catch:TAC ratios from the risk pool.

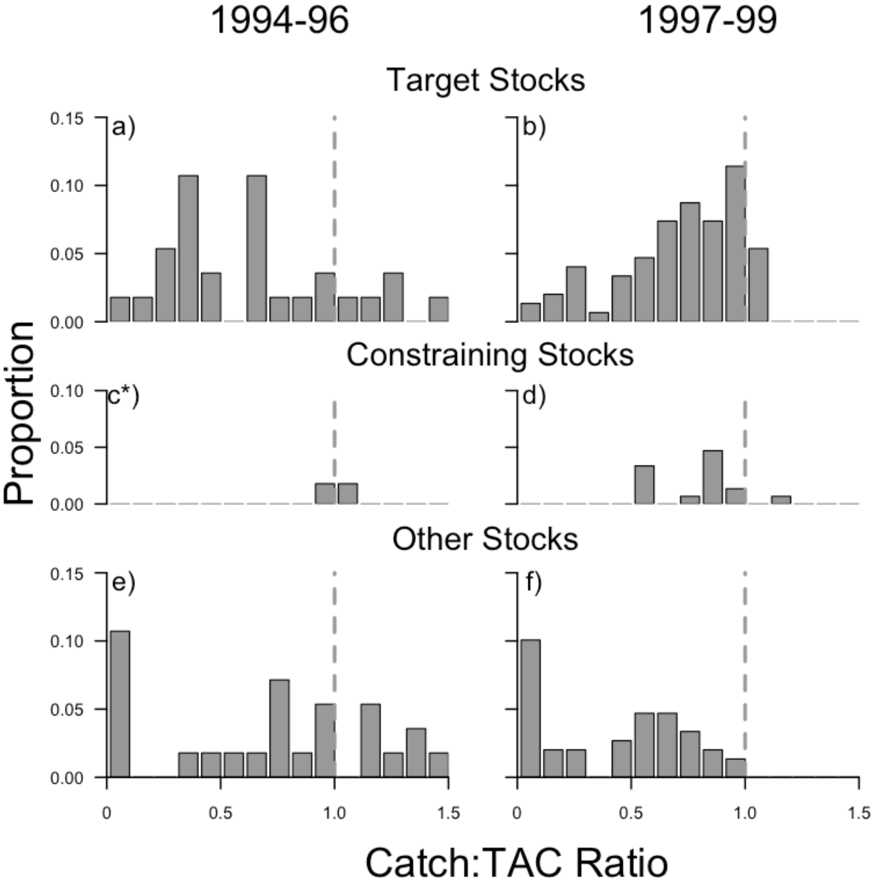

Figure 2.7: Histograms of catch:TAC ratios in the BC fishery. Shown are ratios for the three years before (a, c, e) and three years after (b, d, f) catch share implementation. Management complexes in which multiple species were managed with TACs were excluded from this figure. The exception is the constraining stocks panel in 1994-1996 (indicated by *) in which complexes that contained constraining species were included, since no constraining species were managed as a single species.

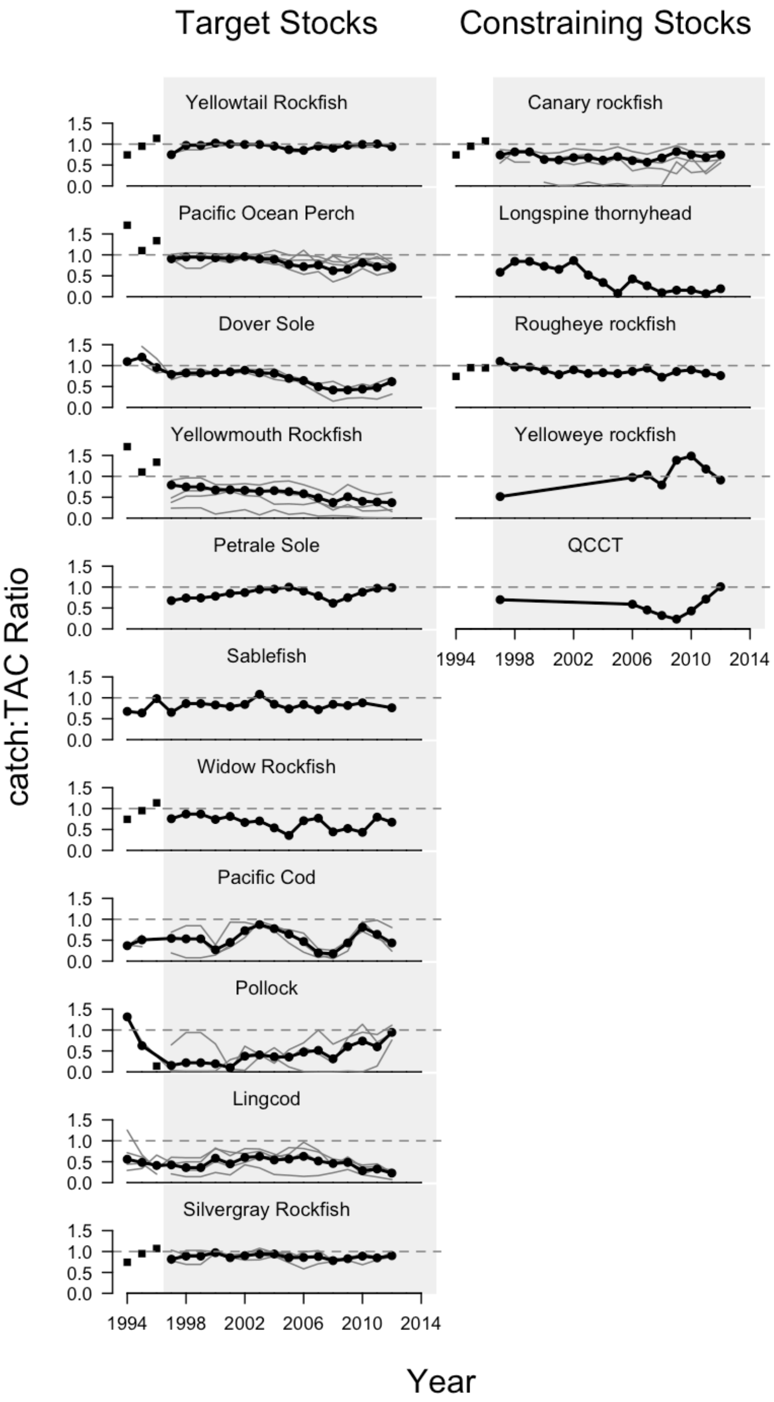

Figure 2.8: Time series of catch:TAC ratios for both target and constraining species in the BC fishery. Catch shares were implemented in 1997, indicated by gray shading. Squares indicate years where stocks were managed as a complex. Gray lines indicate area-specific catch:TAC ratios and connected black points indicate average catch:TAC ratios across areas. The gap in the

yelloweye and quillback, china, copper, tiger rockfish (QCCT) complex is due to years where landings were prohibited.

Chapter 3. Fishing location depends on habit, economics, and distance in a catch-share fishery

3.1 ABSTRACT

Fishers are highly adaptable to management changes, and management often fails when they respond to regulations in unanticipated ways. Catch shares should result in declines in fleet size, while shifts in the spatial effort are difficult to predict. Catch shares were implemented in 2011 in the US West Coast Groundfish fishery. Individual quotas for the most overfished species were as low as one fish per year, and the risk of exceeding overfished species quotas was high. Due to this high risk, the spatial footprint of effort may be expected to contract and concentrate in areas with more predictable species mixes. Additionally, communication and collaboration among fishers may increase. We measured shifts in fishing effort in each of the two years before and four years after catch share implementation, and fit random utility models to these data to measure port-specific behavioral changes. Fishing effort declined and concentrated in areas closer to the coast. Fine-scale individual vessel habits (within five kilometer radii), distance from port and the previous tow, and revenues were significant predictors of fishing locations ($p < 0.05$) in all ports in all years. There was also evidence that in Astoria and Newport, the two biggest ports, fishers were hesitant to fish in areas recently unfished by members of the fleet. Bycatch expectations, accounted for as the cost of purchasing quota for each species, did not affect location choices. Thus, somewhat to our surprise, fishing locations were better explained by habits, distance, and revenue rather than avoidance of costs associated with fishing in areas with the highest quota prices.

3.2 INTRODUCTION

Catch shares are implemented to address the common problem of overcapitalization and lack of flexibility in fisheries. In open-access fisheries, overcapitalization leads to increasing numbers of fishers, who have incentives to outcompete others for dwindling fish amounts (Gordon 1954). Setting an overall catch limit solves the issue of overfishing, but not overcapitalization (Homans and Wilen 1997). Under catch shares (of which the most common type is individual transferable quotas), individual entities are allocated discrete amounts of quota to fish over an extended season and are allowed to buy, sell, and lease their quota. Generally individual accountability increases and entry to the fishery is controlled by market forces, with initial allocations determined by historical participation in most fisheries (Lynham 2014). Catch shares potentially align economic and conservation incentives (Hilborn *et al.* 2005; Hilborn 2007b) and as a result, are often proposed as solutions to improve fisheries management (Grafton *et al.* 2006; Costello *et al.* 2008; Worm *et al.* 2009).

Catch shares result in positive ecological and economic results but their social outcomes are mixed. Catch shares reduce the frequency of fisheries collapses (Costello *et al.* 2008), lead to better tracking of management targets (Melnychuk *et al.* 2011), positively impact target species (Chu 2008; Branch 2009), and reduce variability in ecological indicators (Essington 2010). Fleet sizes typically decrease under catch shares (Branch 2009), and economic efficiencies are improved as fewer boats each catch more fish, which occurred in both New Zealand (Annala 1996) and Iceland (Arnason 1996). Catch shares slow the race to fish (Birkenbach *et al.* 2017) allowing fishers to time landings to fetch optimal prices in the market (Scheld and Anderson 2014). However, fisheries become less diverse under catch shares (Holland *et al.* 2017), and individuals can be excluded from fisheries (Copes 1986), which are intended to be a public good

(Macinko and Bromley 2002). In New Zealand, for example, the Māori have major ownership stakes in fisheries yet face barriers to participation for a variety of reasons including food safety regulations that prohibit direct dock-to-consumer fish sales (Bodwitch 2017). In Iceland, catch shares resulted in quota concentration among a few entities and quota moved out of small single-enterprise communities with few alternative employment opportunities (Eythorsson 2000). Entry to catch share fisheries can become prohibitively expensive for those without access to capital to buy quota, due to concentration and consolidation (Macinko and Bromley 2002; Pinkerton and Edwards 2009). Also, catch share fisheries without accountability lack resource stewardship (Parslow 2010).

The design of catch shares, specifically the forms of flexibility available if catches exceed quotas, dictate the attainment of economic, ecological, and social outcomes. Economic gains come from reduced overcapitalization which improves economic efficiency. Fishers with transferable quota may consider their opportunity costs and decide that they could make more money by selling their quota and changing jobs. Thus, it is expected that the fleet size will decrease, but unlike a buyback plan, those exiting the fishery will receive compensation directly from those who stand to benefit from their exit. Factors like uncertainty over quota prices, vessels that are not suited to alternative fisheries, and of course a lack of alternatives, can limit the degree of fleet reduction (Squires *et al.* 1998).

One key aspect of catch shares is the possibility of dealing with the weak stock problem in multispecies fisheries. This problem occurs when many species are caught together, but some (the “weak stocks”) can sustain much lower fishing mortality than other species. Catch shares promise great flexibility in that quotas can be traded to match catches or fishing strategies, while also adding avoidance incentives through higher quota lease price for weak-stock species with more constraining quotas. Under certain conditions, catch shares might provide sufficient flexibility to fully catch quotas of all species. The types of flexibility to match catches to quotas can include species exchanges in which catch of one species can be converted into catch of another (Woods *et al.* 2015), carryover rules in which a percentage of quota can be available next year, deemed value payments in which fishers pay money for catches that exceed quotas, quota leasing and sales through markets (Sanchirico *et al.* 2006). However, species conversions can lead to overfishing (Woods *et al.* 2016), and monetary quota markets may not develop for species (Holland 2013; 2016). Discarding at sea is another way of avoiding catch limits, requiring some form of at-sea monitoring. Where this is present, discard rates may actually decline under catch shares (Branch *et al.* 2006b).

Under catch shares, the risks of exceeding quota amounts are magnified prior to deploying fishing gear. The ability to buy or lease quota might mitigate some of this risk, although the risk considerations are different under trip limits as fishers have the ability to discard fish at sea. Risks will likely be highest if fishers have quota allocations that are high for target species and low for unavoidable species. In this case, there will always be a risk of exceeding the low quota allocations, thus fishers might be unwilling to make quota for those species available to others until the very end of the season—at which point nobody needs quota. Slow and inefficient market development has been found in the US West Coast Groundfish fishery (Holland 2016) and formal and informal agreements to pool quotas also exist (Holland and Jannot 2012).

Fleet responses to management can be unpredictable and result in unintended outcomes (Branch *et al.* 2006a; Hilborn 2007a; Fulton *et al.* 2010). Here we evaluate the effects of catch shares on the amount of fishing effort, spatial distribution of fishing effort, and location choices in the UW West Coast Groundfish fishery. Catch shares were implemented in this fishery with the goals of increasing net economic benefits, creating individual economic stability, providing for full utilization of trawl sector allocation, considering environmental impacts, and achieving individual accountability of catch and bycatch (Pacific Fishery Management Council and NMFS 2010).

3.2.1 West Coast Groundfish Description

Overcapitalization and overfishing have been problematic in the West Coast Groundfish fishery's roughly 50-year history. Overcapitalization can be traced back to 1976, when US waters were closed to foreign vessels, and the federal government provided loans and tax credits to improve domestic fishing capacity (Mansfield 2001). Harvest guidelines were based on inflated assumptions about rockfish productivity, and in the mid-1990s this assumption resulted in many populations at low levels (Ralston 2011). The high landings through the 1980s and 1990s declined to the point that the fishery was declared a Federal Disaster in 2000, which sparked interest in catch-share management.

In this fishery, catch shares were considered starting in 2004, and eventually implemented in 2011. Prior to this, in 2003, the Pacific Fishery Management Council concluded that 27-41% of the limited entry fleet would be needed to fully catch the sablefish and groundfish allocations (TNC 2008) and purchased 92 of the 284 permits in the fishery as part of a vessel buyback program. Further from the 1980s, the fishery was managed with trip limits in which landing limits for species and area were set for weekly, biweekly, or two-month time periods. Trip limits provide a coarse tool to limit fishing mortality as discarding was permitted and unaccounted for. Managers reduced trip limit amounts to reduce overfishing, which had the unintended consequence of increasing discarding rather than reducing overfishing (Bellman and

Heery 2013). Catch shares were implemented in 2011 with the goals “to increase net economic benefits, create individual economic stability, provide for full utilization of trawl sector allocation, consider environmental impacts, and achieve individual accountability of catch and bycatch (Pacific Fishery Management Council and NMFS 2010).”

In this fishery, catch shares likely increased net economic benefits for some and may have improved individual economic stability, but have not provided for full utilization of trawl sector allocation (Kuriyama *et al.* 2016). Decreases in number of tows and vessel size has reduced encounters with living habitat (Barnett *et al.* 2017) a positive environmental impact. Also, there is now a high degree of individual accountability of catch and bycatch. Communities with the least quota experienced improvements in standard of living, and communities with the most quota experienced improvements in job satisfaction (Russell *et al.* 2016). Low individual quota amounts have likely limited catch-quota balancing (Kuriyama *et al.* 2016) and the effectiveness of quota markets (Holland 2016). Many fishers are reliant on the US West Coast Groundfish fishery, particularly as some ports are less diversified and can be more vulnerable to changes in revenues (Fuller *et al.* 2017).

Here, we evaluate changes in fishing effort, fleet dynamics, and fisher behavior in response to catch shares. We evaluated effort changes in grids on the coast, characterized catch distributions to measure changes in targeting behavior, and fit random utility models to see how fishers weigh different factors in location choices.

3.3 METHODS

3.3.1 Data processing:

For most of our analyses, we combined two data sources for our analysis: logbook data (2007-2010) and observer data (2007-2014). Both data sources contained, for each tow, latitude, longitude, and depth that nets entered and exited the water. Catch compositions were reported by species, although the logbook data did not include discard amounts, while observer data did. Observers monitored roughly 20% of trips prior to 2011, after which observer coverage increased to 100% of all trips (Pacific Fishery Management Council and NMFS 2010). From 2007-2010, we therefore preferred observer records when tows were recorded in both the logbook and observer data.

3.3.2 Spatial Analyses

We divided the coast into grids to measure the spatial changes in fishing effort over time. We hypothesize that effort will likely decline and concentrate in specific areas of the coast. The grids were based on latitude and depth (0.5° by 91 meters, equivalent to 50 fathoms) because the coastline is fairly straight in a north-south direction, and because in some areas of the coast, movement of a few kilometers east or west can result in depth changes of hundreds of meters in the fishery. Tows were assigned to grid cells based on the midpoint between start and end tow locations. To estimate how effort in each grid has changed over time, we fit linear models to the number of tows in each year in each grid cell *g*.

$$Ntows_g = a_g Year + b_g + \varepsilon \text{, where } \varepsilon \sim N(0, \sigma) \tag{3.1}$$

We quantified individual vessel movement before and after catch shares. Vessels that did not remain in the fishery after catch shares. Shifts in fine-scale effort were quantified by calculating the difference between average latitudes and longitudes for the remaining vessels in the four years before and after catch shares. We used ANOVAs for individual-vessel latitude and longitude to calculate significance in the shifts.

3.3.3 Delta Plots

We used the delta plot method developed by Gillis et al. (2008) to measure changes in species targeting before and after catch shares implementation. Delta plots require two values for each species: the skew of catch distribution and proportion of tows that did not capture the species ("zero tows"). Species that are targeted are assumed to be species that are caught in large amounts (negative skew values) and caught frequently (low proportions of zero tows). For each species, skew was calculated from log-10 transformed catch amounts with the equation:

$$\frac{n\sum_{i=1}^{n}(x_i-\bar{x})^3}{(n-1)(n-2)s^3} \tag{3.2}$$

where n is the number of data points, x is the vector of catch values, $\bar{x}$ is the mean of x, and s is the standard deviation of x. The proportion of zero tows was the proportion of tows that did not catch a particular species. For species that are targeted, there will be more tows with higher catches and fewer tows with lower catches, compared to a normal distribution and thus target species will have negative skew values (left-skew distributions) and a low proportion of zero tows, while species that are avoided will have positive skew values and a high proportion of zero tows (Gillis *et al.* 2008).

Before running the delta plot method, we categorized species as targets, constraining species, and groundfish. Target species were Dover sole (*Microstomus pacificus*), lingcod (*Ophiodon elongatus*), longspine thornyhead (*Sebastolobus altivelis*), Petrale sole (*Eopsetta jordani*), sablefish (*Anopoploma fimbria*), and shortspine thornyhead (*Sebastolobus alascanus*). Constraining species were any species under rebuilding plans at some point from 2007-2014: bocaccio (*Sebastes paucispinis*), cowcod (*Sebastes levis*), canary rockfish (*Sebastes pinniger*), darkblotched rockfish (*Sebastes crameri*), Pacific ocean perch (*Sebastes alutus*), and yelloweye rockfish (*Sebastes ruberriumus*). Groundfish species were arrowtooth flounder (*Atheresthes stomias*), bank rockfish (*Sebastes rufus*), chilipepper rockfish (*Sebastes goodei*), English sole (*Parophrys vetulus*), greenspotted rockfish (*Sebastes chlorostictus*), greenstriped rockfish (*Sebastes elongatus*), longnose skate (*Raja rhina*), vermilion rockfish (*Sebastes miniatus*), widow rockfish (*Sebastes entomelas*), yellowtail rockfish (*Sebastes flavidus*).

We calculated the difference in both skew and proportion of zero tows in the four years before (2007-2011) and the four years after (2011-2014) catch share implementation and used permutation tests to estimate if these changes were significant. I resampled the year associated with each tow and calculated skew and proportion of zero tows in the years before and after catch shares. These calculations were repeated 1000 times to evaluate the significance of the actual changes in skew and proportion of zero values. I ran analyses for the combined data set and the 2007-2014 logbook data, to check if the change in data from logbook and observer to purely observer data in 2011 influenced the analysis. The two data types have different levels of accountability, which might result in changes in delta plot values.

3.3.4 Random Utility Modeling

We used random utility modeling to evaluate whether fishers changed how they chose fishing locations before and after catch share implementation. Random utility modeling, also known as discrete choice modeling, assumes that individuals have a set of options (in this case fishing location) and will choose the option that maximizes their utility. Utility is a linear function of distances, revenue expectations, individual habits, and fleetwide habits. Random utility models have been used to study fleet dynamics in US Northeast fisheries (Bockstael and Opaluch 1983; Holland and Sutinen 1999; 2000), Alaskan groundfish fisheries (Abbott and Wilen 2011) and responses to marine reserves (Smith and Wilen 2003).

We expect that fishers under catch shares will fish in new areas and rely on sharing information. Information sharing is likely necessary to catch targets while avoiding constraining species under catch shares. Within a random utility model, fishers will probabilistically weigh their options and fish in the area that maximizes their utility. Their options are formalized through a choice set. A coarse random utility model would divide the coast up in grids and present all grids as possible choices. Here we use a finer-scale choice set that is based on past fleetwide fishing locations (Hicks *et al.* 2014). Fishers have a subset of previous fishing locations to choose from rather than the full history.

3.3.5 Choice Set Specification:

Choice sets were generated by sampling 50 tow locations for each empirical tow in the dataset. Each of the sampled tow locations represents an alternative for fisher consideration. We generated choice sets separately for the top six fleets in the fishery: Astoria, OR; Newport, OR; Charleston, OR; the combined vessels fishing out of Brookings, OR and Crescent City, CA; Eureka, CA; and Fort Bragg, CA. These six fleets account for 75% of the total landings in the fishery. Sampled tow locations came from the same fleet and all previous years. For example, a choice set for the Astoria fleet in 2012 had sampled tow locations from 2007-2012. Vessels were assigned to fleets based on the vessel's most common port of return. Tow locations were sampled in proportion to the depth bins in the empirical data set. Each tow was assigned to a depth bin based on the average recorded depth between start and end tow locations. Depth bins were originally in 50 fathom increments but we report them in meters (0-91 m, 91-183, 183-274, 274-366, 366-549, 549-914, 914-1280).

We considered the three primary factors in location choices to be revenues, distances, and habits. Net revenues for each tow were calculated with the equation:

$$NR = REV - c \tag{3.3}$$

where NR is net revenue for, REV is the total revenue summed across species, and c is the quota costs summed across species. Prices were assigned based on monthly ex-vessel prices for species at each port and assigned without any time lags. Global averages for each species were used for missing values. For annual quota share prices, we used the species-specific four-year average quota costs presented in Holland (2016). Tows that occurred prior to 2011 were not managed under catch shares and had no quota costs, so the net revenue values are equal to total revenues. Revenue and habit variables input to the model were based on a 5 km spatiotemporal radius within a single depth bin and previous 30 days. Fishers might not account for bycatch in monetary terms, as represented here. The challenge is that many target species are often caught with constraining species, and accounting for bycatch with spatial catch expectations, for example, may confound parameter estimation.

We included revenue, distance, and habit variables in the model. Revenue and habit variables were calculated for each empirical and sampled location in the choice set. Note that one choice in the choice set consists of one empirical tow location and 50 sampled locations, and the empirical tow location has an associated tow date. We applied a spatiotemporal radius to filter the combined logbook and observer data to filter tows that occurred within the 30 days prior to the empirical tow date and 5 km of the locations in the choice set. Distances were calculated as either distance from port to start location or previous tow end location to current tow start location. We used the spherical law of cosines for calculating distances in kilometers. Revenues (REV) were calculated with an arithmetic mean for all revenues and vessels within the spatiotemporal radius. Dummy variables are represented with *D* in the equation below. Fleet habit (*Dmiss*) variables were 1 if there were no records within the spatiotemporal radius and 0 if there were. Individual habit variables (*Dhab*) had a value of 1 if an individual vessel had records within the spatiotemporal radius and a value of 0 if not. Prior year individual habit variable ($Dhab_1$) were handled the same way, except that the temporal filter was the past 30 days of the previous year. There also is a variable indicating if the empirical tow is the first ($D_0 = 1$) or later tow of a trip ($D_1 = 1$).

All of this information was incorporated into the conditional logit model:

$$\begin{aligned} V_{ijt} = {} & \beta_{dist1} D_1 DIST_{ijt} + \beta_{dist0} D_0 DIST_{ijt} + \beta_{rev1} D_1 REV_{ijt} + \\ & \beta_{rev0} D_1 REV_{ijt} + \beta_{miss} Dmiss_{ijt} + \beta_{hab} Dhab_{ijt} + \\ & \beta_{hab1} Dhab1_{ijt} + \varepsilon_{ijt} \end{aligned} \tag{3.4}$$

where V_{ijt} is utility for individual *i* at location *j* in time period *t* and ε_{ijt} is the factors that affect location choices and are unaccounted for explicitly with variables. Individual fishers will choose alternative *k* with the highest utility

$$V_{ikt} > V_{ijt} \forall k, j \in S^i \tag{3.5}$$

where S^i is the consideration set for individual *i.* The probability *P* of observing individual *i* choosing alternative *k* at time *t* is:

$$P_{ikt} = \frac{e^{V_{ikt}}}{\sum_{j \in S^i} e^{V_{ijt}}} \tag{3.6}$$

Analyses were conducted in the statistical programming language R (R Core Team 2017). The packages “dplyr” (Wickham *et al.* 2017), “lubridate” (Grolemund and Wickham

2011), “doParallel” (Revolution Analytics and Weston 2015), and “mlogit” (Croissant 2013) were essential for data processing and model fitting.

3.4 RESULTS

3.4.1 Spatial Effort

FISHING EFFORT DECLINED ABOUT 40% AFTER CATCH SHARES. THERE WAS IN 2007-2010, WHICH DECLINED 41% TO 67 VESSELS IN 2011-2014 AFTER CATCH SHARE IMPLEMENTATION (

FIGURE 3.1A; *P* < 0.01). THE NUMBERS OF VESSELS REMAINED RELATIVELY CONSTANT IN THE SIX TOP FLEETS, BUT DECLINED SUBSTANTIALLY IN EACH OF THE FLEETS FISHING OUT OF LESS USED PORTS (

FIGURE 3.1B). THE AVERAGE NUMBER OF TOWS DECLINED BY 40% FROM 14,988 IN 2007-2010 TO 8,927 IN 2011-2014 (

Figure 3.1c; $p < 0.01$).

Areas in the northern region of the fishery had relatively high amounts of concentration compared to those in the southern regions, and most vessels had significant shifts in fishing location after catch shares. Of 406 depth-latitude sites, 56% had negative slopes (16% significant) compared to 14% that had positive slopes (2% significant), and 30% that had insufficient information or zero slopes (Figure 3.2). Of the 74 total vessels, 60% had significant shifts in latitude and depth, 18% had significant shifts in latitude only, 14% in depth only, and 8% had no significant shifts (Figure 3.3). Vessels with significant shifts in depth moved an average of -73 m in Astoria, -20 m in Newport, 18 m in Charleston, 37 m in Crescent City and Brookings, -34 m in Eureka, and -25 m in Fort Bragg. Negative depth changes indicate movement to shallower depths. Vessels with significant shifts in latitude moved an average of -0.07° in Astoria, 0.22° in Newport, -0.09° in Charleston, -0.59° in Crescent City and Brookings, 0.04° in Eureka, and -0.04° in Fort Bragg.

3.4.2 Delta Plots

Evidence of increased targeting after catch shares was mixed. The delta plots show evidence for greater targeting for 9 of 23 species, as evidenced by significant decreases in the proportion of zero-catch tows and more negative skew values (Figure 3.4). Four of six target species had significant decreases in proportion of zero-catch tows (Figure 3.4a-b). Sablefish had significant increases in skew and proportion of zero-catch tows after catch shares (Figure 3.4b). Fifteen of 23 species had significant decreases in skew, and 10 of 23 species had significant decreases in proportion of zero values (Figure 3.4). Note, that these results were from only logbook data from 2007-2014.

Application of the delta plots method to the combined logbook & observer data set shows increased targeting for most species. This is likely due to different data collection protocols for logbook and observer data rather than a true increase in targeting behavior. Logbook data are recorded by captains and discards were not required to be recorded. Observer data are recorded by on-board observers that weigh catches of each species and record both landed and discarded fish. Because this finding suggests that the change in data influenced delta plot results, here we focus on the logbook-only data and relegate the other results to an Appendix B.

3.4.3 Random Utility Modeling

Fishers generally fished in locations closer to their home port on the first tow, and closer to previous tow location for subsequent tows. Coefficients for first-tow distance were always negative and were significant in 30 out of 36 port-year combinations (Table 3.1; Figure 3.5). Later tow distance was significant and negative in all years and all ports (Table 3.1; Figure 3.5).

Fishers generally fished in locations with higher expected revenues. Coefficients for first tow revenue and later tow revenue were always positive and were significant in most ports in most years (Table 3.1; Figure 3.5). Individual habit strongly influenced fishers' location choices. Coefficients for individual habits were positive and highly significant ($p < 0.001$) in all years and all ports (Table 3.1; Figure 3.5).

Contrary to our expectations that fishers would avoid locations with species that had high quota prices ("constraining species"), fisher location choices did not depend on quota prices. To further assess this finding, we ran the random utility models with a 50-fold increase in quota prices to test model sensitivity. The result was reduced significance of revenue coefficients without affecting the distance and habit coefficients. This is consistent with a previous simulation study of the West Coast groundfish fishery which found that increasing quota prices to $50/kg did not noticeably impact fleet dynamics (Kaplan *et al.* 2014).

Fleet habit coefficients had variable significances and signs. In 2010, the year before catch shares, all fleet habit coefficients were positive and significant, indicating that individual fishers were willing to fish in locations that the fleet had not fished in the past 30 days (Table 3.1). After 2011, Astoria fleet habit coefficients were negative and significant in 2011 and 2013-2014 (Table 3.1), and Newport fleet habit coefficients were nonsignificant and negative in 2011 and 2014 and positive in 2012 and 2013 (Table 3.1). In the other ports, coefficients were mostly positive and significant (Table 3.1). Sensitivity tests on these results showed that coefficient significance was consistent when model runs were run with an increased spatiotemporal radius of 8 km instead of 5 km, and based on past information back 14 days instead of 30 days.

3.5 DISCUSSION

Fishing effort and fleet size declined after catch shares in our study. Declines after catch share implementation have occurred in fisheries in Canada (Crowley and Palsson 1992; Grafton 1995), Iceland, New Zealand (Grafton 1996a), and Alaska, USA (Abbott *et al.* 2010). In these cases, the theory of catch shares accurately predicts that fleet sizes and effort will decline as fishers decide to lease or sell their quota and exit the fishery (Grafton 1996b). However, different catch share designs can lead to different outcomes. The US Northeast, for example, gave fishers the option to volunteer to join a catch share program or remain in open access. About half of the permits joined the catch shares program, and fishers moved between catch shares and open access, but the number of fished permits did not decline (Holland *et al.* 2013).

On average effort concentrated in nearshore areas of the coast, although individual vessels showed mixed shifts. Fishing effort can shift due to changes in local fish abundance (Ames 2004; Morato *et al.* 2006), gear bans (Bellman *et al.* 2005), and local bycatch events (Dunn *et al.* 2014; Abbott *et al.* 2015). The shifts in fishing effort have resulted in less frequent interactions with living habitats (Barnett *et al.* 2017). Location choice is one of the many behavioral adjustments fishers can take. Fishers in this fishery have adjusted by fishing at different times of day, with different gear, and with shorter tows (Miller and Deacon 2017), and the same behaviors have been found in fisheries around the world (Baelde 2001; Abbott *et al.* 2015; Mortensen *et al.* 2018). Behavioral changes have resulted in high catch-quota balancing for species like petrale sole and sablefish, but catch for most species was far below available quota (Kuriyama *et al.* 2016). While there was no evidence of increased targeting for either of these species after catch shares, they both were likely strongly targeted before and after catch shares.

Fishers had a core fishing behavior that was unchanged by catch shares; fishers tended to fish in areas that were nearby, had higher expected revenues, and in which they had fished before. Previous studies that used random utility models find fishing to be similarly rational, profit-maximizing, and habit-based (Holland and Sutinen 2000; Haynie *et al.* 2009; Abbott and Wilen 2011), and habit is significant in roughly 75% of reviewed fleet dynamics studies (Girardin *et al.* 2017). Fishers might be willing to fish in new areas for the chance of increasing profits (Holland and Sutinen 1999) but this does not seem to be happening in this fishery. Before catch shares, fishers showed an aversion to follow the rest of the fleet, but after catch shares, behaviors were more mixed. Fishers in Astoria fished primarily in locations that the fleet had recently fished, whereas fishers in Eureka fished away from the rest of the fleet.

Fishers showed mixed inclinations to follow the rest of the fleet. The footprint of fishing effort varies among ports, and those with the biggest footprint may require the most communication. This may be because fishers in smaller ports have stronger expectations of catch amounts. A port like Eureka has a smaller spatial footprint of effort than say Astoria, and as a result fishers perhaps felt more comfortable fishing in locations recently unfished by the fleet. In theory, fishers should feel more comfortable with risk-prone fishing under catch shares, as additional quota can be obtained through markets. However, an efficient quota market has not developed and little quota for constraining species is available during the season (Holland 2016). The risk of exceeding quota of constraining species is likely high and fishers might have to communicate more with others. While there is one formal risk pool, in which fishers coordinate fishing effort and combine their quotas, there are likely many de facto risk pools along the coast that serve the same function.

The West Coast Groundfish fishery is complex, and there are many possible factors that we did not account for. Fishers might have shifted fishing effort to target specific species, although the evidence of increased targeting was likely due to a difference in data collection protocols rather than a true increase in targeting. The combined logbook and observer data set showed the strong increases in targeting after catch shares, but this was likely due to use of observer data. Observer data contain more precise measurements and species identifications and full accounting of both landed and discarded species. Market conditions likely impact effort dynamics (Smith 2012) and were not accounted for here. It is easier to develop seafood markets if companies can guarantee specific amounts of fish within discrete times. Under trip limits, landings arrive on a relatively predictable schedule, while under catch shares, there are no temporal restrictions, and landings can therefore be more variable. As a result, the development of fresh markets that fetch higher market prices may be stymied by catch shares.

Catch shares are often proposed as a panacea to fisheries management, but the reality is more complex. The decrease in fleet size suggests that there may have been an increase in fleetwide economic efficiency although catch-quota balancing decreased under catch shares. Fishers have remained within total allowable catches and demonstrated the ability to adjust fishing behaviors to increase targeting on some species. Some overfished stocks have been declared rebuilt under catch shares, although this is difficult to attribute to catch shares. Improvements in stock assessment and reductions in fishing mortality occurred starting in 2000s, about a decade before catch share implementation. Fishers' have had a core set of fishing behavior from 2009-2014 although fishers in the biggest ports demonstrated adaptability to the new risks of fishing under catch shares. Additionally, the smallest ports had the biggest proportional decreases in numbers of vessels. These vessels may have switched fisheries rather than moving to a different port but such shifts may become problematic socially. While catch shares have not been a panacea, there will likely continue to be economic and ecological improvements in the fishery, while social improvements may require more active interventions.

3.6 TABLES

Table 3.1: Table of random utility model coefficients. Coefficients were significant with p-values less than 0.1 (.), 0.05 (*), 0.01 (**), and 0.001 (***).

Fleet	**Coefficient**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Astoria	First tow distance	-0.0094***	-0.0100***	-0.0064***	-0.0044***	-0.0025*	-0.0003
Astoria	Later tow distance	-0.0452***	-0.0544***	-0.0641***	-0.0590***	-0.0580***	-0.0568***
Astoria	First tow revenue	0.0332***	0.0257***	0.0193***	0.0270***	0.0162***	0.0108**
Astoria	Later tow revenue	0.0196***	0.0155***	0.0111***	0.0094***	0.0111***	0.0095***
Astoria	Fleet habit	0.2940***	0.3578***	-0.1470.	-0.2247*	-0.2070*	-0.2111*
Astoria	Individual habit	2.0935***	2.0925***	2.0591***	2.2004***	2.0506***	2.4470***
Astoria	Individual habit last year	0.1188*	0.4495***	0.2296***	0.2754***	0.5300***	0.4329***
Newport	First tow distance	-0.0194***	-0.0065**	-0.011	-0.0046	-0.0051	-0.0288***
Newport	Later tow distance	-0.0545***	-0.0486***	-0.0601***	-0.0524***	-0.0535***	-0.0518***
Newport	First tow revenue	0.0124***	0.0235***	0.0225***	0.0017	0.0168***	0.0156***
Newport	Later tow revenue	0.0075***	0.0199***	0.0065.	0.0060.	0.0088***	0.0051*
Newport	Fleet habit	0.1919*	0.5832***	0.0318	0.0958	0.1243	-0.126
Newport	Individual habit	1.6473***	1.6934***	1.5738***	1.5071***	1.2242***	1.1114***
Newport	Individual habit last year	0.2486**	0.1952*	0.4270**	0.5105**	0.3464**	0.2231.
Charleston	First tow distance	-0.0076*	-0.0036	-0.0140**	-0.0210***	-0.0035	-0.0139**
Charleston	Later tow distance	-0.0536***	-0.0480***	-0.0521***	-0.0435***	-0.0480***	-0.0458***
Charleston	First tow revenue	0.0095**	0.0154***	0.0168***	0.0159***	0.0174***	0.0103**
Charleston	Later tow revenue	0.0049*	0.0092***	0.0089***	0.0048	0.0003	0.0047.
Charleston	Fleet habit	0.1999.	0.7389***	0.5066***	0.3879**	0.1532	-0.1783
Charleston	Individual habit	1.9115***	2.2506***	2.1685***	2.2005***	2.0807***	1.7898***
Charleston	Individual habit last year	0.2606***	0.6615***	0.3478***	0.6447***	0.7899***	0.7317***
Brookings & Crescent City	First tow distance	-0.0106***	-0.0144***	-0.0276***	-0.0128*	-0.0154*	-0.0295***
Brookings & Crescent City	Later tow distance	-0.0370***	-0.0353***	-0.0387***	-0.0278***	-0.0281***	-0.0360***

Brookings & Crescent City	First tow revenue	0.0101*	0.0095*	0.0132***	0.0136*	0.0204***	0.0048
Brookings & Crescent City	Later tow revenue	0.0090***	0.0082**	0.0140***	0.0211***	0.0165***	0.0070***
Brookings & Crescent City	Fleet habit	0.4596**	0.4507*	0.3019.	0.5063.	1.0204***	0.7270**
Brookings & Crescent City	Individual habit	1.3070***	1.5736***	1.2522***	1.5380***	1.8830***	2.0166***
Brookings & Crescent City	Individual habit last year	0.1966	0.3696***	0.0742	-0.1243	0.1782	0.3554**
Eureka	First tow distance	-0.0074**	-0.0129***	-0.0124***	-0.0193***	-0.0126***	-0.0116***
Eureka	Later tow distance	-0.0558***	-0.0536***	-0.0516***	-0.0512***	-0.0472***	-0.0579***
Eureka	First tow revenue	0.0229***	0.0271***	0.0160***	0.0179***	0.0145***	0.0086**
Eureka	Later tow revenue	0.0228***	0.0227***	0.0109***	0.0181***	0.0209***	0.0142***
Eureka	Fleet habit	0.9502***	1.1989***	0.5742***	0.8666***	1.0044***	0.9568***
Eureka	Individual habit	2.0108***	2.0824***	2.0700***	1.9331***	2.5481***	2.4378***
Eureka	Individual habit last year	0.2559**	0.2389**	0.2910**	0.3334**	0.1425	0.3761***
Fort Bragg	First tow distance	-0.0171***	-0.0103***	-0.0108**	-0.0158***	-0.0056*	-0.0149***
Fort Bragg	Later tow distance	-0.0452***	-0.0453***	-0.0524***	-0.0504***	-0.0531***	-0.0563***
Fort Bragg	First tow revenue	0.0275***	0.0163**	0.0087**	0.0140*	0.0248***	0.0031
Fort Bragg	Later tow revenue	0.0123***	0.0105***	0.0054**	0.0074**	0.0113***	0.0039*
Fort Bragg	Fleet habit	0.1974	0.3383**	0.1978	0.2208	0.7990***	-0.0633
Fort Bragg	Individual habit	1.0109***	1.1369***	1.7111***	1.6346***	1.9679***	1.4410***
Fort Bragg	Individual habit last year	0.1890*	-0.0752	0.3092**	0.3073*	0.4184***	0.4031***

3.7 FIGURES

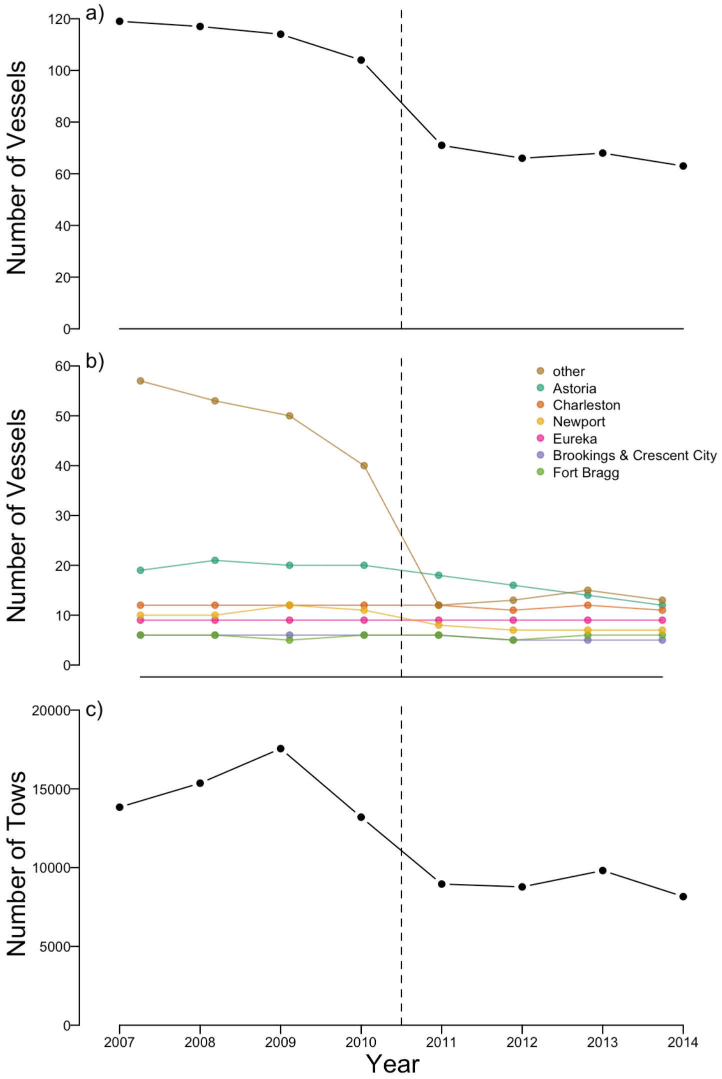

Figure 3.1: Trends in number of total vessels (a), number of vessels in each fleet (b), and number of tows (c) from 2007-2014. The dashed vertical line divides the years prior (2007-2010) and after (2011-2014) catch share implementation.

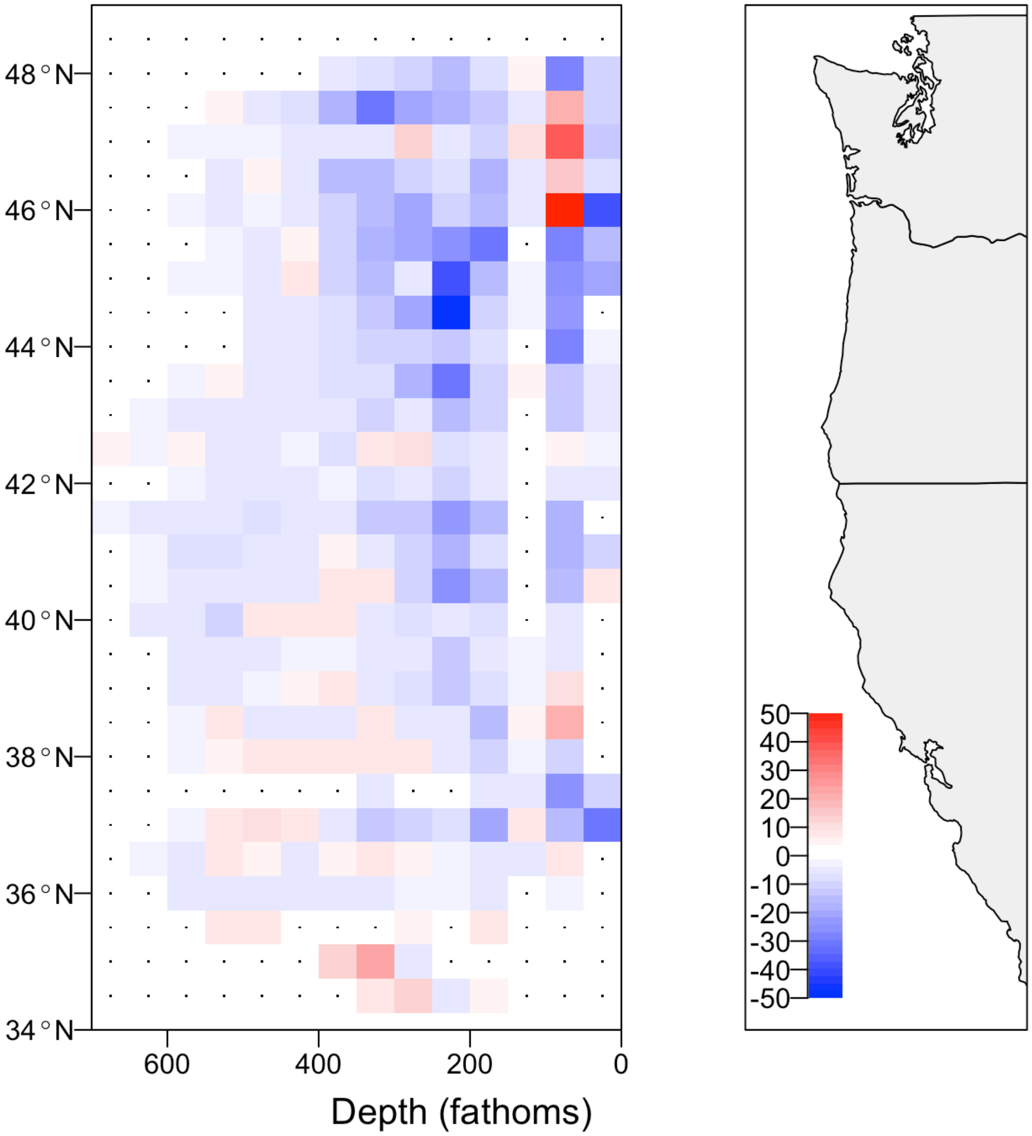

Figure 3.2: Areas of increasing effort (red) and decreasing effort (blue), as measured by the slope of fishing effort vs. year. Shading indicates the magnitude of slope coefficients. Cells are 50 fathoms by 0.5 latitude degrees. An area with insufficient years to fit a linear model or with no fishing records contain a dot.

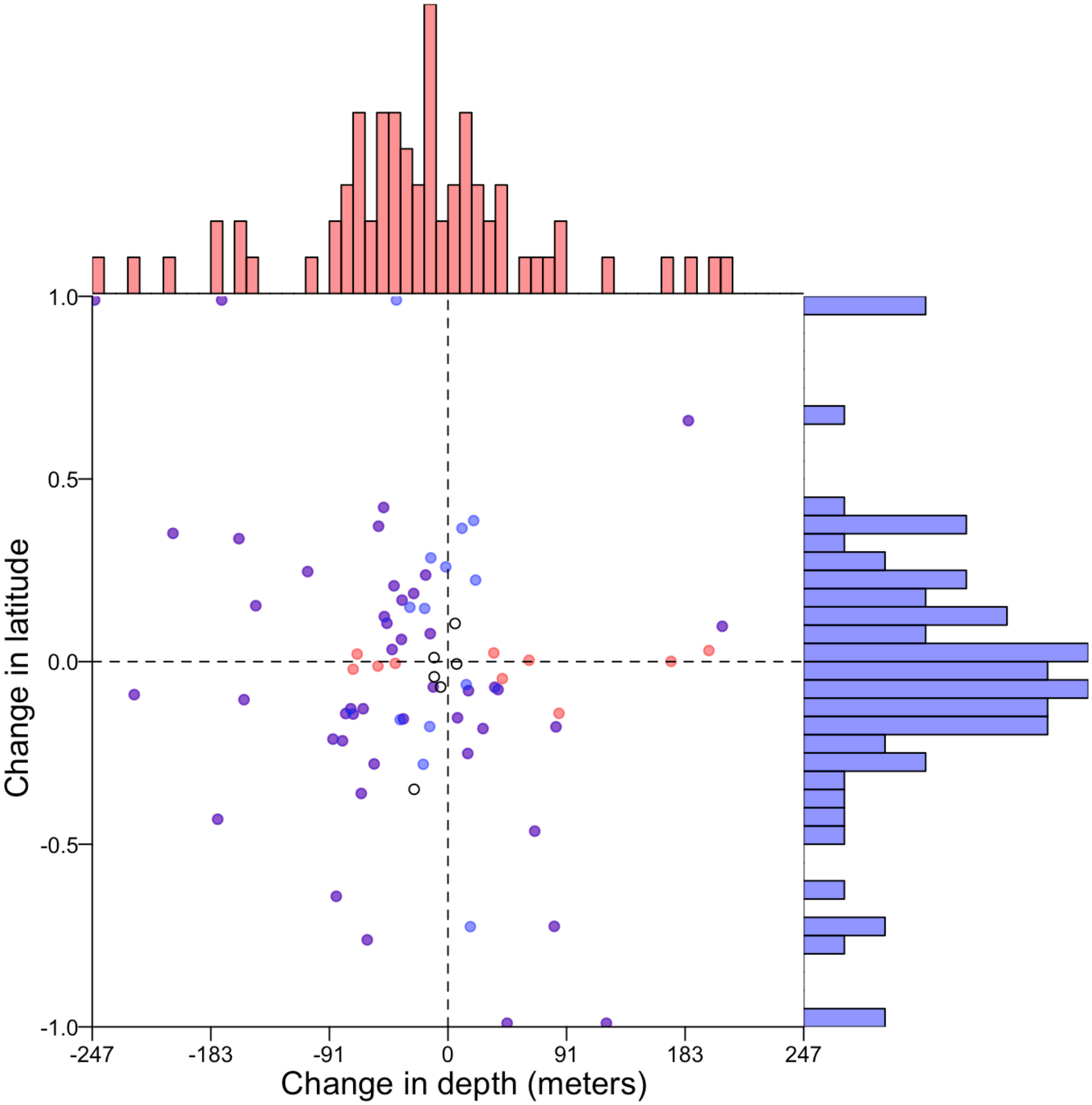

Figure 3.3: Change in depth and latitude for vessels that remained in the fishery after catch shares. Vessels with significant changes in depth and latitude (purple points), depth (red points), latitude (blue points), and no significant change (open points) are shown. Four vessels had changes in latitude greater than one degree and are not shown here.

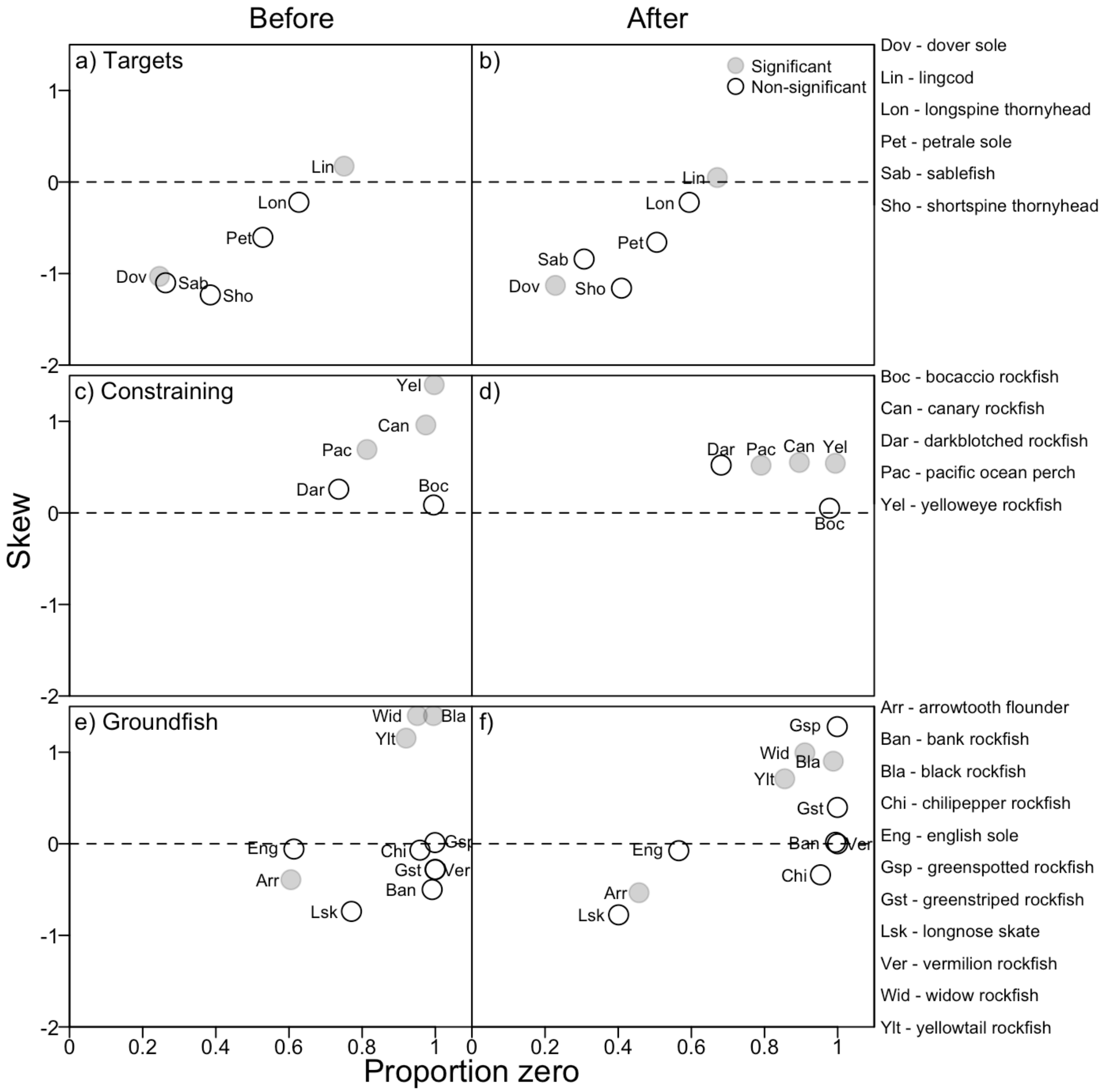

Figure 3.4: Delta plots from only logbook data showing the relation between proportion of tows with zero fish and the skewness of the distribution of catch amounts for the three categories of species: target species (a-b), constraining species (c-d), and other groundfish (e-f). A skew above zero indicates species with fewer large catches than expected, while a skew below zero indicates more large catches than expected. The left column is years before catch shares (2007-2010) and the right column after catch shares (2011-2014). Gray shading indicates species with significant changes in skew values after catch shares. All species had significant changes in the proportion of tows with zero values.

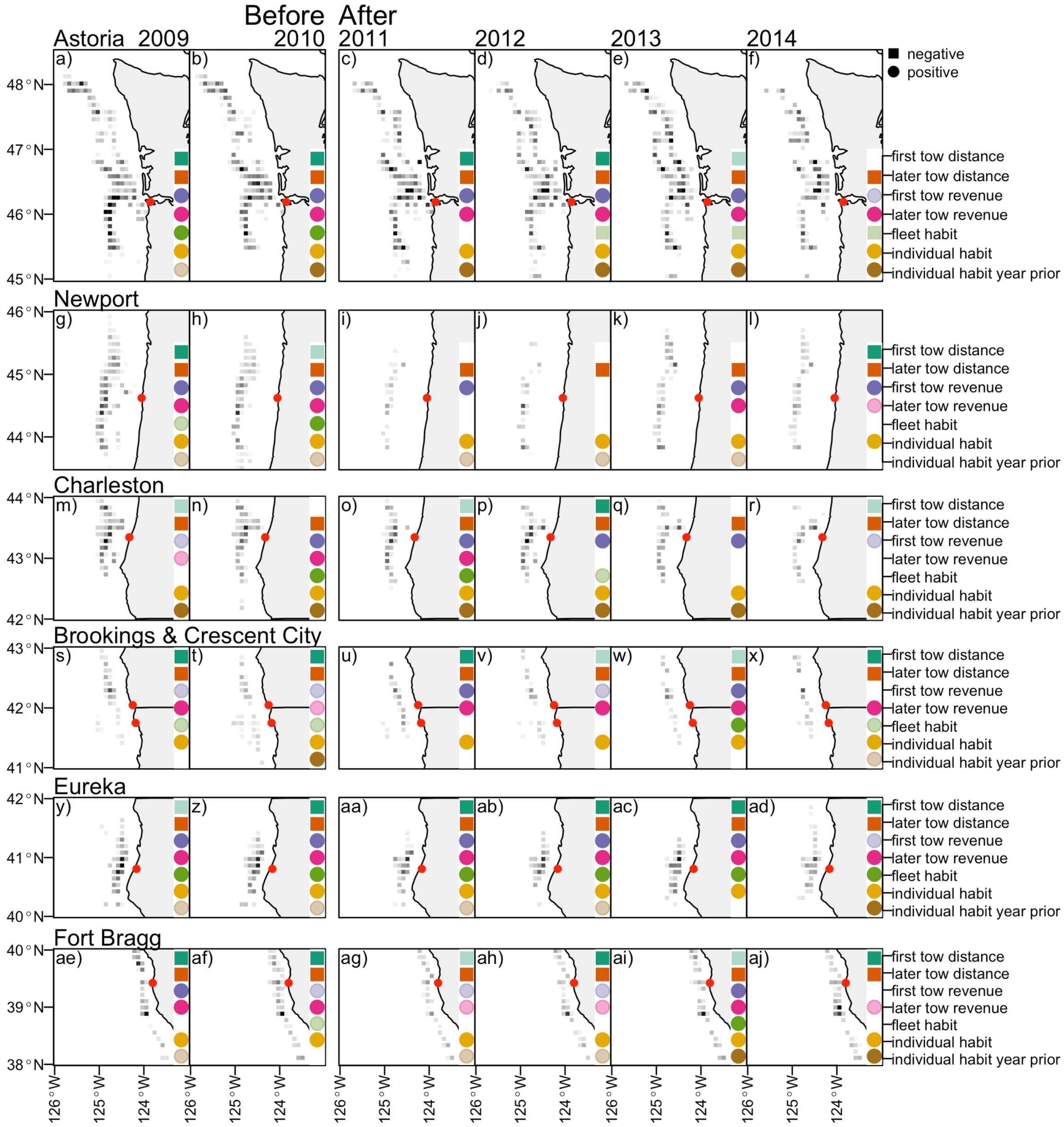

Figure 3.5: Maps showing the number of tows in 10km × 10km grids for each port group (rows) in each year (columns) and the signs and significances of seven random utility model coefficients (first tow distance, later tow distance, first tow revenue, later tow revenue, fleet habit, individual habit, individiual habit year prior). Coefficients were estimated for each port-year combination. Nonsignificant (no color), significant (light shading; $0.001 < p < 0.05$), and highly significant (solid; $p < 0.001$) are shown for positive (circle) and negative (square) coefficients.

Conclusions

My dissertation has explored the limits of inference for fish species that inhabit both untrawlable rocky reef habitats and trawlable fishing grounds. Scientists, managers, and fishers strive to understand fish distributions and abundances in the rocky reef habitats preferred by many species in the West Coast Groundfish fishery. These areas are difficult to survey and uncertainty in fish distributions and abundances affects both assessment and management. Fisheries-independent trawl surveys in the West Coast are a key data source in stock assessments, but are unable to sample rocky reef habitats in which many fish species reside. As a result, assessments might not account for the full range of a population's distribution resulting in inaccurate catch limit recommendations. Catch limits are the primary management tool in US fisheries, but because trawl gear is not able to target individual species perfectly, reducing catch limits for one species can affect fishers' abilities to catch other species. If fishers have a portfolio of individual catch quotas that are not proportional to the distributions in nature, they will be challenged to fully catch their available quotas. A catch share system provides greater flexibility to increase catch-quota balancing, but full catch-quota balancing would require fishers to have near perfect knowledge of fish distributions and abundances. In this dissertation, I have focused on the potential of an alternative survey method in rocky reef habitats and the changes that occur under catch shares and fishers have to fish with imperfect knowledge of fish distributions.

Fishery-independent surveys are a primary data source in stock assessments, but rocky reef habitats are difficult to survey. Hook-and-line methods are unique in their ability to both sample fish in rocky reef habitats and collect biological data such as ages, lengths, weights, and sexes which are also crucial information for stock assessments. Hook-and-line surveys designed to sample fish in rocky reef habitats can have two characteristics that may be statistically challenging to analyze: gear saturation and fixed-site design. Gear saturation arises if there are more fish than available hooks and leads to hyperstability, in which declines in population size are difficult to detect because catch-per-unit-effort values decline more slowly than population size. Fixed-site preferential sampling design complicates standardization methods that assume random sampling design. I found hyperstability in all simulated survey scenarios that included both random and preferential site selection. Preferential site selection, in which the survey occurs mostly in sites that have the most fish, had a greater ability to detect increases and decreases in population size than random site selection. Statistical power was highest when preferentially sampling fish populations with patchy distributions. This simulation lends theoretical support to hook-and-line surveys, particularly when fish are patchily distributed in rocky reef habitats that are otherwise difficult to survey.

Catch shares in the West Coast Groundfish fishery did not improve catch-quota balancing. Fishers under catch shares had to consider the risks of catching certain species prior to deploying gear; under trip limits, fishers had the flexibility to discard fish at sea if they exceeded catch limits. Catch shares introduced new forms of flexibility: the ability to lease quota in the case of overages, reduced incentives to compete against others for fish, and a more relaxed pace of fishing where fishers can fish where and when they want. However, under catch shares, and despite the additional flexibility, catch-quota balancing decreased in the West Coast Groundfish fishery. Catch-quota balancing was also lower in the West Coast fishery than in the similar British Columbia Multispecies Trawl fishery. There are many explanations for decreased catch-quota balancing, some of which are related to the shift to catch shares and others that are not. The increase in individual accountability likely had a strong influence on the decline. Some fishers were allocated individual quota amounts as low as one yelloweye rockfish per year. Total allowable catch amounts in the British Columbia fishery were ten times higher than those in the West Coast fishery for yelloweye rockfish and more than forty times higher for canary rockfish and Pacific ocean perch. In the West Coast Groundfish fishery, species proportions in individual quota allocations can be very different than the proportions found in nature, and the difference is so stark that catch shares might be unable to introduce sufficient flexibility to bridge this divide. For example, fishers can benefit from transferability only if they are confident that quota will be available when they need it. Fishing without yelloweye rockfish quotas was perhaps prohibitively risky, and fishers did not make yelloweye quota available until the end of the season when there was little fishing activity. Catch-quota balancing increased notably for sablefish, the most valuable species in the fishery. This was likely due to the ability to switch from trawl gear to more selective fixed gear. In some sense, fishers reduced uncertainty about fish distributions by using selective gear rather than collecting more information. Another explanation for the decrease in catch-quota balancing is that few stocks in the fishery are valuable and worth catching. Most fishers shifted efforts towards catching sablefish with more selective gear and may have made sufficient profits without expending much effort trawling.

In some areas of the West Coast Groundfish fishery, fishing behavior shifted under catch share implementation, and these results highlight the ways in which fishers might reconcile their individual quota proportions with those found in fishing grounds. I fit a random utility model that used fine-scale information from recent individual vessel and fleet fishing activity. I found that there was a core set of fishing behavior: fishers tend to fish in locations that are nearby, have higher expected revenues, and that individuals had fished before. This result is found in other multispecies trawl fisheries in the United States. Behavioral shifts were greatest in the ports with the most vessels and largest spatial footprint of fishing effort. For example, fishers out of Astoria spanned the entire coast of Washington and the half of the northern coast of Oregon. Before catch shares, Astoria fishers tended to fish in areas that other members of the fleet had not recently fished, and after catch shares, Astoria fishers switched behaviors and tended to fish in areas that other members of the fleet had fished. Smaller ports in the fishery had consistent behaviors in that fishers tended to fish in areas that other vessels had not recently fished both before and after catch shares. The biggest ports had the most fishing locations, and as a result fishers likely had more uncertainty about fish distributions in these locations. Fishers responded to the increased accountability of catch shares by shifting fishing behaviors to mostly fish in areas that had been recently fished by other vessels. This result might indicate that fishers increased information sharing to better identify areas with species compositions that aligned with individual quota compositions. Fishers in smaller ports, with more defined fishing grounds, may not have needed to share information as they already had well-informed expectations. This might explain the consistent fishing behavior before and after catch shares in the smaller ports.

In conclusion, assessment and management in the West Coast Groundfish fishery is greatly affected by uncertainty in fish distributions. Hook-and-line surveys are a means of reducing this uncertainty, and can sample in rocky reef habitats that are otherwise difficult to survey. Uncertainty in fish distributions, specifically in relation to individual quota allocations, affects much of the fleet responses to catch shares. Taken together, I have found that multispecies catch share fisheries are complex systems, and it is difficult to attribute broad changes to one particular factor. Fishers consider multiple dimensions when deciding how to fish, ranging from recent fleet activity, season, market conditions, and alternative gear types. In this case study of the US West Coast Groundfish fishery, I found that responses to management can be unpredictable. It is important for scientists, managers, and fishers to acknowledge the limitations of our predictive abilities but important to look to other examples as we strive to ensure sustainable fisheries in the future.

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Appendix A

1. Calculating Trawl Specific TAC values

If we use a year-specific *P*, our approximation results in a limited entry specific catch:TAC ratio of total catches *F* divided by the management value *MV* for species *x* in year *t*. This algebraic result does not give the metric we are interested in. Algebra below:

$$P_{x,t} = \frac{T_{x,t}}{F_{x,t}}$$

$$TAC = P_{x,t} * MV_{x,t}$$

The limited entry catch:TAC ratio is calculated by dividing trawl catches *T* by the limited entry-specific total allowable catch *TAC*.

$$LERatio = \frac{T_{x,t}}{TAC}$$

$$LERatio = \frac{T_{x,t}}{P_{x,t} * MV_{x,t}}$$

$$LERatio = \frac{T_{x,t} * F_{x,t}}{T_{x,t} * MV_{x,t}}$$

$$LEratio = \frac{F_{x,t}}{MV_{x,t}}$$

Applying our approximation to values from 2011-2013 indicate a strong correlation between the observed and calculated TACs for the limited entry trawl sector (Figure 2.5).

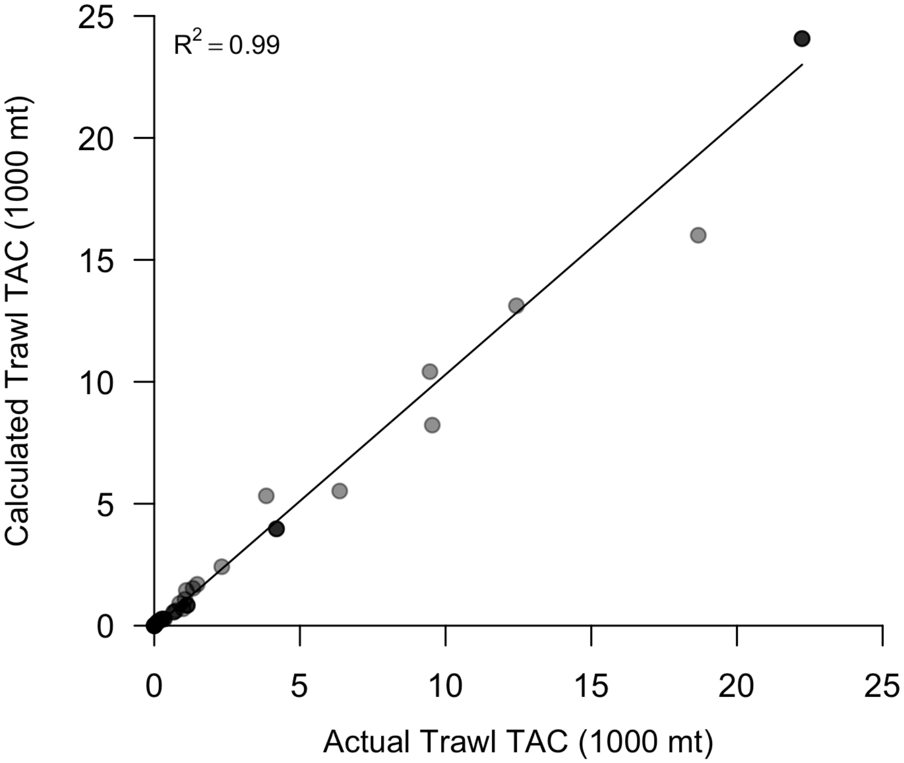

Figure A1: Plot of calculated trawl TACs to actual trawl TACs from the West Coast fishery in 2011-2013. All points are transparent gray, so darker dots indicate multiple points.

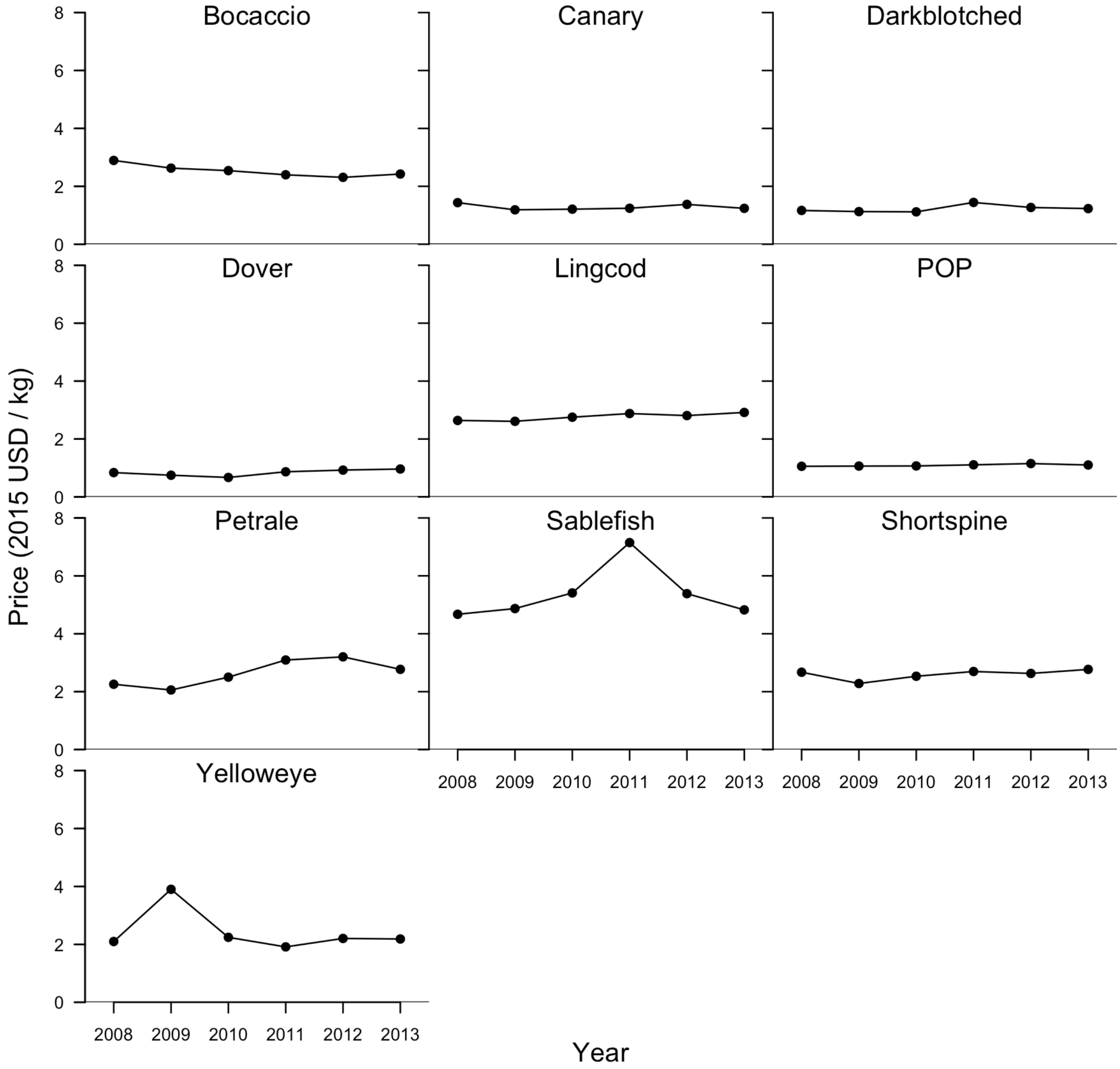

Figure A2: Average prices per kilogram for species in the West Coast fishery from 2008-2013. Only stocks with values in all six years are presented.

Appendix B

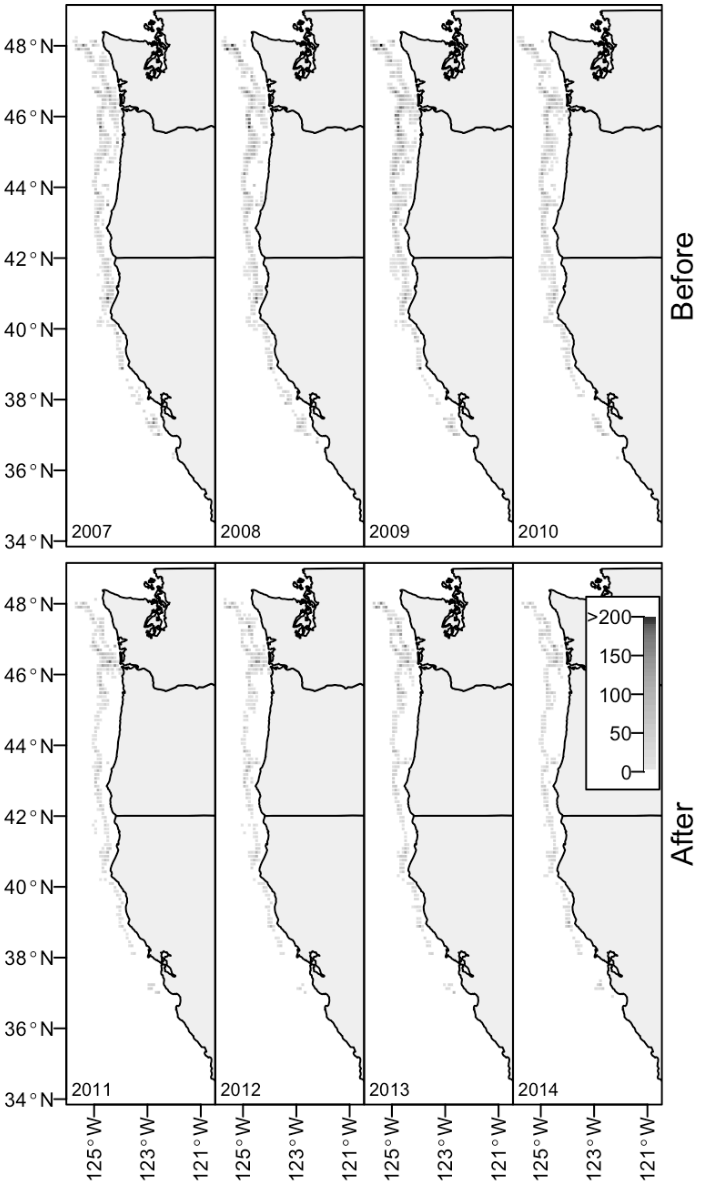

Figure B1: Number of tows in 10km by 10km grids by year. Each grid is filtered to contain at least three tows from at least three vessels. The top row is from years before (2007-2010) and the bottom row is from years after catch shares (2011-2014).

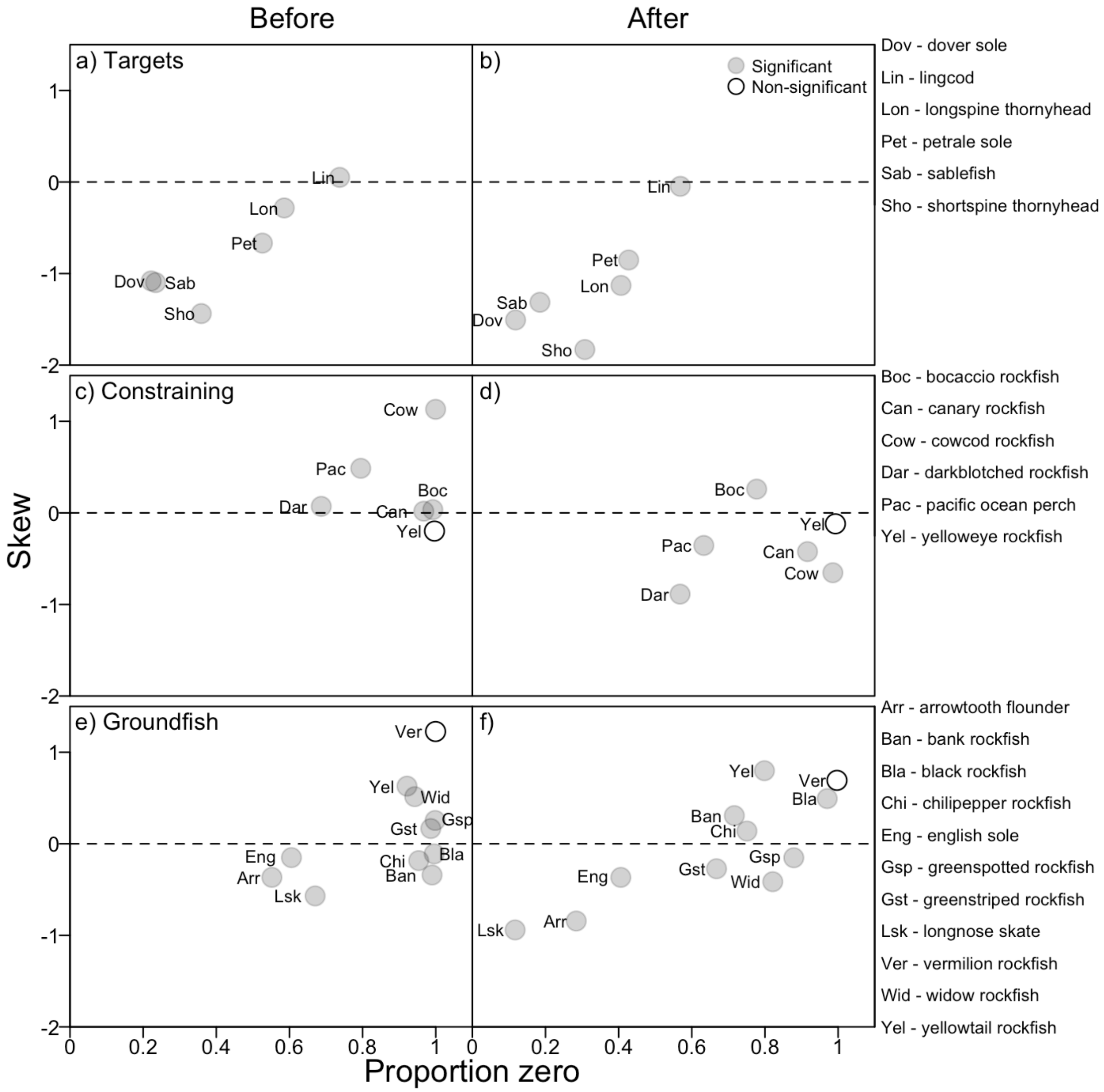

Figure B2: Delta plots from combined logbook and observer data showing the relation between proportion of tows with zero fish and the skewness of the distribution of catch amounts for the three categories of species: target species (a-b), constraining species (c-d), and other groundfish (e-f). A skew above zero indicates species with fewer large catches than expected, while a skew below zero indicates more large catches than expected. The left column is years before catch shares (2007-2010) and the right column after catch shares (2011-2014). Gray shading indicates species with significant changes in skew values after catch shares. All species had significant changes in the proportion of tows with zero values.

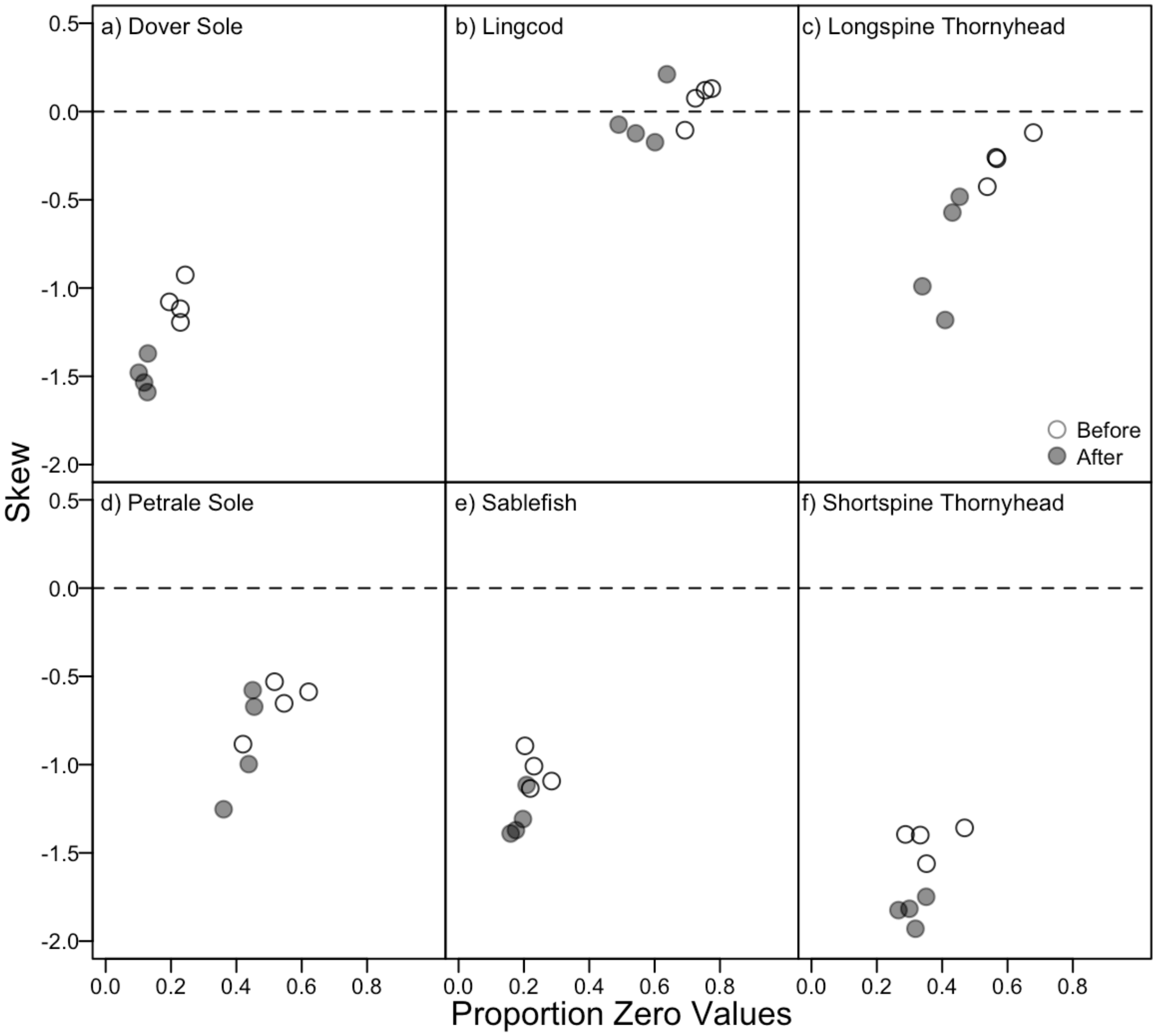

Figure B3: Delta plots for target species from combined logbook and observer data. Values shown are for each year before (2007-2010; white) and after (2011-2014; gray) catch shares.

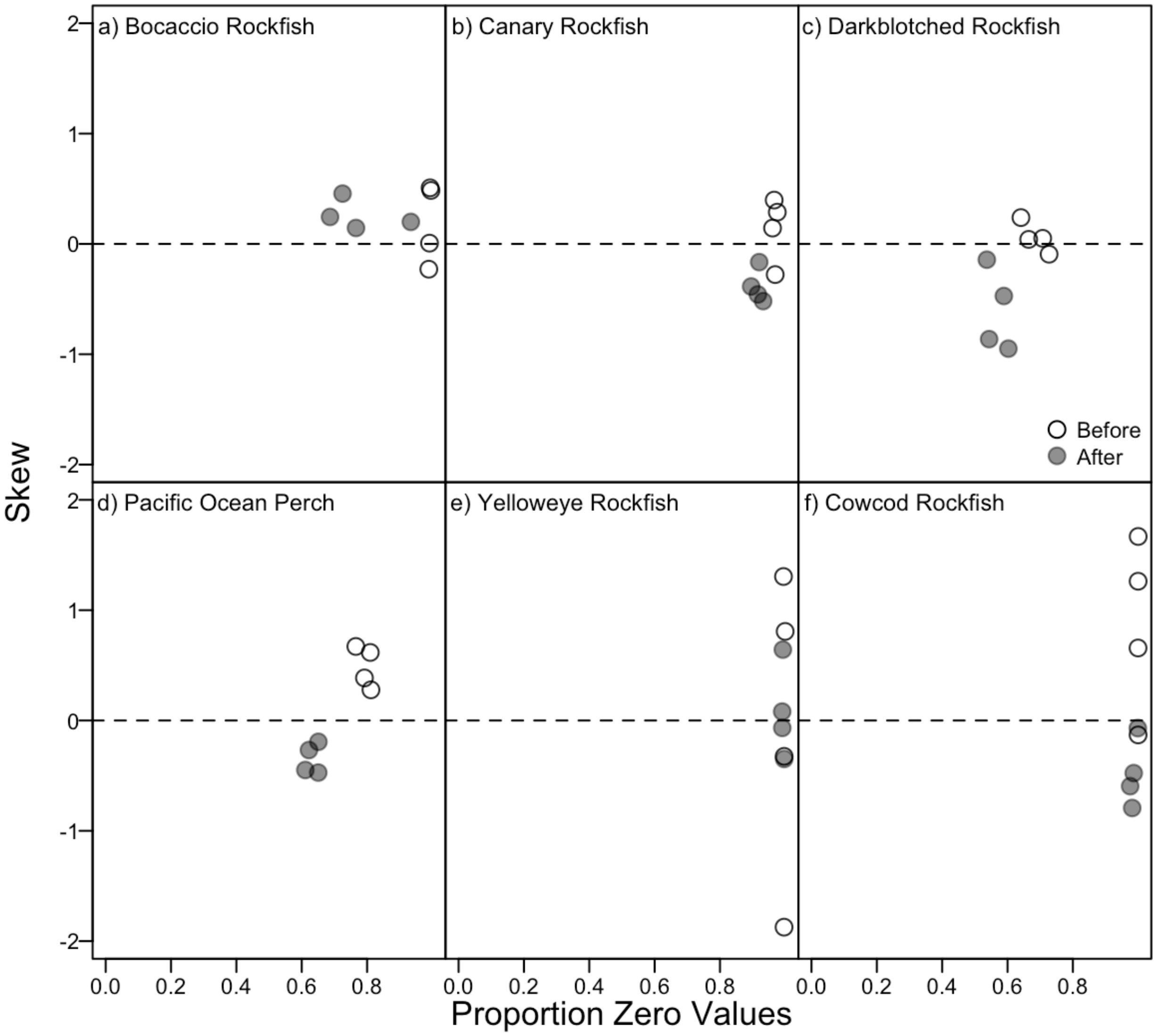

Figure B4: Delta plots for constraining species from combined logbook and observer data. Values shown are for each year before (2007-2010; white) and after (2011-2014; gray) catch shares.

VITA

Peter Kuriyama grew up in Solana Beach, California where formative years were spent in the ocean. He received a B.A. in Biology and a minor in Japanese from the College of Creative Studies at UC Santa Barbara. He received a PhD from the School of Aquatic and Fishery Sciences at the University of Washington and was fortunate to receive a NOAA Fisheries and Sea Grant Population Dynamics Fellowship to fund his research. While at UW he contributed to the petrale sole stock assessment update and a technical guide for Bayesian analysis in AD Model Builder. In addition to a paper on catch-quota balancing in this dissertation, he also wrote two papers about stock assessment methodologies and a paper about the reauthorization of the Magnuson-Stevens fisheries act. Next he is excited to return home and become a postdoctoral researcher at Scripps Institution of Oceanography and NOAA's Southwest Fisheries Science Center. He hopes to continue working in fisheries management and population dynamics.

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