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Management strategies to prevent overfishing while achieving optimum yield vary according to the available data and life history of the fished stock. I evaluated two sets of management strategies for Pacific coast rockfish: strategies to set harvest limits for data-poor stocks, and strategies intended to protect the age structure of fished stocks. *Setting Harvest Limits for Data-poor Stocks* - The collapse of canary rockfish, *Sebastes pinniger*, in the northeast Pacific began more than two decades before the stock was officially declared overfished. The 2006 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act requires a scientifically-based harvest limit for all fished stocks, including those with data limited to catch. Two such "data-poor" methods are currently in use for the management of west coast stocks, depletion-corrected average catch (DCAC) and depletion-based stock reduction analysis (DB-SRA). To evaluate the performance of each method when challenged with catch and biological uncertainty, I retrospectively applied the methods to the catch and biological data available at the time of the first and second canary rockfish stock assessments in 1984 and 1990. In 1980 canary rockfish would be classified as "data-poor", and in 1990 as "data-rich". To evaluate the sensitivity of DCAC and DB-SRA to error in the catch data, harvest limits were estimated using both the historic catch data from each assessment, and the reconstructed catch data from the most recent stock assessment. In addition, harvest limits were estimated using simulated catch data sets for the years 1916 to 1983 with increasing variability around the true catch. DCAC and DB-SRA estimated harvest

limits were significantly lower than the catch recommended in both the data-poor and data-rich stock assessments, but higher than the "true" overfishing limit. Use of current catch data improved the estimated harvest limit when the stock was data-poor, but not when the stock was data-rich. The simple methods responded to increasing error in the catch time series with decreasing mean estimates of the harvest limit, indicating that these methods are highly precautionary for this species, when the catch time series is the only source of error. *Age Structure Management Strategies* - In a variable oceanographic environment, a population with many reproductive age classes benefits not only from the increased fecundity of older fish; but also, in some species, an increase in larval fitness. Older females may also spawn at different times or over longer periods than younger females, increasing the probability of larvae encountering favorable environmental conditions. Despite the accumulating evidence for the importance of age structure to long-term population viability in harvested fish populations, long-lived west coast rockfish (Genus *Sebastes*) are managed with a biomass-based harvest control rule. I compared three strategies for age structure management, and evaluated the strategies relative to the status quo, biomass-based harvest control rules, across three rockfish life histories. I examined the tradeoff between yield and traditional management reference points, as well as performance measures that could serve as management reference points for age structure. Yield was reduced by strategies that maintain "old growth" age structure, but annual variation in the catch and the probability of becoming overfished were also reduced. The longest-lived rockfish benefited the most from strategies that maintained older fish in the population through dome-shaped selectivity. The shorter-lived rockfish benefited from adjustments in the catch limit based on the age composition of the catch one year previous. Achieving "pretty good yield" with management strategies that also decrease the potential for overexploitation is an important goal for stocks that are well-studied and those that are poorly understood; these investigations contribute to a growing literature on alternative approaches to sustainable fisheries management.

Evaluation of Data-poor and Age-structure Management Strategies for West Coast Rockfish

by
Linsey M. Arnold

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Linsey M. Arnold, Author

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In memory of Bill Pierce

July 21, 1950 – June 8, 2011

Thank you for bringing me into the world of rockfish

CHAPTER 1 INTRODUCTION

In the United States, the National Oceanic and Atmospheric Administration's mission is to "protect, restore, and manage the use of coastal and ocean resources…" (U.S. Department of Commerce). To help achieve this mission, the Magnuson-Stevens Fishery Conservation and Management Act sets forth ten national standards for fisheries management that define the goals for federally managed fisheries. The goal outlined in National Standard I is the prevention of overfishing while achieving optimum yield (OY) on a continuing basis. Optimum yield is the amount of fish that provides the greatest overall benefit to the United States with respect to food production and recreational opportunities…" (MSFMCA). The over-arching strategy to achieve optimum yield is to determine the maximum sustainable yield (MSY) for a fishery and reduce the catch prescribed by MSY according to "any relevant economic, social, or ecological factor…" (MSFMCA).

The Pacific Fisheries Management Council (PFMC) is responsible for achieving the goal of National Standard I for the fisheries of the northeast Pacific states of Washington, Oregon, and California. The PFMC defines MSY as "an estimate of the largest average annual catch or yield that can be taken over a significant period of time from each stock under prevailing ecological and environmental conditions", and utilizes MSY as an upper limit reference point from which yield is reduced to obtain the acceptable catch limit (PFMC, 2011). Strategies to meet the goal of National Standard 1 and achieve optimum yield while preventing overfishing can vary according to the available the fishery data and the life history of the fished stocks.

In this study I evaluated two sets of management strategies for northeast Pacific rockfish (*Sebastes spp.*), strategies to determine harvest limits for data-poor stocks, and strategies to enhance or maintain the age structure of long-lived rockfishes. My goal was twofold: test data-poor methods for setting harvest limits by comparing the performance of each method using the historic data and current data from an overfished rockfish stock; and test strategies for maintaining the age structure of three rockfish life history types while working within the current management framework by adjustments to the catch or adjustments to the selectivity of the stock to the fishery in order to model management measures that impact fleet dynamics.

DATA-POOR MANAGEMENT

The substantial decline of canary rockfish, *Sebastes pinniger*, in the northeast Pacific began more than two decades before the stock was officially declared overfished (Stewart, 2009). The 2006 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act requires a scientifically-based harvest limit for all fisheries, including those with data limited to catch. In response, much recent progress has been made in the development of simple, data-poor methods to set harvest limits (Honey et al., 2010). Two such methods are currently in use for the management of west coast stocks: depletion-corrected average catch (MacCall, 2009) and depletion-based stock reduction analysis (Dick and MacCall, 2011).

In Chapter 2, I evaluate the performance of these two simple methods when challenged with uncertainty in the catch and biological data. I retrospectively apply each method to the data available at the time of the first and second canary rockfish stock assessments in 1984 and 1990. The retrospective approach allows for direct comparison between the harvest limits estimated when a stock was data-poor and data-rich. In 1984 canary rockfish would be classified as “data-poor”, and in 1990 as “data-rich”. To evaluate the sensitivity of each method to error in the catch data, harvest limits were calculated using both the historic catch data from each assessment and the reconstructed catch data from the most recent assessment. In addition, harvest limits were estimated with simulated catch data sets for the years 1916 to 1983 with increasing variability around the true catch.

AGE-STRUCTURE MANAGEMENT

In a variable oceanographic environment, longevity reduces the risk of reproductive failure at the level of the individual, and recruitment failure at the population level (Secor, 2000; Longhurst, 2002). A population with many reproductive age classes, a "long-tailed" age structure (Hsieh et al., 2010), benefits not only from the increased fecundity of older fish; but also, in some species, an increase in larval fitness (Berkeley et al., 2004; Vallin and Nissling, 2000). Older females may also spawn at different times or over longer periods than younger females, increasing the probability of larvae encountering favorable environmental conditions (Sogard et al., 2008; Bobko and Berkeley, 2004). For an increasing number of stocks, it is recognized that the reproductive contribution at age is not proportional to the product of maturity-at-age and weight-at-age (Scott et al., 1999; Secor, 2000; Vallin and Nissling, 2000; Hsieh et al., 2006; Berkeley, 2006; Longhurst, 2006).

Populations with fishing pressure experience juvenescence (Ricker 1963), a phenomenon in which the population structure is shifted toward a younger age distribution. Age truncation is not necessarily reflected in total biomass estimates, therefore, a population may maintain an acceptable biomass yet still lose the older females, reducing the probability of producing strong year-classes (Martiensdottier and Thorarinsson, 1998). Modeling studies that incorporate a relationship between larval survival and maternal age show biomass-based management reference points will over-estimate productivity, leading to less precautionary harvest recommendations, if reproductive potential per unit of mature female biomass is a function of age (Murawski et al., 2001; O'Farrell and Botsford, 2006; Spencer et al., 2007).

It is increasingly recognized that preserving the age structure of fished populations will enhance resilience to both human exploitation and environmental change; however, long-lived west coast rockfish (Genus *Sebastes*) are managed with a biomass-based harvest control rule. In Chapter 3, I compare three strategies for age structure management, and evaluate the strategies relative to the status quo biomass-based harvest control rules across three rockfish life histories. I explicitly examine the tradeoff between yield and traditional management reference points, as well as performance measures that could serve as management reference points for age structure.

MANAGEMENT STRATEGY EVALUATION

My evaluation of data-poor methods to set harvest limits and methods that incorporate considerations of population age structure to set harvest limits focus on the method alone. The management strategy evaluations in chapters 2 and 3 do not attempt to model all aspects of the management process, including the important step that evaluates risk and uncertainty to reduce the harvest limit to the final acceptable biological catch limit. A formal definition for management strategy evaluation includes "user- and resource-oriented objectives set by managers… that take into account the various stakeholders' views and needs" (Butterworth et al., 2010). My analysis does not explicitly account for "stakeholders' views and needs" beyond the general goal to achieve optimum yield and prevent overfishing. My work contributes an exploratory analysis of data-poor and age-structure management strategies that could be used to refine the questions and approach of a formal MSE.

CHAPTER 2 SIMPLE EVALUATION METHODS CAN IMPROVE CONSERVATION OF DATA-POOR STOCKS: A RETROSPECTIVE EVALUATION OF AN OVERFISHED GROUNDFISH, CANARY ROCKFISH (*SEBASTES PINNIGER*)

INTRODUCTION

In the United States, there are 528 managed marine fish stocks, of which fewer than half have adequate data to determine stock status; and of the stocks that have been assessed, 23% are “overfished” (NMFS, 2010). Uncertainty in stock status and uncertainty in the level of catch that can be removed from a population increases the likelihood of a stock being listed as overfished (Rosenberg et al., 2007) due to requirements of precautionary management. To better estimate management reference points and reduce uncertainty, stock assessment models have become increasingly complex data-fitting exercises.

Complex, quantitative assessments are generally statistical catch-at-age models or virtual population analyses that are fit to time-series of commercial, recreational, and fishery independent data (Smith et al., 2009). The large amount of data required for such assessments comes from landings receipts, commercial logbooks, port samplers, on-board observers, trawl surveys, larval and juvenile surveys, age- and length-composition sampling, and biological samples obtained to estimate weight-, maturity-, and fecundity-at-age parameters (Hilborn and Walters, 1992). Data collection for stock assessment represents a large investment of time and money, yet the status of approximately 60% of fished stocks in the U.S. remains unknown due to a lack of data for a standard stock assessment (NMFS, 2010).

The 2006 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act requires scientifically-based acceptable catch limits (ACLs) for all fisheries included in a Fishery Management Plan, regardless of the quantity or quality of the currently available data. The term “data-poor” generally describes the stocks for which a standard, quantitative assessment that estimates changes in population biomass through time cannot be conducted (Smith et al., 2009; Honey et al., 2010). On the west coast, the Pacific Fishery Management Council (PFMC) places groundfish stocks into three categories, with Category 1 representing the relatively few "data-rich" stocks, and Categories 2 and 3 representing the majority of stocks that fall along a continuum of data quantity and quality (PFMC, 2011). To meet the ACL requirement, the PFMC evaluated and approved the use of two new data-poor methods, depletion-corrected average catch (DCAC) and depletion-based stock reduction analysis (DB-SRA) (MacCall, 2009; Dick and MacCall, 2011).

DCAC and DB-SRA utilize historic catch time series and basic life history data to determine a "sustainable yield", and an overfishing limit (OFL), respectively. MacCall (2009) defines the sustainable yield calculated using DCAC as "a moderately high yield that is likely to be sustainable, while having a low probability that the estimated yield level greatly exceeds MSY." DCAC calculates sustainable yield by adjusting the average catch to account for the "windfall" catch associated with stock depletion, and is applicable in severely data-limited situations as it does not require a complete catch history. DB-SRA is a technique that borrows aspects from both DCAC and stochastic stock reduction analysis (Walters et al. 2006) to calculate probability distributions of management reference points, including the overfishing limit. For west coast rockfish, the OFL is defined as the catch resulting from fishing the current stock at the maximum sustainable yield (MSY) fishing rate (PFMC, 2011). As implemented in the management of the U.S. west coast rockfish resource, the median of the sustainable yield distributions calculated using DCAC and the OFL of DB-SRA are upper limits to harvest (PFMC, 2011), and will be referred to hereafter as "harvest limits" (HL).

The harvest limit can have significant biological and economic impacts. If set too high, the HL will deplete the resource, potentially leading to an overfished state. If set too low, the HL will restrict commercial and recreational fishing opportunities. Therefore, it is important to evaluate thoroughly new methods for setting harvest limits. To this end, DCAC and DB-SRA have been applied to both data-poor (Dick and MacCall, 2010) and data-rich groundfish (Dick and MaCall, 2011). The analysis of 50 data-poor stocks for the U.S. west coast found that current management catch limits ranged from sustainable to potential overfishing. When applied to data-rich stocks, DB-SRA estimates of MSY and unfished biomass were between one-half to double the “true” values from the data-rich stock assessments. If this result extends to data-poor stocks, it represents a significant reduction in the uncertainty about MSY and the unfished biomass for data-poor stocks. Wetzel and Punt (2011) tested the impact of parameter misspecification on DCAC and DB-SRA estimates of sustainable yield with simulation analyses. For a rockfish life history, they found that both DCAC and DB-SRA are highly sensitive to the assumed ratio of current biomass to starting biomass (“depletion”), over-estimating the harvest limit when assumed depletion is optimistic relative to actual depletion. As with most evaluations of assessment tools and management approaches, these evaluations of data-poor methods used hypothetical distributions of potential catch and population response.

I propose an additional approach to evaluate the utility of data-poor methods: a retrospective analysis of a currently data-rich stock using the data that were available when the stock was data-poor. The data-rich assessment can be viewed as providing the “truth” and the historic data-poor assessments show the effects of both error in the catch time series and mis-specified biological parameters. In addition, the data-poor methods can be applied to different points in time if there are multiple historic assessments, testing the methods with data that is presumably increasing in both quantity and quality between each successive assessment. I evaluate the performance of DCAC and DB-SRA with retrospective analysis of an overfished, data-rich west coast groundfish, the canary rockfish, *Sebastes pinniger*.

The first canary rockfish stock assessment was conducted in 1984 when the stock was data-poor (Golden and Demory, 1984). Uncertainty in the available biological and catch data restricted the analysts to a subjective, non-quantitative assessment that found no evidence for stock decline. By the second canary rockfish stock assessment in 1990, enough data had been collected for a quantitative, age-structured assessment in Stock Synthesis (Golden and Wood, 1990). The assessment concluded that the spawning stock biomass (SB) had dropped below 30% of the unfished SB, the current canary stock assessment estimates SB in 1990 to be 22% of unfished. Golden and Wood recommended a fishing mortality rate that would produce a 35% reduction in unfished SB under equilibrium yield modeling. Canary rockfish were assessed again in 1994 and 1996, when the stock was approximately 12% of unfished SB, according to the most recent stock assessment (Stewart, 2009). The official “overfished” designation was made in 1999 with an immediate 70% reduction in catch, followed by serial 70% reductions over the next two years. According to the most recent canary rockfish assessment (Stewart 2009), spawning biomass fell below the current management target of 40% of unfished SB in 1983, and declined below the current overfished threshold, 25% of unfished SB, in 1990. During the 1980s, canary rockfish annual average catch was more than twice the current estimate of maximum sustainable yield (Stewart 2009).

Relative to our current state of knowledge, which is much more complete but also imperfect, the 1984 and 1990 assessments were conducted with flawed catch data, inaccurate biological information, and less conservative reference points relative to current management. In addition to error in the catch time series (Fig 1.1), the full catch history extending back to 1916 was not available to either the 1984 or 1990 assessment. The estimated natural mortality rate was updated in the 1990 assessment, but to an even less accurate estimate than the 1984 assessment, relative to current knowledge. The uncertainty surrounding natural mortality propagated into uncertainty in population production. The only biological parameter accurately specified according to current knowledge is the age at maturity in the 1990 assessment. The confounding errors in the catch time series and biological parameters represent the less-than-ideal, real-world mess of data typical of some data-poor stocks. Thus, my retrospective evaluation of canary rockfish may serve as an example for future evaluations for data-poor species.

In this study I address two questions: (1) how do DCAC and DB-SRA perform when confronted with bad data characterized by multiple sources of error, and (2) how does performance change as the data available to the stock assessment is updated and revised? Using the canary rockfish historic data sets, I test the hypotheses that harvest limits estimated with DCAC and DB-SRA would have better approximated the "true" HL for a data-rich stock relative to the estimated HL of the same stock when it was data-poor; and when the HL estimate is calculated with updated catch data relative to the historic catch data.

METHODS

DCAC AND DB-SRA

DCAC (MacCall 2009) estimates distributions of sustainable yield by adjusting the historical average catch to account for depletion associated with the initial "windfall" catch:

$$DCAC = \frac{\sum C_t}{n + \Delta\left[B_{peak}\left(\frac{F_{MSY}}{M}\right)M\right]^{-1}} \qquad Eq. 1$$

where C_t is the catch in year t, n is the number of years in the catch time series, Δ is a measure of stock status defined as the absolute change in biomass from the first year of the catch time series to the last, B_{peak} is the biomass at maximum sustainable yield (MSY) relative to the unfished state or carrying capacity (B_{MSY}/K), F_{MSY} is the instantaneous fishing mortality rate that produces B_{peak}, and M is the instantaneous rate of natural mortality.

DB-SRA (Dick and MacCall, 2011) generates probability distributions of the maximum sustainable yield (MSY), the unfished biomass, and the overfishing limit. DB-SRA is implemented using a delay-difference production model:

$$B_t = B_{t-1} + P(B_{t-a}) - C_{t-1} \qquad Eq.2$$

where B_t is biomass at time t, P is latent annual production (based on a preceding parental biomass), and a is the age at reproductive maturity. The latent production function used in this analysis is the alternative hybrid Schaefer-PTF model developed by Dick and MacCall (2010) that approximates a Beverton-Holt stock-recruitment relationship without restricting peak productivity to one-half of the unfished biomass. DB-SRA requires the same four input parameters (M, F_{MSY}/M, B_{peak}, and Δ) as DCAC, with an additional parameter for age of maturity. In both DCAC and DB-SRA, Monte Carlo simulation is used to model uncertainty in the input parameters with 10,000 draws from the assumed distribution for each parameter (Table 1.1).

RETROSPECTIVE APPLICATION OF DCAC AND DB-SRA

I applied DCAC and DB-SRA to the biological and catch data available in the year of the first (1984) and second (1990) canary rockfish stock assessments (Table 1.1, Figure 1.1). The catch time series in the first stock assessment constitutes a minimum estimated catch for years the 1963-1983 by the United States and foreign trawlers, summed across the International North Pacific Fisheries Commission (INPFC) Vancouver, Columbia, and Eureka areas (Tables 1-3 *in* Golden and Demory, 1984). The catch time series in the second stock assessment includes the years 1967-1989, and was compiled from the PFMC Data Series and agency reports (Table 1 *in* Golden and Wood, 1990).

Parameter values (Table 1.1) applied in retrospective analyses were derived from stock assessments and included estimates of M and a. Due to the lack of data available to estimate F_{MSY} in 1984, I used the common assumption that $F_{MSY}/M = 1$

(Clark, 1991). The 1990 stock assessment estimates a range of F_{MSY} from 0.08 to 0.19. Due to the uncertainty in the estimate of F_{MSY} in 1990, and the fact that the estimated F_{MSY} values bracket the value for natural mortality, I chose a value of 1.0 for the 1990 F_{MSY}/M parameter. For the historic value of B_{peak}, I chose a value of 0.35 based on the management goal in 1990 of achieving the F that reduced the spawning biomass to 35% of unfished spawning biomass. In a data-poor situation, the Δ parameter is a subjective estimate of stock status relative to the unfished state (for DB-SRA) or the state at some point in the past (DCAC). Wetzel and Punt (2011) found that DCAC and DB-SRA estimates of sustainable yield are highly sensitive to misspecification of Δ. To account for this sensitivity, I tested a range of delta values (0.6-0.8) that bracketed the assessment authors' subjective estimate in 1984 (0.6), and analysis-based estimate in 1990 (<0.70).

The 2009 canary rockfish stock assessment included an updated historic catch time series accounting for the California groundfish catch reconstruction (Ralston et al., 2010) (Figure 1.1). To evaluate the sensitivity of historic HL estimates to error in the catch data, I estimated HL distributions with the reconstructed catch time series. The parameter values and number of years of catch data remained the same. The HL estimates calculated with historic catch and parameters are termed "historic," and the HL estimates calculated with the reconstructed catch and historic parameters are termed "current" (Figure 1.2).

The harvest limit distributions estimated with DCAC and DB-SRA in the retrospective analysis were evaluated relative to four metrics: (1) the "true" HL in each assessment year (1984 and 1990), (2) the recommended HL reported in the 1984 and 1990 stock assessments, (3) the "best case" HL estimated with current parameter values (Stewart, 2009) and the reconstructed catch time series to each assessment year (1916-1983 and 1916-1989), and (4) the sensitivity of each method to assumed depletion in each assessment year.

The PFMC estimates management references points based on a spawning potential ratio (SPR) proxy for MSY. Following this practice, I calculated the “true” harvest limit (HL_{TR}) in 1984 and 1990 as:

$$HL_{TR,y} = B_{exp,y} \cdot U_{SPR(MSY)} \qquad Eq. 3$$

where U is the exploitation rate corresponding to the spawning potential ratio at MSY (SPR_{MSY}), and $B_{exp,y}$ is the exploitable biomass (age 5+ biomass) in year y (1984 and 1990). The estimates of exploitable biomass in each assessment year, and the estimate of the exploitation rate resulting in the proxy-based MSY were taken from the 2009 canary stock assessment (Table 1.2).

I defined the DCAC and DB-SRA harvest limit distributions calculated using the full reconstructed catch time series and current parameter estimates as the “best case” harvest limit (HL_B). The HL_B is the DCAC and DB-SRA estimated harvest limit had the current canary rockfish data been available to the 1984 and 1990 stock assessments. Point estimates of M and a come from the most recent stock assessment (Stewart, 2009). The exploitation rate at SPR_{MSY} from the 2009 assessment is used as a proxy for F_{MSY} in calculating the F_{MSY}/M parameter value. The value of B_{MSY}/K was defined by current management proxies for the biomass that produces MSY (PFMC, 2011). Harvest limit abbreviations and definitions contained in Table 1.3.

For each historic and current harvest limit estimate, I calculated the percent relative error, %RE, for both the true harvest limit (HL_{TR}) and the best case harvest limit (HL_B) performance metrics. For example, the %RE of the historic HL (HL_H) estimate to the true HL was as follows:

$$\%RE = \frac{(HL_H - HL_{TR})}{HL_{TR}} \qquad Eq. 4$$

SIMULATED CATCH ANALYSIS

Retrospective application of DCAC and DB-SRA to the 1984 and 1990 assessment data evaluates the performance of each method when the input is characterized by multiple sources of error and uncertainty, in both the catch data and parameter estimates. Previous work has investigated the effect on harvest limit estimates of parameter mis-specification with no error in the catch data (Wetzel and Punt, 2011). In this study I investigated the effect of error in the catch data with properly specified input parameters. To isolate the effect of error in the catch data on the DCAC and DB-SRA estimated harvest limits, I created five catch history scenarios defined by increasing error in the catch data relative to the “no-catch-error” baseline. The reconstructed catch time series for canary rockfish over the period 1916-1983 was defined as the “no-catch-error” baseline into which temporally autocorrelated error was incorporated, such that:

$$C_y^{sim} = C_y^{true} e^{\phi_y - 0.5\sigma_{sim}^2};$$

$$\phi_y = \rho_{sim}\phi_{y-1} + \sqrt{1-\rho_{sim}^2}\,\delta_y; \;\; \delta_y \sim N(0;\sigma_{sim}^2) \qquad Eq. 5$$

where C_y^{true} is the catch in year y of the reconstructed catch time series, ρ_{sim} is the extent of temporal autocorrelation in the simulated catch; δ_y is a normally distributed random variable; and σ_{sim} is the standard deviation of δ_y.

Four catch history scenarios were defined by alternative constant σ_{sim} values (0.2, 0.4, 0.6, 0.8). A fifth catch history scenario shifted from high to low variation, where the first 49 years of catch were simulated with σ_{sim}=0.6 and the last 20 years with σ_{sim}=0.2. The timing of the switch coincides with the beginning of rockfish species composition sampling, and therefore a presumed increase in the accuracy of the catch estimate. A temporal autocorrelation factor of 0.7 was applied, which is consistent with autocorrelation factors reported in previous simulation studies of west coast groundfish (Punt et al., 2008).

For each catch history scenario, I simulated 200 catch histories, and each catch history was analyzed with 10,000 runs of DCAC and DB-SRA. Input parameter values were defined by current biological knowledge of canary rockfish (Table 1.4). I ended the catch histories in 1983, the year of the first stock assessment. Example catch trajectories are shown in Figure 1.3.

I evaluated the performance of DCAC and DB-SRA in the simulation analysis relative to two metrics: (1) the “true” simulation harvest limit (HL_{TS}), and (2) the median HL estimate of the no-catch-error baseline, parameter values Table 1.4.

The true harvest limit for the simulation analysis was calculated according to *Eq. 4*, but the exploitation rate was not defined by the SPR_{MSY} from the 2009 canary rockfish stock assessment, as in the retrospective analysis. Instead I used a value for F_{MSY}/M of 0.8, based on an analysis of northeast Pacific demersal stocks (Walters and Martell, 2004), and consistent with the application of DCAC and DB-SRA to data-poor west coast rockfish (Dick and MacCall, 2010). To calculate an exploitation rate proxy of F_{MSY} for *Eq. 4*, I multiplied 0.8 by the natural mortality rate of 0.097, for an F_{MSY} value of 0.07. I used this value as a proxy for the exploitation rate at MSY in calculating HL_{TS}.

RESULTS

HISTORIC AND CURRENT CATCH DATA

Canary rockfish catch history extends back to 1916; however, the full catch time series was not available to either the 1984 or 1990 stock assessments (Figure 1.1). The historic catch available to the 1984 stock assessment covered 20 years, 1963-1983, representing 65% of total canary rockfish catch to that point. The average catch from 1963-1983 as estimated in 1984 was 800 t more than as estimated in 2009. The historic catch available to the 1990 stock assessment covered 22 years of a 73-year catch history, 1967-1989, also representing 65% of the total catch. The average 1990 historical catch was closer to the current catch average over the same time period, at 2300 and 2400 t, respectively. The "best case" data scenarios use the full reconstructed catch history from 1916 to the respective assessment year.

DATA-POOR ASSESSMENT, 1984

The 1984 stock assessment recommended setting catch at 100-130% of the average catch in the INPFC Eureka and Vancouver areas. In the Columbia area, a lower limit to catch was defined as the average catch prior to a recent trend of increasing catch. An upper limit was set at the peak catch. The recommended catch for the Columbia area was the mean of the lower and upper limits. This early data-poor method set the coast-wide harvest limit 2600 t above the true harvest limit (HL_{TR}), as defined by the 2009 canary stock assessment.

DCAC

In 1984, DCAC median harvest limits overestimated both the "true" (HL_{TR}) and the "best case" (HL_B) harvest limits when calculated with both the historic and current catch data, across all depletion levels (Table 1.5, Figure 1.4). Use of the current catch data reduces the positive bias in the HL estimate, as well as the sensitivity of the median HLs to the assumed depletion. Use of current catch data decreased the range of the estimated HLs between the high and low depletion values by 50 t relative to the harvest limits calculated with the historic data. Despite overestimating the 1984 HL_{TR}, all harvest limit distributions calculated with historic and current catch data for all depletion levels were below the recommended catch in 1984.

DB-SRA

DB-SRA distributions of the estimated harvest limits varied markedly across depletion values, and all HL distributions included the 1984 harvest limit (Figure 1.5). All but three of the DB-SRA estimated median harvest limits calculated with historic data overestimated the HL_{TR} and HL_B (Table 1.5, Figure 1.5). The median HL_B was equal to the true harvest limit (HL_{TR}). Use of the current catch data at the actual depletion (0.40) overestimated the HL_{TR} by 890 t, a 94% relative error (Table 1.6). Use of current catch data reduced the HL estimates relative to the HL estimates calculated with historic catch data. Use of current catch data improved the median HL approximation of the HL_{TR} for the least pessimistic depletion values of 0.30-0.40. At depletion levels below 0.30, use of the historic data provided a better approximation of the true harvest limit. The use of current catch data reduced the range of estimated harvest limits by 480 t. All median harvest limit estimates calculated using the historic and current catch data for all depletion levels were below the recommended catch in 1984.

DATA-RICH ASSESSMENT, 1990

The 1990 stock assessment recommended a harvest limit of 1,500 t for the INPFC Columbia area based on an age-structured Stock Synthesis model, and recommended no change in the Eureka or Vancouver harvest limits of 600 and 800 t. This method overestimated the true HL by 2300 t. The assessment accurately predicted that the spawning stock biomass had dropped below 30% of unfished spawning biomass (the "true" depletion in 1990 was 25% of unfished spawning biomass).

DCAC

In 1990, DCAC harvest limits calculated with both the historic and current catch data overestimated the "true" and "best case" harvest limits (HL_{TR}, HL_B) across all depletion levels (Table 1.5, Figure 1.6). The HL_B was positively biased relative to the true harvest limit. In contrast to the 1984 results, use of the current catch data increases the positive bias in the HL estimates, such that the range of median estimates calculated with the current catch and historic catch are non-overlapping (Figure 1.6). The increase in the median estimates calculated with current catch data is minimally associated with an increase in the sensitivity of the HL estimates to depletion. Despite overestimating the true HL, all harvest limits calculated with historic and current catch data for all depletion levels were below the recommended catch in 1984.

DB-SRA

The 1990 DB-SRA harvest limits estimated using both historic and current catch data were positively biased across all depletion values (Table 1.5, Figure 1.7). The "best case" HL underestimated the "true" HL, consistent with previously reported results (Dorn et al., 2011; Wetzel and Punt, 2011). Use of the current catch data at the actual depletion (0.25), overestimated the true HL by 780 t, and increased the median HL estimates relative to the HL estimates calculated with the historic catch data. As depletion increased from 60% to 80% (i.e., 0.40 to 0.20), the difference was reduced between the HLs calculated with the historic catch and HLs calculated with current catch data. At the most pessimistic depletion level, the historic and current HL estimates are approximately equal (978 and 989 t, respectively). In contrast to the 1984 results, not all estimates of the harvest limit fell below the recommended catch in 1990. Use of the most optimistic depletion and current catch data resulted in an HL estimate 160 t above the recommended harvest.

CATCH HISTORY ANALYSIS

DCAC

The median harvest limit calculated using the reconstructed catch data (defined in my analysis as the "no-catch-error" scenario) underestimated the true simulation harvest limit (HL_{TS}) (Table 1.6, grey line Figure 1.8). The mean harvest limit estimates from each catch error scenario (the mean harvest limit of 200 catch time series per error scenario) underestimated the harvest limit of the no-catch-error scenario. The mean HL estimate generally decreased with increasing sigma values, but the trend reverses with σ=0.8. This result could be an artifact of the relatively small sample size. The probability of exceeding the no-catch-error scenario harvest limit by more than 10% increased with increasing sigma values. There is a higher probability in each catch scenario of underestimating the no-catch-error HL by more than 10%, and this increased with increasing sigma values, with the exception of σ=0.8.

DB-SRA

The mean harvest limit of the no-catch-error scenario underestimated the true harvest limit (HL_{TS}) (Table 1.6, Figure 1.8). The mean harvest limit estimates across all catch error scenarios underestimated the mean HL of the no-catch-error scenario. As with DCAC, the mean HL estimate decreased with increasing sigma values. The probability of a catch error scenario exceeding the HL for the no-catch-error scenario by more than 10% increased with increasing sigma values. There is a higher probability in each catch scenario of underestimating the no catch error HL by more than 10%, and this increased with increasing sigma values, with the exception of σ=0.8.

DISCUSSION

Retrospective analysis of the canary rockfish stock with DCAC and DB-SRA resulted in more precautionary harvest limits than the recommended harvest limits in the 1984 and 1990 stock assessments, using either the historic or current catch data. DCAC was not just an improvement over the simple method used to set catch in 1984, it was also an improvement over the more complex method used in the 1990 stock assessment. Considering that the retrospective analysis violated one of the central requirements of a stock reduction analysis, that the catch time series is complete, DB-SRA performed well relative to the recommended harvest limits in 1984 and 1990. Of note, the 1990 stock assessment estimated that the stock had dropped below 30% of the unfished biomass. An analyst using the estimated depletion from the more complex model to inform a DB-SRA or DCAC estimate would have estimated an harvest limit at least 1,000 t less than the actual recommendation; however, would still exceed the true harvest limit defined by current knowledge and assessment.

The data-poor review panel concluded that DCAC and DB-SRA are robust across a wide range of scenarios (Dorn et al., 2011). This conclusion is not well-supported by the retrospective analysis, but is supported by the catch simulation analysis. The retrospective analysis found that the use of historic data generally resulted in an over-estimate of the "true" harvest limit by DCAC and DB-SRA across depletion values. The catch simulation analysis resulted in a consistent negative bias in the mean harvest limit with a zero probability of over-estimating the true harvest limit by both DCAC and DB-SRA across error values. Notably, as catch error increased, the mean HL decreased for both DCAC and DB-SRA. The methods became more precautionary with increased uncertainty in the catch data.

Simulations have found that the median HL estimate of DCAC is higher than the true HL when the stock is assumed to be much less depleted than it actually is (Wetzel and Punt, 2011). Although my results also show a positive bias in the DCAC median HL estimate when depletion is mis-specified, the difference between median estimates across assumed depletion levels were small. DCAC was consistent across a wide range of data scenarios with a less variable median HL estimate than DB-SRA. As well, with assumed depletion decreasing, DB-SRA distributions of the HL became increasingly right-skewed relative to DCAC. These results indicate that, in this study, an incorrect depletion estimate is less of a factor in the overestimation of the true HL for DCAC than DB-SRA.

The Retrospective Approach and Data Uncertainty

The catch data in 1990 was closer to the reconstructed catch than the catch data available in 1984 (Figure 1.1). This refinement of the catch data available to DCAC and DB-SRA did not significantly improve the harvest limits between the 1984 and 1990 assessments. This result is in direct contrast to the results of the catch error simulation analysis, which resulted in precautionary HL estimates generated by both methods, regardless of error in the catch data. Further, the HL estimate improved with decreasing error in the catch history. When evaluated without error in the point estimates of the input parameters, reducing the catch error reduced the negative bias of the mean HL estimate. From the catch error simulation analysis results, one could reasonably expect an improvement in the HL estimate between the 1984 and 1990 assessments.

An improved estimate of the HL between 1984 and 1990 did not materialize with the improved catch history data due to the increase in the point estimate of natural mortality (Table 1.1). The explanation for this result lies in both the direction of the natural mortality bias, which was positive, and the reduction in the average catch between the 1984 and 1990 historic data sets. The ratio of F_{MSY}/M remained at a value of 1 between 1984 and 1990. As M increased in 1990, so then did F_{MSY}. An increase in the fishing mortality rate at MSY combined with a lower average catch, could feasibly lead to an increase in the positive bias of the HL relative to the true HL for both DCAC and DB-SRA. Any improvement to the HL estimates between 1984 and 1990 that could have stemmed from an updated catch history were diminished by the mis-specified natural mortality parameter.

The natural mortality estimate used in the 1984 and 1990 stock assessment represented the best available biological information at the time. The parameters used in current stock assessments also represent the best available biological information. If the presupposition is that improved data will lead to better estimates of the harvest limit with DCAC and DB-SRA, the results of this study show that this will not always be the case. The catch time series for west coast rockfish is currently under further revision as the states of Oregon and Washington complete catch reconstructions. Without improved estimates of natural mortality rates for data-poor stocks, the catch reconstruction alone may not improve estimates of the harvest limit. For stocks with positively biased estimates of natural mortality, catch reconstructions that reduce the average catch could have the consequence of increasing the positive bias of the estimated sustainable yield or overfishing limit.

Retrospective application of new data-poor techniques to an overfished stock suggests that had these simple techniques been available to the analysts in 1984 and 1990, lower harvest limits might have been recommended. However, with the data available to the 1984 and 1990 stock assessments, DCAC and DB-SRA still over-estimated the true harvest limit, meaning that these methods may not have prevented canary rockfish from becoming overfished. DCAC and DB-SRA could have slowed the decline of the population, giving management more time to detect a problem. However, the 1994 stock assessment estimated spawning stock biomass could be as low as 4% of unfished spawning biomass, and determined that the fishing mortality rate was in excess of the overfishing limit. Yet dramatic reductions in catch were not implemented until 1999. The delay between the assessment results and management action suggests that had DCAC or DB-SRA been available for the early stock assessments, canary might still be overfished today.

TABLES

Table 1.1 Retrospective analysis point estimates, standard deviation (SD), and distribution type for DCAC and DB-SRA input parameters reflecting historic (1984, 1990) and current (2009) catch and biological information.

	1984 assessment	1990 assessment	2009 assessment	SD	Distribution
$A_{50\%}$	12	9	9	NA	NA
M	0.10	0.148	0.097	0.40	Lognormal
F_{MSY}/M	1.00	1.00	0.41	0.20	Lognormal
Δ	0.60-0.80[1]	0.60-0.80	0.60/0.75[2]	0.10	Beta
B_{peak}	0.35	0.35	0.40	0.05	Beta
Catch	1963-1983	1967-1989	1916-‘83/’89	NA	NA

[1]Δ values for 1984 and 1990 range between 0.60 and 0.80 in increments of five.[2]0.60 and 0.75 are the estimated values for 1984 and 1990 by the most recent stock assessment. $A_{50\%}$ is the age at 50% maturity, *M* is the instantaneous natural mortality rate, F_{MSY} is the instantaneous fishing mortality rate corresponding to MSY, Δ is depletion, B_{peak} is the biomass corresponding to a harvest at MSY.

Table 1.2 The “true” harvest limit (HL_{TR}) defined for the retrospective analysis in each assessment year.

Year	Exploitable Biomass (B_{exp})	Exploitation Rate ($U_{SPR(MSY)}$)	HL_{TR}
1984	24,310	0.04	970
1990	16,077	0.04	640

Exploitable biomass and exploitation rate as per the 2009 canary rockfish stock assessment (Stewart, 2009). HL_{TR} calculated according to *Eq. 4*

Table 1.3 Definition of each harvest limit symbol for the retrospective and catch simulation analysis.

Harvest Limits	
HL_{TR}	"True" HL for the retrospective analysis, $F_{MSY}/M = 0.41$, *Eq. 4*
HL_{TS}	"True" HL for the catch simulation, $F_{MSY}/M = 0.80$, *Eq. 4*
HL_B	"Best case" HL, catch data and parameter values from 2009 assessment, Table 1.2

Table 1.4 Catch analysis point estimates of DCAC and DB-SRA input parameters, including the exploitable biomass and exploitation rate used to calculate the "true" HL (HL_{TS}) for the catch analysis simulation.

	Mean	SD	Distribution
$A_{50\%}$	9	NA	NA
M	0.097	0.40	Lognormal
F_{MSY}/M	0.80	0.20	Lognormal
Δ	0.60	0.10	Beta
B_{peak}	0.40	0.05	Beta

Exploitable Biomass (B_{exp})	*Exploitation Rate*	HL_{TS}
24,310	0.07	1702

Exploitable biomass as per the 2009 canary rockfish stock assessment. Exploitation rate is defined as a proxy for F_{MSY}. HL_{TS} calculated according to *Eq. 4*

Table 1.5 DCAC and DB-SRA estimated median harvest limits calculated using the historic catch or current catch data across depletion values. Bold numbers indicate estimates at the true depletion level in that year.

	1984				**1990**			
	DCAC		DB-SRA		DCAC		DB-SRA	
Depletion	Historic	Current	Historic	Current	Historic	Current	Historic	Current
0.40	**1587**	**1245**	**2558**	**1884**	1502	1692	2834	3063
0.35	1522	1188	1976	1426	1456	1635	2301	2423
0.30	1463	1150	1481	1048	1417	1595	1801	1918
0.25	1418	1106	1080	748	**1386**	**1556**	**1373**	**1438**
0.20	1354	1064	710	512	1346	1518	978	989
HL_B	880		968		906		582	
HL_{TR}	970				640			
$HL_{assessment}$	3500				2900			
Actual Catch	2216				2897			

HL_B is the estimated harvest limit distribution calculated using catch data and parameter values from the 2009 canary stock assessment. HL_{TR} is the "true" harvest limit for the retrospective analysis, and $HL_{assessment}$ is the harvest limit recommended in each assessment year.

Table 1.6 Percent relative error (%RE) of the harvest limits calculated using the historic and current catch data across depletion values. Bold values indicate estimates at the true depletion level in that assessment year.

	1984				**1990**			
	DCAC		DB-SRA		DCAC		DB-SRA	
Depletion	Historic	Current	Historic	Current	Historic	Current	Historic	Current
0.40	**63**	**28**	**163**	**94**	134	163	341	376
0.35	57	22	103	47	126	154	258	277
0.30	51	18	52	8	120	148	180	198
0.25	46	14	11	-23	**116**	**142**	**114**	**124**
0.20	39	9	-27	-47	109	136	52	54
$\boldsymbol{HL_B}$	-0.09		0.00		0.41		-0.09	

HL_B is the estimated harvest limit distribution calculated using catch data and parameter values from the 2009 canary stock assessment.

Table 1.7 The mean harvest limit estimates calculated from 200 simulated catch histories per catch error parameter (σ), the probability of overestimating (over) or underestimating (under) the harvest limit estimated with no catch error by more than 10%, and the percent relative error (%RE) of the true HL (HL_{TS}).

	DCAC				**DB-SRA**			
	Mean	Over	Under	%RE	Mean	Over	Under	%RE
σ(0.20)	1147	0.00	0.00	-33	1362	0.00	0.00	-20
σ(0.40)	1093	0.01	0.25	-36	1294	0.02	0.37	-24
σ(0.60)	1040	0.08	0.61	-39	1190	0.13	0.59	-28
σ(0.80)	1059	0.17	0.53	-38	1342	0.26	0.47	-21
σ(0.20/0.80)	1096	0.01	0.27	-36	1346	0.01	0.05	-21
No catch error	***1168***				***1388***			
HL_{TS}	***1702***							

FIGURES

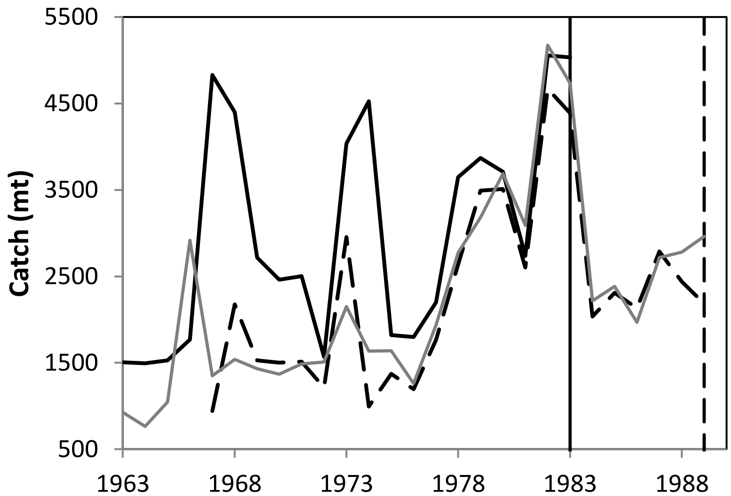
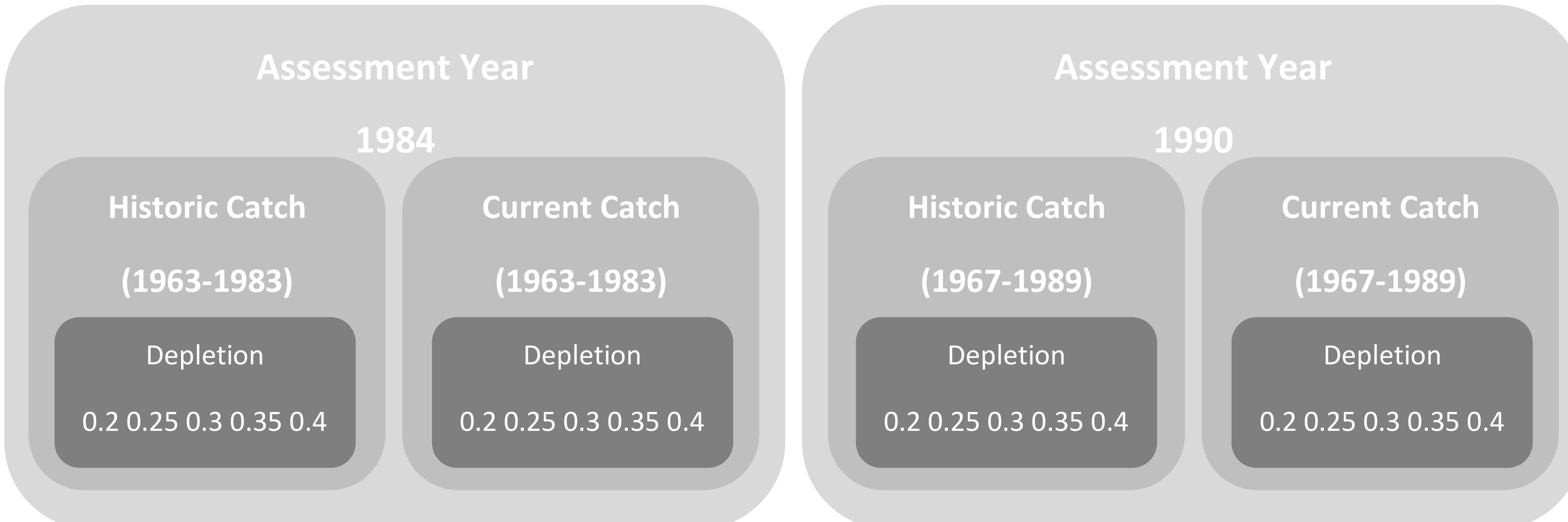


Figure 1.1 Catch time series available to the 1984 (solid black line), and 1990 (dashed line) canary rockfish stock assessments. Grey line indicates the current catch, as reported in the 2009 canary rockfish stock assessment (Stewart, 2009).

Figure 1.2 Nested design of the retrospective analysis. DCAC and DB-SRA applied to each assessment year, using both the estimated historic and estimated current catch data sets, and calculated with different assumed depletion levels.



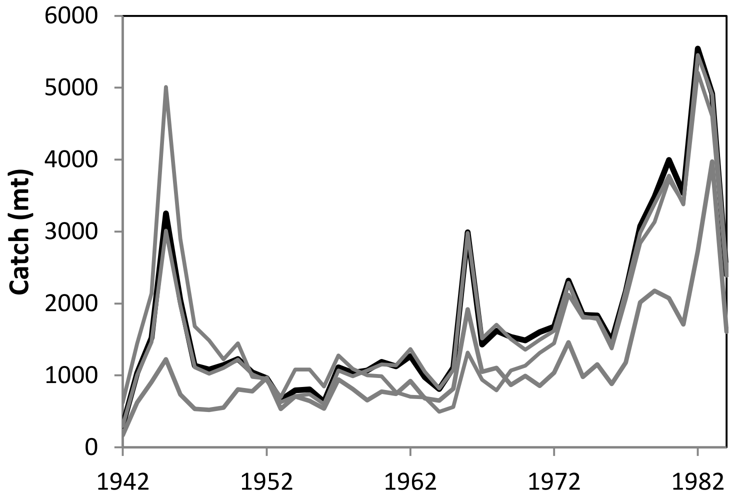


Figure 1.3 True canary rockfish catch for years 1942-1983 (black line) as reported in the 2009 canary stock assessment, and three representative simulated catch histories defined by increasing error (σ0.2, σ0.6, and σ0.6/0.2).

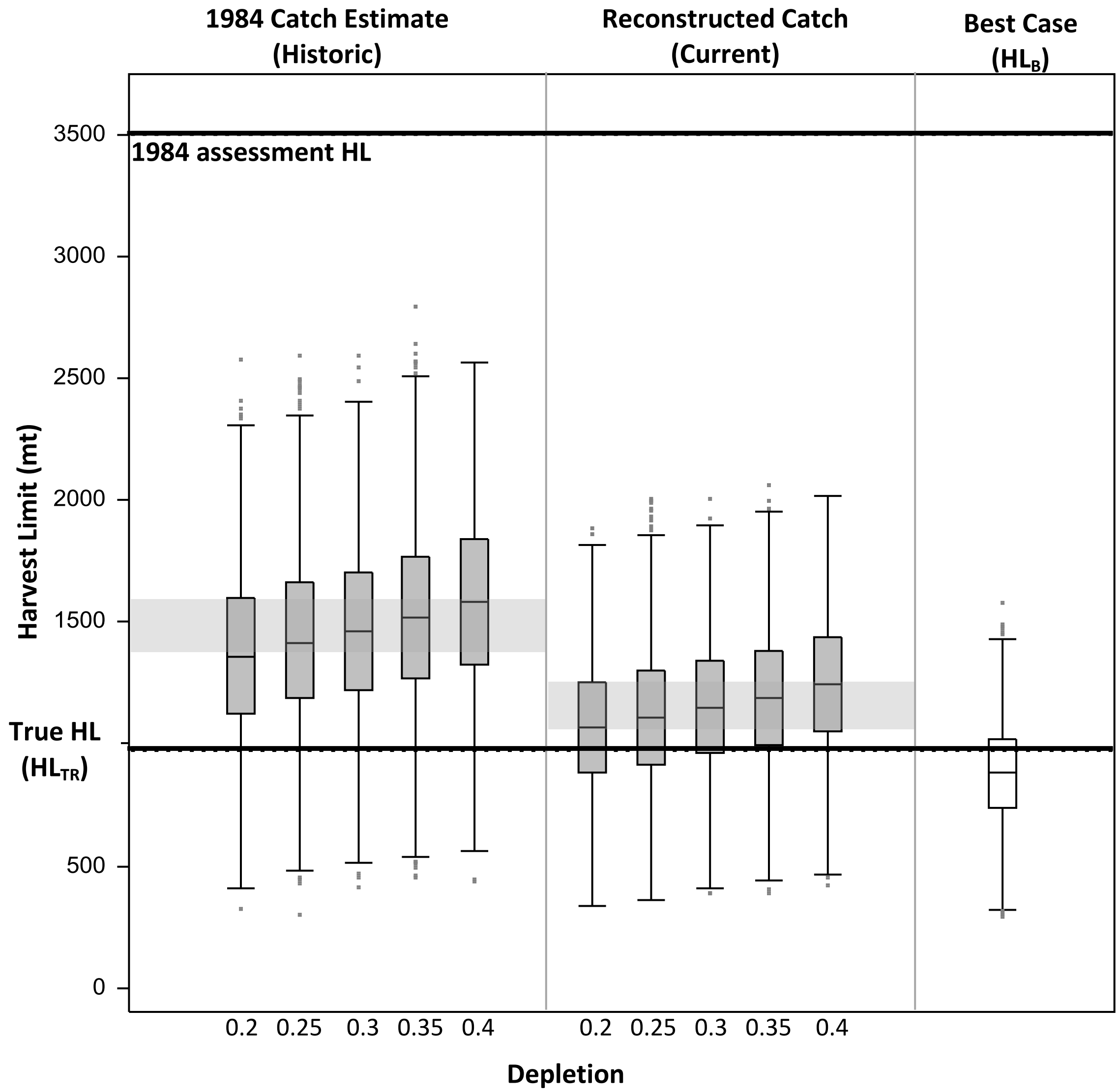


Figure 1.4 Distributions of DCAC estimated harvest limits in assessment year 1984 calculated with historic data and the current (reconstructed) catch data over a range of depletion values. The “best case” harvest limit distribution (HL_B) was estimated using the reconstructed catch data and parameter values from the 2009 canary stock assessment, including the estimated depletion in 1984 of 0.40. Shaded areas denote the range between median HL estimates over assumed depletion levels.

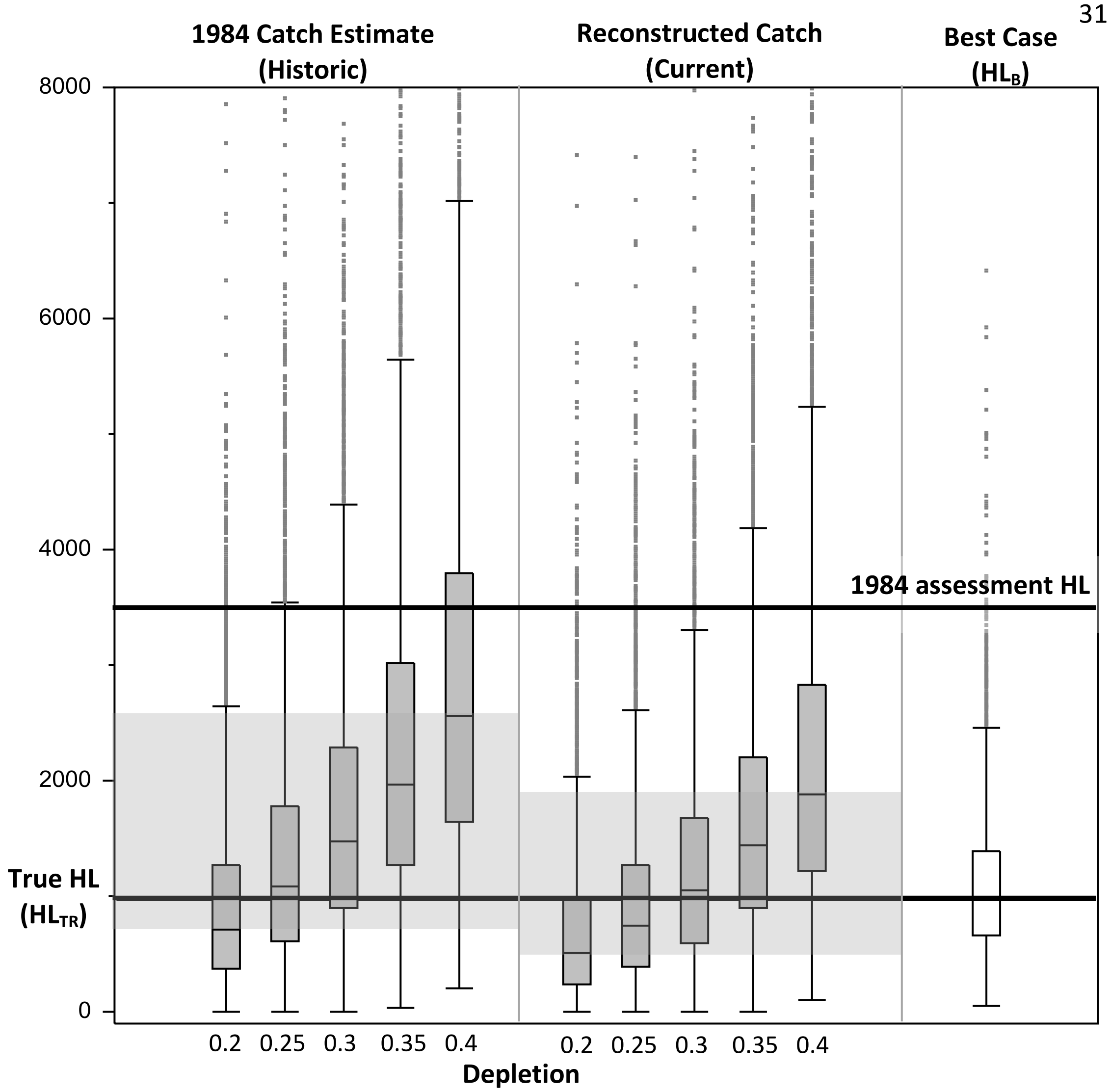


Figure 1.5 Distributions of DB-SRA estimated harvest limits in assessment year 1984 calculated using historic catch and the current (reconstructed) catch data over a range of depletion values. The "best case" harvest limit distribution (HL_B) was estimated using the reconstructed catch data and parameter values from the 2009 canary stock assessment, including the estimated depletion in 1984 of 0.40. Shaded areas denote the range between median HL estimates over assumed depletion levels.

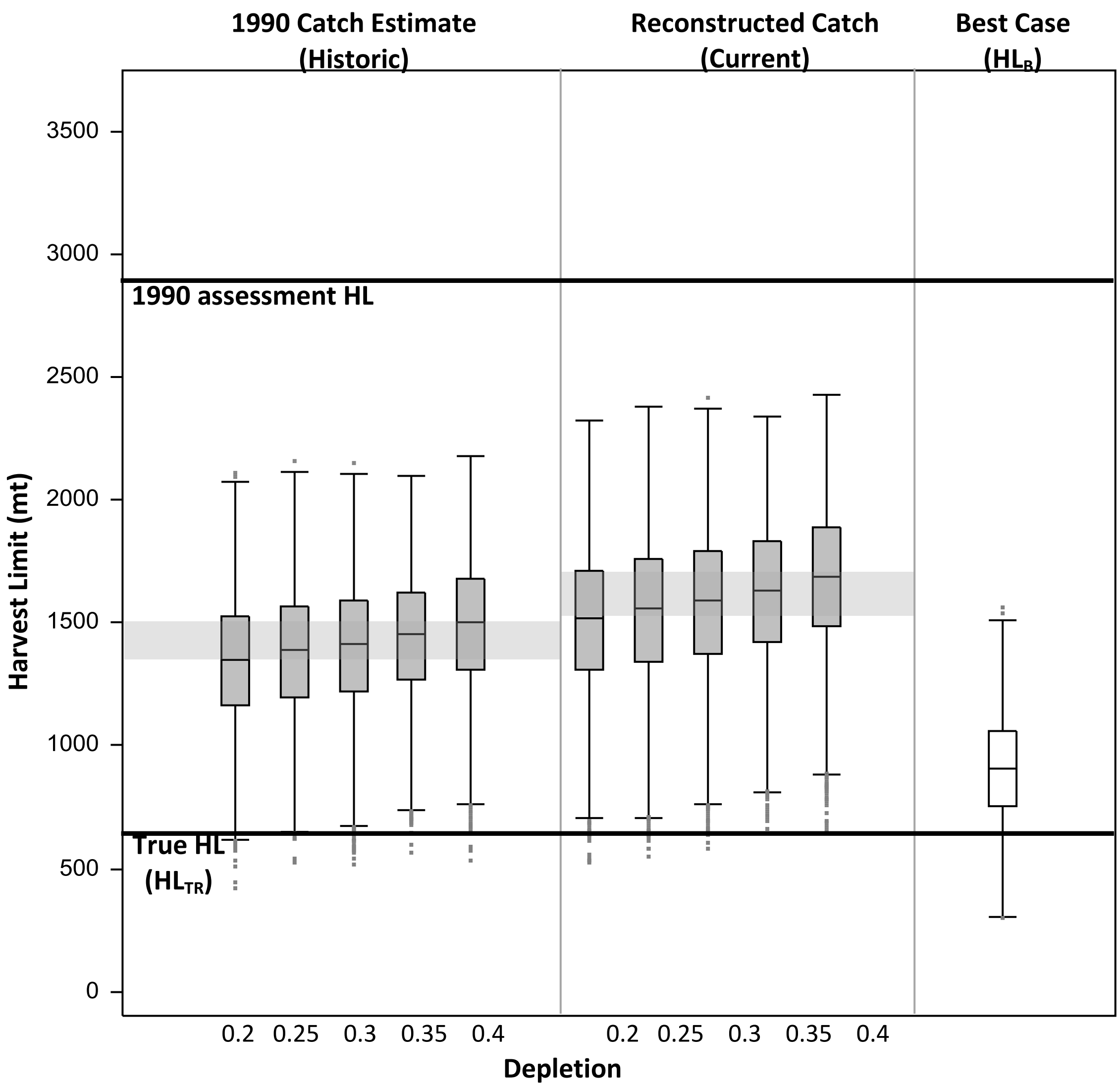


Figure 1.6 Distributions of DCAC estimated harvest limits in assessment year 1990 calculated using historic catch and the current (reconstructed) catch data over a range of depletion values. The "best case" harvest limit distribution (HL_B) was estimated using the reconstructed catch data and parameter values from the 2009 canary stock assessment, including the estimated depletion in 1990 of 0.25. Shaded areas denote the range between median HL estimates over assumed depletion levels.

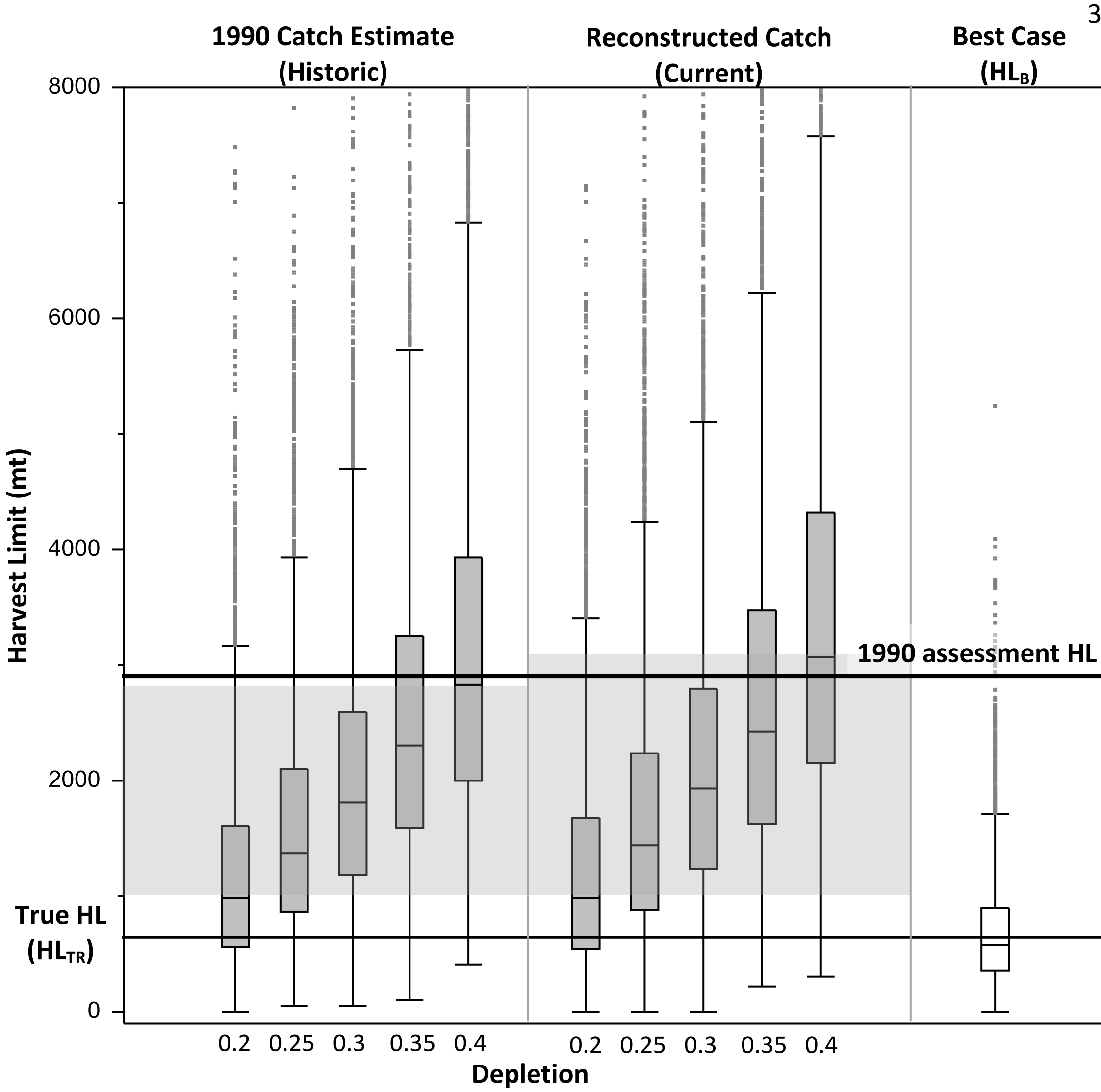


Figure 1.7 Distributions of DB-SRA estimated harvest limits in assessment year 1990 calculated using historic catch and the current (reconstructed) catch data over a range of depletion values. The "best case" harvest limit distribution (HL_B) was estimated using the reconstructed catch data and parameter values from the 2009 canary stock assessment, including the estimated depletion in 1990 of 0.25. Shaded areas denote the range between median HL estimates over assumed depletion levels.

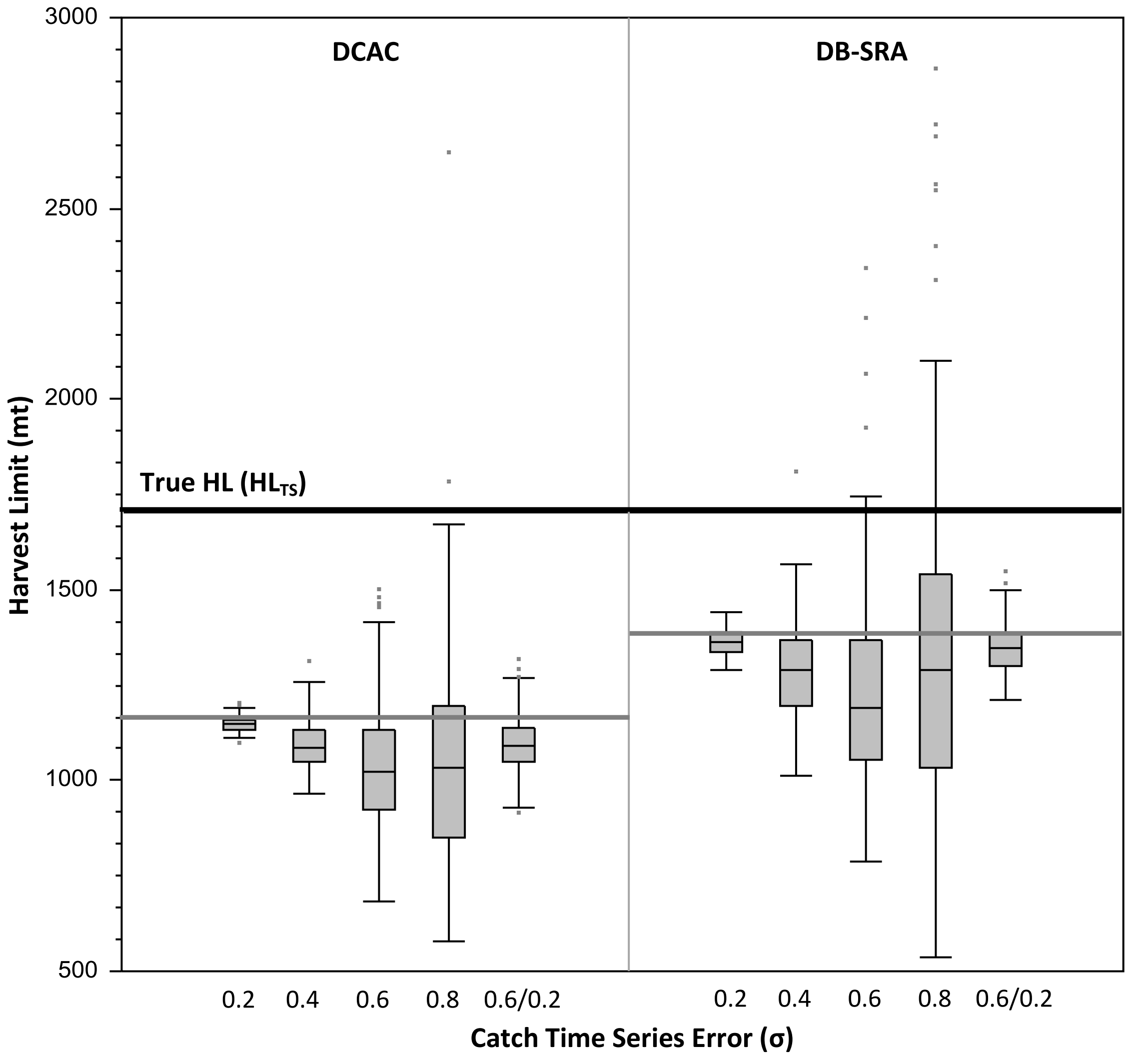


Figure 1.8 Harvest limit distributions for the catch error analysis. Distributions represent the harvest limits calculated from 10,000 runs of DCAC and DB-SRA for each of the 200 catch time series per error scenario. The grey lines denote the median estimated harvest limit calculated using the reconstructed catch data (no catch error) and current canary rockfish parameter values. Black line is the "true" harvest limit (HL_{TS}).

CHAPTER 3 EVALUATION OF MANAGEMENT STRATEGIES TO PRESERVE THE AGE STRUCTURE OF LONG-LIVED ROCKFISH, *SEBASTES*, IN THE NORTHEAST PACIFIC

INTRODUCTION

In commercially exploited, long-lived fish species, age structure plays an important role in population stability and resilience to human and environmental impacts (Hsieh et al., 2010). Reduction in the relative abundance of older age classes due to fishing is a necessary consequence of exploitation, which will be exacerbated if selection is focused on the largest fish (Berkeley et al. 2006). Consequences of the reduced abundance in older age classes include increased population variability perpetuated through increases in recruitment variability (Marteinsdottir and Thorarinsson, 1998), as well as changes in demographic parameters, such as the growth rate (Secor, 2000), that lead to unstable, non-linear, population dynamics (Anderson et al., 2008). Older females of long-lived species can contribute to population stability through an increase in both the quantity and quality of larvae, and by more variable spawn timing and locations. An increase in energy allocation per offspring can improve larval survival through an increased time to starvation and higher likelihood of encountering favorable environmental conditions once released (Berkeley et al., 2004; Bobko and Berkeley, 2004; Sogard et al. 2008).

The implications of the reduced abundance of older age groups for the management of fished stocks are evident in a variety of species. O'Farrell and Botsford (2006) found that large errors in the estimate of lifetime reproductive potential in rockfish, *Sebastes* spp., can result if the relationship between larval survival and maternal age is not properly characterized. Accounting for uncertainty in the relationship between maternal age and reproductive potential in Pacific ocean perch, *Sebastes alutus*, increased the relative level of equilibrium spawning per recruit that corresponds to maximum sustainable yield (MSY), although the fishing mortality rate at MSY was basically unchanged (Spencer et al., 2007). Murawski et al. (2001)

showed fishing mortality rates based on the spawning stock biomass overestimated the resiliency of the Georges Bank stock of Atlantic cod (*Gadus morhua*), specifically when estimating the maximum fishing mortality rate. In addition to the particular rockfish and Atlantic cod examples, a meta-analysis of 25 long-lived species in the north temperate and Arctic latitudes found that exploited populations with an extended age structure had higher reproductive rates than truncated populations, independent of absolute spawning stock biomass (Venturelli et al., 2009).

Despite the growing body of evidence that maintenance of age structure enhances reproductive potential and reduces instability of certain fished populations, management actions are determined by spawning biomass thresholds for west coast rockfish that do not explicitly include maintenance of biomass in the oldest age classes. The Magnuson-Stevens Fishery Conservation and Management Act (2007) does not stipulate that the managing Councils utilize biomass-based management reference points. The MSFCMA sets forth a legal requirement to “prevent overfishing while achieving, on a continuing basis, the optimal yield from each fishery…”. The optimum yield for fisheries in the U.S. is set relative to the maximum sustainable yield (MSY) from the fishery, a concept that has engendered decades of debate over interpretation, estimation, and proper implementation (Holling, 1973; Larkin, 1977; Jackson et al., 2001; Punt and Smith, 2001; Pikitch et al., 2004; Hilborn, 2004). The mandated use of MSY, however, does not preclude management reference points that include age structure metrics.

MSY is defined by the Pacific Fisheries Management Council as an estimate of the largest average annual catch that can be taken over an extended period of time under the prevailing ecological and environmental conditions (PFMC, 2011). The catch history, in units of landed biomass, is the simplest form of data available to fisheries scientists. With advances in otolith ageing techniques and long time series of catch composition data, management reference points, such as MSY, have the potential to expand beyond biomass to age structure.

On the U.S. west coast, rockfishes, *Sebastes* spp., are managed with a “default adjustment to catch” (i.e., harvest control rule) termed the “40-10” rule (PFMC 2011). The “40-10” adjustment is defined by two spawning biomass thresholds. The first threshold is reached at a spawning biomass that is 40% of the unfished spawning biomass ($0.4SB_0$). The PFMC (2011) defines $0.4\mathrm{SB}_0$ as a general proxy for the biomass that produces maximum sustainable yield, B_{MSY}. Below the B_{MSY} precautionary threshold, catch is reduced in a straight line from the catch at F_{MSY} to F = 0 at the minimum abundance threshold of 10% unfished spawning biomass. The catch at F_{MSY} is the catch resulting from the fishing mortality rate at MSY (F_{MSY}). The “40-10” adjustment modeled with a logistic selectivity function, is defined in this study as the “status quo” (SQ) management strategy.

Two potential avenues for incorporating additional age structure considerations into current management are measures that lead to dome-shaped fisheries selectivity, and adjustments to the recommended catch based on age structure indicators other than spawning biomass. Neither of these options need necessarily abandon the status quo strategy of setting catch limits as prescribed by MSY. Selectivity is a function of the age or length classes caught by the fishery. Two general forms of selectivity exist: asymptotic selectivity in which essentially all fish after a certain age are available to the fishery, and dome-shaped selectivity in which selectivity peaks and declines such that the oldest fish are harvested less intensively. Management measures that impact selectivity include gear modifications (Bellman and Heppell, 2005) or time/area closures. On the west coast, mandatory modifications to trawl gear implemented in 1994 were meant to end trawling in high-relief rocky habitat. This management measure lead to dome-shaped selectivity in the canary rockfish, *Sebastes pinniger*, fishery, because larger fish tend to inhabit rocky areas that cannot be trawled with current gear requirements (Stewart, 2009).

A second option for age structure management is through modifications of the status quo harvest control rule that respond to the age composition of the catch. Froese

(2004) proposed yearly adjustments to harvest limits based on the proportion of the catch that was mature, optimal length, and of advanced age. The goal of the “Froese sustainability recommendations” (Cope and Punt, 2009) is to target only mature fish that have reached the size class which maximizes cohort biomass while constraining the proportion of the “mega-spawners” in the catch. The term “mega-spawner” generally refers to the oldest age classes. While Froese (2004) did not define a specific harvest control rule to achieve the sustainability recommendations, I propose a simple upward or downward adjustment to the status quo catch based on the proportion of mature fish and mega-spawners in the previous year’s catch. These modifications to the status quo are termed the “Froese adjustments”.

In this study I asked two primary questions: (1) within the existing management framework for west coast rockfishes, can constraints on selectivity and adjustments to the status quo control rule enhance age structure, and (2) what are the impacts of these alternative strategies on yield and stock productivity? To answer these questions, I defined three management strategies based on the status quo harvest control rule for west coast rockfishes, and applied the strategies to three rockfish life histories.

The effects of management strategies designed to enhance or protect the age structure of fished populations need to be evaluated in terms of “standard” performance measures, such as yield and biomass depletion; but also in terms of age structure metrics that could become reference points in a management scheme that included the maintenance of age structure as an explicit goal. Therefore, I used a wide range of performance measures to compare the models, any number of which could be used as reference points when managing explicitly for age structure. My focus is on evaluation of trade-offs among management strategies across life history types within rockfish, with a general hypothesis that life history has a large effect on management strategy performance.

METHODS

SPECIES LIFE HISTORY PATTERNS

I selected black rockfish, *Sebastes melanops*, canary rockfish, *Sebastes pinniger*, and yelloweye rockfish, *Sebastes ruberrimus* to represent the range of life history strategies within the rockfishes (Table 2.1). Black rockfish are the fastest growing and shortest-lived of the three species, canary represents the mid-range, and yelloweye are one of the longest-lived of the genus (Love et al., 2002). Life history and population parameters for each species were taken from the most recent stock assessments (Sampson, 2007; Stewart, 2009; Stewart et al., 2009).

THE POPULATION DYNAMICS MODEL

The population dynamics model is age- and sex-structured with recruitment defined by the Beverton-Holt form of the stock-recruitment relationship:

$$N_{y+1,s,a} = \begin{cases} 0.5R_{y+1} & if\ a = 0 \\ N_{y,s,a-1}e^{-(M_{s,a-1}+S_{s,a-1}F_y)} & if\ 1 \leq a < x \\ N_{y,s,x-1}e^{-(M_{s,a-1}+S_{s,a-1}F_y)} + N_{y,s,x}e^{-(M_{s,a}+S_{s,a}F_y)} & if\ a = x \end{cases} \quad Eq. 1$$

where $N_{y,s,a}$ is the number of fish of sex *s* and age *a* at the start of year *y*; *x* is the maximum age in the model, treated as a plus group; $M_{s,a}$ is the instantaneous rate of natural mortality for fish of sex *s* and age *a*, assumed constant through time; $S_{s,a}$ is the selectivity of the fishery on fish of sex *s* and age *a*, assumed constant through time, but varies by the management scenario described below. F_y is the fully selected fishing mortality rate in year *y*; R_y is recruitment during year *y* that includes temporal autocorrelation in the residuals about the stock-recruit relationship, $\mathcal{E}_y$ (Punt et al. 2008):

$$R_y = \frac{4hR_0SB_y}{SB_0(1-h)+(5h-1)SB_y}e^{\varepsilon_y-\sigma_R^2/2}$$

$$\varepsilon_y = \rho_R \varepsilon_{y-1} + \sqrt{1-\rho_R^2}\,\eta_y \; and \;\; \eta_y \sim N(0;\sigma_R^2) \qquad Eq.2$$

where h is the steepness of the stock-recruit curve (the fraction of virgin recruitment, R_0, expected when spawning biomass is 20% of unfished, or virgin, spawning biomass, SB_0). SB_y is the spawning biomass in year y; ρ_R is the extent of temporal autocorrelation in recruitment set at 0.7; η_y governs the fluctuation about the stock-recruitment relationship in year y; and σ_R is the standard deviation of η_y set at 0.5. The derivation for temporal autocorrelation is described in Punt et al. (2008).

Spawning biomass, SB_y, is defined by the sum of mature female biomass from age 2 to the plus group, $a_{max:}$

$$SB_y = \sum_{a=2}^{a_{max}} p_a N_{fem,a} w_{fem,a} \qquad Eq.3$$

where $N_{fem,a}$ is the number of females at age a, $w_{fem,a}$ is the sex-specific weight-at-age, and p_a is the proportion mature at each age, characterized by a logistic equation:

$$p_a = \frac{1}{1+\exp(-\theta'(a-a'_{50}))} \qquad Eq.4$$

where a'_{50} is the age at which 50% of the females are mature and θ' is 4x the slope of the maturity curve at a'_{50}. Weight-at-age is an allometric function of length-at-age defined by:

$$w_a = XL_a^Y \qquad Eq.5$$

HARVEST

The harvest control rule that sets catch based on current spawning biomass in all management scenarios follows the formulation described in Punt et al. 2008:

$$\tilde{C}_y = \begin{cases} 0 & if \frac{SB_y}{B_0} < \alpha \\ \frac{\beta SB_0}{SB_y} * \frac{\left(\frac{SB_y}{SB_0} - \alpha\right)}{(\beta - \alpha)} * C(F_{MSY})_y & if\ \alpha \leq \frac{SB_y}{SB_0} < \beta \\ C(F_{MSY})_y & if \frac{SB_y}{SB_0} \geq \beta \end{cases} \qquad Eq.6$$

where β is the threshold reference point and α is the stock size below which target catch is 0. For west coast rockfish management, a widely utilized threshold reference point is $0.40B_0$, below which catch is linearly reduced to the limit reference point of $0.10B_0$, after which catch is zero. This harvest control rule is also known as the “40-10 rule”. For the purposes of this study, the alpha and beta parameters are set to 0.10 and 0.40, respectively. Above the threshold reference point, catch is determined by a proxy of the fishing mortality rate that produces maximum sustainable yield, F_{MSY}. The catch for year *y* corresponding to a fishing mortality rate of F_{MSY} is calculated as:

$$C(F_{MSY})_y = \sum_s \sum_a w_{s,a} N_{y,s,a} \frac{S_{s,a} F_{MSY}}{(M_{s,a} + S_{s,a} F_{MSY})} \left(1 - e^{-(M_{s,a} + S_{s,a} F_{MSY})}\right) \qquad Eq.7$$

The F_{MSY} proxy used in this study is the constant fishing mortality rate that reduces the lifetime egg production, *LEP*, of a stock to x% of that in the unfished condition, $F_{x\%}$ (Clark 1991, 2002). For this study, I chose $F_{50\%}$ following the PFMC F_{MSY} proxy for rockfish defined in the 2011 Fishery Management Plan. The ratio of *LEP* in the fished to unfished condition is termed the spawning potential ratio, *SPR*:

$$SPR = \frac{LEP_{fished}}{LEP_{unfished}} \qquad Eq.8$$

LEP is a function of the proportion mature at age, p_a, the relative fecundity at age, Φ_a, and female survival from age 1 to age a, such that:

$$LEP = \frac{\sum_{a=0}^{amax} \exp(-(M \cdot a + \sum_{a=0}^{a} F_a)) \cdot \Phi_a \cdot p_a}{\sum_{a=0}^{amax} \exp(-M \cdot a) \cdot \Phi_a \cdot p_a} \qquad Eq. 9$$

where the relative fecundity (eggs per kg), Φ, is a linear function of weight (Methot, 2005), such that:

$$\frac{\Phi}{w} = x + bw \qquad Eq. 10$$

Species-specific life history parameter values (Table 2.1) are from the current stock assessments (Sampson, 2007; Stewart, 2009; Stewart et al., 2009).

IMPLEMENTATION ERROR AND ESTIMATION ERROR

Implementation error and estimation error are included as sources of uncertainty common to west coast rockfish stock assessments. Implementation error is defined as the difference between the catch calculated with *Eq. 6*, $\tilde{C}_y$, and the actual catch removed from the population, C_y^{act}, following Punt et al 2008:

$$C_y^{act} = \tilde{C}_y \exp\left(\phi_y - \sigma_I^2/2\right);$$
$$\phi_y = \rho_I \phi_{y-1} + \sqrt{1-\rho_I^2}\varphi_y; \;\; \varphi_y \sim N(0; \sigma_I^2) \qquad Eq. 11$$

where ρ_I is the extent of autocorrelation in the implementation error and φ_y is the extent of implementation error. Estimation error is added to depletion, the ratio of current spawning biomass (*Eq. 3*) to unfished spawning biomass (SB_y/SB_0), which is used in *Eq. 6* to determine catch. As formulated, Estimation error is assumed to be influenced by the uncertainty in both the current spawning biomass and the unfished spawning biomass as follows:

$$\left(SB_y/SB_0\right)^{est} = \left(SB_y/SB_0\right)\exp\left(\delta_y - \sigma_E^2/2\right);$$
$$\delta_y = \rho_E \delta_{y-1} + \sqrt{1-\rho_E^2}\varphi_y; \qquad Eq.12$$

MANAGEMENT STRATEGIES

The impact of management on the population is modeled with direct removals, and with selectivity functions designed to reflect the Froese sustainability recommendations. Two methods to set catch and two selectivity functions are crossed to create four management strategies (Table 2.2).

The first method to set catch, utilized in the status quo (SQ) and dome (D) strategies, is the 40-10 rule defined by *Eq. 6* with implementation error, *Eq. 11*. The second method for setting catch, utilized in the Froese-logistic (FrL) and Froese-dome (FrD) strategies, is an adjustment to the 40-10 rule, *Eq 6*, based on the length composition of the catch in the previous year, referred to here as the "Froese adjustment", FR 40-10:

$$\tilde{C}_y = \begin{cases} 0.8(C_{40-10}) & if\ P_{MAT} < 0.95\ and\ P_{MEGA} > 0.25 \\ 0.9(C_{40-10}) & if\ P_{MAT} < 0.95\ and\ P_{MEGA} < 0.25 \\ C_{40-10} & if P_{MAT} \geq 0.95\ and\ P_{MEGA} < 0.25 \end{cases} \qquad Eq.13$$

where P_{MAT} is the life-history-specific proportion of the catch greater than the length at 50% maturity, L_{MAT}, and P_{MEGA} is the life-history-specific proportion of the catch in the "mega-spawner" (MSB) group:

$$P_{MAT} = \sum_{L_{MAT}}^{L_{MAX}} P_L \qquad P_{MEGA} = \sum_{1.1L_{OPT}}^{L_{MAX}} P_L \qquad Eq. 14$$

where P_L is the proportion of the catch that is in length bin L, L_{MAX} is the maximum length and L_{OPT} is the length at maximum biomass of a cohort, calculated following Beverton (1992):

$$L_{OPT} = L_{inf}\left(\frac{3}{3+\frac{M}{k}}\right) \qquad Eq. 15$$

where L_{inf} is the asymptotic length and k is the slope of the von Bertalanffy growth curve:

$$L_a = L_{inf}\left(1 - e^{-k(a-a_0)}\right) \qquad Eq. 16$$

Catch set with the FR 40-10 is also subject to implementation error, *Eq. 11*.

Selectivity is modeled with a double normal selectivity function, the most commonly used functional form for west coast stock assessments conducted using Stock Synthesis (Methot, 2005). The double normal selectivity curve is comprised of two normal curves joined by a horizontal line. Parameters include the selectivity at the youngest and oldest ages, the age where the selectivity first reaches full selectivity, the length of the plateau, and two parameters controlling the slope of the ascending and descending limbs.

The two selectivity patterns I use in this study are variations on the Froese sustainability recommendations with a flat-top (logistic-like shape) and dome-shaped curve. The peak of the double-normal selectivity curves for both the flat-top and dome-shape corresponds to the optimum length, L_{opt} (Beverton, 1992). The shape of the dome is such that selectivity equals 0.5 at $0.9L_{opt}$ and $1.1L_{opt}$ (Figure 2.1).

The approach for analysis of the management scenarios is to project a population dynamics model forward 100 years for each life history type. I used Monte Carlo analysis with 10,000 replicates to model stochastic recruitment dynamics, implementation error, and estimation error.

PERFORMANCE MEASURES

Performance measures are broken down into two categories, those related to current management goals for west coast rockfish stocks, and performance measures related explicitly to the maintenance of age structure in the population (Table 2.3).

Management

Each strategy is evaluated by two management reference points, the minimum stock size threshold (MSST) and the threshold defined by the spawning biomass at MSY (SB_{MSY}). The MSST is defined for west coast rockfish at 25% of the unfished spawning biomass, $0.25SB_0$. The SB_{MSY} threshold is defined at 40% of the unfished spawning biomass, $0.40SB_0$. The management performance measures included the probability of spawning biomass dropping below the MSST (<MSST) and the probability of the spawning biomass falling within 10% of $0.40SB_0$ ($0.10SB_{40\%}$,). Management scenarios were also evaluated by the average depletion (SB/SB_0), spawning biomass (SB), and yield for years 76-100 of the simulation . The absolute annual variation (AAV) was used as a measure of volatility in the catch limit between years:

$$AAV = \frac{\sum_{y>75}|C_y - C_{y-1}|}{\sum_{y>75} C_y} \qquad Eq. 17$$

Age Structure

The maintenance of age structure was evaluated by measures related to the abundance of mega-spawners in year 100 of the model. These measures included mega-spawner depletion (*MB/MB₀*), and the proportion of the spawning biomass in the mega-spawner stage (*MB/SB*).

Relative Measures

The performance measures for each strategy are evaluated relative to the status quo strategy (40-10 rule with logistic selectivity), such that all results are scaled so that the status quo is the "zero" reference line and the alternative strategies are some percentage above or below the SQ reference line.

RESULTS

AGE STRUCTURE

For each life history, the percent of unfished total spawning biomass composed of "mega-spawner" biomass (MSB) was 41, 58, and 60% for black, canary, and yellow eye rockfish, respectively (Table 2.4). Status quo management reduced the MSB for each life history to 22, 39, and 46% of the total spawning biomass, reflecting a reduction of approximately 60% across life histories. For the black rockfish, status quo management reduced the unfished total spawning biomass (all adult age classes) by 57%, showing that the oldest age classes are disproportionately impacted by fishing relative to the total population in this life history (57% reduction for total spawning biomass versus 78% for mega-spawner biomass). For the canary and yelloweye life histories, however, the impact on the oldest age classes is less pronounced, with total spawning biomass reductions of 64 and 66%, relative to the 70% reduction in the MSB. As defined by the management rule (target spawner biomass B_{40}), each stock was to be maintained at approximately a 60% reduction in total spawning biomass.

Dome-shaped selectivity with the Froese adjustment (FrD, *Eq. 13*) was generally the most effective strategy across life histories for minimizing the loss of MSB relative to the unfished state, and for maximizing the percent MSB in the terminal population (Table 2.4). Both of the dome-shaped strategies (D and FrD) were nearly equally effective for the canary and yelloweye rockfish life histories (Figure 2.2). The Froese adjustments, regardless of selectivity, out-performed the non-Froese strategies for the black rockfish life history (Figure 2.2). The dome shaped-strategies represent an approximate 20% increase over the status quo in maintaining MSB relative to the unfished population, and a 10% increase over the status quo in maintenance of MSB relative to the total spawning biomass in the current population for both the canary and yelloweye life histories (Figure 2.2). The Froese adjustment strategies maximized MSB relative to the status quo for the black rockfish life history.

Adding the Froese adjustment to dome-shaped selectivity improved the performance of dome-shape selectivity alone by 20% for the MB/MB_0 performance measure.

MANAGEMENT MEASURES

No single management strategy minimized the probability of spawning biomass crossing the MSST for all life history types evaluated (Figure 2.3). The Froese adjustment with dome-shaped selectivity (FrD) had the lowest probability for the canary and yelloweye life histories, and the Froese adjustment with logistic selectivity (FrL) had the lowest probability for the black rockfish life history (Table 2.4). The strategies leading to the greatest probability of SB<MSST for the canary and yellow eye life histories were the logistic selectivity scenarios with (FrL) and without (SQ) the Froese adjustment. For the black rockfish life history, the selectivity scenarios without the Froese adjustments (SQ, D) led to the greatest probability of crossing the MSST (Table 2.4).

Relative to the status quo management strategy, the only strategy that increased the probability of SB<MSST was the dome-shaped selectivity scenario (D) applied to the black rockfish life history, representing a 44% increase over the status quo (Figure 2.3). The Froese adjustment strategies (FrL and FrD) returned 56 and 44% reductions in the probability of SB<MSST relative to the status quo for the black rockfish life history. The dome-shaped selectivity scenarios (D, FrD) applied to canary and yelloweye life histories resulted in the greatest percent reduction relative to the status quo, with the Froese dome strategy (FrD) resulting in 54 and 67% reductions in the probability of spawning biomass dropping below MSST over the status quo management strategy.

A similar pattern across life histories emerged for the probability of spawning biomass remaining within 10% of the target spawning biomass, $0.4SB_0$ (Figure 2.2). The longer-lived rockfish are more likely to remain within 10% of the target with dome-shaped management scenarios (D, FrD). However, the probability of staying within 10% of target spawning biomass for the relatively shorter-lived rockfish was little impacted by the different management scenarios (Table 2.4).

YIELD

Across the life history types in this study, the status quo management strategy maximized yield, with the FrL strategy closely approximating the status quo yield for the canary and yelloweye life histories (Figures 2.2 and 2.3). The difference in yield between the status quo and the FrL management strategy was 70 t for the black rockfish life history, representing the greatest difference in yield between two management strategies across life histories. The difference between the high and low yield for the canary and yellow eye life history scenarios is 24 and 10 t, respectively. For the canary and yelloweye life histories, yield is the only measure that a dome-shaped selectivity strategy does not optimize relative to the status quo (Table 2.4), with one exception: The absolute annual variation in catch (AAV) for the dome-shaped strategy applied to the canary life history was 83% higher than the status quo strategy. For all other life histories and management strategies, the status quo had the least optimal AAV values (Figure 2.3).

DISCUSSION

The simulation results presented here indicate that rockfish management is not a "one size fits all" situation. Management strategies that optimize biological performance measures for the longer-lived, slower-growing *Sebastes spp.* do not necessarily represent the best management practices for their shorter-lived cousins. A management strategy characterized by a dome-shaped selectivity pattern was optimal across the majority of performance measures for the canary and yelloweye life history strategies. For the black rockfish life history, the management strategies with Froese adjustments to the catch optimized most performance measures, regardless of the selectivity. Yield is the only measure for which the status quo management option consistently out-performed the other management strategies across life history types.

A study utilizing a deterministic equilibrium yield model applied to black rockfish concluded that yield and age structure performance metrics could both be maximized when the management strategy included marine reserves (Berkeley, 2006). The management strategy in the marine reserve example increased yield over the status quo by 10%. However, in addition to the marine reserve management strategy, larval survival was modeled as a function of female age. The current study showed that the Froese adjustment strategy maintained a higher biomass of the older age classes than the status quo. Had a maternal effect (Berkeley et al. 2004) been included in the model, the additional mega-spawner biomass obtained through the Froese adjustment strategy may have increased larval output to recover some or all of the "lost" yield relative to the status quo (Scott et al., 1999).

A future extension to this study could assess management strategy performance under increasing variability about the stock-recruit relationship. Rockfish of the northeast Pacific are characterized by episodic recruitment events (Hollowed et al. 1987). The longevity of *Sebastes* is one piece of a life history strategy that ensures individual reproductive success and population sustainability through long periods of failed recruitment (Leaman and Beamish, 1984; Longhurst, 2000). With only one model of recruitment variability, the current study may not adequately characterize the potential yield of a population sustained by the "storage effect" of older and larger females (Berkeley et al., 2004; Warner and Chesson, 1985). A management strategy evaluation that includes explicit hypotheses on maternal effects and environmental drivers of recruitment in the population dynamics model is the next step for fully characterizing the utility and feasibility of age structure management.

In terms of implementation of management strategies that incorporate dome-shaped selectivity, there is a long history of industry-science collaboration to devise gear types and fishing behavior strategies that can meet yield and conservation objectives. Although some authors have argued that large marine reserves are the only viable option for increasing the abundance of the oldest age groups , there may be alternative strategies that are less detrimental to fisheries operations. Scott and Sampson (2011) suggest two possibilities for managers to influence selectivity: through alternative fishing mortality rates for fisheries with different gear selectivity, or through spatial allocations of catch quotas. Ultimately, before the method of achieving explicit age structured management objectives is discussed, managers need to be presented with the tradeoffs. All of the alternative management strategies that I tested provided yield predictions that were within 20% of the status quo, which I conclude represents "pretty good yield" (Hilborn, 2010) relative to the preservation of old growth age structure.

TABLES

Table 2.1 Parameter values for each rockfish life history type and unfished population parameters as provided in the most recent stock assessments.

	Black		Canary		Yelloweye	
	Female	**Male**	**Female**	**Male**	**Female**	**Male**
Growth Parameters						
avg. asymptotic length (L_{inf})	52.62	51.26	59.82	52.31	63.93	66.49
growth coefficient (k)	0.171	0.259	0.131	0.170	0.049	0.048
age at length 0 (A_0)	-0.447	0.008	0.102	0.202	-5.924	-5.746
Weight-Length						
coefficient (a)	0.000017		0.0000155		.0000098	0.000017
exponent (b)	3		3.03		3.17	3.03
Maturity						
maturity logistic slope	-0.41		-0.25		-0.437	
length at 50% maturity (L_{mat})	39.5		40.5		38.8	
Fecundity						
eggs/kg slope	103,076		103,076		36,500	
intercept	289,406		289,406		137,900	
Natural Mortality (M)	males, females < age 10: 0.16 females age 16+: 0.24, linear ramp age 10 to 16		males, females < age 6: 0.06 females age 14+: 0.097, linear ramp age 6 to 14		0.047	0.047
Population Parameters						
virgin recruitment (R_0)	7,852		3,335		227	
unfished spawning biomass (SB_0)	9,278		25,574		3,619	
steepness (h)	0.6		0.511		0.417	
recruitment variation (sigma_r)	0.5		0.5		0.5	

Table 2.2 Management scenarios applied to each life history type.

Scenario	Selectivity	Harvest Control Rule
SQ	Logistic	40-10
D	Dome	40-10
FrL	Logistic	40-10 with Froese adjustment
FrD	Dome	40-10 with Froese adjustment

Table 2.3 Performance measures

Management	
SB	Spawning biomass in metric tons
SB/SB_0	Ratio of current SB to unfished SB
<MSST	Probability of SB dropping below the minimum stock size threshold (MSST), $0.25SB_0$
$0.10SB_{40}$	Probability of SB within 10% of the target SB, $0.40SB_0$
Yield	Biomass removed from the population through fishing
AAV	Absolute annual variation in catch, *Eq. X*
Age Structure	
MB/MB_0	Ratio of current mega-spawner biomass (MB) to unfished MB
MB/SB	Proportion of the SB in the mega-spawner age group

Table 2.4 Management performance measures for each life history type. Bold indicates the management scenario that best approximates the management target or goal.

		SB/SB_0	<MSST	$0.1SB_{40}$	SB (mt)	MB/MB_0	MB/SB	Yield	AAV
Black	SQ	0.43	0.09	**0.22**	4,980	0.30	0.38	**1440**	0.852
	D	**0.41**	0.13	**0.22**	4,700	0.29	0.40	1330	0.704
	FrL	0.48	**0.04**	**0.22**	**5,540**	**0.36**	0.41	1370	**0.493**
	FrD	0.46	0.05	0.21	5,280	0.35	**0.42**	1280	0.677
	unfished				*9,278*	*100*	*0.58*		
Canary	SQ	0.36	0.13	0.26	9,300	0.26	0.39	**1130**	0.580
	D	0.38	0.09	0.29	9,735	0.30	**0.44**	1010	1.063
	FrL	0.37	0.12	0.27	9,470	0.26	0.39	**1130**	0.558
	FrD	**0.40**	**0.06**	**0.30**	**10,107**	**0.32**	**0.44**	1006	**0.542**
	unfished				***25,574***		*0.58*		
Yellow eye	SQ	0.34	0.09	0.25	1,220	0.30	0.46	**60**	0.560
	D	0.35	0.04	0.30	1,280	0.35	**0.51**	50	0.560
	FrL	0.34	0.09	0.25	1,220	0.30	0.46	**60**	0.554
	FrD	**0.36**	**0.03**	**0.33**	**1,310**	**0.36**	**0.51**	50	**0.476**
	unfished				***3,619***		*0.60*		

FIGURES

Figure 2.1 Double normal selectivity curves for the Black rockfish (A), Canary rockfish (B), and Yelloweye rockfish (C) life history strategies.

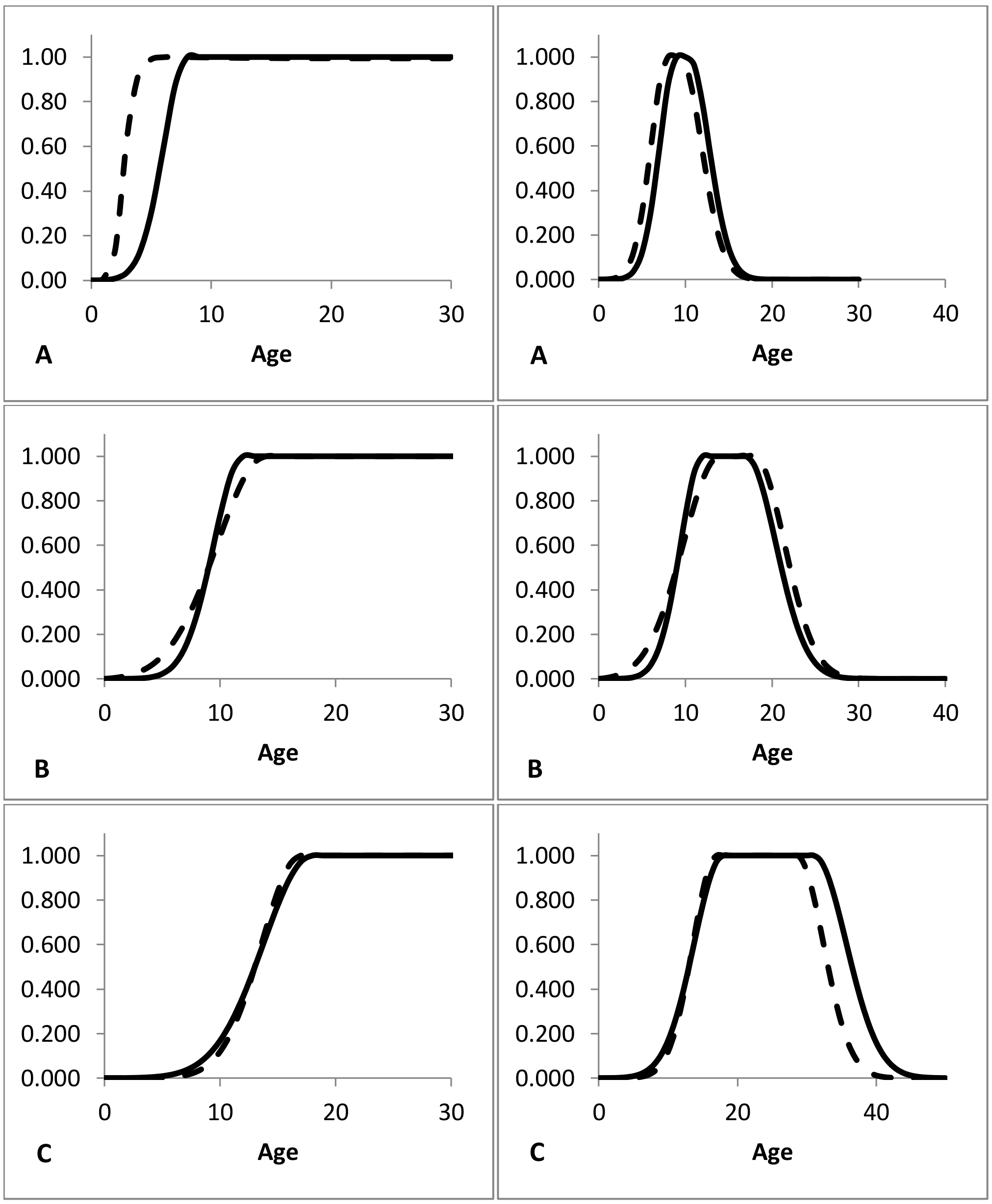


Figure 2.2 Performance of the Dome (D), Froese-logistic (FrL), and Froese-dome (FrD) management strategies relative to the status quo (SQ) for each rockfish life history type. Performance measures defined in Table 2.2

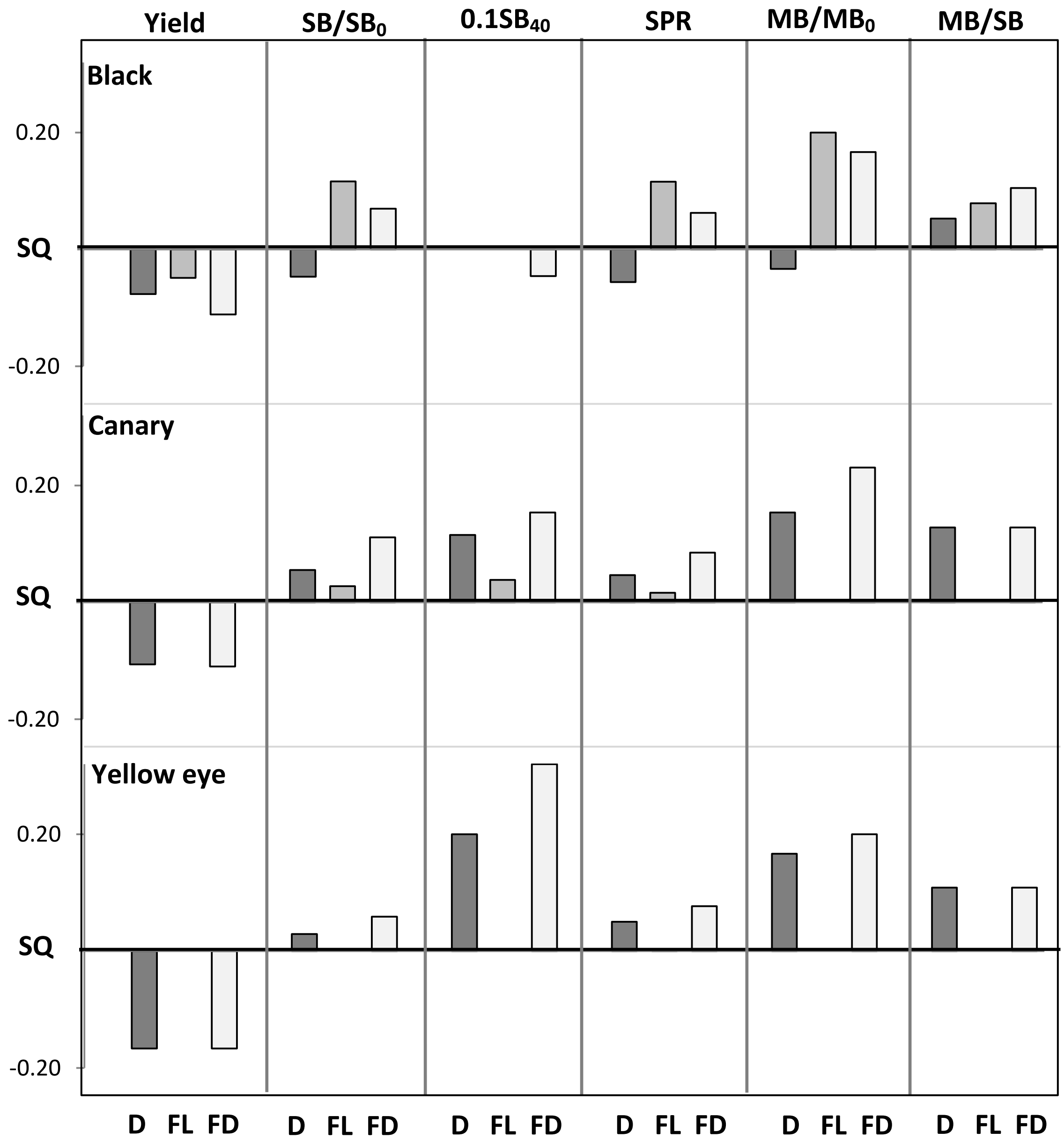
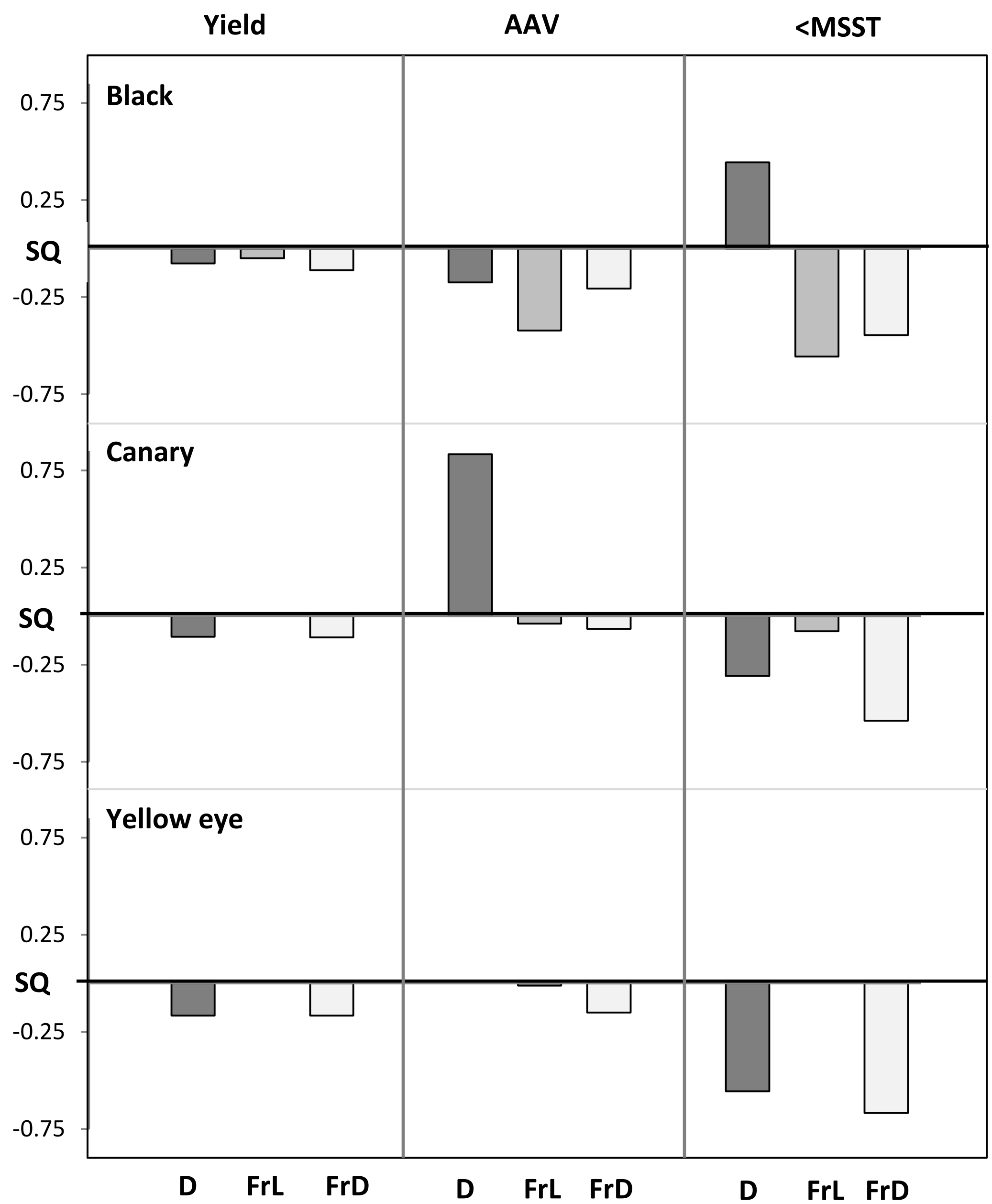


Figure 2.3 Performance of the Dome (D), Froese-logistic (FrL), and Froese-dome (FrD) management strategies relative to the status quo (SQ) for each rockfish life history.



CHAPTER 4 CONCLUSION

SEBASTES AND WHITE LAB RATS

Rockfish are featured in my research as the "model organism", which is to say that *Sebastes* are the "white lab rats" upon which my experiments were performed. A valid concern with any model organism is the applicability of the results to other organisms. In my work I focused particularly on black, canary, and yelloweye rockfish. My intent in the retrospective study of data-poor methods was to test the methods with "real" data, and utilized canary rockfish as my case study. I implicitly expect the reader to believe that the results of the retrospective study are applicable outside of the very specific time and circumstance of the canary rockfish historic and current data. The question then becomes, "What are the management implications of the retrospective analysis?" Are the results applicable outside of the canary rockfish stock of the 1980s? I argue, yes.

The fishery management plan for west coast groundfish includes 64 different species of rockfish. While the genus *Sebastes* covers a range of life histories, each individual species is not so unique in vital rates, distribution, and habitat that generalizations across an assemblage of rockfish species cannot be made. Love et al. (2002) identify "communities" of rockfishes by depth, two of which (shallow and deep shelf) contain 40% of the species. The trawl fishery has operated over the shelf and slope since the early 1900s, targeting the "*Sebastes* complex", a market category that includes mixed-rockfish species (Stewart, 2007). It was not until 1967 that management agencies began port sampling programs to monitor the species composition of the *Sebastes* complex. The indiscriminate nature of the trawl vessels targeting slope rockfish suggests that exploitation rates of rockfish co-occurring within the slope community are similar. Canary rockfish are often caught with yellowtail, yelloweye, bocaccio, and sharpchin rockfishes (Yoklavich, 2002). In addition to canary rockfish, yelloweye and bocaccio are designated "overfished" by the PFMC.

My final argument for the applicability of the retrospective analysis of canary rockfish is that it is the *nature* of the error in the canary data, not the particular values for input parameters or catch data, that may inform current management concerns. Canary and yellowtail rockfishes may not have the same natural mortality rate or age at maturity; but the bias in the estimate of these parameters may be similar. At the very least, the retrospective analysis indicates patterns in the performance of DB-SRA and DCAC consistent with the results of Wetzel and Punt (2011). Both studies show that median estimates of the harvest limit underestimate the true harvest limit when the distributions of FMSY/M and M are centered about the true values. Both studies found an increase in the median estimates of the DCAC harvest limit with a positively-biased FMSY/M parameter. Finally, both studies found the largest increase in the harvest limit estimates with mis-specified distributions for both the FMSY/M and M parameters.

What the retrospective analysis adds to our understanding of DCAC and DB-SRA is the effect on the harvest limits of error in the catch data together with error in the input parameters. Specifically, that increasing catch error can lead to more precautionary estimates of the harvest limit; however, when combined with parameter mis-specification, decreasing error in the catch does not necessarily lead to a closer approximation of the true harvest limit. This result suggests that biological data may be more influential than catch data on data-poor harvest limit estimates. Further simulation studies are needed to investigate this relationship, which will not only assist managers when interpreting the results of DCAC or DB-SRA, but also help prioritize research needs. The retrospective analysis showed that an increase in the quality of the catch data, without an accompanying increase in the quality of the biological data, can potentially decrease the accuracy of the harvest limit estimate. The catch reconstruction efforts that are currently underway in Oregon and Washington should be considered carefully when used in a DB-SRA analysis if the result of the reconstruction is a decrease in the average catch.

BIG OLD FAT FECUND FEMALES

Setting harvest limits for data-poor species became a national research priority with the 2006 reauthorization of the Magnuson-Stevens Act, and with the recognition that setting catch limits for all fisheries could keep more stocks from becoming overfished. The application of DB-SRA to fifty data-poor groundfish on the west coast identified a number of data-poor rockfish with current catch levels that could lead to an overfished state (Dick and MacCall, 2010). Identifying data-poor stocks in danger of overfishing, and those that are not, helps to prioritize data collection and assessment efforts. If a stock is in danger of overfishing, then more resources and effort can be devoted to data collection and assessment of that stock. More data will not necessarily improve the management of a stock, however, if the management strategy itself is flawed.

In his paper *Pacific Rockfish Management: Are we circling the wagons around the wrong paradigm?* (2006), Berkeley concluded that yield could be maximized with management strategies that considered both age structure and spawning biomass. The age structure management strategies that I evaluated did not maximize yield relative to the status quo management strategy, and the trade-off between yield and other performance measures was life-history specific. The results of my management strategy evaluation are not as straightforward as Berkeley's conclusion and highlight the challenge facing managers trying to meet the federal mandate of optimum yield and maximum sustainable yield.

The status quo management strategy provided the largest average annual yield, but did it also provide the "greatest overall benefit to the U.S."? The alternative management strategies reduced the absolute annual variation in catch (AAV) relative to the status quo in all instances except the dome-shaped strategy for canary rockfish. Less variability in the harvest limit from year to year helps the fleet better estimate future costs and revenues. The alternative management strategies also reduced the probability of a stock becoming overfished. An overfished stock can have serious economic consequences, particularly for mixed-stock fisheries like west coast rockfish. Canary rockfish are overfished, but a trawl vessel cannot completely avoid catching canary rockfish. When the low harvest limit of canary rockfish is met, the trawl fishery closes for the year, whether or not the catch quotas of the target stocks have been met. The harvest limit for canary was met one season when one truly unfortunate fishermen caught nearly the entire canary quota in one haul (B. Pettinger, personal communication). Managers must weigh maximum yield against other considerations, such as variability in the catch, to achieve the "greatest overall benefit".

Managers must also take into account the "prevailing ecological and environmental conditions" when estimating MSY. On the U.S. west coast, ocean productivity varies with shorter-term climate events such as the El Niño Southern Oscillation (ENSO), as well as the long-term cycle of the Pacific Decadal Oscillation (PDO). A long-lived rockfish will likely experience multiple ENSO and PDO events. It was within this variable environment that the life history strategies of rockfish evolved, including longevity. Management for spawning biomass alone, without regard for the population age structure of a long-lived fish, does not account for the evolutionary context of the species nor the environmental conditions that selected for such traits as longevity.

Longevity confers fitness in multiple ways. First, fecundity may increase not only because the female grows, but because the number of eggs/kg may increase with age. Second, the larvae of older females may have increased fitness over the larvae of younger females in controlled experimental settings (Berkeley et al., 2004; Trippel, 1998). Potential increased survival of the larvae of older females has also been documented in natural populations (Venturelli et al., 2010; Beldade et al., 2012). Older females of some species may spawn at different times or over longer periods of time than younger females (Bobko and Berkeley, 2004; Sogard et al., 2008), increasing the likelihood that their larvae encounter favorable environmental conditions. Finally, older females may be better able to withstand environmental variation and periods of low productivity. If the mortality rate of younger cohorts increases during periods of low productivity (due to lack of food, poor body condition, decreased ability to avoid predators), then older females may be, in a sense, spawning for two or three younger females that will not survive the unfavorable environmental conditions. The benefit to longevity and an age structure with a long right tail may in part come from the older cohorts' ability to dampen population fluctuations between favorable environmental conditions.

Managing for spawning biomass alone can underestimate the reproductive capacity lost to reduced abundance of the oldest age groups, which can lead to overestimates of MSY-based reference points (Murawski et al., 2001; Hsieh et al., 2010). Berkeley (2006) suggested that marine reserves are the best option for protecting old growth age structure. My work suggests that we can achieve management for explicit age structure objectives within the current management paradigm. The status quo (40-10 rule), does not necessarily need to be abandoned. If actions can be taken to create dome-shaped selectivity, then management can increase the abundance of the oldest age groups in long-lived rockfish. Also, while shorter-lived rockfishes, like the black rockfish, may not benefit from dome-shaped selectivity,; a simple adjustment to the status quo control rule based on the age composition of the catch one year previous resulted in an increase in the age structure performance measures. Hilborn (2010) suggested that "pretty good yield" is any yield within 80% of optimum yield. The yield from each of the alternative management strategies tested was within 80% of the "status quo" yield. Ultimately, it will be the monetary value of the lost yield weighed against the value of risk reduction (lower probability of becoming overfished, less variability in catch) that will determine if the age structure management strategies are "good enough" to replace the current management paradigm.

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