Rebuilding mixed stock fisheries: lessons from the U.S. West Coast

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Abstract

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Management of commercial fisheries is imperative to global food security, economies, and sustainability. However, common management frameworks are often challenged when species with differing sustainable exploitation rates are caught simultaneously in a mixed stock fishery. The tradeoffs which emerge are often magnified when overfished stocks are persistent in the system. As observed in the U.S. West Coast groundfish fishery, the priority to rebuild overfished stocks according to a strict timeline can result in forgone yield of abundant species and negative impacts on communities. In this thesis, I retrospectively analyzed alternative rebuilding scenarios for the West Coast to test if a management approach based on meeting fishing mortality targets could result in fewer tradeoffs for stakeholders while still meeting conservation objectives. I then developed a two-area single species age structure model to evaluate if marine closures can be

used as an alternative management approach to single-species catch limits and provide adequate rebuilding protection while minimizing forgone yield of abundant stocks. The analyses on alternative management approaches described in this thesis can be applied to global fishery managers as they address similar challenges in their respective fisheries.

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DEDICATION

To my husband — Axel
To my parents – Kurt and Kimberlee

I could not have done this without you, thank you.

Chapter 1 Introduction

Fisheries management must often balance tradeoffs and unanticipated consequences of policy decisions. Challenges may occur when ecological, economic, and social objectives for management outcomes diverge (Asche et al. 2018). For instance, maximizing food production and profitability is often a common goal and while it requires sustainability of the resource, it may be incompatible with some conservation objectives. Contributing to the complexity of fisheries management, objectives may not be interpreted equally among stakeholders - Hilborn et al. (2015) reviewed the numerous ways in which sustainable fisheries are defined.

Several management approaches have evolved out of the recognition that common pool resources, if left to the tragedy of the commons, will fail to meet the objectives described above (Hardin 1968; Anderson et al. 2018). Thus, management often begins by limiting the number of fishery participants and setting a fleet-wide catch limit for each species, followed by a series of regulations designed to discourage exceedance of said limits. Input regulations, such as days at sea or constraints on mesh sizes, have historically been used to control effort (Anderson et al. 2018). Rights based management, in the form of catch shares or individual fishing quotas, are increasingly popular for the economic and ecological benefits they can provide (Asche et al. 2018). Although tpatial closures are also a common feature of many management frameworks, protecting sensitive or critical habitat from commercial activity, their effectiveness to manage directed fisheries is debated in the literature (Hilborn et al. 2004; Lester et al. 2009; Hastings et al. 2017; Hilborn 2017).

Mixed stock fisheries often test the bounds of fisheries' management approaches. Tradeoffs among yield maximization and conservation objectives are inevitable when stocks of differing sustainable exploitation rates are caught simultaneously. The ‘weak’ stock with the lowest sustainable exploitation rate may be susceptible to overfishing if the yield of the mix of stocks is maximized by fishing at higher exploitation rates associated with ‘stronger’ stocks (Worm et al. 2009; Hilborn et al. 2012). Likewise, if a management framework prohibits overfishing of any stocks, yield of the strong stocks will be forgone due to the constraining, weak stocks. This challenging dynamic is exacerbated when overfished stocks persist in a mixed stock fishery, where managers are committed to rebuilding depleted resources.

Fisheries managers are frequently tasked with identifying the best approach that minimizes tradeoffs among objectives, where possible. In this thesis, a retrospective analysis explores alternative scenarios for rebuilding overfished stocks to identify which harvest rule results in fewer tradeoffs for stakeholders while meeting conservation requirements compared to the outcome under the actual adopted rebuilding plans for the US West Coast groundfish. The second chapter develops a single-stock age-structured model to analyze the potential for spatial closures to solve the mixed stock dilemma. The chapter further explores if marine closures can be used in the place of single-species catch limits and provide adequate protection for rebuilding stocks in respect to management targets. The aim of this thesis is to gain insight into alternative management approaches for rebuilding species in mixed stock fisheries. While this work focuses on the US West Coast, the expectation is the findings will be informative to a global audience of fishery managers and aid their decisions as they address similar challenges in their respective fisheries.

CHAPTER 2 EVALUATING ALTERNATIVE REBUILDING PLANS FOR MIXED STOCK FISHERIES

ABSTRACT

Rebuilding overfished stocks is central to fisheries policy, with the United States Magnuson-Stevens Act aligning with the United Nations Sustainable Development Goals 14.4 “to restore fish stocks in the shortest time feasible at least to levels that can produce maximum sustainable yield.” In mixed stock fisheries, very low allowable catches for rebuilding species can lead to an inability to harvest abundant stocks. There are consequently trade-offs between the maximum sustainable yield of the stock mix and rate of rebuilding. We retrospectively evaluate rebuilding plans in the U.S. West Coast groundfish fishery to identify alternative rebuilding scenarios that could have minimized adverse impacts to stakeholders while still achieving stock rebuilding targets. We use current assessments of 13 groundfish stocks to project spawning biomass and catch under different harvest policies. We estimate that an additional $886 million USD in ex-vessel revenue could have been obtained had an F_{MSY} policy permitting slower rebuilding rates been adopted. We also examined what catch limits would have been under a F_{MSY} policy using the information available at the time rebuilding plans were put in place. These alternative catch limits would have provided much greater fishing opportunity while still rebuilding the stocks. Our findings support those of the National Research Council, which in 2014 reported that rebuilding plans based on fishing mortality rates may be preferable to those focused on meeting strict rebuilding timelines.

INTRODUCTION

Tradeoffs between food production, profitability and abundance of marine resources are inevitable, particularly when managing mixed stock fisheries. A common management objective is to maintain the biomass of each single species at the level that produces maximum sustainable yield (*MSY* – the greatest long-term average catch a population can sustain; B_{MSY} being the biomass corresponding to *MSY*). Applying this single-species management concept within a multispecies system has proven difficult, as managers must balance overfishing of less productive stocks and underfishing of more abundant and productive stocks (Ricker 1958; Paulik et al. 1963; Worm et al. 2009). If there are differing productivities within a single fishery and the management objective is to have no overfishing, then only the 'weakest' stocks will be at levels producing MSY and considerable potential yield will be lost from the more productive stocks (Hilborn et al. 2011). Worm et al. (2009) estimated that if total yield from a mixed stock fishery was maximized, up to 40% of stocks would be at very low abundance, some likely even considered overfished from a biomass perspective. Thus, there is always a trade-off between the total yield from the mix of stocks and the number of stocks that will be substantially below the target biomass of B_{MSY}.

The United Nations commitment to end world hunger and extreme poverty by 2030 has led to Sustainable Development Goal (SDG) 14.4, which prioritizes an end to overfishing and rebuilding of stocks to levels producing MSY, as quickly as possible (FAO). Like the UN, the U.S. is committed to ending overfishing, as supported by its governing legislation, the Magnuson Stevens Fisheries Conservation and Management Act (MSFCMA). The motivation to rebuild stocks was based on the understanding that maintaining stock biomass about B_{MSY} will provide the greatest net benefits to the nation (National Research Council 2014). In 1996, the Act was reauthorized and mandated that rebuilding plans for all overfished stocks be implemented, further stipulating that a stock be rebuilt within 10 years with limited exceptions (MSFCMA, 16 U.S.C 1801-1891(d)). The 1996 reauthorization provided the foundation upon which 79 rebuilding plans were implemented across the U.S. between 1997 and 2011 (National Research Council 2014). The National Standard 1 Guidelines, which operationalize the rebuilding mandate of the MSFCMA, states that stocks that cannot fulfill the 10-year rebuilding requirement due to biological limitations, may be allowed a rebuilding timeline equivalent to the time to rebuild in the absence of fishing plus the species mean generation time. The MSFCMA includes a mixed stock exception, recognizing the challenges discussed in the previous paragraph. However, the exception has never been invoked due to the strict criteria that a fishery must meet and uphold under the exception (National Research Council 2014). Neither SDG 14.4 or the National Standard 1 Guidelines appear to recognize that *MSY* cannot be achieved simultaneously for all stocks in a mixed stock fishery, and that a mandated 10 year timeline for some stocks may cause a serious loss of harvest of other species in mixed fisheries, thus causing the fishery to fail to achieve anything like total potential *MSY*.

The U.S. West Coast is accustomed to the rebuilding requirement, with 10 groundfish stocks declared overfished between 1999 and 2010 (PFMC 2017). The Pacific Fishery Management Council (PFMC), tasked with managing U.S. West Coast fisheries under the MSFCMA, dramatically reduced catch limits to adhere to the strict rebuilding timeline mandated by US law. Catches of some species were reduced to as low as 1.26% of their peak annual levels (McQuaw and Hilborn 2020). In a comprehensive study of 18 regions, the US. West Coast was found to have the lowest fishing pressure relative to the fishing mortality that produces *MSY*

(F_{MSY}) (Hilborn et al. 2020). The dramatic reductions in catch limits seriously impacted harvesters, processors and fishing-dependent communities as total nonwhiting groundfish catches dropped from greater than 80,000 mt to less than 30,000 mt. Processors and access to markets were lost, as the number of first receivers declined from 113 between 1996 and 2000, to 40 in 2011 (PFMC 2017). The fishery was declared a federal failure in 2000 in response to the economic disaster resulting from the reduced catch limits (DOC news). Despite the above conseqeunces, the rebuilding efforts were successful in terms of achieving biological objectives, as 9 out of 10 stocks were assessed to be above the rebuilding target by 2019.

Many of the overfished stocks on the West Coast were long-lived rockfish (Sebastes) species, which led to a biological challenge as the time to rebuild in the absence of fishing was often estimated to be greater than 50 years, thus allowing for very low catches during a prolonged period of rebuilding. The low natural mortality rate means that annual recruitment is a small fraction of the spawning biomass and thus it takes longer to rebuild the spawning biomass than it would for a species with a higher natural mortality rate. In addition to the rebuilding challenges posed by low natural mortality rates, recruitment was previously assumed to be nearly proportional to spawning biomass (i.e. limited density-dependence), so once a stock was depleted, the rebuilding time would be much longer than if year class strength was less dependent on spawning biomass. The relationship between spawning biomass and year-class strength is often modeled using a parameter known as steepness (often denoted in assessments as h) , the value of which greatly influences rebuilding rates. Steepness ranges from 0.2 to 1.0, where a value of 1.0 suggests that recruitment (i.e. year-class strength), is independent of the size of the spawning biomass and a value of 0.2 implies a linear relationship between spawning biomass and recruitment. Multiple meta-analyses were conducted at the time of the overfished declarations to estimate probability distributions for steepness for West Coast rockfishes. The results of these studies varied, with estimated values of h = 0.39 (Meyers et al. 1999) and h =0.65 (Dorn 2002). Some stock assessments, such as the 2003 assessment for widow rockfish, estimated a steepness value as low as 0.217 (He et al. 2003). Representative steepness estimates (posterior means of meta-analysis distributions) have changed over time (Table 2.1) with subsequent meta-analyses, influencing the expected rate of rebuilding for overfished rockfish. Thorson et al. (2018) provides an example of canary rockfish: the stock would be rebuilding in 2015 given the 2007 value for h = 0.58 in the 2015 assessment model, whereas the stock would have rebuilt by 2008 had the 2009 estimate of h = 0.69 been used. At the time of the overfished declarations, the understanding of groundfish productivity was very different from today's knowledge, leading to low steepness values and long estimated rebuilding timelines.

The extremely low catch limits mandated under National Standard 1, led to severe constraints on the ability of the fleet to target healthy stocks. Motivated by the National Research Council's report on U.S. rebuilding plans, where they concluded "*rebuilding plans that focus more on meeting selected fishing mortality targets than on exact schedules for attaining biomass targets may be more robust to assessment uncertainties, natural variability and ecosystem considerations, and have lower social and economic impact*." (National Research Council 2014), our objective was to explore this recommendation for the West Coast groundfish fishery. We used current knowledge of stock biomass and productivity to model alternative harvest strategies based on fishing mortality rates and simulate outputs of spawning biomass and catch. We aimed to evaluate the conservation, economic and community outcomes under alternative policies, compared to what happened under the actual rebuilding plans.

The analyses are based primarily on the results of alternative rebuilding projections using the biological parameters from the most recent assessments, up to the 2017 assessment cycle (there are now updated assessments for Widow rockfish, Petrale sole and Sablefish that were not used in this analysis). A feature in the history of management for these stocks is that at the time the rebuilding plans were formulated, the assessment models estimated these stocks were very unproductive (Table 2.1), and the rebuilding harvest control rules were very conservative (often with an rebuilding fishing mortality $< 0.02 yr^{-1}$). Thus, the anticipated rebuilding times even under no fishing were many decades (more than 70 years in some cases), and the dramatic declines in catch were necessary, based on the assumptions of the stock assessment. Decision makers used the best available science at the time to guide the development and impelemantation of the rebuilding plans. Relying on best available science is foundational to the MSFCA guidelines. Current analysis suggests past assessments were wrong, the productivity of the stocks proved to be much higher and the estimate of the key parameter determining recruitment is higher for all stocks in assessments that have taken place since the rebuilding plans were initiated. The underestimation of the stock productivity is the primary reason that rebuilding has occurred much faster than anticipated. Thus, we will explore policies using current knowledge, but also examine what a fishing mortality rate policy using the estimates of F_{MSY} and stock abundance at the time the rebuilding plans were formulated would have achieved, given the importance of managing with best available science.

METHODS

Data collection

We identified 13 stocks (Table 2.2) meeting the following criteria: (1) they were assessed using Stock Synthesis (SS; Methot and Wetzel 2013) between 2011 and 2017; and (2) they were either declared overfished or were not declared overfished but were commercially valuable or caught simultaneously with an overfished stock. While cowcod (*Sebastes levis)* was declared overfished, we did not analyze this stock because it was assessed in SS for the first time in 2019. Cowcod is also primarily found in Southern California and a majority of the groundfish trawl fleet now operates off Oregon and Washington. We did not analyze Pacific whiting (*Merluccius productus)* because while once declared overfished, this stock is managed by an international treaty agreement with the U.S. and Canada and is a targeted pelagic fishery with limited interaction with demersal species. The assessment results (abundance and catch time series and estimates of biological parameters) were obtained from NOAA. Catch was in metric tons (mt) and spawning biomass in either mt or millions of eggs. The annual average ex-vessel price for each stock for the years 1995 to 2019 was obtained from the Pacific Fisheries Information Network (PacFIN 2020).

Projection model

We modeled spawning biomass and potential catch for each stock under various rebuilding strategies (rates of fishing mortality) using the projection model in Privetera-Johnson and Punt (2019). The populations were projected from 1995 through the final year in the assessment (one less the year in which the assessment was published; Table 2.2). We set the recruitment deviates (the differences in log-space between realized recruitment and the value expected from the stock-recruitment relationship) to the values estimated in the recent assessment, listed in Table 2.2.

Three harvest scenarios were analyzed alongside what occurred under the actual rebuilding plans. The first harvest scenario held the fishing mortality rate from 1995 constant over the projection period, and we refer to this as the '1995 F policy' hereafter. In the second scenario, fishing mortality was reduced to the rate estimated in the most recent assessment to produce *MSY* (F_{MSY}). For the third scenario, fishing mortality was set equal to 0.8 F_{MSY} (estimated in the most recent assessment). The latter scenario was choosen in recognition of other fisheries management objectives, such as those used in Australia. Australian federal fisheries management uses biomass reference points which aim to maximize econonomic yield (B_{MEY}), thus setting a proxy for B_{MEY} at 1.2 B_{MSY} (Pascoe et al. 2015).

It is challenging to assume full utilization in a fishery for which average landed catch divided by TAC from 2011 to 2017 was less than 30% (McQuaw and Hilborn 2020). To address this challenge, we reduced the fishing mortality used in the F_{MSY} and $0.8F_{MSY}$ projections by the average utilization rate observed for each of the stocks from 1991 to 1995. In this way, the model assumes full attainment of the TAC for each stock is unlikely and the projected fishery can harvest at the average utilization rate observed in the period before the reauthorization of the MSFMCA. Several stocks did not have individual catch limits prior to 1996, but were managed as market categories, meaning a single catch limit was set for a group of stocks. For these stocks, we assumed a utilization rate of 100%. The historical utilization rate was already implied in the model under the 1995 F policy; therefore, we did not apply an additional utilization rate reduction for this policy. A constraint on catch to not exceed the maximum observed amount was also added to the model. This applied primarily to Dover sole, and other non-overfished stocks as catches for these species were predicted to greatly exceed historical catches under an F_{MSY} policy, and it is unlikely that processing and market capacity could have supported the increased volume.

Three exceptions to the methods described above applied to canary rockfish, lingcod and sablefish. The stock assessments for these species allow for time-varying parameters, which the projection model in Privetera-Johnson and Punt (2019) was not designed to address. To remedy this, we created a simplified model with a single fleet for each of these stocks. The model applied the biological parameters estimated in the assessment for females (year provided in Table 2.2) to both sexes. We fit the model to the time-series estimates of spawning biomass, catch and recruitment from the most recent assessment and found the simplifications did not impact the fit of the simplified model to the assessment output. Fishing mortality was manipulated according to each rebuilding scenario and catch and spawning biomass were simulated, as was done in the other projections previously described.

Evaluation of model outputs

To evaluate the alternative rebuilding scenarios, we compared the projected spawning biomass in terms of depletion (spawning biomass divided by unfished spawning biomass) at the end of the projection period relative to management reference points. The PFMC sets a groundfish management target and an overfished threshold for rockfish stocks, 40% and 25% of the unfished spawning biomass respectively. 40% of the unfished spawning biomass is a proxy for the biomass corresponding to *MSY*. The corresponding reference points for flatfish are 25% and 12.5%. The Pacific Council applies these default *MSY* proxies, as there is insuffiecient information regarding stock density-dependence, which is needed to estimate F_{MSY} (PFMC 2019). The assessment models estimate B_{MSY}, but the proxy reference point is used for management purposes in determining the status of stocks and setting annual catch limits. We evaluated the projected spawning biomass under each rebuilding strategy compared to the B_{MSY} proxy and the estimated B_{MSY}. These comparisons allowed us to determine if the results for each harvest scenario were projected to rebuild a stock or not.

We also evaluated the predicted yield and subsequent revenue for each harvest scenario. The ex-value prices and the estimated catch for each year of the projection period were used to determine the potential ex-vessel value of each scenario. For the time between the last year of the projection and 2019, we assumed catch remained constant under each policy, but applied the actual ex-vessel price to each year.

Comparison of results based on past and present best available science

The analysis described above relies on current best available science (i.e. the results of the most recent assessment). Outcomes from alternative rebuilding scenarios would likely have differed from our projections, had information available at the time rebuilding began been used as the basis for the projections. We collected estimates of F_{MSY} and summary biomass for every year a stock was assessed, going back to 2002 and used these values to calculate equilibrium catch at F_{MSY}. Exploitable biomass was not readily available going back to 2002. Thus, the average ratio of exploitable biomass to summary biomass from the most recent year assessed was used to scale the summary biomasses used to calculate catches at $F_{MSY.}$ The actual catch limit for the corresponding year was summarized as the percentage of the equilibrium catch at F_{MSY}. Four stocks had only been assessed once, thus the F_{MSY} in the single assessment was used along with the estimates of annual summary biomass to calculate potential catch under F_{MSY} for prior years. We tabulated our projections of catch under the F_{MSY} scenario for the same years to identify differences in using past or present best available science.

RESULTS

The projections infer spawning biomass for seven out of eight stocks previsously declared overfished would have either increased naturally or remained constant if rebuilding plans were not implemented and the fishery continued harvesting at the 1995 fishing mortality rate; it is projected that only yelloweye rockfish would have collapsed had fishing mortality not been reduced (Figure 2.1). The current stock assessments estimate the spawning biomass for widow rockfish and Pacific ocean perch never fell below the overfished threshold. The model projections for widow rockfish are shown in Figure 2.1, where the stock assessment's estimate of SB_{MSY} is slightly lower than the overfished threshold of 25% of the unfished spawning biomass. Based on these estimates, it would be illegal under the MSFCMA to harvest widow rockfish at the level estimated to produce maximum sustainable yield.

Spawning biomass is projected to increase under an F_{MSY} policy for all six of the stocks which are currently considered to have been accurately declared overfished (Figure 2.1). However, not all would have rebuilt to their target biomass under the F_{MSY} policy. Under the 0.8 F_{MSY} scenario, five of the six stocks would have rebuilt by the end of the projection period, with yelloweye rockfish no longer below the overfishing threshold, but remaining below the biomass target.

The F_{MSY} and 0.8 F_{MSY} policies are estimated to reduce fishing mortality enough that spawning biomass can rebuild, albeit at a slower rate than the actual adopted rebuilding plans. A consequence of slower rebuilding is increased harvest (Figure 2.2). Figure 2.2 shows the projected catches for the eight stocks originally declared overfished, as well as for five abundant stocks which were caught with the overfished stocks (Dover sole, sablefish, longspine thornyhead rockfish, shortspine thornyhead rockfish and yellowtail rockfish). There is no conservation concern for these five species, yet we observe a decline in landings after rebuilding plans were implemented. As this is a mixed stock fishery, the abundant species are caught with the overfished species, and more access to rebuilding stocks (i.e. higher catch limits) would have reduced fishery constraints, allowing harvesters the flexibility to catch more of the abundant stocks.

The adopted rebuilding plans that provided faster rebuilding (Figure 2.3), but less harvest, were costly to harvesters, processors, and fishing-dependent communities (Figure 2.4). The policy estimated to have maximized revenue is F_{MSY}, with a total ex-vessel value of $2 billion USD across all species over the projection period, which is $886 million USD more than the actual value of the fisheries for the same period (Table 2.3). The 0.8 F_{MSY} and 1995 F policies also provide greater economic opportunity, with $684 million and $610 million, respectively, more than the actual value. These policies are all based on fishing mortality rates and are estimated to eventually rebuild stocks while still providing economic stability to those dependent on the resource – something that was forgone under the objectives to meet strict schedules for rebuilding.

The magnitude of sustainable catch under an F_{MSY} policy is notably different when using current versus past best available science. If a rebuilding plan based on F_{MSY} had been adopted in 2003 for canary rockfish, allowable catches would be less than our projections using current information (Table 2.4). For the larger and more valuable stocks, such as widow rockfish, Dover sole and yellowtail rockfish, an F_{MSY} policy using the past best available science would have permitted much higher catches than the projection model using current science (Tables 2.4 and 2.5). Table 2.6 shows the divergence between the harvest control rule selected under the rebuilding plan and the estimated F_{MSY} at the time rebuilding began.

DISCUSSION

The West Coast groundfish rebuilding plans have been heralded as a great success of fisheries management, with some calling it the *"Comeback of the century"* (NOAA 2019a). In an article by SeafoodSource, the Environmental Defense Fund praises the efforts, saying *"The fishery, which consists predominantly of species of rockfish and flatfish, was near collapse due to overfishing two decades ago. Thanks to conservation efforts, a recovery effort has been massively successful… This story though is proof that with trust, collaboration, and smart management, even severely depleted fisheries can rebound and that's why it's so important to share it"* (SeafoodSource 2020). If the objective was to rebuild stocks, the plans have certainly been successful, but at a very high cost to food production, jobs, and the economy.

The common perception is that the fishery as a whole would have collapsed in the absence of rebuilding plans (NOAA 2019b). In contrast, our analysis suggests that the outcome would have been much better in terms of benefits to the fishery had the 1995 F persisted. Our projections, based on current assessment estimates, infer an additional $610 million dollars could have been attained by catcher vessels, had the fishery continued to operate as it was in 1995. While yelloweye rockfish was predicted to collapse under the 1995 F, the spawning biomass of the remaining seven overfished stocks would not have collapsed but instead, would have increased or stabilized leading to substantial benefits to the fishery.

While this analysis is based on today's best available science, we recognize that the understanding at the time of the overfished declarations was dramatically different. If a rebuilding plan based on a fishing mortality rate had been adopted, sustainable catches for some species with a steepness value as low as 0.32 (Table 2.1) would have still been low, and certainly for some species, less than our projections using the current parameter estimates (Table 2.4). As the understanding of stock productivity changed and steepness increased over time (Table 2.2), the estimates of sustainable yield and the time needed to rebuild would have also changed. The NRC study reports, *"Rebuilding plans that focus more on meeting selected fishing mortality targets than on exact schedules for attaining biomass targets may be more robust to assessment uncertainties, natural variability, and ecosystem considerations, and may have lower social and economic impact (National Research Council 2014)."* A rebuilding plan based on F_{MSY} may have provided more flexibility as the best available science evolved, as opposed to stringent plans based only on rebuilding stocks as quickly as possible.

Given that the understanding of steepness, productivity and even the magnitude of spawning biomass was different at the time of the overfished declarations, it may appear unlikely that an F_{MSY} policy could have provided the kind of economic returns projected in our analysis. If past assessments had been used for forecasting, equilibrium catches at F_{MSY} at the time rebuilding began would likely have been lower for some species than was predicted in our analysis (Table 2.4). However, sustainable catch calculations using F_{MSY} in 2003 for the larger and more valuable stocks were greater than our projection model (Tables 2.4 and 2.5). This comparison further illustrates that an F_{MSY} policy (even using past best available science) could have permitted substantially higher catch limits than those selected under the actual rebuilding plan. The catch limit for widow and canary rockfish in 2003 was 12% and 16%, respectively, of what it could have been under an F_{MSY} policy using the information available at the time (Table 2.4). It is difficult to determine exactly how much additional utilization of abundant stocks could have occurred had there been access to higher quotas for rebuilding species (like those under an F_{MSY} policy), but it is clear that this would have noticeably reduced constraints on the fleet. Here lies the opportunity for further analysis which could include assumptions about fleet dynamics and supply and demand relationships. Additional work could also expand the analysis beyond just the ex-vessel impact on harvesters and look at foregone revenue to processors and subsequent economic benefits to fishing-dependent communities.

The need for management flexibility is uniquely highlighted by the case of the widow rockfish, which was declared overfished in 2001 and rebuilt in 2012. The stock assessment in 2005 estimated the spawning biomass had never actually fallen below the overfished threshold (He et al. 2005). Despite this finding, the stock remained under a rebuilding plan until 2012 as the MSFCMA mandates a stock declared overfished be rebuilt to the biomass target level, regardless of whether the current best available science suggests the initial overfished declaration to no longer be accurate. To minimize adverse tradeoffs to harvesters, communities and supply chains, legislation guiding rebuilding plans needs to be flexible enough to recognize that the scientific understanding of stocks is evolving – adopting a rebuilding plan based on fishing mortality rates may provide more opportunity for this.

We observe the consequences of declaring a stock overfished when it is not as opposed to failing to declare a stock overfished when it actually is. Failing to take conservation action has been referred to as miss, while restricting fishing above what is needed for sustainability objectives has been coined as a false alarm (Rice 2011). From a conservation perspective, a miss is far riskier than a false alarm and can prompt ecologists and conservation biologists to be risk adverse (Rice 2011). Petrale sole provides an example of a miss, as current estimates suggest the stock was overfished beginning in 1980 but was not declared overfished until 2010. However, the failure to detect overfishing did not lead to the collapse of the petrale sole stock. Comparatively, Widow rockfish could be described as a false alarm. The stock was declared overfished and placed under a rebuilding plan for eight years, even after a subsequent assessment determined it was never overfished. The incorrect overfished declaration of widow rockfish prevented harvesters from accessing one of the most valuable groundfish stocks in the region and the the false alarm further inhibited the harvest of yellowtail rockfish, as the two stocks are often caught simultaneously.

Our findings support those of the NRC (2014) and provide evidence that a rebuilding plan based on F_{MSY} or a reduction from F_{MSY}, could provide far greater food production and profitability than a rebuilding plan meant to meet a strict timeline. In fact, a rebuilding plan based on fishing mortality may have provided an additional $886 million USD in ex-vessel revenue to the West Coast non-whiting groundfish trawl fleet. Fishery managers looking to adopt rebuilding policies need to carefully weigh their objectives and the associated tradeoffs. The U.S. West Coast sacrificed fishing opportunities and community stability to rebuild stocks quicker than the maximum time permitted under the MSFCMA (PFMC 2019). As a mixed-stock fishery, this decision magnified the economic devastation, reducing harvesters' access to other abundant stocks. Our retrospective analysis demonstrates that a rebuilding plan based on reducing fishing mortality to the level that produces *MSY*, or slightly lower, provides more flexibility and can minimize adverse impacts to stakeholders while still achieving conservation objectives.

While sustainability is often interpreted in a multitude of ways (Hilborn et al. 2015), one perspective suggests the objective of sustainable development is to prevent human well-being from declining (Matson et al 2016). Granted, this requires maintaining resources to provide the desired good and services. Fisheries management in the U.S. has long focused on sustaining stock status and prioritized not overfishing any stocks. Our analysis of the U.S. West Coast groundfish fishery suggests human well-being declined more than it needed to. The results show that alternative management frameworks, while increasing the time needed to rebuild overfished stocks, are perhaps more suited to sustaining human well-being by providing for more food production and profitability, without jeopardizing the resource.

TABLES

Table 2.1 Values for steepness, *h*, in the assessment for the year in the column header. Assessments available at: https://www.pcouncil.org/stock-assessments-star-reports-stat-reports-rebuilding-analyses-terms-of-reference/groundfish-stock-assessment-documents/

	2002/2003	2005	2007	2009	2011	2013	2015	2017	2019
Widow rockfish	0.217	0.281	0.290	0.406	0.760	-	0.798	-	0.720
Canary rockfish	0.320	0.320	0.510	0.510	0.510	-	0.773	-	-
Pacific Ocean perch	0.532	0.550	0.652	0.514	0.400	-	-	0.500	-
Darkblotched rockfish	0.500	0.950	-	0.600	0.760	0.779	0.773	0.720	-
Petrale sole	-	0.875	-	0.950	0.860	0.860	0.900	-	0.840
Yelloweye rockfish	0.437	0.440	-	0.417	0.441	-	-	0.718	-
Lingcod	0.900	0.900	-	0.800	-	-	-	0.700	-
Bocaccio rockfish	-	-	-	0.210	0.570	0.600	0.620	0.773	0.718

Table 2.2 The stocks modeled in this study, the assessment year used, and the years they were declared overfished and rebuilt, where applicable. T_{max} is the estimated time to rebuild in the absence of fishing plus one mean generation time. A stock had to be rebuilt by that year, under the initial rebuilding plan. The species catch limits are shown for one year before and one year after the overfished declaration.

Common name	Scientific name	Year of assessment used	Year declared overfished (OF)	Year declared rebuilt	T_{max} (year)	TAC year before OF	TAC year afer OF
Bocaccio rockfish	*Sebastes paucispinis*	2017; He and Field	1999	2017	2032	230	100
Canary rockfish	*Ophiodon elongates*	2015; Thorson and Wetzel	2000	2015	2076	1,130	228
Darkblotched rockfish	*Sebastes crameri*	2017; Wallace and Gertseva.	2001	2017	2047	NA	168
Lingcod, North	*Sebastes pinniger*	2017; Haltuch et al.	1999	2005	2009	559	450
Pacific Ocean perch	*Sebastes alutus*	2017; Wetzel et al.	1999	2017	2042	650	595
Petrale sole	*Eopsetta jordani*	2013; Haltuch et al.	2010	2015	2021	2,433	976
Widow rockfish	*Sebastes entomelas*	2015; Hicks and Wetzel	2001	2012	2042	5,090	856
Yelloweye rockfish	*Sebastes ruberrimus*	2017; Gertseva and Cope	2002	In progress	2071	NA	14
Dover sole	*Solea solea*	2011; Hicks and Wetzel	NA				
Longspine thornyhead rockfish	*Sebastolobus altivelis*	2013; Stephens and Taylor	NA				
Sablefish	*Anoplopoma fimbria*	2015; Johnson et al.	NA				
Shortspine thornyhead rockfish	*Sebastolobus alascansus*	2013; Stephens and Taylor	NA				
Yellowtail rockfish	*Sebastes flavidus*	2017; Stephens and Taylor	NA				

Table 2.3 Total ex-vessel revenue in millions of USD, for each species and harvest policy. 'Forgone revenue under F_{MSY}' is the revenue of the F_{MSY} policy less the actual revenue for that species. Rows are ordered by descending forgone value under the F_{MSY} policy.

	F_{1995}	F_{MSY}	0.8 F_{MSY}	Actual	Forgone revenue under F_{MSY}
Dover sole	$319	$432	$432	$166	$266
Shortspine thornyhead	$161	$195	$161	$64	$131
Lingcod, North	$130	$135	$115	$24	$111
Widow rockfish	$117	$138	$130	$45	$93
Sablefish	$581	$679	$596	$593	$86
Yellowtail rockfish	$101	$108	$95	$42	$66
Pacific Ocean perch	$25	$40	$33	$5	$35
Bocaccio	$29	$35	$30	$6	$29
Longspine thornyhead	$117	$84	$73	$58	$26
Canary rockfish	$26	$28	$25	$8	$20
Petrale sole	$125	$136	$120	$119	$17
Darkblotched rockfish	$17	$13	$12	$6	$7
Yelloweye rockfish	$1	$1	$1	$3	($2)
Total revenue (1995 - 2019)	$1,748	$2,025	$1,823	$1,139	
Total forgone revenue (1995 – 2019)	$610	$886	$684		

Table 2.4 Estimates of fully-selected F_{MSY} (units yr^{-1}) in each assessment for the year in the column header, the calculated equilibrium catch at that F_{MSY}, the simulated retrospective catches under the most recent assessment F_{MSY} estimates, the actual catch limit adopted each year and the actual TAC as a percent of the equilibrium catch at F_{MSY}.

		2002/ 2003	**2005**	**2007**	**2009**	**2011**	**2013**	**2015**	**2017**	**2019**
Widow rockfish	F_{MSY} estimated in the assessment for the year in column header	0.118	0.1154	0.121	0.0337	0.079	-	0.113	-	0.096
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	3,962	6,316	8,492	1,841	3,149	-	9,116	-	10,143
	Catch from projection model, using recent assessment F_{MSY} estimates	6,626	6,344	6,503	5,940	5,830	-	7,262	-	-

	Actual TAC	832	285	368	522	600	1,500	2,000	13,508	11,831
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	21%	5%	4%	28%	19%		22%		117%
Canary rockfish	F_{MSY} estimated in the assessment for the year in column header	0.060	0.02	0.0457	0.0353	0.0285	-	0.044	-	-
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	247	91	1,062	488	393		1,414	-	-
	Catch from projection model, using recent assessment F_{MSY} estimates	1,056	1,137	2,726	2,884	3,001	-	3,008	-	-
	Actual TAC	44	47	44	105	102	116	122	-	-
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	18%	52%	4%	21%	26%		9%		
Pacific Ocean perch	F_{MSY} estimated in the assessment for the year in column header	-	0.031	0.0388	0.031	0.0322	-	-	0.028	-
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	-	501	742	533	591	-	-	2,593	-
	Catch from projection model, using recent assessment F_{MSY} estimates	-	1,529	1,771	1,847	1,717			2,637	
	Actual TAC	-	447	150	189	180	150	158	281	4,340
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent		89%	20%	35%	30%			11%	
Darkblotched	F_{MSY} estimated in the assessment for the year in column header	0.03	-	0.038	0.037	0.036	0.042	0.041	0.037	-
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	200		390	410	433	602	633	661	-
	Catch from projection model, using recent assessment F_{MSY} estimates	484	-	692	592	604	647	717	713	
	Actual TAC	168	269	290	285	298	317	338	641	-
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	84%		74%	70%	69%	53%	53%	97%	
Petrale sole	F_{MSY} estimated in the assessment for the year in column header	-	0.12	0.1185	0.112	0.2	0.17	0.18	-	0.182
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment	-	1,771	2,246	712	1,176	1,614	2,508	-	3,706

	for the year in column header									
	Catch from projection model, using recent assessment F_{MSY} estimates	-	2,641	2,583	2,384	2,464	2,808	-		-
	Actual TAC	2,762	2,762	2,499	2,433	976	2,592	2,816	3,136	2,921
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent		156%	111%	342%	83%	161%	112%		79%
Yelloweye rockfish	F_{MSY} estimated in the assessment for the year in column header	0.023	0.021	0.022	0.015	0.016	-	-	0.025	-
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	44	35	35	25	29	-	-	76	-
	Catch from projection model, using recent assessment F_{MSY} estimates	20	20	21	23	25	-	-	30	
	Actual TAC	22	26	23	17	17	18	18	20	-
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	50%	75%	65%	69%	59%			26%	
Lingcod, North	F_{MSY} estimated in the assessment for the year in column header	0.12	-	-	0.085	-	-	-	0.126	-
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	-	-	-	2,393	-	-	-	3,804	-
	Catch from projection model, using recent assessment F_{MSY} estimates	-	-	-	1,969	-	-	-	2,596	-
	Actual TAC	-	-	-	-	2,330	3,036	2,830	3,333	-
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent								88%	
Bocaccio rockfish	F_{MSY} estimated in the assessment for the year in column header	0.0638	0.0632	0.0768	0.0666	0.065	0.068	0.086	0.093	-
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	374	445	-	701	665	1,064	1,487	1,934	-
	Catch from projection model, using recent assessment F_{MSY} estimates	1,069	867	-	604	562	832	1,470	1,845	
	Actual TAC	20	307	218	288	263	320	349	790	-
		5%	69%		41%	40%	30%	23%	41%	

	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent									
Sablefish	F_{MSY} estimated in the assessment for the year in column header	-	-	0.0333	-	0.057	-	0.0526	-	-
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header	-	-	6,374	-	10,074	-	8,677	-	-
	Catch from projection model, using recent assessment F_{MSY} estimates	-	-	6,972	-	5,584	-	5,002	-	-
	Actual TAC			5934		6813		6512		
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent			93%		68%		75%		

Table 2.5 Table 2.4, except that stocks displayed were only assessed once. Thus, the F_{MSY} estimated in that assessment was used in accordance with the estimates of annual summary biomass to calculate what the catch could have been for prior years under F_{MSY}.

		2002/ 2003	**2005**	**2007**	**2009**	**2011**	**2013**	**2015**	**2017**
Dover sole	F_{MSY} estimated in the assessment for the year in column header					0.131			
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header with an estimated F_{MSY}	72,050	74,818	76,064	73,630	70,749			
	Catch from projection model, using recent assessment F_{MSY} estimates	20,872	20,872	20,872	20,872	20,872			
	Actual TAC	7,440	7,476	16,500	16,500	25,000			
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	10%	10%	22%	22%	35%			
Longspine	F_{MSY} estimated in the assessment for the year in column header						0.071		
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header with an estimated F_{MSY}	3,066	3,325	3,626	3,842	3,934	3,976		
	Catch from projection model, using recent assessment F_{MSY} estimates	2,428	2,413	2,454	2,544	2,660	2,713		
	Actual TAC	2,656	2,461	2,696	2,626	2,495	2,430		
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	87%	74%	74%	68%	63%	61%		
Shortspine	F_{MSY} estimated in the assessment for the year in column header						0.018		
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header with an estimated F_{MSY}	3,729	3,708	3,692	3,661	3,625	3,615		
	Catch from projection model, using recent assessment F_{MSY} estimates	3,080	3,027	2,976	2,927	2,879	2,855		
	Actual TAC	955	999	2,055	2,022	1,978	1,836		
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	26%	27%	56%	55%	55%	51%		
Yellowtail	F_{MSY} estimated in the assessment for the year in column header								0.089
	Catch determined by F_{MSY} and the summary biomass estimated in the assessment for the year in column header with an estimated F_{MSY}	10,150	10,571	10,515	10,269	9,914	9,681	9,558	7,937
	Catch from projection model, using recent assessment F_{MSY} estimates	5,565	5,298	5,328	5,257	4,805	4,266	3,951	2,892
	Actual TAC	3,146	3,896	4,585	4,562	4,364	4,378	6,590	6,196
	Actual TAC / catch under the historical F_{MSY} (row 2) shown as a percent	31%	37%	44%	44%	44%	45%	69%	78%

Table 2.6 Years stocks were declared overfished and a rebuilding plan was adopted. This table compares the harvest control rule of the rebuilding plan and the F_{MSY} selected at the time; along with the average catch 10 years before being declared overfished and the average catch under the rebuilding plan until the time the stock was declared rebuilt, if applicable. *25:5,* $F_{30\%}$ - Flatfish have a target reference point of 25% of the unfished level, an overfished threshold at 12.5%, a limit reference point at 5% and a fishing mortality target to not exceed of $F_{30\%}$ with a spawning potential ratio of 30% ($SPR_{30\%}$).

Stock	**Year Declared Overfished**	**Year rebuilding plan adopted**	**Rebuilding plan Harvest Control rule**	**F_{MSY} estimated at time of rebuilding plan (yr^{-1})**	**Avg. catch 10 years before OF declaration (mt)**	**Average catch under rebuilding plan (mt)**	**Catch under rebuilding / catch prior to rebuilding**
Widow	2001	2004	0.009 yr^{-1}	0.118	6,044	355	6%
Petrale	2010	2010	25:5, $F_{30\%}$	0.112	2,065	1,620	78%
Canary	2000	2003	0.022 yr^{-1}	0.060	1,941	68	4%
Lingcod	1999	2003	0.053 yr^{-1}	0.120	1,520	235	15%
Bocaccio	1999	2004	0.050 yr^{-1}	0.064	1,415	133	9%
POP	1999	2003	0.008 yr^{-1}	0.031	1,072	86	8%
Darkblotched	2000	2003	0.027 yr^{-1}	0.032	977	132	14%
Yelloweye	2002	2004	0.015 yr^{-1}	0.023	228	10	4%

FIGURES

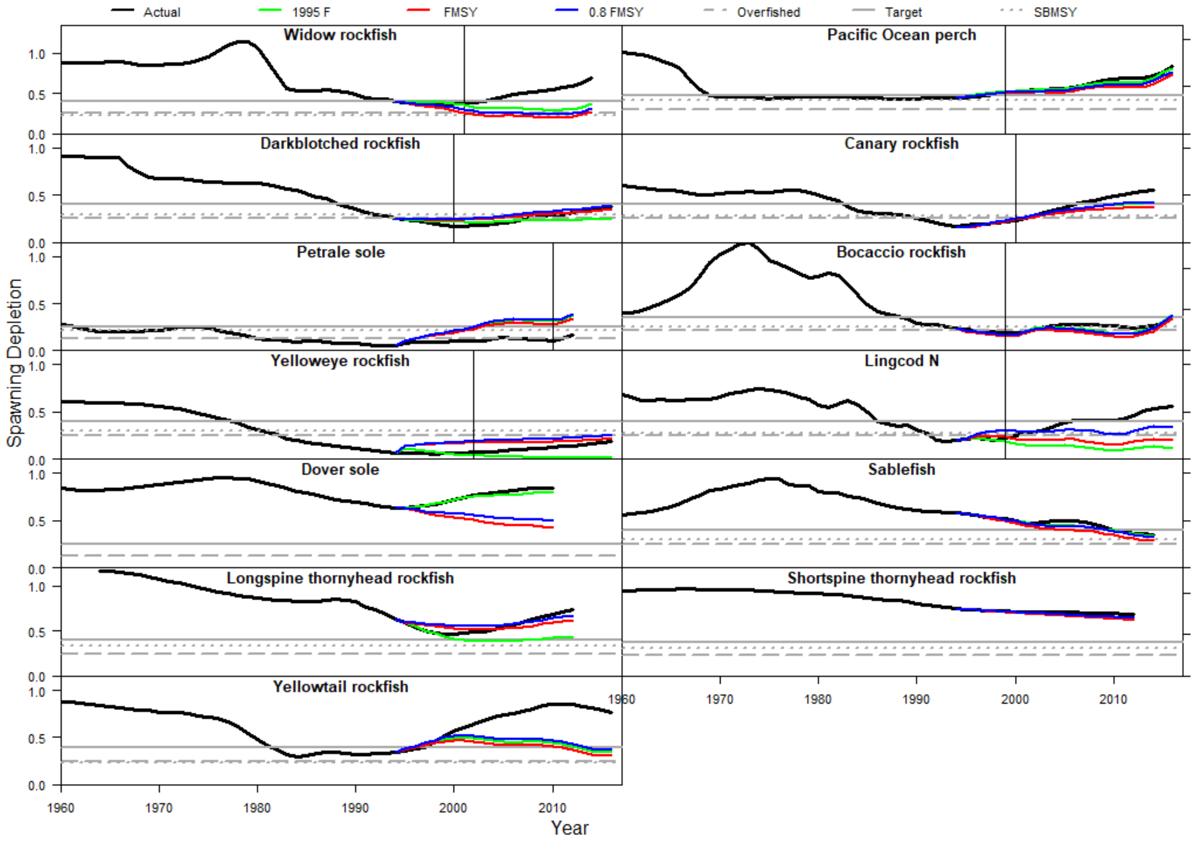

Figure 2.1 Estimated and projected spawning depletion. The solid grey line is the biomass target, and the dashed grey line the overfished threshold. The dotted grey line is the estimate of the SB_{MSY} from the stock assessment and the thick black line the corresponding estimates of the spawning biomass. The green line is the model output of spawning depletion under the 1995 F policy, the red line is the estimate under the F_{MSY} policy, and the blue line is the projection under the 0.8 F_{MSY} policy. The vertical black line is the year the stock was declared overfished, if applicable.

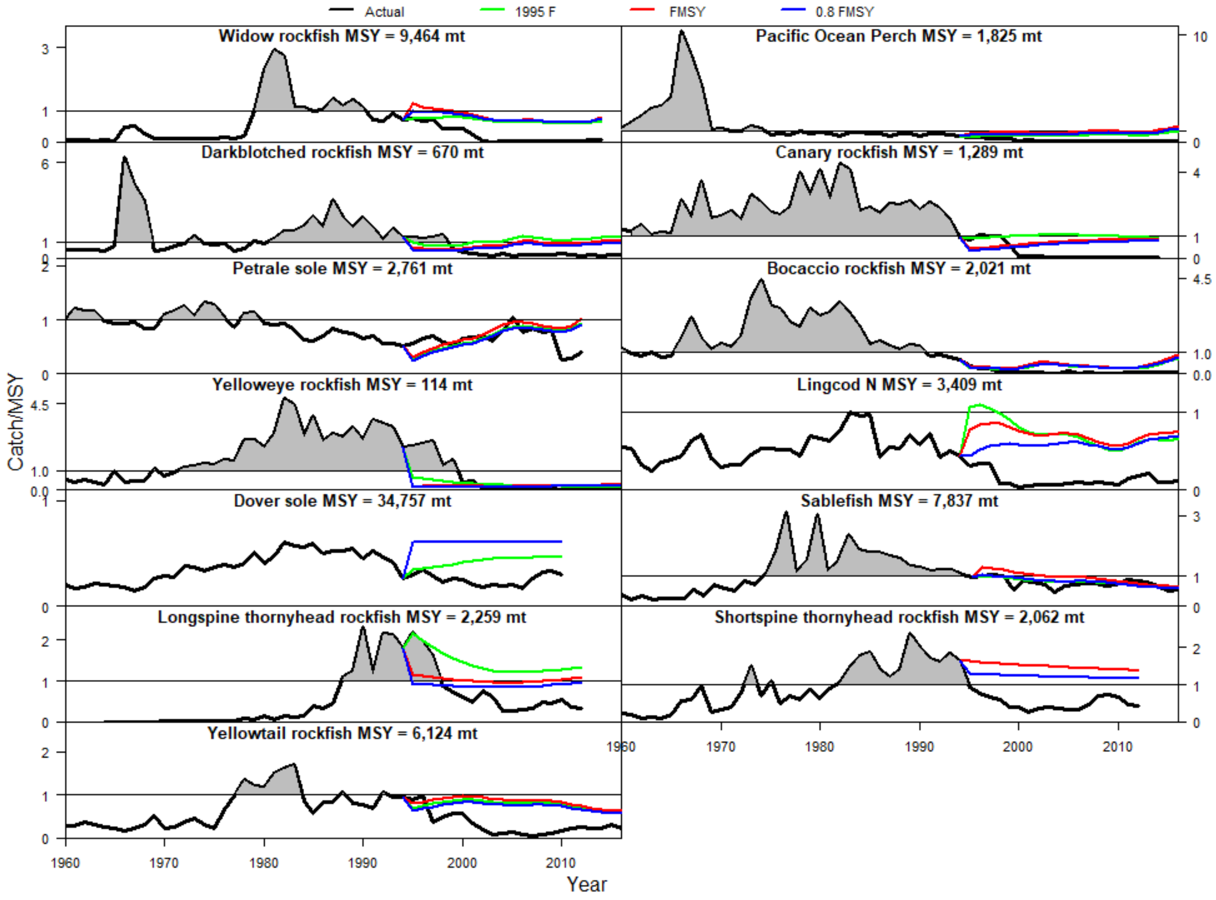

Figure 2.2 Catch under each harvest policy, scaled to *MSY*. The thick black line is the actual catch time series taken from the assessment. The green line is the model output under the 1995 F policy, the red line is the estimate under the F_{MSY} policy, and the blue line is the projection under the 0.8 F_{MSY} policy. The shaded area is when catch was greater than *MSY*.

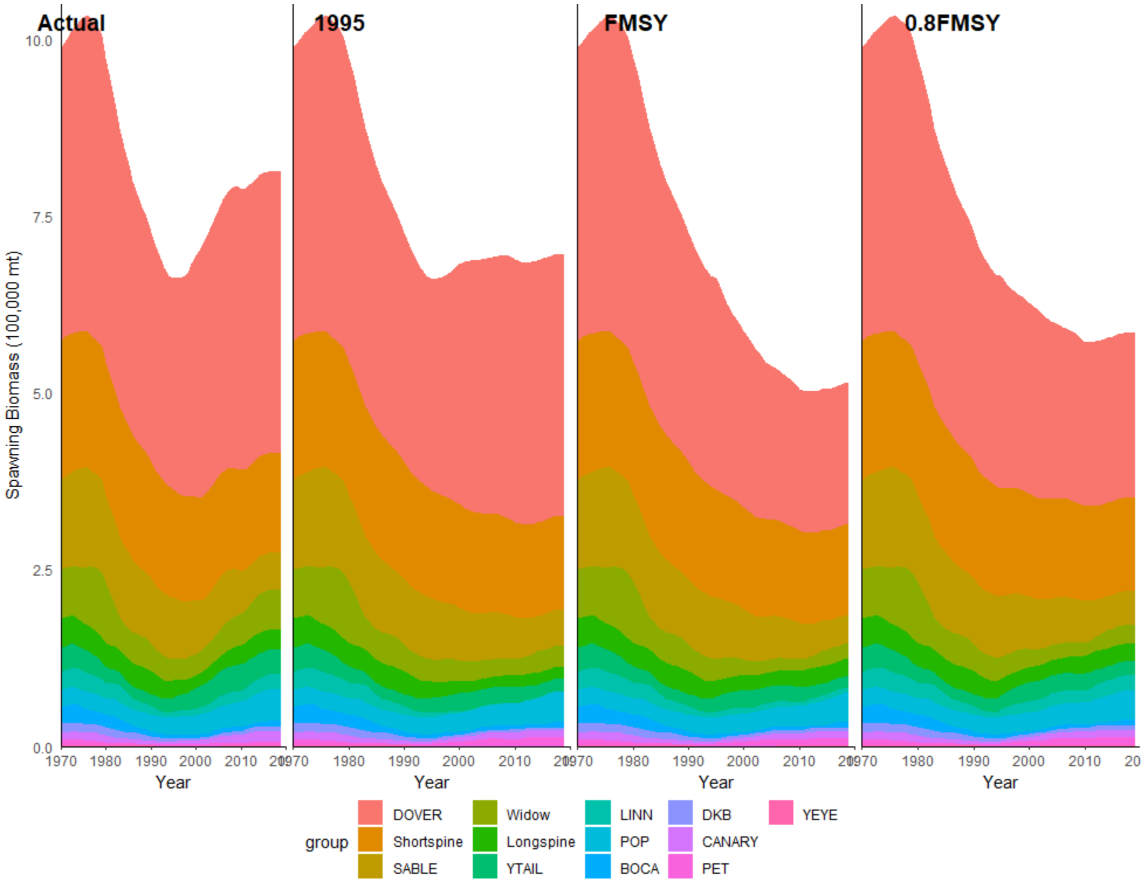

Figure 2.3. The total spawning biomass for each harvest policy. The panels are shaded accorded to biomass (dover sole is most abundant; yelloweye is the least).

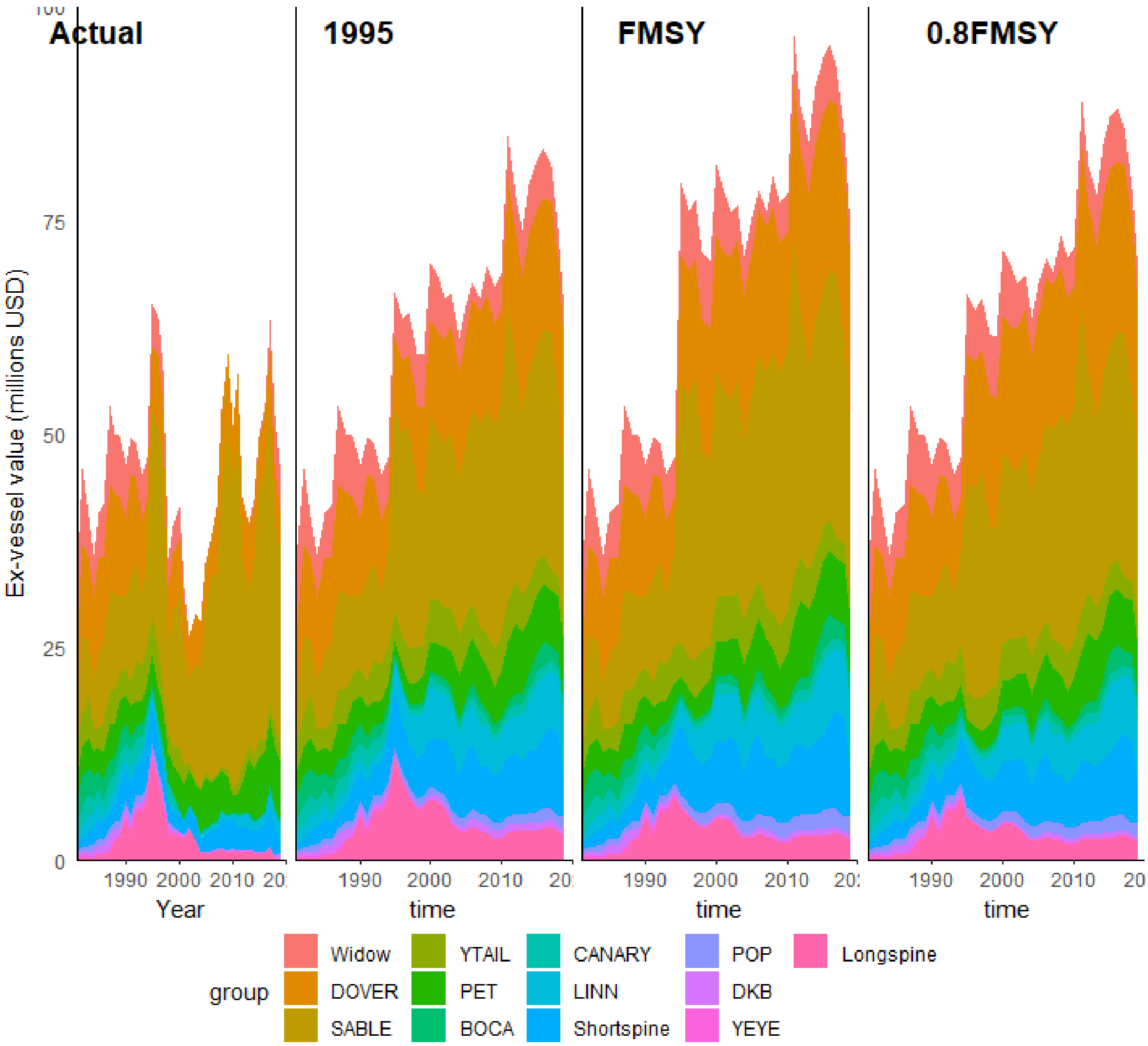

Figure 2.4. The total ex-vessel value, in millions of USD for each scenario. The panels are shaded according to value, with widow rockfish having the highest value and longspine being the least valuable.

CHAPTER 3 ARE CLOSED AREAS ALONE AN EFFECTIVE TOOL TO MEET CONSERVATION TARGETS FOR WEAK STOCKS IN A MIXED STOCK FISHERY?

ABSTRACT

Meeting conservation targets in mixed stock fisheries can be challenging when stocks with differing sustainable exploitation rates are caught simultaneously. Current U.S. fisheries management that relies on single species-catch limits can result in limits on unproductive or overfished (‘weak’) stocks that constrain catches of productive stocks. An alternative solution is to close a large enough portion of the habitat of the weak stocks to assure their abundance meets minimum management targets, and not limit the catch of the weak stocks outside the closed areas. We evaluated the potential to meet minimum conservation targets using a two-area single-stock age structured model across a range of model parameters including 1) proportion of the weak stock in the closed area, 2) fishing mortality outside the closed area, 3) whether recruitment takes place globally or is local, and 4) adult movement rates between areas. The results were most sensitive to assumptions regarding adult movement. If adults were thought to be sedentary, a reserve covering 30 – 40% of the stock was projected to maintain spawning output at the management target while withstanding intense fishing mortality, up to 30%, outside the closure. Conversely, if there was adult movement, the level of fishing intensity outside the reserve was more influential on the resulting stock status than the proportion of the stock protected by a closure.

INTRODUCTION

The mixed stock dilemma, when ‘weak’ and ‘strong’ stocks are caught simultaneously in the same fishing gear, has long been recognized (Ricker 1958, Paulik et al. 1963). Strong stocks are frequently characterized as highly productive and abundant, making them common fisheries targets. Weak stocks have lower sustainable exploitation rates and are often vulnerable to depletion if yield of the strong stock is optimized. The root of this dilemma lies among the differences in single-species sustainable exploitation rates of the mix of species. A mixed fishery cannot harvest each stock at its optimum rate. “Weak stock” management that maintains all stocks in a system above their *MSY* target biomass consequentially forgo potential yield of the strong stocks (Worm et al. 2009; Hilborn et al. 2012).

The US West Coast (WC) groundfish fishery has been greatly affected by its diverse mix of weak and strong stocks. Sustainable exploitation rates (F_{MSY}) for many long-lived rockfish, such as yelloweye or cowcod (*Sebastes ruberrimus; Sebastes levis*) are on the order of 5% per year (Gertseva and Cope 2017; Dick and He 2019); whereas some larger more productive stocks such as petrale sole and widow rockfish (*Eopsetta jordani; Sebastes entomelas)* have F_{MSY}’s of 18% and 11%, respectively (Wetzel 2019; Hicks and Wetzel 2015). Using a generic model multispecies model, Worm et al. (2009) estimated that the ecosystem-wide *MSY* would be maximized when 40% of stocks were collapsed (less than 10% of unfished abundance) and they estimated that half of *MSY* would be forgone if fishing pressure was reduced to the level where no stocks were collapsed. Hilborn et al. (2011) quantified these tradeoffs between yield maximization and stock abundance for the WC groundfish fishery. They found that only 57% of *MSY* would be attained if no stock were overfished, while achieving the ecosystem *MSY* would lead to 13 stocks either overfished or collapsed, concluding that more food production was lost due to low exploitation rates than due to overfishing. Thus, to reduce tradeoffs in food production and profitability, some weak stocks would be overfished.

This is not to say that there is no ability to harvest weak stocks at a lower rate than strong stocks in the West Coast (WC) groundfish fishery. The Pacific Fishery Management Council (PFMC) implemented several measures to redirect relative fishing mortality on the ten stocks that were declared overfished (Figure 3.1). The implementation of rebuilding plans following the 1996 reauthorization of the Magnuson Stevens Act reduced catch limits by as much as 80% within two years for select species (and by as much as 95% over a five-year period), as was necessary to meet strict rebuilding timelines. The Council redistributed demersal fishing effort by enacting the Rockfish Conservation Area (RCA) at the end of 2002. The closure ranged from shore to 250 fathoms, protecting coast-wide rebuilding rockfish habitat.

Furthermore, in 2011 the Council allocated single species catch limits to participants in the form of transferable fishing quotas (IFQ's). The IFQ fishery required 100% monitoring, and greatly reduced regulatory and economic discards. In the event a vessel exceeds its quota for a single species, the fishery management plan prohibits the vessel from leaving the dock in pursuit of groundfish until enough quota can be leased or bought to cover the deficit. If no such leasing arrangements can be made, the vessel forfeits the duration of its season. This incentivized individual vessels to find ways to avoid weak stocks for which low quotas were constraining to optimize their harvest of strong stocks. Similar incentives were implemented for the directed groundfish fishery for Pacific Whiting (*Merluccius productus*), prompting most of the participants to form cooperatives. The cooperatives employed a range of tools such as excluder devices and real time spatial/temporal closures to minimize incidental catch of non-whiting species (Holland and Martin 2019).

Despite actions by managers and stakeholders, non-whiting utilization averaged less than 30% between 2011 and 2017, further suggesting the fishery remains challenged by multispecies dynamics (McQuaw and Hilborn 2020). Hastings et al. (2017) proposed an alternative solution, arguing marine reserves address the mixed stock dilemma, stating "maximum yields of strong stocks are not compromised by spatial closures that guarantee the persistence of weak stocks." The authors used a multispecies model to test their analytical results on several WC groundfish stocks. They found yelloweye rockfish could persist at 20% of its unfished level, but the absence of a marine reserve would result in a 32% loss in yield of the strong stock, while a 21% closure reduced forgone yield to 9%. Upon these findings, they concluded marine reserves may be a superior management option for the WC groundfish fishery, given its mix of over 90 species and commitment to rebuild stocks declared overfished.

Spatial closures have routinely been used as a management tool in the fishery, with the RCA in place for seventeen years. Depth-based management measures were first implemented in September 2002 to prevent the catch limit for Darkblotched rockfish from being exceeded (NMFS 2002). In 2003, the Council continued the use of spatial closures to protect Canary rockfish alongside Darkblotched, by prohibiting trawl fishing in depths where the species were most frequently caught (100 – 250 fathoms; NMFS 2002). The protections of the closure were expected to benefit other rebuilding stocks and have remained in effect, at variable boundaries, as the RCA. The surveys conducted on the West Coast were reconstructed at the time the RCA was implemented, making it difficult to determine the effectiveness of the spatial closures in rebuilding overfished stocks as data prior to their implementation are not comparable to current surveyed stock distributions (Keller et al. 2014).

We modeled alternative scenarios built on the recommendation by Hastings et al. (2017) to evaluate whether the use of closed areas on the West Coast could protect rockfish stocks, while allowing full utilization of other species. If species of conservation concern are primarily found in certain areas such as a specific depth range or bottom type, those areas could be closed to demersal fishing, and the abundance of the species within the closed area could meet total biomass targets. Then the constraining species could be unregulated outside the closed areas, so the fleet could fully exploit the other species. We would expect fishing mortality outside the reserve to not exceed the maximum rate of 27%, observed across stocks (Figure 3.1). This hypothesis would depend on two key factors; (1) what proportion of the weak stock is found in the closed area and (2) how much movement of adults and larvae is there was between the open and closed areas. We used a two-area age structured model for Darkblotched rockfish (which is often constraining) and compared the outcome of spawning biomass across a range of closure sizes and assumptions on movement. We explored if the species could rebuild to and be sustained at its biomass reference point with the sole use of a spatial closure.

METHODS

Proportion of stocks inside closed area

The boundaries of the RCAs changed frequently, coinciding with the attainment of catch limits; the seaward boundary ranged from 150 to 250 fathoms and the shoreward boundary ranged from 100 fathoms to shore (Hamel 2008). Despite modifications, the span of coastline from 100 to 150 fathoms remained closed to demersal gear from 2003 to 2019 (PFMC, 2019). Based on the spatial coverage of the RCA, the NWFSC bottom trawl survey was used to calculate the proportion of 16 stocks found inside 30-50 fathoms, 30-75 fathoms, 30-100 fathoms and 30-150 fathoms; there is not comparable data shoreward as the survey begins at 30 fathoms. The survey utilizes stratified random sampling such that the proportion of stations sampled in each depth range is proportional to the area within each stratum (Bradburn et al. 2011). The survey catch per unit effort (CPUE) for a specified depth range was compared to the total CPUE for a stock to determine the proportion found inside the range.

Population dynamics

The analysis is based on a simple age-structured model that replicated the 2017 assessment of Darkblotched rockfish (Wallace and Gertseva 2017). Recruitment deviations, numbers-at-age in 1980, and the female biological parameters were extracted from the assessment (Table 3.1). The model was simplified to a single fleet and assumed biological parameters to be the same for males and females. The simplifications did not impact the model's ability to fit match the estimates of spawning biomass and catch from 1980 through 2016 in the full assessment.

The initial population numbers were divided into two areas, inside and outside the closed area. The 2002 numbers-at-age calculated in the initial one-area model were subdivided such that a proportion (p_{in}) of the stock was placed inside the closure.

$$N_{2002,a,in} = N_{2002,a} * p_{in} \quad (1)$$

$$N_{2002,a,out} = N_{2002,a} * (1 - p_{in}) \ (2)$$

The parameters m_{in-out} and m_{out-in} are the proportions of the stock that move from inside to outside and outside to inside at the start of the year. m_{in-out} decreases linearly with the proportion of the population in the closure and is scaled by species mobility (b) given by equation 3. m_{in-out} and m_{out-in} are equal to zero when there is no adult movement. Equation 5 and 6 describe the dynamics of numbers-at-age in the closed area and outside. The plus group for the numbers-at-age are given in equations 7 and 8. Fishing mortality was applied solely to the component of the stock outside the closure provided by equations 11 and 12.

$$m_{in-out} = b(1 - p_{in}) \quad (3)$$

$$m_{out-in} = b * p_{in} \quad (4)$$

$$N_{t+1,a,in} = \left(N_{t,a-1,in}(1 - m_{in-out}) + N_{t,a-1,out}m_{out-in}\right) e^{-Z_{a-1,in}} \quad \text{t>= 2002, 1<a<A}$$

(5)

$$N_{t+1,a,out} = \left(N_{t,a-1,out}(1 - m_{out-in}) + N_{t,a-1,in}m_{in-out}\right) e^{-Z_{a-1,out}} \quad \text{t>= 2002, 1<a<A}$$

(6)

$$N_{t+1,a,out} = (N_{t,a-1,out} + N_{t,a-1,in}(1 - m_{in-out}) - N_{t,a-1,out}(1 - m_{out-in}))\, e^{-Z_{a-1,out}} \quad \text{t>= 2002, 1<a<A} \quad (3b)$$

$$N_{t+1,45^+,in} = (N_{t,45^+-1,in}(1 - m_{in-out}) + N \quad m_{out-in})\, e^{-Z_{45^+-1,in}} + (N_{t,45^+,in}(1 - m_{in-out}) + N_{t,45^+,out}(1 - m_{out-in}))e^{-Z_{45^+,in}}$$

(7)

$$N_{t+1,45,out} = (N_{t,45-1,out}(1 - m_{out-in}) + N_{t,45-1,in}m_{in-out})\, e^{-Z_{45-1,out}} + (N_{t,45,out}(1 - m_{out-in}) + N_{t,45,in}\, m_{in-out})e^{-Z_{45,out}} \quad (8)$$

$$Z_{a,in} = M_a \quad (9)$$

$$Z_{a,out} = M_a + F_tV_a \quad (10)$$

$$C_{t,a,out} = N_{t,a,out}\frac{F_tV_a}{F_tV_a + M_a} * (1 - e^{-Z_a}) \quad (11)$$

$$W_{t,out} = \sum_a C_{t,a}w_a \quad (12)$$

Global recruitment was calculated using equation 13 and 14 for inside and outside, with steepness (h), of the Beverton-Holt stock recruit relationship. $e^{\varepsilon_{t+1}-\vartheta_r{}^2/2}$ is the recruitment multiplier with bias correction, where ε_{t+1} is normally distributed with mean zero and standard deviation ϑ_r . The unfished recruitment (R_0) and spawning biomass (SB_0) was apportioned by p_{in} (equations 15 – 18). Density-dependence in recruitment may be global or local. For the latter scenario, recruitment at the start of year *t* inside/outside the closure are given by equations 19 and 20. Symbols used in equations 1 through 20 are defined in Table 3.2.

$$N_{0,t+1,in} = \frac{4hR_{0,in}SSB_{t+1,in}/SSB_{0,in}}{(1-h)+(5h-1)(\frac{SSB_{t+1,in}}{SSB_{0,in}})} e^{\varepsilon_{t+1}-\vartheta_r{}^2/2} \quad (13)$$

$$N_{0,t+1,out} = \frac{4hR_{0,out}SSB_{t+1,out}/SSB_{0,out}}{(1-h)+(5h-1)(\frac{SSB_{t+1,out}}{SSB_{0,out}})} e^{\varepsilon_{t+1}-\vartheta_r{}^2/2} \quad (14)$$

$$R_{0,in} = R_0 * p_{in} \quad (15)$$

$$R_{0,out} = R_0 * (1 - p_{in}) \quad (16)$$

$$SSB_{0,in} = SSB_0 * p_{in} \quad (17)$$

$$SSB_{0,out} = SSB_0 * (1 - p_{in}) \quad (18)$$

$$N_{0,t+1,in} = p_{in} \frac{4hR_0SSB_{t+1,}/SSB_0}{(1-h)+(5h-1)(\frac{SSB_{t+1}}{SSB_0})} e^{\varepsilon_{t+1}-\vartheta_r{}^2/2} \quad (19)$$

$$N_{0,t+1,out} = (1 - p_{in}) \frac{4hR_0SSB_{t+1}/SSB_0}{(1-h)+(5h-1)(\frac{SSB_{t+1}}{SSB_0})} e^{\varepsilon_{t+1}-\vartheta_r{}^2/2} \quad (20)$$

Projections

150-year projections of the two-area model starting in 2002 were run for scenarios including all possible combinations of the following: 1) proportion of the stock inside the closure

(1% to 50%); 2) exploitation rate outside the closure (1% to 30%); 3) whether density-dependence is global or local; and 4) the adult movement rate (0 to 10%). Ten simulations of 150-years were averaged for each scenario to account for recruitment variation. The average spawning biomass for the last 30 years for a given scenario was compared to the management target of 40% of the unfished level, which for Darkblotched rockfish is estimated at 1,418 million eggs (Wallace and Gertseva 2017).

RESULTS

The trawl survey CPUE demonstrates that the stocks are not uniformly distributed (Figures 3.2-3.5). A large proportion of constraining species such as canary, cowcod, bocaccio and yelloweye were found inside of 100 fathoms (Figure 3.4). Concurrently, target stocks such as petrale sole, widow and yellowtail rockfish were concentrated inside 100 fathoms (Figure 3.4). Darkblotched and Pacific ocean perch, both weak stocks, were most frequently intercepted outside of 100 fathoms, as they are characterized as slope rockfish. A closure from 30 to 150 fathoms would cover nearly all of the weak and strong stocks aside from Dover sole, sablefish, shortspine and longspine thornyhead (Figure 3.5). On average from 2003 to 2019, the survey found 27% of the darkblotched population within 100 to 150 fathoms, i.e. the RCA depth range that remained closed to bottom contact gear for the same period.

There was considerable variability in stock distribution between survey years, particularly in depths of 50 to 100 fathom, as shown in Figures 3.2 – 3.4. The survey does not tow in untrawlable rocky habitat, resulting in lower sample sizes for yelloweye and cowcod. Additionally, several stocks such as widow and yellowtail rockfish move throughout the water column to feed, potentially impacting the survey’s catchability. Many rockfish species are assumed to move deeper as they mature (SAFE 2020), which may contribute to uncertainty or survey catchability. Darkblotched rockfish was selected as an example for the analysis described above, as the stock's distribution starts near the end of the RCA's seaward boundary and its life history is typical of unproductive stocks.

150-year projections of spawning biomass with a closure covering 27% of the stock and fishing mortality held constant at F_{MSY} (5.2%) are shown in Figure 3.6 A for four combinations of assumptions concerning density-dependent global or local recruitment and adult movement. In all projections where fishing morality was 5.2%, the stock rebuilt and surpassed the biomass reference point within 25 years. When fishing mortality was held constant at the highest rate historically observed for the stock (14%), the projected spawning biomass surpassed the reference point at year 50 when there was local recruitment and no movement among adults (Figure 3.6 B); none of the other scenarios met management objectives. Under the Magnuson Stevens Act, where stocks are biologically unable to rebuild within 10 years, the time to rebuild in the absence of fishing plus one mean generation time is used to govern rebuilding; for darkblotched, the maximum timeline permitted was 45 years (SAFE 2020).

The projection results over a range of harvest rates and closure sizes varied with model assumptions. For two distinct populations with no movement, on average, a closed area covering 27% of the stock provided adequate protection from fishing mortality up to 30% outside the closure, such that spawning biomass reached the management target, as shown in Figure 3.7A. On average, the same results were projected when recruitment was assumed to be global (Figure 3.7 B). When adults moved between areas, the resulting spawning biomass was more influenced by harvest rate than by the size of the closure, as shown in Figures 3.7C and 3.7D. In order to achieve the biomass target on average in the last 30 years of the projection, when both larvae and adults are assumed to move (Figure 3.7D), effort controls would be necessary to keep fishing mortality near 7% with a reserve covering 20% of the stock, or a mortality of 12% with a closure spanning 50% of the stock.

Given the influence of assumptions on adult movement, the projections were run for a range of harvest and movement rates, for a closure covering 10%, 20% and 30% of the stock (Figure 3.8). Assuming 3% of adults annually move from inside to outside with local recruitment, a closure covering 30% of the population was projected to meet the stock's biomass reference point (Figure 3.8, panel 3A). Regardless of closure size and density-dependent recruitment assumptions, when more than 4% of adults moved from inside to outside, additional regulations were needed to limit fishing mortality outside the closure to meet management objectives for the weak stock.

DISCUSSION

The inherent challenge of mixed stock fisheries remains largely unsolved. A major constraint persists when co-occurring species have differing sustainable exploitation rates. In the case of the West Coast groundfish fishery, it is imperative to understand the diverse life histories and habitats that contribute to the degree of co-occurrence among the mix of stocks. The survey demonstrates that stocks are not uniformly distributed along the continental shelf and slope. Weak and strong stocks mix between 75 and 150 fathoms (Figures 3.3-3.5), where stocks at highest density in 50 – 100 fathoms overlapped with species distributions that began at 100 fathoms. Flatfish inhabit soft substrate of fine sand and mud bottoms and seasonally migrate between inshore and offshore (SAFE 2020). The groundfish stocks with the lowest sustainable exploitation rates are rockfishes, many of which were previously overfished, such as canary and darkblotched rockfish (PFMC 2019). These stocks have an affinity to rocky habitat with many undergoing ontogenetic movement (SAFE 2020). Under the right incentives, managers and harvesters can use differences in stock distributions to shift effort away from weak stocks. However, challenges remain when stock distributions overlap and gear is indiscriminate.

Determining if a closed area alone can be used to protect constraining stocks depends on t adult and larval movement, the proportion of the stock within the closure and the level of fishing mortality permitted outside. The projections infer it is possible to use a spatial closure and achieve the biomass target for a weak stock while withstanding high exploitation rates outside the closure, if adults are sedentary (Figure 3.7). The ability to maintain stock biomass about the reference point depends on the fishing mortality outside the closure than the proportion of the stock spatially protected if the rate of adult movement rate from inside the reserve exceeds 4% a year (Figures 3.7-3.8). Furthermore, a spatial closure alone is not sufficient to meet stock status objectives and instead, requires additional management action to limit the exploitation rate of the weak stock outside the reserve.

The conclusions depend greatly on the assumed rate of movement Life history studies report older larval stages and juveniles for many rockfishes are pelagic prior to settling (Love et al. 2002, SAFE 2020). Other studies have found adults migrate to deeper waters as they mature and grow more fecund, possibly related to density-dependence (Lenarz 1993; Nichol 1990; SAFE 2020). In addition to exhibiting ontogenetic movement, it is thought that several rockfish species spend time off bottom, as adults are bycaught in the pelagic whiting fishery (Wallace and Gertseva 2017). Widow rockfish, while once declared overfished, is now the focus of a directed midwater rockfish fishery, as it moves up in the water column at night to feed (Adams et al. 2019). While annual movement rates have yet to be determined for many groundfish stocks (Wallace and Gertseva 2017), studies on life history suggest there is at least some degree of movement of adults.

It is probable to assume darkblotched rockfish, used as an example in this study, is representative of the other constraining species in the fishery. Seven of the ten previously declared overfished stocks were rockfish. The life history of darkblotched in terms of juvenile larvae, ontogenetic movement, natural mortality, stock productivity and sustainable exploitation rate is comparable to the other six rockfishes (SAFE 2020). While not an exhaustive list, differences among the constraining rockfish lie in their distribution along the continental shelf and slope, time spent up in the water column and schooling characteristics. For instance, darkblotched and Pacific ocean perch (*Sebastes alutus)* are characterized as slope rockfish whereas yelloweye and cowcod are most frequently found on the shelf (SAFE 2020). Furthermore, an aim of the RCA was specifically to protect darkblotched rockfish, in addition to the closure's general protection of rebuilding stocks (Hamel 2008; Keller et al. 2014), making it a candidate to apply the recommendation in Hastings et al. (2017).

The survey CPUE indicated that the highest density of stocks analyzed in this study in 50 to 100 fathoms (Figures 3.2- 3.5). Instituting a marine reserve in this depth range would cover a large proportion of the constraining, rebuilding stocks. However, it would also cover economically important stocks such as petrale sole, sablefish, widow rockfish and yellowtail rockfish, likely leading to substantial forgone yield. Furthermore, darkblotched and Pacific ocean perch are slope rockfish, found most frequently beyond 100 fathoms. Single-species catch limits would still be needed to protect at least darkblotched and Pacific ocean perch, as a 50 to 100 fathom closure would not be adequate. A larger closure, i.e. out to 150 fathoms, would cover a greater proportion of the two constraining stocks as well as more of the abundant target stocks, leading to forgone yield. The success of either a 50 to 100 fathom or 50 to 150 fathom closure would depend on the level of adult movement, as demonstrated in this analysis. There is considerable variability in the survey CPUE in 30 to 75 fathoms and 30 to 100 fathoms (Figures 3.3-3.4). This could be due to sample sizes and the inability to survey extreme rocky habitat, or substantial movement contributing to uncertainty.

The findings in this analysis vary greatly, depending on the rate of adult movement. The projections infer that it is possible to solve the mixed stock dilemma by closing a large enough proportion of the stock and allowing high fishing mortality outside the reserve when there are two distinct populations. In the scenario where adults migrate between areas, our results diverge from those in Hastings et al. (2017), as maintaining the biomass of a weak stock about its reference point dependent more on controlling fishing mortality than on the use or size of a closure. In this scenario, an area closure does little to solve the current challenge facing mixed stock fisheries, as single-species catch limits would still be necessary. Furthermore, the stock distribution from the survey suggests a closure would restrict access to fishing grounds productive for strong, economically important stocks. Thus, leading to forgone yield in excess of that which already results from the constraining weak stocks.

In the current fishery management plan, where quotas for each species are allocated and 100% monitoring is required, individuals are fully accountable for their catch. Considering the uncertainty around movement rates, this analysis does not find marine closures to be a superior management tool to the current framework. Instituting an area closure in lieu of single-species catch limits for the constraining species was found to be inadequate for achieving biomass objectives when adults were not sedentary. Adding marine closures on top of the existing framework only adds to the current constraints challenging the fisheries ability to achieve *MSY*.

TABLES

Table 3.1 Parameters from the most recent assessment of Darkblotched rockfish (Wallace and Gertseva 2017).

Value	**Parameter**
0.72	steepness, h
3,006 million eggs	unfished recruitment, R_0,
3,544 mt	unfished spawning biomass, SSB_0
0.75	recruitment standard deviation, ϑ_r
N(0, ϑ_r)	recruitment deviations, ε_t
0.052 yr^{-1}	F_{MSY}
0.054 yr^{-1}	natural mortality, M
9 yr	age at 50% maturity
8 yr	age at 50% selectivity
$1.15e^{-5}$	weight at length coefficient, a
3.13	weight at length exponent, b
42cm	asymptotic length, L_∞
0.19 yr^{-1}	von Bertalanffy K

Table 3.2 Definition of symbols used in equations 1 through 20

Symbol	Definition
$N_{2002,a}$	Numbers at age in 2002 from stock assessment
p_{in}	Proportion of stock inside closure
$m_{in\text{-}out}$	Proportion of stock that moves from inside to outside at the start of the year
$m_{out\text{-}in}$	Proportion of the stock that moves from outside to inside at the start of the year
b	Species mobility, the proportion of fish moving from in to out when p_{in} is very small
$N_{t,a}$	Numbers of animals of age *a* at the time *t* in area in or out
$N_{0,t}$	Recruitment during year *t*
SSB_t	Spawning biomass at the start of year *t* for area in or out
SSB_t	Spawning biomass at the start of year *t*
$N_{t,45^+}$	Numbers at age 45^+ for the plus group at the start of year *t*
Z_a	Total mortality age *a*
F_t	Fully-selected fishing mortality during year *t*
V_a	Vulnerability at age *a*
w_a	Weight at age *a*
$C_{t,a,out}$	Catch of animals of age *a* during year *t*
$W_{t,out}$	Catch in weight during year *t*

FIGURES

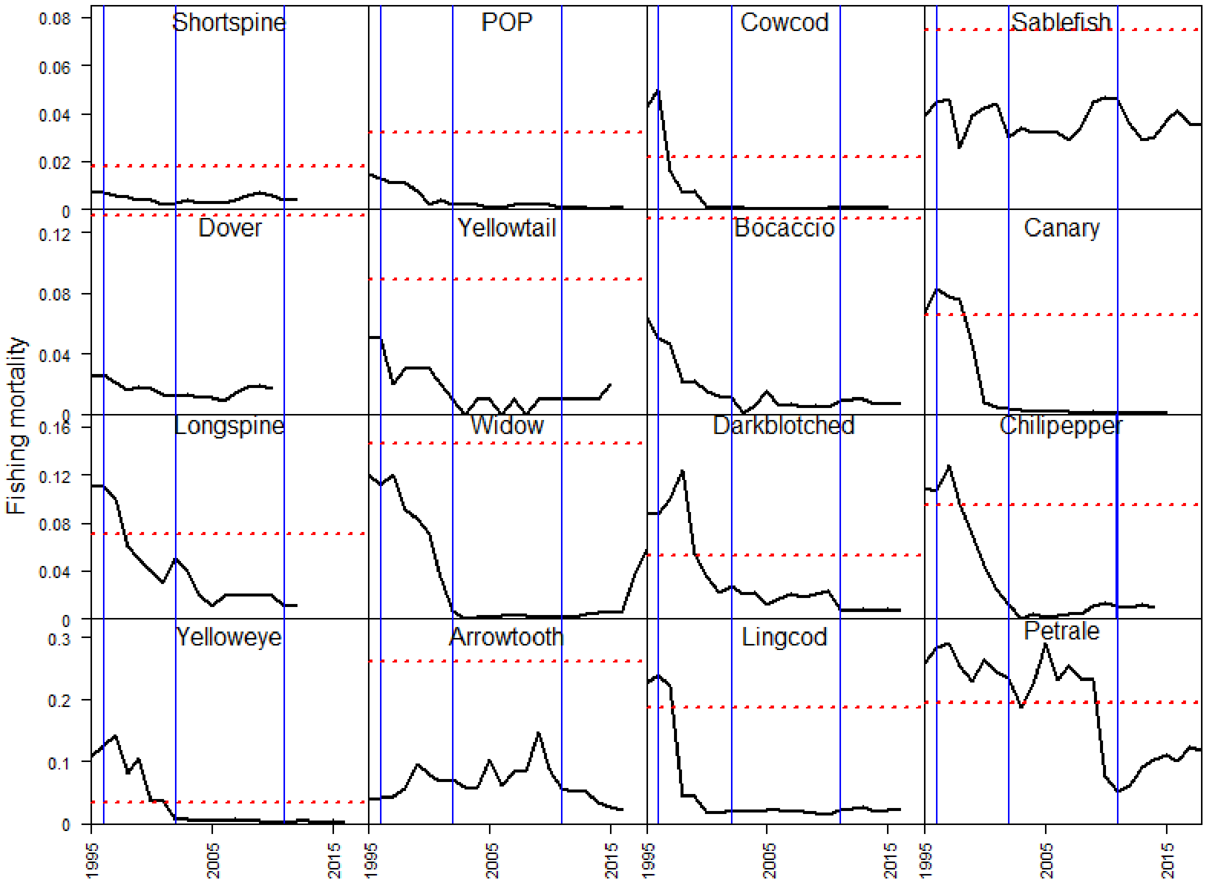

Figure 3.1 The fishing mortality rate over time estimated in the most recent assessment. The vertical lines in 1996, 2002 and 2011 represent the following management events: reauthorization of the Magnusson Stevens Act mandating that overfished stocks be rebuilt, implementation of the RCA, and start of the IFQ fishery. The red horizontal dashed line corresponds to each stocks F_{MSY}, as estimated in the most recent assessment.

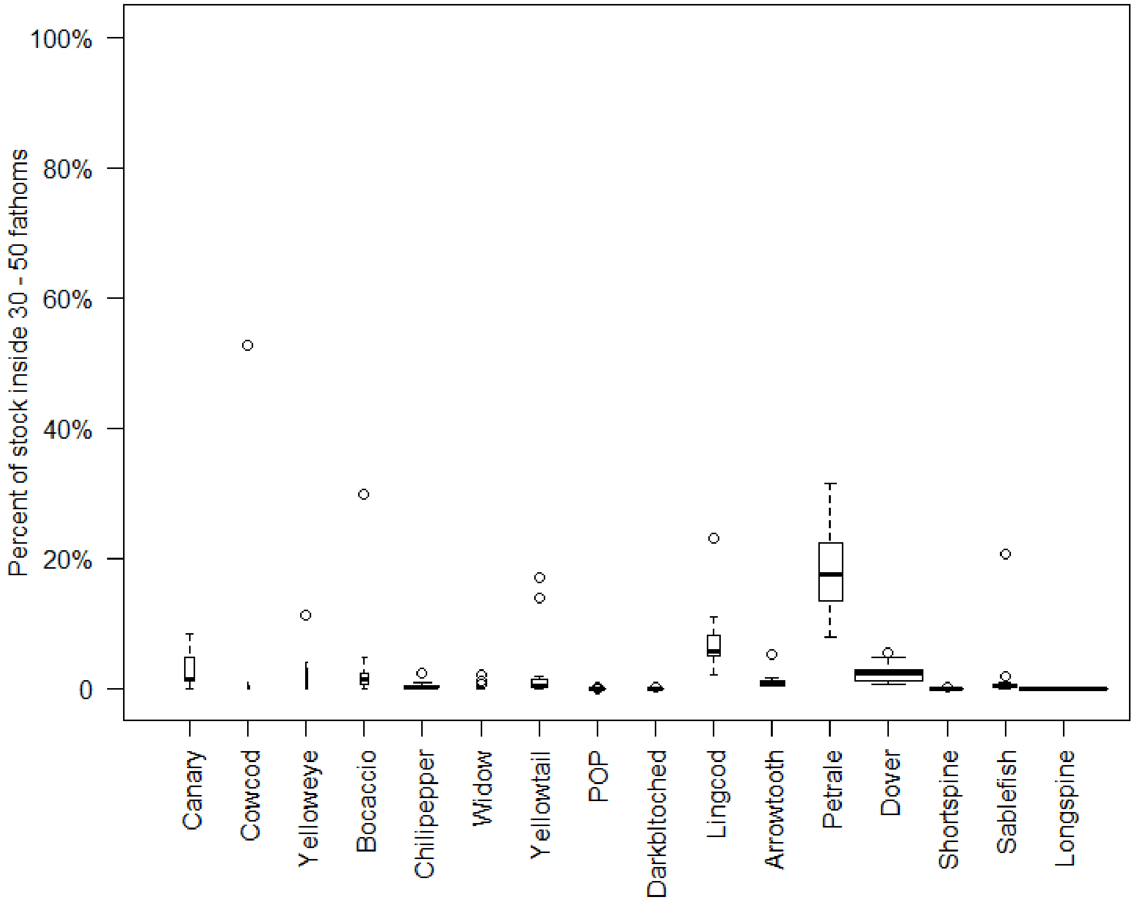

Figure 3.2 Percent of stocks inside 30 to 50 fathoms from 2003 to 2019. Box width is scaled according to the square root of the sample size (the number of fish sampled by the survey for a species).

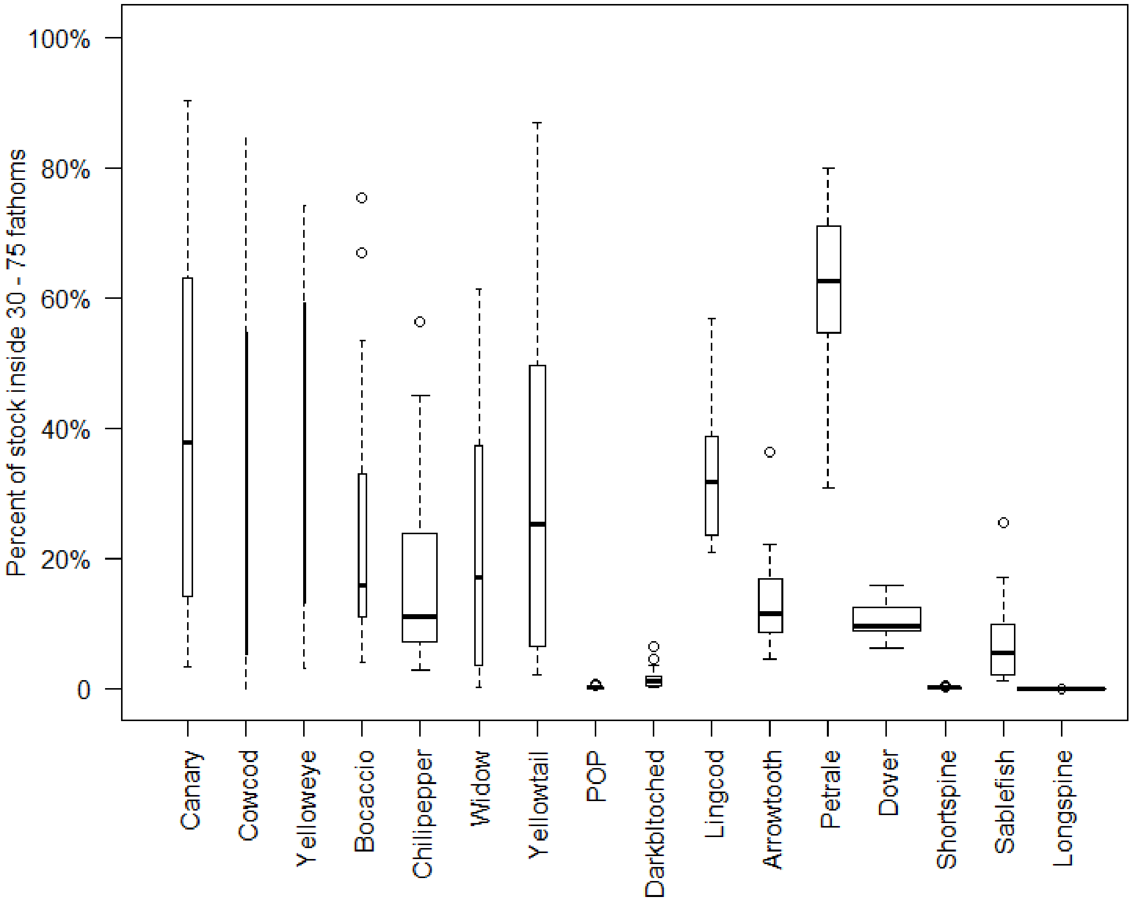

Figure 3.3 Percent of stocks inside 30 to 75 fathoms from 2003 to 2019. Box width is scaled according to the square root of the sample size (the number of fish sampled by the survey for a species).

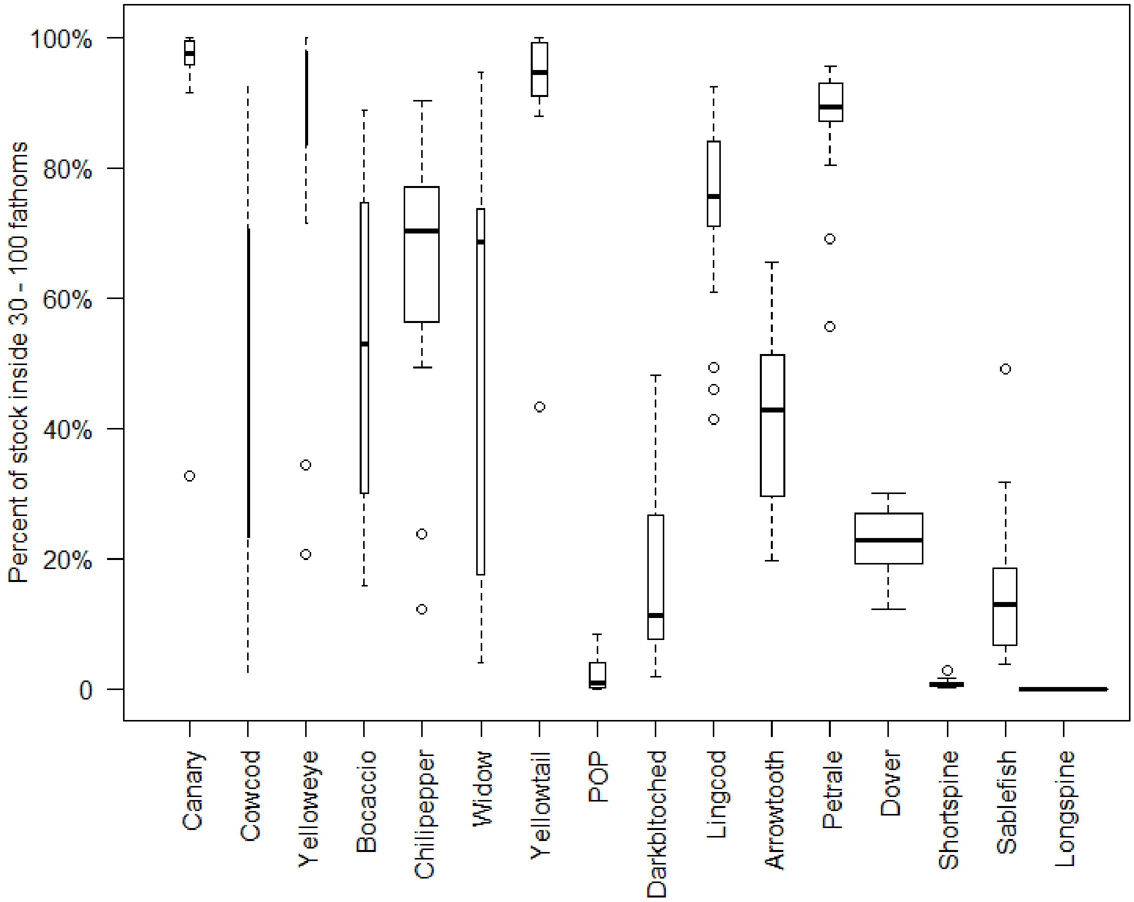

Figure 3.4 Percent of stocks inside 30 to 100 fathoms from 2003 to 2019. Box width is scaled according to the square root of the sample size (the number of fish sampled by the survey for a species).

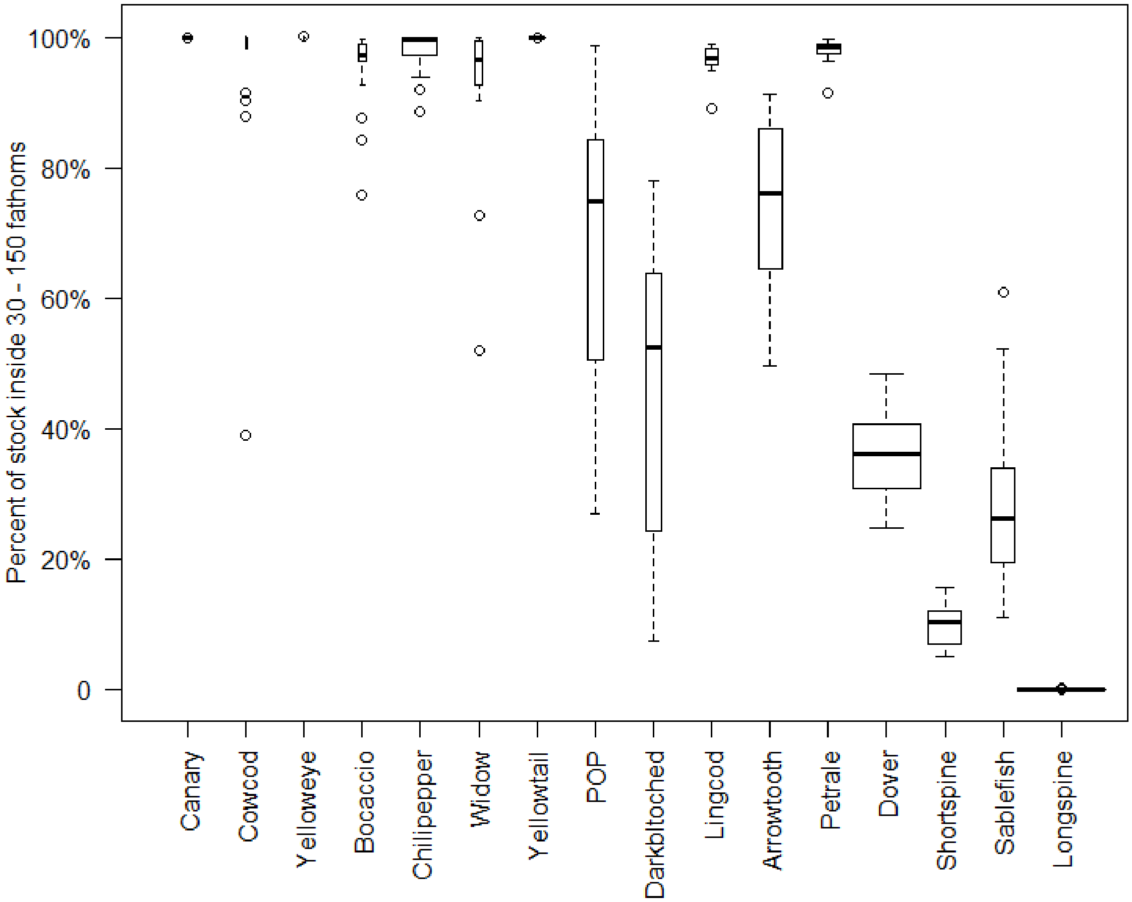

Figure 3.5 Percent of stocks inside 30 to 150 fathoms from 2003 to 2019. Box width is scaled according to the square root of the sample size (the number of fish sampled by the survey for a species).

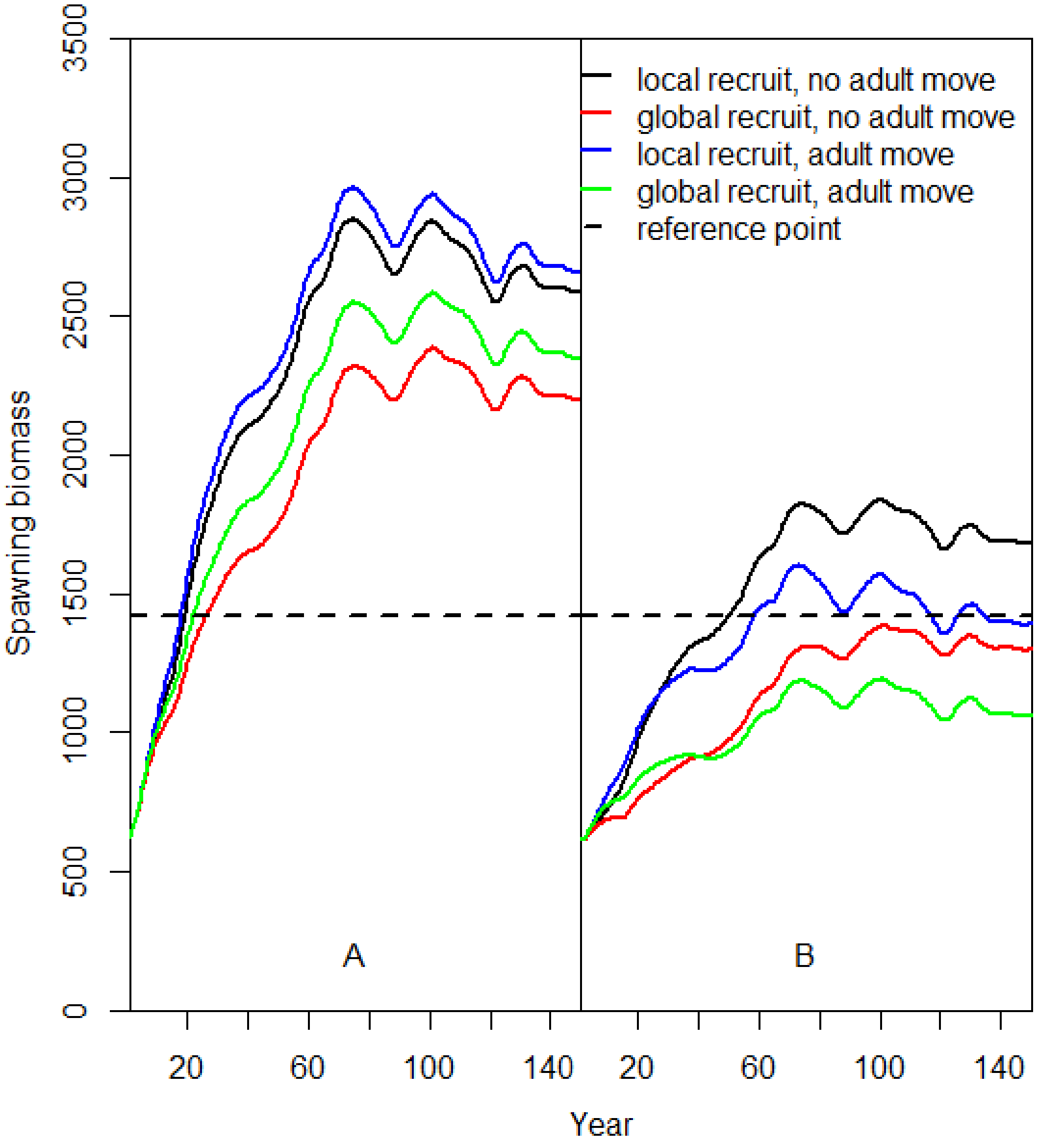

Figure 3.6 The average (over replicate simulations) spawning biomass for 150-year projections for a range of assumptions on recruitment and adult movement with an area closure covering 27% of the population. In panel A, fishing mortality outside the closure is 5.2%; in panel B, fishing mortality is 14%.

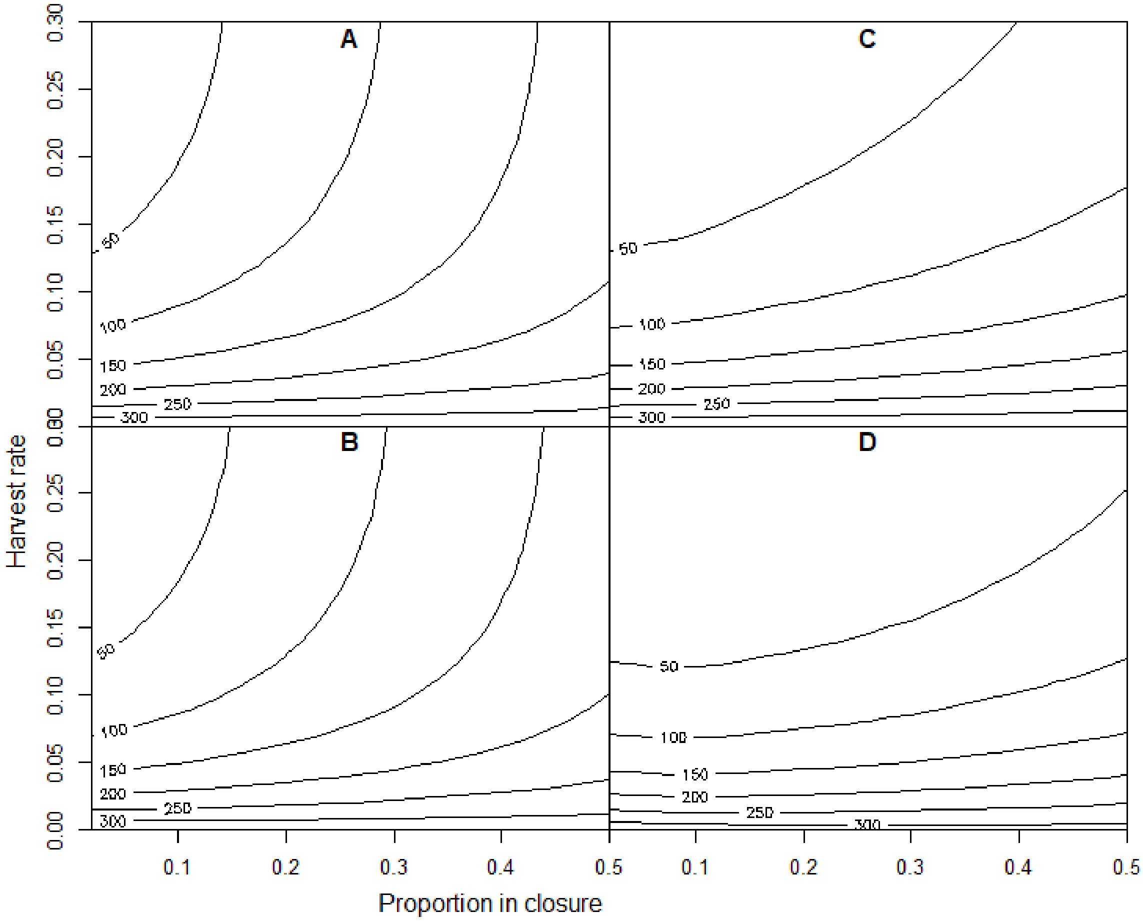

Figure 3.7 The average of ten, 150-year projections for which the mean spawning biomass in the last 30 years is displayed relative to the biomass target, (shown as a percent such that a value of 100 equates to the target), for a range of harvest rates and proportions of the stock in the closure. In panel A, recruitment is local and there is no adult movement. Panel B assumes larval recruitment is global, but adults are sedentary. Panel C has local recruitment and 10% of adults moving from inside to outside. Panel D assumes 10% of adults move from inside to outside and global recruitment occurs.

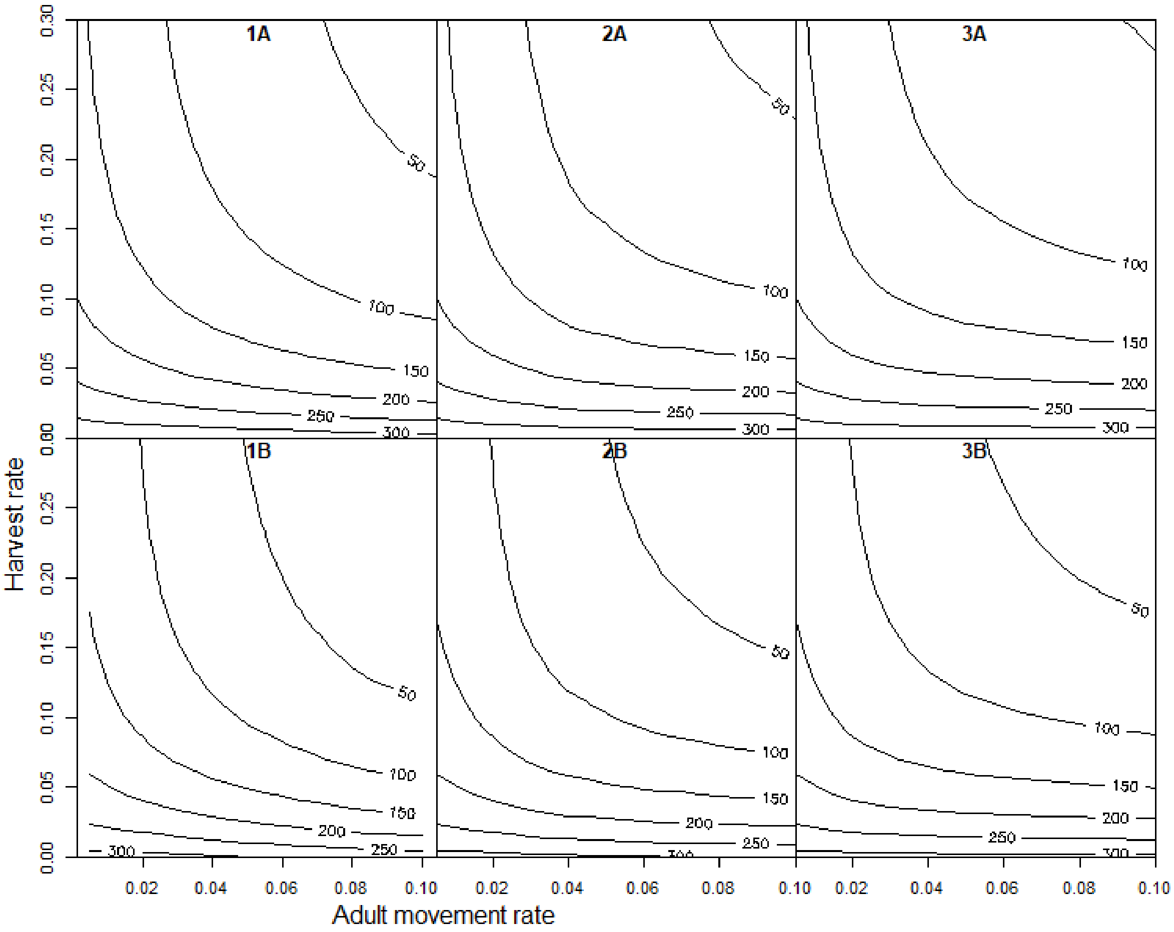

Figure 3.8 The average of ten, 150-year projections where spawning biomass for the last 30 years in the 150-year projection is shown relative to the biomass target for range of harvest rates and proportions of the stock moving from inside to outside each year. Results are provided for the following scenarios: a closed area covers 10% of the population and recruitment is local (panel 1A), 10% of the population in a closure with global recruitment (panel 1B), 20% of the population is covered by the closure and local recruitment (panel 2A), the closure covers 20% of the population and recruitment is global (panel 2B), 30% of the population is covered by the closure and recruitment is local (panel 3A), and the closure covers 30% of the population and recruitment is global (panel 3B).

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