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A Review of Available Life History Data and Updated Estimates of Natural Mortality for Several Rockfish Species In Alaska

J. Y. Sullivan, C. A. Tribuzio, and K. B. Echave

August 2022

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National Oceanic and Atmospheric Administration
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ABSTRACT

Natural mortality (*M)* was estimated for 11 rockfish species of the genera *Sebastes* and *Sebastolobus* in the southeastern Bering Sea (BS), Aleutian Islands (AI), and the Gulf of Alaska (GOA) management areas, including dusky rockfish (*Sebastes variabilis*), harlequin rockfish (*Sebastes variegatus*), redbanded rockfish (*Sebastes babcocki*), redstripe rockfish (*Sebastes proriger*), rougheye rockfish (*Sebastes aleutianus*), blackspotted rockfish (*Sebastes melanostictus*), sharpchin rockfish (*Sebastes zacentrus*), shortraker rockfish (*Sebastes borealis*), silvergray rockfish (*Sebastes brevispinis*), yelloweye rockfish (*Sebastes ruberrimus*), and shortspine thornyhead (*Sebastolobus alascanus*). Four estimators of *M* based on life history characteristics were selected, including life span ($M_{t_{max}}$), somatic growth (M_{VBGF}), reproductive biology (M_{GSI}), and metabolism (M_{temp}). We found that $M_{t_{max}}$ and M_{GSI} yielded similar results that were often several times lower than M_{VBGF} and M_{temp} (e.g., GOA harlequin rockfish M_{GSI} = 0.049, $M_{t_{max}}$= 0.115, M_{temp} = 0.278, and M_{VBGF} = 0.359). Each species and area combination had unique considerations, therefore a universal approach is not recommended by this analysis. Instead, ranges of values are provided for each species and area, with discussions of species-specific considerations.

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INTRODUCTION

Harvest rates for rockfish species managed by the North Pacific Fishery Management Council (NPFMC) are based on various stock assessment procedures used to estimate spawning or total biomass-based biological reference points, which requires accurate estimates of life history parameters, such as growth rate, natural mortality (*M*), and age of maturity (Goodyear 1993, Quinn and Deriso 1999). Stock assessment methods and harvest control rules in Alaska are applied using a tier system that accommodates a continuum of data-rich to data-limited cases (NPFMC 2020). Tiers 1-3 are reserved for data-rich stocks and use statistical catch-at-age assessment models (Fournier and Archibald 1982), Tiers 4 and 5 use modeled estimates of fisheries-independent survey biomass (Hulson et al. 2021), and Tier 6 assessments rely on historical catch. In particular, the harvest controls rules for Tier 5 stocks in Alaska define fishing mortality rates for overfishing (F_{OFL}) and Acceptable Biological Catch (F_{ABC}) as a function of natural mortality, where $F_{OFL} = M$ and $F_{ABC} = 0.75 * M$. The reliance on *M* in the harvest control rule highlights the importance of this parameter for managing data-limited stocks in Alaska. However, *M* is also among the most difficult parameter to estimate, particularly for data-limited stocks without reliable age information (Maunder and Wong 2011, Vetter 1988, Zheng 2005).

Currently, there is limited information about the rates of *M* for several of the *Sebastes* and *Sebastolobus* species in Alaska. Many estimates of *M* are either based on life history characteristics of other rockfish species or from other regions of the United States West Coast (WC) and British Columbia (BC). These estimates have not been updated for some time. Additionally, there has been extensive work in recent years on improved methods for predicting natural mortality (e.g., Hamel 2015, Then et al. 2015, Cope and Hamel in review, Hamel and Cope in review). For these reasons, our objective is to reexamine and provide updated estimates of *M* for the following rockfish species in the Gulf of Alaska (GOA), southeastern Bering Sea (BS), or Aleutian Islands (AI; Table 1): dusky rockfish (*Sebastes variabilis*), harlequin rockfish (*Sebastes variegatus*), redbanded rockfish (*Sebastes babcocki*), redstripe rockfish (*Sebastes proriger*), rougheye rockfish (*Sebastes aleutianus*), blackspotted rockfish (*Sebastes melanostictus*), sharpchin rockfish (*Sebastes zacentrus*), shortraker rockfish (*Sebastes borealis*), silvergray rockfish (*Sebastes brevispinis*), yelloweye rockfish (*Sebastes ruberrimus*), and shortspine thornyhead (*Sebastolobus alascanus*). Updated estimates of *M* may allow for more accurate stock assessments for *Sebastes* and *Sebastolobus* species in Alaskan waters.

A literature review revealed an extensive number of approaches available for estimating *M;* however, only a subset were used in this analysis. Many methods were determined to be inappropriate for our rockfish species and are therefore not mentioned. Methods used in this study were selected based on recommendations in Then et al. (2015), Hamel and Cope (in review), and Cope and Hamel (in review), whether methods were developed using *Sebastes* or *Sebastolobus* species data, and if reliable and empirically-based input values from Alaska were available for our species.

METHODS

Natural mortality (*M*) was estimated by NPFMC management region using four different methods including maximum age (Hamel and Cope in review), growth parameters k and L_∞ (Then et al. 2015), gonadosomatic index (GSI, Gunderson 1997, Hamel 2015), and water temperature and dry weight (McCoy and Gillooly 2008, Hamel 2015). We provide a brief review of each of the methods used in this study. All of these empirical methods were developed using *Sebastes* or *Sebastolobus* species from Alaska in their meta-analyses. Direct methods of *M* estimation such as catch curve analysis were not considered here, due to the lack of consistent age sampling for the majority of the species reviewed in this paper. Additionally, most fish stocks in Alaska have received some fishing pressure; therefore, a catch curve analysis may result in total mortality (*Z*), not *M*.

Life history parameter estimates were obtained through a review of literature, recent stock assessments, and through personal communication with age and growth scientists at the Alaska Fisheries Science Center (AFSC) and the Alaska Department of Fish and Game (ADF&G). Additionally, independent maximum age estimates were obtained using all available age specimen data from the AFSC bottom trawl survey and fishery observer program databases (RACEBASE and NORPAC, respectively). Two maximum age estimates were obtained from combined survey and fishery age data, 1) the observed maximum age in the sample, and 2) the mean of the top five ages in the sample. Maximum observed age is a commonly used proxy for population-level maximum age or average life span (e.g. Then et al. 2015); however, if the observed maximum age is an outlier, this approach can result in estimates of life span that are biased high. The mean top five approach is intended to provide a sensitivity to the observed maximum age and is assumed to be robust to outliers. For the purposes of this analysis, we are also assuming that the observed maximum age, or the mean of the top five ages, is not an underestimate of maximum age.

Hamel and Cope (in review) reevaluated Then et al. (2015) and Hoenig's (1982, 1983) methodology for estimating M based on observed maximum age (t_{max}). Hamel and Cope (in review) re-estimated the regression coefficient assuming a logarithmic transformation of M and t_{max} to account for heteroscedasticity in the data. In natural space, the formula for the updated estimator is

$$M_{t_{max}} = \frac{5.4}{t_{max}}.$$

Then et al. (2015) reevaluated Pauly's (1980) M estimator which utilizes temperature and the estimated k and L_∞ parameters from each species' von Bertalanffy growth equation (VBGF). Estimated parameter k is the growth rate and L_∞ is the asymptotic fork length (cm) at which growth is zero (von Bertalanffy 1938). The resultant model omitted temperature because it did not improve model performance:

$$M_{VBGF} = 4.11k^{-0.27}0.73L_\infty{}^{-0.33}.$$

Gunderson (1997) developed an M estimator using the GSI (wet ovary weight/somatic weight, where the ovarian stage is just after vitellogenesis, but prior to hydration; Gunderson and Dygert 1988). This approach builds on the theory of the trade-offs between reproductive effort and adult growth or survival (Roff 1992; Stearns 1992). Similar to the $M_{t_{max}}$ estimator, Hamel (2015) re-estimated the regression coefficient assuming a logarithmic transformation of M and GSI to account for heteroscedasticity in the data. In natural space, the formula for the updated estimator is

$$M_{GSI} = 1.871 * GSI.$$

McCoy and Gillooly (2008) developed theoretical models based on the relationship of body size and temperature to the metabolic rate. This model predicts rates of M based on the body size in dry weight m (g) and water temperature T (ºC) dependence of individual metabolic rate (McCoy and Gillooly 2008). We use the parameterization of this method presented in Hamel (2015):

$$M_{temp} = 3.2\left[\frac{m}{4}\right]^{-0.27} e^{\left[-7540\left(\frac{1}{273+T}\right)-\left(\frac{1}{293.15}\right)\right]}.$$

All analyses were conducted using R version 4.1.2 (R Core Team 2021), and code is available at: https://github.com/JaneSullivan-NOAA/rockfishM.

SPECIES PROFILES AND RESULTS

Region-specific *M* estimates are presented along with background information in the following species profiles (Table 1). Data input values for the four *M* estimators were not available in all regions of Alaska for every rockfish species; age data were the most prevalent data type available for this study, and the majority of data for all species were from the GOA (Table 1). A summary of available AFSC age data sample sizes are provided in Table 2 and Figures 1-3, along with auxiliary biological data (e.g., year sampled, sex, length, and weight) associated with the five oldest AFSC specimens by species and region (Table 3).

DUSKY ROCKFISH

Background

Dusky rockfish are broadly distributed in the North Pacific Ocean, ranging from British Columbia to Hokkaido Island, Japan, and north to the BS (Fenske et al. 2020). They inhabit depths of 100 to 200 m along the outer continental shelf, with concentrations near gullies and on offshore banks (Reuter 1999; Fenske et al. 2020). Relative to other *Sebastes* species, dusky rockfish exhibit mid-range longevity (maximum observed age 67 and 75 years in the AI and GOA, respectively; Table 1) and early maturation (age at 50% maturity of female dusky rockfish in the GOA and range from 9.2 to 11.3 years; Chilton 2010, Fenske et al. 2018). Dusky rockfish are most abundant in the GOA, where they support a directed bottom trawl fishery and are often caught with Pacific ocean perch (*Sebastes alutus*; POP) and northern rockfish (*Sebastes polyspinis*). The most recent GOA dusky rockfish assessment (Tier 3, Fenske et al. 2020) assumes a fixed *M* of 0.07, which was based on Hoenig's (1983) maximum age estimator in Malecha et al. (2007). Prior to 2007, the GOA dusky rockfish assessment assumed an *M* of 0.09, which was considered to be high relative to other rockfish species with similar life histories (Lunsford et al. 2007).

Dusky rockfish in the AI and BS are far less abundant than in the GOA and consequently do not support a directed commercial fishery in this region. They are caught as bycatch in Atka mackerel (*Pleurogrammus monopterygius*) and POP trawl fisheries, especially in the eastern AI (Sullivan et al. 2021). They are assessed as a part of the Bering Sea and Aleutian Islands (BSAI) Other Rockfish (OROX) stock complex, which is separated into two species groups and uses a fishery-independent biomass-based approach for calculating ABCs (Tier 5, Sullivan et al. 2021). The species first group is made up exclusively of shortspine thornyhead (SST) rockfish, which account for approximately 95% of the total BSAI OROX exploitable biomass. The second, much smaller group is made up of all non-SST species, which include dusky and harlequin rockfish, along with at least ten other *Sebastes* and *Sebastolobus* species. The *M* for the non-SST component of BSAI OROX is assumed to be 0.09, based on historical values of *M* for GOA dusky rockfish (Lunsford et al. 2007).

Results

Dusky rockfish life history parameter inputs were available for three *M* estimators ($M_{t_{max}}$, M_{VBGF}, and M_{GSI}) in the GOA, but only maximum age data were available in the AI (Table 1). Estimates of *M* varied broadly across estimators, with the M_{GSI} estimator yielding the lowest (0.029), and M_{VBGF} yielding the highest (0.327). Like many *Sebastes* species, dusky rockfish tend to approach their asymptotic size at a young age relative to their maximum ages. As such, the M/k ratio has been shown to be low for *Sebastes* species (e.g., Thorson et al. 2017), and therefore we consider the M_{VBGF} estimate outside the range of reasonable values. The $M_{t_{max}}$ estimator ranged from 0.072 in the GOA to 0.085 in the AI (Table 1), though these differences may be the result of limited sampling in the AI (Table 2). The $M_{t_{max}}$ estimates are most similar to the values used in recent stock assessments (0.09 and 0.07 in the BSAI and GOA, respectively; Sullivan et al. 2020, Fenske et al. 2020).

HARLEQUIN ROCKFISH

Background

Harlequin rockfish are distributed from the southeastern BS and AI to Oregon, U.S.A., but they are most commonly found in the central and western GOA and AI (Love et al. 2002). Harlequin rockfish exhibit mid-range longevity relative to other *Sebastes*, mature at an early age compared to other *Sebastes* (female 50% maturity-at-age and length = 4.7 years and 18.7 cm; TenBrink and Helser 2021). The maximum known age of harlequin rockfish is 47 years in the GOA and 79 years in the AI (Table 1; Todd TenBrink, AFSC, pers. comm.). The break and burn method was used to assess the age of harlequin rockfish for a validation study and the results suggested that ages for older fish may be biased low by 3-4 years (Kastelle et al. 2020).

There is no directed fishing for harlequin rockfish in Alaska, though they often occur as bycatch in trawl fisheries. Harlequin rockfish are managed as components of two separate OROX stock complexes, one in the GOA and one in the BSAI. This species is the most commonly caught OROX species in the GOA; however, due to its high affinity for untrawlable habitats, it is poorly sampled by surveys (Jones et al. 2012). The OROX complexes are managed as Tier 5 complexes, using a biomass-based approach using data from trawl surveys (Sullivan et al. 2020, Tribuzio et al. 2021). The GOA assessment currently assumes an M = 0.092 reported in Malecha et al. (2007), which was based on a combination of approaches using growth parameters and maximum age (Alverson and Carney 1975, Hoenig 1983). The BSAI assessment currently assumes M = 0.09 based on a historically used value for dusky rockfish.

Results

Harlequin rockfish life history parameter inputs were available for all four M estimators ($M_{t_{max}}$, M_{VBGF}, M_{temp}, and M_{GSI} estimators) in the GOA, but only maximum age data were available in the AI (Table 1). Estimates of M varied broadly across estimators, with the M_{GSI} estimator yielding the lowest M (0.049), and M_{VBGF} yielding the highest (0.359). The $M_{t_{max}}$ estimator ranged from 0.068 in the AI to 0.131 in the GOA (Table 1), though the large difference in observed t_{max} between the GOA (47 years) and the AI (79 years) suggests these differences may be the result of sampling or exploitation history (Table 2, Fig. 1). We did not account for the potential ageing bias in this analysis; however, shifting the maximum age by 4 years would not substantially change the resultant M estimates (e.g., if the AI max age is increased to 83 years, M = 0.065, down from 0.068).

REDBANDED ROCKFISH

Background

Redbanded rockfish are distributed from the BS to southern California, in offshore reefs and seamounts at depths of 150 to 400 m (Love et al. 2002; Mecklenberg et al. 2002). They are considered a slow-growing, long-lived species with a reported maximum age of 106 years (Munk 2001) and age at maturity of 19 years (Mangel et al. 2006). The maximum size is about 64 cm. There is little biological research on this species.

There is no directed fishing for redbanded rockfish in Alaska, though they often occur as bycatch in trawl fisheries. Redbanded in the GOA are managed as part of the GOA OROX stock complex (Tribuzio et al. 2021). Due to limited biological data, redbanded rockfish are assessed using a biomass-based approach for calculating ABCs, incorporating fishery independent data from trawl surveys. Redbanded rockfish catch limits are set under Tier 5 ABC/OFL control rules. The current value of *M* used for redbanded rockfish in the GOA OROX assessment is 0.06 (Echeverria 1987; O'Connell 1987; Munk 2001; Love et al. 2002). This value was estimated using data from other regions.

Results

Reliable life history information was only available to estimate *M* using $M_{t_{max}}$, M_{VBGF} , and M_{temp} estimators. Updated estimates of *M* ranged between $M_{t_{max}}$ = 0.051 and M_{temp} = 0.155 (Table 1). Both $M_{t_{max}}$ and M_{temp} estimators utilized data from the GOA. The M_{VBGF} estimate (*M* = 0.123) used data from BC.

REDSTRIPE ROCKFISH

Background

Redstripe rockfish range from the southeastern Bering Sea to southern Baja California. They are most commonly found in schools over high-relief, rocky bottoms at depths between depths of 55 and 300 m (Love et al. 2002; Mecklenburg et al. 2002). The maximum age reported for redstripe rockfish comes from BC, where age at 50% maturity is reported to be 8 years (Archibald et al. 1981; Chilton and Beamish 1982; Munk 2001; Love et al. 2002). The maximum size is about 61 cm. There is little biological research on this species.

There is no directed fishing for redstripe rockfish in Alaska, though they often occur as bycatch in trawl fisheries. Redstripe in the GOA are managed as part of the OROX stock complex (Tribuzio et al. 2021). Due to limited biological data, redstripe rockfish are assessed using a biomass-based approach for calculating ABCs, incorporating fishery independent data from trawl surveys. Redstripe rockfish catch limits are set under Tier 5 ABC/OFL control rules. The current assessment uses an *M* of 0.1 as computed from a catch curve analysis, under the assumption that this stock is lightly exploited and therefore Z=M (Archibald et al. 1981). This is the highest mortality rate of all rockfish species within the GOA OROX stock complex (Tribuzio et al. 2021).

Results

Only maximum age data were available to estimate M ($M_{t_{max}}$), using two values of t_{max} from two regions (BC and GOA), as well as the mean of the top five ages from AFSC survey data. Updated M estimates ranged from 0.098 (BC, t_{max}= 55 years) to 0.138 (AFSC survey mean top 5, t_{max}= 39 years; Table 1). Ageing methods for redstripe rockfish have been validated, and they were close to accurate with a small probability of under-ageing (Kastelle et al. 2020). Therefore, the maximum age estimates may be slightly underestimated for this species.

ROUGHEYE AND BLACKSPOTTED ROCKFISH

Background

Rougheye and blackspotted (RE/BS) rockfish have broad distributions in the North Pacific Ocean, ranging from Point Conception, California, to Hokkaido Island, Japan, and north to the BS (Kramer and O'Connell 1988). They inhabit a narrow depth range (300-500 m) in the outer continental shelf and upper continental slope in the eastern North Pacific Ocean and are commonly caught as bycatch in bottom trawls and hook-and-line gear concurrently with shortraker rockfish. Due to the cryptic nature of these species (i.e., species that are morphologically similar such that they were historically considered a single species) and their sympatric distributions, the classification of RE/BS rockfish as separate species was not formalized until relatively recently (Orr and Hawkins 2008). Consequently, RE/BS rockfish are managed as a complex and have separate stock assessments in the GOA and BSAI (Spencer et al. 2020, Sullivan et al. 2021).

Rougheye and blackspotted rockfish demonstrate slow growth and late maturation, and they are among the longest lived vertebrates in the world. The maximum age reported by the AFSC is a 132 years (Table 1). Munk (2001) reported a maximum age of 205 years in the GOA, though this maximum age is often considered an outlier by contemporary ageing experts (Todd TenBrink, AFSC, pers. comm.). The most recent GOA RE/BS stock assessment (Tier 3, Sullivan et al. 2021) estimated M as a parameter (M=0.034) in a statistical catch-at-age model using an informed prior mean of 0.03 and coefficient of variation (CV) of 0.10 based on study using GSI data collected in the

BS, AI, GOA, BC, and WC that followed M_{GSI} methods described in Gunderson and Dygert (1988). The M prior for this complex has not been updated for the GOA stock assessment since it was separated from shortraker and other slope rockfish in 2004 (Shotwell et al. 2005). The most recent BSAI RE/BS stock assessment (Tier 3, Spencer et al. 2020) estimated M as a parameter in a statistical catch-at-age model using a prior mean of 0.045 and CV of 0.05. This value was updated in 2020 from a previously used prior mean of 0.03 and CV of 0.05 using the $M_{t_{max}}$ estimator recommended in Then et al. (2015).

The McDermott (1994) GSI study, which was conducted prior to the formalization of RE/BS as separate species, found M to range between 0.030 and 0.039 depending on if Stage V (late vitellogenesis) and Stage VI (containing at least some oocytes in the migratory nucleus stage) ovaries were used to determine GSI versus strictly Stage VI ovaries. McDermott (1994) recommended GSI estimates determined using Stage VI samples but cautioned this approach could result in an overestimation of GSI and thus M if oocytes hydrate in the migratory nucleus stage before the coalescence of yolk. The GSI data from this study were revisited here using updated M_{GSI} methods (Gunderson 1997, Hamel 2015).

Recent studies have shown differences in growth (Shotwell et al. 2019) and maturity (Conrath 2017) between RE/BS using a combination of genetic and field identification methods. These results have renewed interest in understanding and accounting for biological differences between the two species in stock assessment. In an effort to make our results readily applicable to current and future stock assessments, we present RE/BS M data inputs and M results by species when available and also combined. Data used to obtain species-specific results were not used in subsequent analyses for RE/BS combined.

Results

For RE/BS rockfish identified to species, reliable life history information was only available to estimate M using the $M_{t_{max}}$and M_{VBGF} estimators (Table 1). AFSC trawl surveys began identifying RE/BS to species using field identification in 2006 in the AI, 2007 in the GOA, and 2008 in the BS, and they have never been identified separately in the fishery (Table 2, Fig. 3). Therefore, species-specific $M_{t_{max}}$ are limited by short time series of data collection. The $M_{t_{max}}$ estimates from the AI, BS, and GOA were comparable between the two species, with BS rockfish ranging from 0.040 to 0.074, and RE rockfish ranging from 0.040 to 0.056 (Table 1). The upper range of $M_{t_{max}}$ for both species came from maximum ages reported in the BS from the EBS slope survey, and these results are limited by low sample sizes (Table 2, Fig. 3).

Species-specific estimates of M_{VBGF}, which were exclusive to the GOA, resulted in M values that were approximately three to four times higher than estimates of $M_{t_{max}}$ for BS (M_{VBGF} = 0.152) and RE (M_{VBGF} = 0.219), respectively (Table 1). Blackspotted rockfish, which are estimated to grow more slowly than RE, have a lower M_{VGBF} than RE (Shotwell et al. 2019). However, like many *Sebastes* species, both RE and BS tend to approach their asymptotic size at a young age relative to their maximum ages.

For RE/BS combined (i.e., using samples that were not identified to species), data were available for all four estimators considered in this study (Table 1). The $M_{t_{max}}$ ranged from 0.026 to 0.045 across all regions. The $M_{t_{max}}$ The M_{GSI} estimates, which were based on data collected from the WC, BC, GOA, AI, and BS, ranged between 0.023 and 0.032. These values are substantially lower than the M_{GSI} estimates reported in McDermott (1994) despite using the same GSI inputs. This was an expected outcome based on updates to M_{GSI} methodology over time (Gunderson and Dygert 1988, Gunderson 1997, Hamel 2015). The range of M_{GSI} estimates reflects uncertainty in ovarian development, and specifically, uncertainty in which stages of development are most appropriate to use when calculating GSI for this species (McDermott 1994). Results from the $M_{t_{max}}$ and M_{GSI} estimators are very similar to the prior mean values used in current stock assessments, 0.045 and 0.03 in the AI and GOA, respectively (Spencer et al. 2020, Sullivan et al. 2021). This result was expected given our study used similar but updated data sets and methodology. However, the difference between $M_{t_{max}}$ and M_{GSI} estimates is notable and warrants further investigation. Maximum ages of 235 and 168 years would be required to yield an M equal to the range of M_{GSI} values reported in this study (0.023 and 0.032, respectively; Table 1). Given that these theoretical maximum ages are 103 and 36 years greater than the maximum ages recorded at the AFSC, it is unlikely these values are representative of the population. Consistent with species-specific results, the M_{VBGF} estimates for RE/BS combined were the highest of the four estimators and should at best be considered an upper limit (0.144 and 0.195 in the AI and GOA, respectively). The M_{temp} estimate for RE/BS of 0.092 in the GOA was closest to the M_{VBGF} estimates.

SHARPCHIN ROCKFISH

Background

Sharpchin rockfish are distributed from the eastern AI across the GOA and south to southern California. This species is generally found over hard bottoms down to 350 m, and often associated with sponge or crinoids (Echave et al. 2015 [Appendix 16B in Tribuzio and Echave 2015]). Within the GOA the biomass is predominantly within the eastern GOA. Maximum age for the species has been reported to be 58 years on the WC (Cope et al. 2015), and similarly reported in the GOA, however the GOA reports are considered unreliable. Age at 50% maturity is 10 y in the Cook Inlet (Bechtol 1998), and 6 years on the WC (Cope et al. 2015). They reach a maximum length of about 40 cm (Orr et al. 1998) and they mature at a relatively large size compared to the maximum size, 26.5 cm (Bechtol 1998).

This species is one of the primary species of the GOA OROX stock complex and there are no directed fisheries for sharpchin rockfish. Sharpchin rockfish are generally caught as bycatch in trawl fisheries. Sharpchin are the only OROX species that is considered a Tier 4 species, and as such, M is a component of the estimation of F_{OFL} and F_{ABC}. The current GOA assessment uses M = 0.06 (Malecha et al. 2007) and the WC uses M = 0.08 (Cope et al. 2015).

Results

Sharpchin rockfish life history parameter inputs were available for three of the four M estimators ($M_{t_{max}}$, M_{VBGF}, and M_{temp} estimators) in the GOA. For comparison, life history parameters from BC for M_{VBGF} and the WC for $M_{t_{max}}$ and M_{VBGF} were also available. Resultant M values ranged from 0.093 to 0.355. The maximum age estimates may be limited by samples in the GOA, the most recent of which were collected in 1996 (n = 648, Table 2). Maximum age estimates from the WC may be more reflective of the maximum age of the species; however, it is unclear if that would be representative of the portion of the population within the GOA. Size ranges are similar, so for the purposes of this analysis, assuming a maximum age of 58 for the GOA is reasonable.

SHORTRAKER ROCKFISH

Background

Shortraker rockfish are distributed from Japan around the Pacific Rim to Southern California, including the BSAI and the GOA. In Alaska, adults are especially concentrated along the continental slope in the 300-500 m depth interval (Ito 1999). Shortraker rockfish attain the largest size of all *Sebastes*, with a maximum reported length of 120 cm, and have long been considered among the most difficult rockfish species to age. Shortraker rockfish have been aged using a thin sectioning technique, as opposed to the standard break and burn method (Hutchinson 2004). A comparison between Hutchinson's (2004) results and those of a previous radiometric study of shortraker rockfish age (Kastelle et al. 2000) indicated general agreement and provided a limited degree of validation (Hutchinson 2004). To provide direct validation of Hutchinson's aging method, a validation study was conducted in 2008 based on ^{14}C levels in shortraker rockfish otoliths from nuclear bomb testing in the 1960s. Results were unsuccessful, however, because ^{14}C could not be found in sufficient quantities in the otoliths (Charles Hutchinson, AFSC, Jan. 2009, pers. comm.; Kastelle et al. 2020). The most recent ageing work conducted by the ADF&G Age Determination Unit, using bomb-derived carbon ageing methods, reported a maximum age of 160 years (Kevin McNeel. ADF&G, Jan. 2022, pers. comm.; https://mtalab.adfg.alaska.gov/ADU/analysis.aspx#maxage).

There is no directed fishing for shortraker rockfish in Alaska, though they are common bycatch in trawl and longline fisheries. Due to limited biological data, the shortraker assessment in the GOA uses a biomass-based approach for calculating ABCs, incorporating fishery independent data from trawl and longline surveys, and in the BS data from the trawl survey (Echave et al. 2021, Shotwell et al. 2020). Shortraker rockfish catch limits are set under Tier 5 ABC/OFL control rules. Both the current GOA and BSAI shortraker rockfish stock assessments uses a proxy estimate of M where the ratio of maximum age of rougheye to shortraker (140/120) from BC is multiplied by the mid-point of the range of Z for rougheye rockfish in BC (mid-point = 0.025) to yield an M = 0.03 for shortraker rockfish (Echave et al. 2021, Shotwell et al. 2020).

In a study using samples from the WC, BC, GOA, and AI, McDermott (1994) applied the Gunderson and Dygert (1988) version of the M_{GSI} estimator and found M to range between 0.027 and 0.042 depending on the stage of ovarian development used to determine GSI. This range encompasses variability in GSI on the lower bound when using both Stage V (late vitellogenesis) and Stage VI (containing at least some oocytes in the migratory nucleus stage) ovaries and on the upper bound when using only Stage VI ovaries. McDermott (1994) recommended the use of GSI determined using Stage VI samples; however, she cautioned that this could result in an overestimation of GSI and thus *M* if oocytes hydrate in the migratory nucleus stage before the coalescence of yolk. The GSI data were revisited in this study using updated M_{GSI} methods (Gunderson 1997, Hamel 2015).

Results

Life history information was available for all four estimators considered in this study (Table 1). Input parameters for the M_{temp} estimator were only available for shortraker rockfish in the GOA and was the highest of the four estimators (*M* = 0.093). The M_{VBGF} estimator, which used parameters from combined regions (AI/BS/GOA), was *M* = 0.073 (Table 1). Estimates of $M_{t_{max}}$ range from 0.034 to 0.042 in the GOA, with slightly higher estimates in the AI (0.044 to 0.049; Table 1). These values are higher than current stock assessments in both the GOA and BSAI, which suggests these assessments may benefit from reevaluating *M.* However, while ageing methodology of shortraker rockfish is not validated, it is possible that ages are underestimated rather than over-estimated (Kastelle et al. 2020), and therefore the resultant *M* values may be higher than true *M*. Use of $M_{t_{max}}$ estimates will require further consideration of the t_{max} input value, such as weighted mean of observed t_{max}.

The M_{GSI} estimates, which were based on data collected from the WC, BC, GOA, and AI, ranged between 0.019 and 0.036. These values are substantially lower than the M_{GSI} estimates reported in McDermott (1994) despite using the same GSI inputs. This was an expected outcome based on updates to M_{GSI} methodology over time (Gunderson and Dygert 1988, Gunderson 1997, Hamel 2015). The range of M_{GSI} estimates reflects uncertainty in ovarian development, and specifically, uncertainty in which stages of ovarian development are most appropriate to use when calculating GSI for this species (McDermott 1994).

SILVERGRAY ROCKFISH

Background

Silvergray rockfish are distributed throughout the GOA and south to Baja California. Within Alaska, this species is most abundant in the eastern GOA. This species tends to inhabit the outer continental shelf between 100 and 300 m, generally associated with hard bottoms (Stanley and Kronlund 2005). Silvergray rockfish are somewhat long-lived, with a maximum age of 82 reported in BC (https://mtalab.adfg.alaska.gov/ADU/analysis.aspx#maxage) and 75 in the GOA (Malecha et al. 2007), but mature at a relatively early age of 10 years in BC (Stanley and Kronlund 2005). They are moderately sized, reaching a maximum length of about 70 cm (Orr et al. 1998).

Silvergray rockfish are one of the primary component species of the GOA OROX stock complex but there are no directed fisheries for silvergray rockfish. They are generally caught as bycatch in trawl fisheries, and to a lesser extent longline fisheries. Silvergray rockfish are a Tier 5 species, and the current GOA assessment uses M = 0.05 (Malecha et al. 2007).

Results

Reliable life history information was only available to estimate M using $M_{t_{max}}$, and M_{temp} estimators. Malecha et al. (2007) estimated VBGF growth parameters, but the models would not converge unless t_0 was fixed, therefore it was deemed unreliable for inputs in this analysis. Updated M estimates ranged from 0.067 to 0.180. This species is not often aged, and all of the GOA t_{max} values are from trawl survey samples, the most recent being 2005 (Tables 2 and 3). The AFSC is beginning to examine this species and updated t_{max} values may be available in the next few years.

YELLOWEYE ROCKFISH

Background

Yelloweye rockfish are distributed from Baja California through Dutch Harbor, Alaska, tending to inhabit nearshore rocky reef habitats (Love et al. 2002, Echave et al. 2015 [Appendix 16B in Tribuzio and Echave 2015], Wood et al. 2021). This species is one of the longer-lived of the

Sebastes in Alaskan waters, with estimates of maximum age 114 in Cook Inlet (Bechtol 1998) to 122 in Southeast Alaska (https://mtalab.adfg.alaska.gov/ADU/analysis.aspx#maxage). Age at 50% maturity estimates range from 15 in the northern GOA (Arthur 2020) to 23 in Cook Inlet (Bechtol 1998). Growth model estimates were not readily available for this species, however, the ageing method has been validated and otoliths from this species have been used to establish reference curves from which to validate other species ageing methods (Kerr et al. 2004).

Yelloweye rockfish are targeted in some GOA longline fisheries, both in federal and State of Alaska waters (Tribuzio et al. 2021, Wood et al. 2021). The species is managed as part of the OROX in NMFS statistical areas 610-640, as part of the Demersal Shelf Rockfish Stock Complex (DSR) in NMFS statistical areas 650 and under the ADF&G fisheries management in both Southeast Alaska and Prince William Sound. In the OROX assessment, yelloweye rockfish are currently considered Tier 6 (catch-based); however, the species is likely a candidate for Tier 4 or Tier 5 in the future, where M is a critical parameter. The DSR assessment uses an ROV survey and is considered Tier 4, with M = 0.02 for the species (O'Connell and Brylinsky 2003, assuming total mortality, Z, as a proxy for M in areas with little directed fishing). For comparison, this value of M, if used for management, would be the lowest of any of the 27 species in the OROX complex. The WC assessment uses M = 0.0439 (Gertseva and Cope 2017) and the BC assessment uses either M = 0.02 or 0.04 (DFO 2015).

Results

Yelloweye rockfish life history parameter inputs were available for three of the M estimators ($M_{t_{max}}$, M_{temp}, and M_{GSI} estimators) in the GOA, as well as a maximum age from BC (Table 1). The estimated M from both the M_{GSI} and $M_{t_{max}}$ methods were similar, ranging from M = 0.044 to 0.052, with no regional difference. Both methods are well-informed with either recent, regional research, or validated ageing results (Arthur 2020, Kerr et al. 2004).

SHORTSPINE THORNYHEAD

Background

Shortspine thornyhead rockfish are distributed along the Pacific Rim from the Seas of Okhotsk and Japan in the western north Pacific, throughout the BSAI, GOA, and south to Baja California in the eastern north Pacific (Love et al. 2005). They inhabit continental slope habitat and are frequently caught in depths ranging between 300 and 700 m (Echave et al. 2020). While thornyhead species in the *Sebastolobus* genus are considered rockfish, they are distinguished from the "true" rockfish in the genus *Sebastes* primarily by reproductive biology; all *Sebastes* rockfish are live-bearing (ovoviviparous) fish, while thornyheads are oviparous, releasing fertilized eggs in floating gelatinous masses. Thornyheads are also differentiated from *Sebastes* rockfish species in that they lack a swim bladder (Eschmeyer et al. 1983, Love et al. 2002). Precise information on age, growth, and *M* remains elusive for SST in Alaska, but various ageing studies over time have all indicated that SST are long-lived (Echave et al. 2020). A recent age validation study using ^{14}C bomb radiocarbon was inconclusive for SST (Kastelle et al. 2020). However, best available data suggests that life span may be as long as 100 years in SST (Butler et al. 1995), with female age at 50% maturity around 13 years (Todd TenBrink, AFSC, pers. comm.).

There is no directed fishing for SST in Alaska, though they are common bycatch in longline and trawl fisheries. In the GOA, SST are part of the thornyhead stock complex (Echave et al. 2020). Due to limited biological data, the thornyhead assessment uses a biomass-based approach for calculating ABCs, incorporating fishery independent data from trawl and longline surveys. Thornyhead rockfish catch limits are set under Tier 5 ABC/OFL control rules. The current GOA thornyhead stock assessment uses a proxy estimate of *M*, assumed to be 0.03, the average over a range of published values for this species (Echave et al. 2020). In the BSAI, SST are the dominant species in the Tier 5 BSAI OROX stock complex, followed by dusky, harlequin, and at least 10 other species of *Sebastes* and *Sebastolobus* (Sullivan et al. 2020). The *M* value used in the BSAI assessment is the same as that of the GOA assessment (Echave et al. 2020, Sullivan et al. 2020).

Results

Reliable life history information was available to estimate *M* using the $M_{t_{max}}$, M_{GSI}, and M_{temp} estimators, and only GSI information was available specifically from each region (AI, BS, and GOA). The M_{GSI} estimates from the three regions were comparable, ranging from 0.013 in the GOA to 0.017 in the AI and BS (Table 1), and all were lower than the currently assumed *M* = 0.03. The order of magnitude difference in the *GSI* input values in comparison to other rockfish species is surprising (Table 1). This could be from the differences in reproductive mode and how SST ovaries develop. For most rockfish, late vitellogenesis occurs prior to hydration. For SST, late vitellogenesis is followed by a gelatinous material stage (Pearson and Gunderson 2003). Considering the originator of the M_{GSI} method (Gunderson 1998) also conducted the research providing the SST input data (Pearson and Gunderson 2003), the M_{GSI} method results presented in this report are well supported.

Input parameters for the M_{temp} estimator were only available for SST in the GOA. The estimate of M_{temp} was the highest of the three estimators (M = 0.112; Table 1) and much higher than the current M of 0.03.

Estimates of $M_{t_{max}}$ range from 0.036 to 0.108 (Table 1). This broad range of estimates mimics the broad range of input values (50 – 150 years; Table 1). $M_{t_{max}}$ estimates in the GOA range from 0.041 to 0.087, from 0.054 to 0.108 for combined regions (GOA/WC), and from 0.036 to 0.054 in the WC (Table 1). We include the estimates from the WC region because different ageing techniques were used to estimate t_{max} (Jacobson 1990, Kline 1996). In the GOA region, the most recent ageing work of SST estimated a t_{max} of 133 years (Kevin McNeel, ADF&G, pers. comm.), resulting in a $M_{t_{max}}$ of 0.041 (Table 1). While ageing methodology of SST is not validated, it is more likely that ages are underestimated than over estimated (Kastelle et al. 2020), and therefore the resultant M values may be higher than true M. Use of $M_{t_{max}}$ estimators will require further consideration of the t_{max} input value.

CONCLUSIONS

Natural mortality is central to our understanding of fisheries population dynamics and is influential to the estimation of population productivity (Brodziak et al. 2011, Punt et al. 2022). It follows that incorrect specification of M in stock assessment can lead to biased estimates of stock size, stock status, and relevant management reference points, including the fishing mortality resulting in maximum sustainable yield (F_{MSY}; Punt et al. 2022). In this study, we provide updated M estimates for 11 commercially important rockfish species in Alaska using four natural mortality estimators based on life history characteristics, including life span ($M_{t_{max}}$), somatic growth (M_{VBGF}), reproductive biology (M_{GSI}), and metabolism (M_{temp}). In most cases, results from updated M estimates are similar to values assumed in current stock assessments and determined from other recent studies (e.g., Malecha et al. 2007).

For species where data were available for all four estimators (e.g., harlequin, rougheye, and blackspotted rockfish), M_{GSI} estimates were most similar to $M_{t_{max}}$, whereas M_{temp} was most similar to M_{VBGF}. These diverging patterns in M estimates can lead to very different stock assessment results and conclusions; therefore, individual stock assessment authors must decide to select a single *M*, take an average or weighted mean of multiple *M* estimates, or use a range of *M* estimates to develop a prior *M* for running sensitivity analyses or as an approach to incorporating uncertainty directly into stock assessments and management advice (Hamel 2015, Cope and Hamel in review).

The M_{VBGF} and M_{temp} estimators consistently resulted in *M* values that were several times higher than $M_{t_{max}}$ and M_{GSI} (Table 1). In the case of M_{VBGF}, this result can be attributed to the fact that rockfish often grow rapidly and can attain maximum sizes at relatively young ages despite their tendency towards extreme longevity. This growth pattern violates the M/k ratio underpinning the M_{VBGF} method, and consequently this estimator has been demonstrated to not fit *Sebastes* (and likely *Sebastolobus*) species well (Thorson et al. 2017). Estimates of *M* from this method should therefore be considered limits, not point estimates. In the case of M_{temp}, the high estimates of *M* derived using this method were harder to explain. The M_{temp} estimator was developed using data from a broad range of plant and animal taxa, including many Alaskan *Sebastes* and *Sebastolobus* species. This method relies on the theory that mortality rates should follow the same functional relationship as observed between individual metabolic rates, body size, and temperature (McCoy and Gillooly 2008). While this appears to hold true for most plant and animal taxa, including fish, a more detailed look at the rockfish used in McCoy and Gillooly (2008) reveal that their method consistently overestimated *M* for these species. While this discrepancy is not addressed explicitly in their paper, the authors highlight variation in *M* that cannot be explained by body size and temperature alone. They articulate that taxa-specific anomalies, as observed here in Alaskan rockfish species, may be indicative of trade-offs in life history strategies for maximizing fitness. For example, mortality may be overestimated by M_{temp} if the species has evolved to invest disproportionately more energy in the reduction of cell damage and mitigation of free radical production. In the case of scorpaenids, longevity has been shown to increase exponentially with maximum depth of occurrence, which may be related to physiological adaptations to extreme environments characterized by high pressure and low temperature, light, and dissolved oxygen (Cailliet et al. 2001). Although the underlying process or mechanism for the overestimation of M for Alaskan rockfish is unknown, these findings suggest that estimates from M_{temp} should be considered upper limits at best, and not point estimates.

Then et al. (2015) found that the $M_{t_{max}}$ estimator exhibited superior predictive performance relative to both growth-based estimators like M_{VBGF} and combined approaches like averaging multiple M estimates. However, estimators like $M_{t_{max}}$ depend on reliable estimates of maximum age, which require unbiased sampling of the population and may be influenced by a variety of factors, including ageing error or bias and exploitation history (Brodziak et al. 2011, Then et al. 2015). Ageing error and bias is of particular concern for many of the rockfish presented in this study, including harlequin depending on which ageing methodology is used (Kastelle et al. 2020), shortraker (Kastelle et al. 2000, Kastelle et al. 2020), and shortspine thornyhead rockfish (Kastelle et al. 2020). Additionally, most rockfish occupy rocky, high-relief habitats, and therefore may not be well-sampled by survey bottom trawls (Zimmerman 2003). One recent study in the GOA using combined acoustics and stereo-camera tools found relative densities of dusky and harlequin rockfish were approximately three times higher in untrawlable versus trawlable areas (Jones et al. 2021). Whether or not differences in densities between habitat types translate to differences in the age- or size-specific availability, and thus the samples available for ageing, is likely species and area-specific (Rooper et al. 2012).

In our study we compared $M_{t_{max}}$ estimates using the observed maximum age and the mean of the top five ages available (Tables 1-3). The latter approach is assumed to be more robust to outliers, and in cases when the observed t_{max} values are close to one another suggests that the age sample is representative of the true maximum of the population (Table 2). In most cases, we found that the mean of the top five ages was within 20% of the maximum age observed. Notable exceptions included AI harlequin, rougheye, and blackspotted rockfish (Table 2). In the case of harlequin and rougheye rockfish in the AI, this was attributed to low sample sizes and sparse sampling across years (there were only five years of sampling and a sample size of less than 250 for both species). In the case of AI blackspotted rockfish, however, there are nearly 2,500 aged specimens available, yet the mean of the top five ages (106.2 years) was nearly 30 years less than the maximum age in the sample (134 years; Table 2). This discrepancy could be attributed to a relatively short time series (rougheye and blackspotted rockfish have only been identified to species since 2006), exploitation history of this species in this region, or sampling issues in untrawlable habitat. These examples highlight the need to critically evaluate available age data, including sample size and spatiotemporal representativeness, before accepting a single $M_{t_{max}}$estimate (Table 2).

Given that our understanding of M for most of these rockfish species has remained relatively constant over time, future studies would benefit on focusing efforts on incorporating uncertainty in the magnitude of M and evaluating the influence of bias in M on management reference points (Cope and Hamel in review, Punt et al. 2022). All but three of the species in this study (dusky, rougheye, and blackspotted rockfish) are managed as data-limited fish stocks in Alaska under NPFMC Tier 4 and 5 harvest control rules that specify target and overfishing rates as a function of *M*. Currently, these control rules do not incorporate uncertainty in either *M* or biomass estimation into management decisions. Additionally, the method used to specify *M* for stock complexes is another area ripe for further research. All of the species in this study, except for shortraker rockfish, are managed as multispecies or stock complexes in the GOA or BSAI, which necessitates the estimation of a composite or weighted *M* for a species group (e.g., GOA OROX; Tribuzio et al. 2021), or the use of single species *M* that serves as a proxy for an entire species group (e.g., BSAI OROX; Sullivan et al. 2020). A recent review of these contrasting approaches highlighted the need for consistency and to evaluate the performance of these approaches in management (Monnahan et al. 2021).

In conclusion, results presented here provide updates to *M* for multiple rockfish species in Alaska. Although many of the methods used in this analysis have roots in the 1980s (e.g. Hoenig 1982, Hoenig 1983, Pauly 1980), the underlying equations have been refined in recent years using improved statistical assumptions (Hamel 2015, Then et al. 2015, Cope and Hamel in review, Hamel and Cope in review). Our analysis highlighted continued data gaps in life history information for many rockfish species in Alaska, including redbanded, redstripe, sharpchin, silvergray, and yelloweye rockfish. Additionally, our study underscores the importance of continued and consistent age data collection in fishery and surveys and staff support for ageing and ageing research, given that Alaskan rockfish include some of the longest-living vertebrate species on the planet. Finally, our results showed broad variability in *M* estimates depending on the estimator used, and future research should focus on evaluating the sensitivity of stock assessment results to this source of uncertainty and incorporating it into the fisheries management process.

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Table 1. -- Species- and region-specific estimates of natural mortality (M) estimates with associated life history parameter inputs, where 'Max age (y)' is the proxy age used in the life span estimator $M_{t_{max}}$ (Hamel and Cope in review), 'GSI' is gonadosomatic index (wet ovary weight/somatic weight) used in M_{GSI} (Gunderson 1997, Hamel 2015), 'VBGF L_{∞} (cm) / k) are the length-based von Bertalanffy parameters used in the growth estimator M_{VBGF} (Then et al 2015), and 'Temperature (Temp; °C) / Dry weight (wt; g) are the inputs for the M_{temp} estimator based on metabolic rate (McCoy and Gillooly 2008, Hamel 2015). When available, M estimators for maximum age are reported using the maximum age observed in Alaska Fisheries Science Center (AFSC) survey (RACEBASE) and fishery (NORPAC) databases (i.e. 'AFSC max age') and the arithmetic mean of the five oldest specimens at the AFSC (all data combined; 'AFSC mean top 5').

Region	Parameter(s)	Parameter values(s)	*M*	Reference
Dusky rockfish				
AI	Max age (y)	67	0.081	AFSC max age
AI	Max age (y)	63	0.085	AFSC mean top 5
GOA	GSI	0.016	0.029	Conrath 2019
GOA	Max age (y)	75	0.072	AFSC max age
GOA	Max age (y)	68	0.079	AFSC mean top 5
GOA	Max age (y)	67	0.081	Munk 2001
GOA	VBGF L_{∞}(cm) / k	48.3 / 0.180	0.327	Fenske et al. 2020
Harlequin rockfish				
AI	Max age (y)	79	0.068	AFSC max age
AI	Max age (y)	63	0.085	AFSC mean top 5
GOA	GSI	0.027	0.049	TenBrink 2022, pers. comm.
GOA	Max age (y)	47	0.115	AFSC max age
GOA	Max age (y)	41	0.131	AFSC mean top 5
GOA	Temp (°C) / Dry wt (g)	5.5 / 226	0.278	McCoy and Gillooly 2008
GOA	VBGF L_{∞} (cm) / k	30.9 / 0.167	0.359	pers. comm. TenBrink 2022
Redbanded rockfish				
BC	VBGF L_{∞}(cm) / k	54.8 / 0.050	0.123	Haigh and Starr 2006
GOA	Max age (y)	106	0.051	ADF&G Age Determination Unit website
GOA	Temp (°C) / Dry wt (g)	5.5 / 1,960	0.155	McCoy and Gillooly 2008
Redstripe rockfish				
BC	Max age (y)	55	0.098	ADF&G Age Determination Unit website
GOA	Max age (y)	46	0.117	AFSC max age

Region	Parameter(s)	Parameter values(s)	M	Reference
GOA	Max age (y)	39	0.138	AFSC mean top 5
Rougheye and blackspotted rockfish (unid.)				
AI	Max age (y)	131	0.041	AFSC max age
AI	Max age (y)	120	0.045	AFSC mean top 5
AI	VBGF L_∞(cm) / k	51.5 / 0.060	0.144	Spencer et al. 2020
BS	Max age (y)	130	0.042	AFSC max age
BS	Max age (y)	120	0.045	AFSC mean top 5
GOA	Max age (y)	132	0.041	AFSC max age
GOA	Max age (y)	128	0.042	AFSC mean top 5
GOA	Max age (y)	205	0.026	Munk 2001
GOA	Temp (°C) / Dry wt (g)	4.5 / 9,380	0.092	McCoy and Gillooly 2008
GOA	VBGF L_∞(cm) / k	49.6 / 0.090	0.195	Shotwell and Hanselman 2019
WC, BC, GOA, AI, BS	GSI	0.0127	0.023	McDermott 1994 (Stage V and VI)
WC, BC, GOA, AI, BS	GSI	0.0178	0.032	McDermott 1994 (Stage VI only)
Rougheye rockfish				
AI	Max age (y)	116	0.047	AFSC max age
AI	Max age (y)	96	0.056	AFSC mean top 5
BS	Max age (y)	107	0.05	AFSC max age
BS	Max age (y)	104	0.052	AFSC mean top 5
GOA	Max age (y)	135	0.04	AFSC max age
GOA	Max age (y)	113	0.048	AFSC mean top 5
GOA	VBGF L_∞(cm) / k	53.6 / 0.109	0.219	Shotwell et al. 2019
Blackspotted rockfish				
AI	Max age (y)	134	0.04	AFSC max age
AI	Max age (y)	106	0.051	AFSC mean top 5
BS	Max age (y)	84	0.064	AFSC max age
BS	Max age (y)	73	0.074	AFSC mean top 5
GOA	Max age (y)	103	0.052	AFSC max age
GOA	Max age (y)	94	0.057	AFSC mean top 5
GOA	VBGF L_∞(cm) / k	51.9 / 0.065	0.152	Shotwell et al. 2019
Sharpchin rockfish				
BC	VBGF L_∞(cm) / k	34.9 / 0.095	0.228	Archibald 1981
GOA	Max age (y)	48	0.112	AFSC max age

Region	Parameter(s)	Parameter values(s)	M	Reference
GOA	Max age (y)	43	0.124	AFSC mean top 5
GOA	Temp (°C) / Dry wt (g)	6.0 / 533	0.232	McCoy and Gillooly 2008
GOA	VBGF L_∞(cm) / k	32.6 / 0.131	0.295	Malecha et al. 2007
WC	Max age (y)	58	0.093	Cope et al. 2015
WC	VBGF L_∞(cm) / k	33.2 / 0.170	0.355	Cope et al. 2015
Shortraker rockfish				
AI	Max age (y)	124	0.044	AFSC max age
AI	Max age (y)	110	0.049	AFSC mean top 5
BC	Max age (y)	120	0.045	Chilton and Beamish 1982
GOA	Max age (y)	146	0.037	AFSC max age
GOA	Max age (y)	128	0.042	AFSC mean top 5
GOA	Max age (y)	157	0.034	Munk 2001
GOA	Max age (y)	160	0.034	ADF&G Age Determination Unit website
GOA	Temp (°C) / Dry wt (g)	4.5 / 9,300	0.093	McCoy and Gillooly 2008
GOA, AI, BS	VBGF L_∞(cm) / k	84.6 / 0.030	0.073	Hutchinson 2004
WC, BC, GOA, AI	GSI	0.0107	0.019	McDermott 1994 (Stage V and VI)
WC, BC, GOA, AI	GSI	0.0199	0.036	McDermott 1994 (Stage VI only)
Silvergray rockfish				
BC	Max age (y)	81	0.067	ADF&G Age Determination Unit website
GOA	Max age (y)	79	0.068	AFSC max age
GOA	Max age (y)	71	0.076	AFSC mean top 5
GOA	Max age (y)	75	0.072	Malecha et al. 2007
GOA	Temp (°C) / Dry wt (g)	7.0 / 1,960	0.18	McCoy and Gillooly 2008
Yelloweye rockfish				
BC	Max age (y)	115	0.047	DFO 2018
GOA	GSI	0.0285	0.052	Arthur 2020
GOA	Max age (y)	122	0.044	ADF&G Age Determination Unit website
GOA	Max age (y)	114	0.047	Bechtol 1998
GOA	Max age (y)	118	0.046	O'Connell and Funk 1987
GOA	Temp (°C) / Dry wt (g)	6.0 / 4,200	0.133	McCoy and Gillooly 2008

Region	Parameter(s)	Parameter values(s)	*M*	Reference
Shortspine thornyhead				
AI	GSI	0.0094	0.017	Pearson and Gunderson 2003
BS	GSI	0.0091	0.017	Pearson and Gunderson 2003
GOA	GSI	0.0072	0.013	Pearson and Gunderson 2003
GOA	Max age (y)	62	0.087	Miller 1985
GOA	Max age (y)	133	0.041	ADF&G Age Determination Unit website
GOA	Temp (°C) / Dry wt (g)	2.8 / 2,470	0.112	McCoy and Gillooly 2008
GOA, WC	Max age (y)	50	0.108	Kastelle et al. 2000 (minimum)
GOA, WC	Max age (y)	100	0.054	Kastelle et al. 2000 (maximum)
WC	Max age (y)	150	0.036	Jacobson 1990
WC	Max age (y)	115	0.047	Kline 1996 (conventional ageing)
WC	Max age (y)	100	0.054	Kline 1996 (radiochemical ageing)

Table 2. -- Sample size (N) summary of survey and fishery age data available at the Alaska Fisheries Science Center (AFSC) by rockfish species and area (AI = Aleutian Islands, GOA = Gulf of Alaska, BS = Eastern Bering Sea). 'Max age' is the maximum age observed in the sample (survey and fishery combined) and 'Mean top 5' is the arithmetic mean of the five oldest specimens. Survey and fishery years indicate the years for which data were collected.

Region	Survey N	Fishery N	Max age	Mean top 5	Survey years	Fishery years
Dusky rockfish						
AI	1,020	-	67	63.2	2002, 2004, 2006, 2010, 2012, 2014, 2016	-
GOA	5,479	3,939	75	68.2	1996, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019	2008, 2010, 2012, 2014, 2016, 2018, 2020
Harlequin rockfish						
AI	227	-	79	63.4	2004, 2006, 2010, 2014, 2016	-
GOA	1,069	-	47	41.2	1978, 1996, 1999, 2011, 2015	-
Redstripe rockfish						
GOA	706	-	46	39.2	1978, 1996, 2011, 2013	-
Rougheye and blackspotted rockfish (unid.)						
AI	3,358	2,101	131	119.8	1986, 1991, 1994, 1997, 2000, 2002, 2004	2004, 2005, 2006, 2007, 2008, 2009, 2011, 2013, 2015, 2017, 2019, 2020
BS	320	638	130	120.2	2002, 2004	2004, 2005, 2007, 2008, 2009, 2011, 2013, 2015, 2017, 2019, 2020
GOA	4,493	3,715	132	127.6	1978, 1979, 1984, 1987, 1990, 1993, 1996, 1999, 2003, 2005, 2009	1990, 2004, 2006, 2008, 2009, 2010, 2012, 2014, 2016, 2018, 2020
Rougheye rockfish						
AI	150	-	116	95.6	2006, 2010, 2012, 2014, 2018	-
BS	208	-	107	104.2	2008, 2010, 2012, 2016	-
GOA	2,196	-	135	113.4	2007, 2009, 2011, 2013, 2015, 2017, 2019	-

Region	Survey N	Fishery N	Max age	Mean top 5	Survey years	Fishery years
Blackspotted rockfish						
AI	2,426	-	134	106.2	2006, 2010, 2012, 2014, 2016, 2018	-
BS	439	-	84	72.6	2008, 2010, 2012, 2016	-
GOA	2,037	-	103	94.2	2007, 2009, 2011, 2013, 2015, 2017, 2019	-
Sharpchin rockfish						
GOA	648	-	48	43.4	1978, 1990, 1996	-
Shortraker rockfish						
AI	1,084	-	124	110	2004, 2006	-
GOA	1,851	-	146	127.8	1978, 1996, 1999, 2003, 2005	-
Silvergray rockfish						
GOA	1,047	-	79	70.8	1978, 1993, 1996, 1999, 2005	-

Table 3. -- Survey and fishery years indicate the years for which data were collected. Detailed sex (M = male, F = female), age (y), length (cm), and weight (kg) data for the five oldest specimens in the AFSC survey (RACEBASE) and fishery (NORPAC) databases.

Region	Year sampled	Sex	Age (y)	Fork length (cm)	Weight (kg)	Gear	Source
Dusky rockfish							
AI	2016	F	67	49	1.880	AFSC bottom trawl survey	RACEBASE
AI	2016	F	66	49	2.124	AFSC bottom trawl survey	RACEBASE
AI	2014	F	62	49	1.620	AFSC bottom trawl survey	RACEBASE
AI	2014	F	61	47	1.638	AFSC bottom trawl survey	RACEBASE
AI	2014	F	60	41	1.398	AFSC bottom trawl survey	RACEBASE
GOA	2013	F	75	50	2.320	AFSC bottom trawl survey	RACEBASE
GOA	2017	F	69	50	1.928	AFSC bottom trawl survey	RACEBASE
GOA	2008	M	66	45	1.710	Non-pelagic trawl fishery	NORPAC
GOA	2012	M	66	46	1.710	Non-pelagic trawl fishery	NORPAC
GOA	2015	M	65	45	1.436	AFSC bottom trawl survey	RACEBASE
Harlequin rockfish							
AI	2004	F	79	33	0.424	AFSC bottom trawl survey	RACEBASE
AI	2004	F	69	35	0.492	AFSC bottom trawl survey	RACEBASE
AI	2004	M	61	30	0.400	AFSC bottom trawl survey	RACEBASE
AI	2006	F	56	33	0.468	AFSC bottom trawl survey	RACEBASE
AI	2004	M	52	28	0.316	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	47	28	0.256	AFSC bottom trawl survey	RACEBASE
GOA	2011	M	44	29	0.320	AFSC bottom trawl survey	RACEBASE
GOA	1996	F	41	34	0.552	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	41	27	0.268	AFSC bottom trawl survey	RACEBASE
GOA	1996	F	37	33	0.520	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	37	29	0.332	AFSC bottom trawl survey	RACEBASE
Rougheye and blackspotted rockfish (unid.)							
AI	2017	F	131	87	12.220	Non-pelagic trawl fishery	NORPAC
AI	2004	M	121	63	4.024	AFSC bottom trawl survey	RACEBASE
AI	2011	M	117	78	8.640	Non-pelagic trawl fishery	NORPAC
AI	2017	F	116	51	2.280	Non-pelagic trawl fishery	NORPAC
AI	2002	M	114	51	2.042	AFSC bottom trawl survey	RACEBASE
BS	2017	M	130	67	4.880	Hook-and-line fishery	NORPAC

Region	Year sampled	Sex	Age (y)	Fork length (cm)	Weight (kg)	Gear	Source
BS	2019	F	127	63	4.050	Pelagic trawl fishery	NORPAC
BS	2019	F	119	63	4.110	Pelagic trawl fishery	NORPAC
BS	2004	M	115	74	6.150	Hook-and-line fishery	NORPAC
BS	2019	F	110	62	4.010	Pelagic trawl fishery	NORPAC
GOA	1993	M	132	60	-	AFSC bottom trawl survey	RACEBASE
GOA	1993	M	130	54	-	AFSC bottom trawl survey	RACEBASE
GOA	1999	M	129	59	2.962	AFSC bottom trawl survey	RACEBASE
GOA	2008	M	126	50	1.900	Hook-and-line fishery	NORPAC
GOA	1993	M	121	58	-	AFSC bottom trawl survey	RACEBASE
Rougheye rockfish							
AI	2006	M	116	60	4.272	AFSC bottom trawl survey	RACEBASE
AI	2006	F	97	54	2.508	AFSC bottom trawl survey	RACEBASE
AI	2006	M	96	64	4.674	AFSC bottom trawl survey	RACEBASE
AI	2006	M	85	55	3.148	AFSC bottom trawl survey	RACEBASE
AI	2006	M	84	61	3.924	AFSC bottom trawl survey	RACEBASE
BS	2012	M	107	61	3.464	AFSC bottom trawl survey	RACEBASE
BS	2008	M	106	54	2.640	AFSC bottom trawl survey	RACEBASE
BS	2008	M	105	61	3.706	AFSC bottom trawl survey	RACEBASE
BS	2008	M	103	62	4.044	AFSC bottom trawl survey	RACEBASE
BS	2016	M	100	63	4.020	AFSC bottom trawl survey	RACEBASE
GOA	2009	M	135	64	3.342	AFSC bottom trawl survey	RACEBASE
GOA	2009	M	113	49	1.762	AFSC bottom trawl survey	RACEBASE
GOA	2013	M	113	52	2.146	AFSC bottom trawl survey	RACEBASE
GOA	2019	M	108	60	3.710	AFSC bottom trawl survey	RACEBASE
GOA	2009	F	98	48	1.570	AFSC bottom trawl survey	RACEBASE
Blackspotted rockfish							
AI	2016	M	134	59	3.286	AFSC bottom trawl survey	RACEBASE
AI	2016	M	105	50	2.002	AFSC bottom trawl survey	RACEBASE
AI	2010	M	103	54	2.212	AFSC bottom trawl survey	RACEBASE
AI	2010	F	100	62	4.616	AFSC bottom trawl survey	RACEBASE
AI	2010	M	89	53	2.676	AFSC bottom trawl survey	RACEBASE
BS	2008	M	84	61	4.254	AFSC bottom trawl survey	RACEBASE
BS	2008	M	75	60	3.216	AFSC bottom trawl survey	RACEBASE

Region	Year sampled	Sex	Age (y)	Fork length (cm)	Weight (kg)	Gear	Source
BS	2008	M	73	56	2.380	AFSC bottom trawl survey	RACEBASE
BS	2008	M	71	63	4.134	AFSC bottom trawl survey	RACEBASE
BS	2008	F	60	54	2.610	AFSC bottom trawl survey	RACEBASE
GOA	2013	F	103	53	2.482	AFSC bottom trawl survey	RACEBASE
GOA	2009	M	97	47	1.622	AFSC bottom trawl survey	RACEBASE
GOA	2013	M	91	50	2.126	AFSC bottom trawl survey	RACEBASE
GOA	2009	M	90	54	2.406	AFSC bottom trawl survey	RACEBASE
GOA	2013	M	90	53	2.462	AFSC bottom trawl survey	RACEBASE
Redstripe rockfish							
GOA	2013	M	46	33	0.490	AFSC bottom trawl survey	RACEBASE
GOA	2013	M	41	38	0.746	AFSC bottom trawl survey	RACEBASE
GOA	2013	F	37	46	1.252	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	36	36	0.592	AFSC bottom trawl survey	RACEBASE
GOA	2013	M	36	35	0.560	AFSC bottom trawl survey	RACEBASE
Sharpchin rockfish							
GOA	1996	F	48	35	0.550	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	48	29	0.340	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	43	27	0.290	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	39	28	0.344	AFSC bottom trawl survey	RACEBASE
GOA	1996	F	39	36	0.606	AFSC bottom trawl survey	RACEBASE
Shortraker rockfish							
AI	2006	F	124	96	14.260	AFSC bottom trawl survey	RACEBASE
AI	2006	F	115	84	10.670	AFSC bottom trawl survey	RACEBASE
AI	2006	F	107	111	23.720	AFSC bottom trawl survey	RACEBASE
AI	2004	M	104	102	20.100	AFSC bottom trawl survey	RACEBASE
AI	2004	F	100	57	3.756	AFSC bottom trawl survey	RACEBASE
GOA	2003	M	146	79	8.665	AFSC bottom trawl survey	RACEBASE
GOA	1996	F	136	63	4.482	AFSC bottom trawl survey	RACEBASE
GOA	1996	F	127	81	10.865	AFSC bottom trawl survey	RACEBASE
GOA	2005	F	116	67	5.054	AFSC bottom trawl survey	RACEBASE
GOA	2005	F	114	77	7.750	AFSC bottom trawl survey	RACEBASE
Silvergray rockfish							
GOA	2005	M	79	68	4.724	AFSC bottom trawl survey	RACEBASE

Region	Year sampled	Sex	Age (y)	Fork length (cm)	Weight (kg)	Gear	Source
GOA	1999	M	75	65	4.230	AFSC bottom trawl survey	RACEBASE
GOA	1996	M	67	64	3.408	AFSC bottom trawl survey	RACEBASE
GOA	2005	F	67	64	3.270	AFSC bottom trawl survey	RACEBASE
GOA	1999	M	66	59	2.436	AFSC bottom trawl survey	RACEBASE

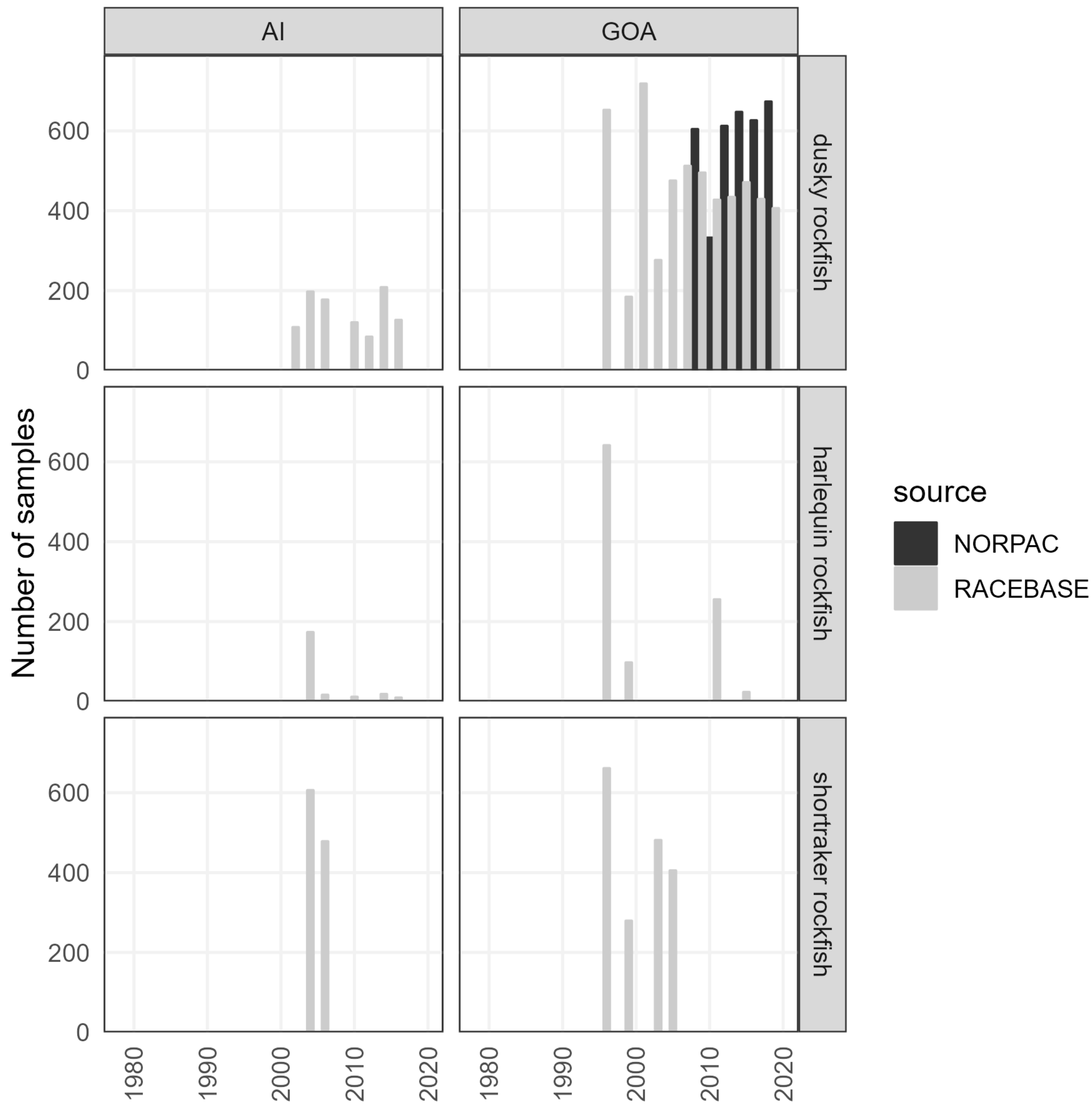

Figure 1. -- Annual sample sizes of dusky, harlequin, and shortraker rockfish ages in the Alaska Fisheries Science Center (AFSC) survey (RACEBASE) and fishery (NORPAC) databases. There are only age data available for these species in the Aleutian Islands (AI) and Gulf of Alaska (GOA).

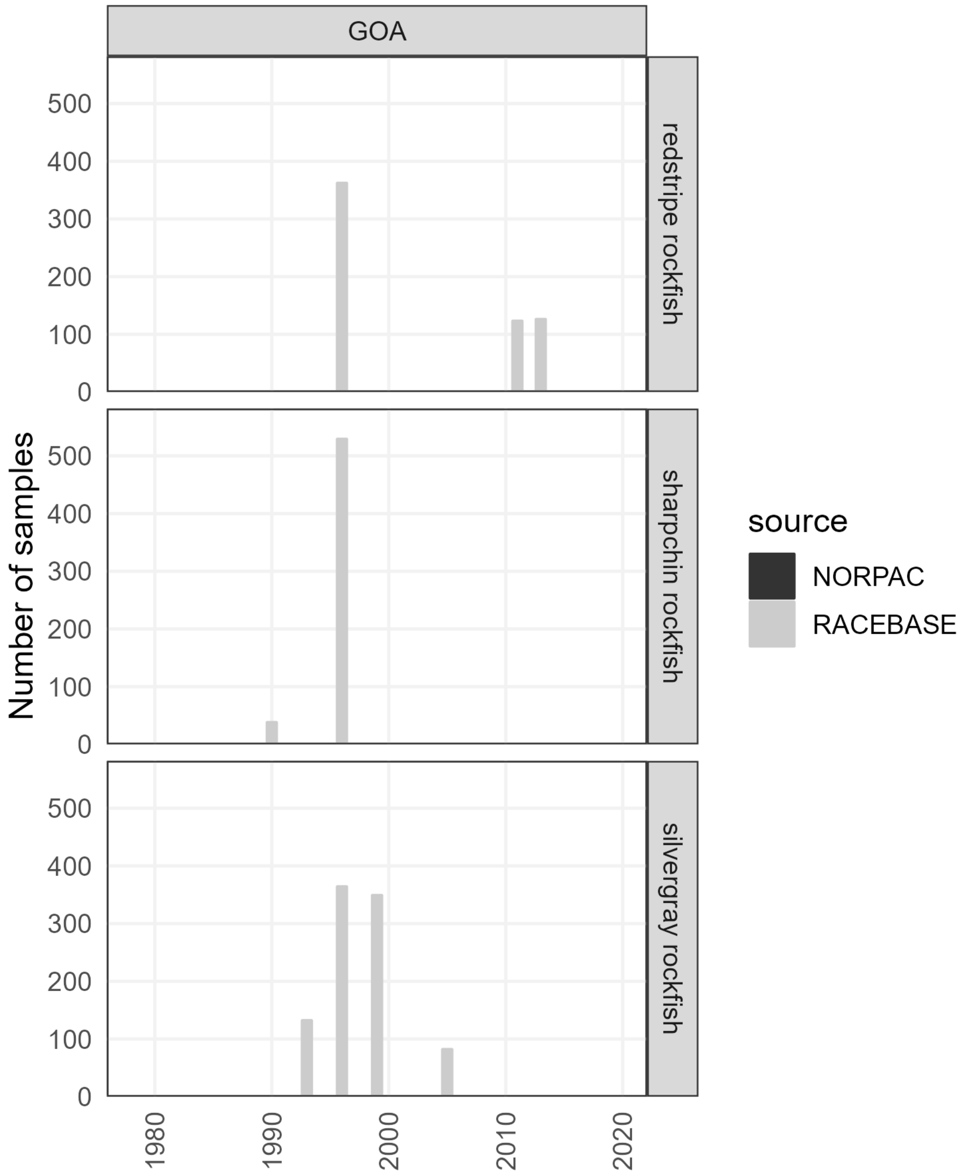

Figure 2. -- Annual sample sizes of redstripe, sharpchin, and silvergray rockfish ages in the Alaska Fisheries Science Center (AFSC) survey (RACEBASE) and fishery (NORPAC) databases. There are only age data available for these species in the Gulf of Alaska (GOA) and in RACEBASE.

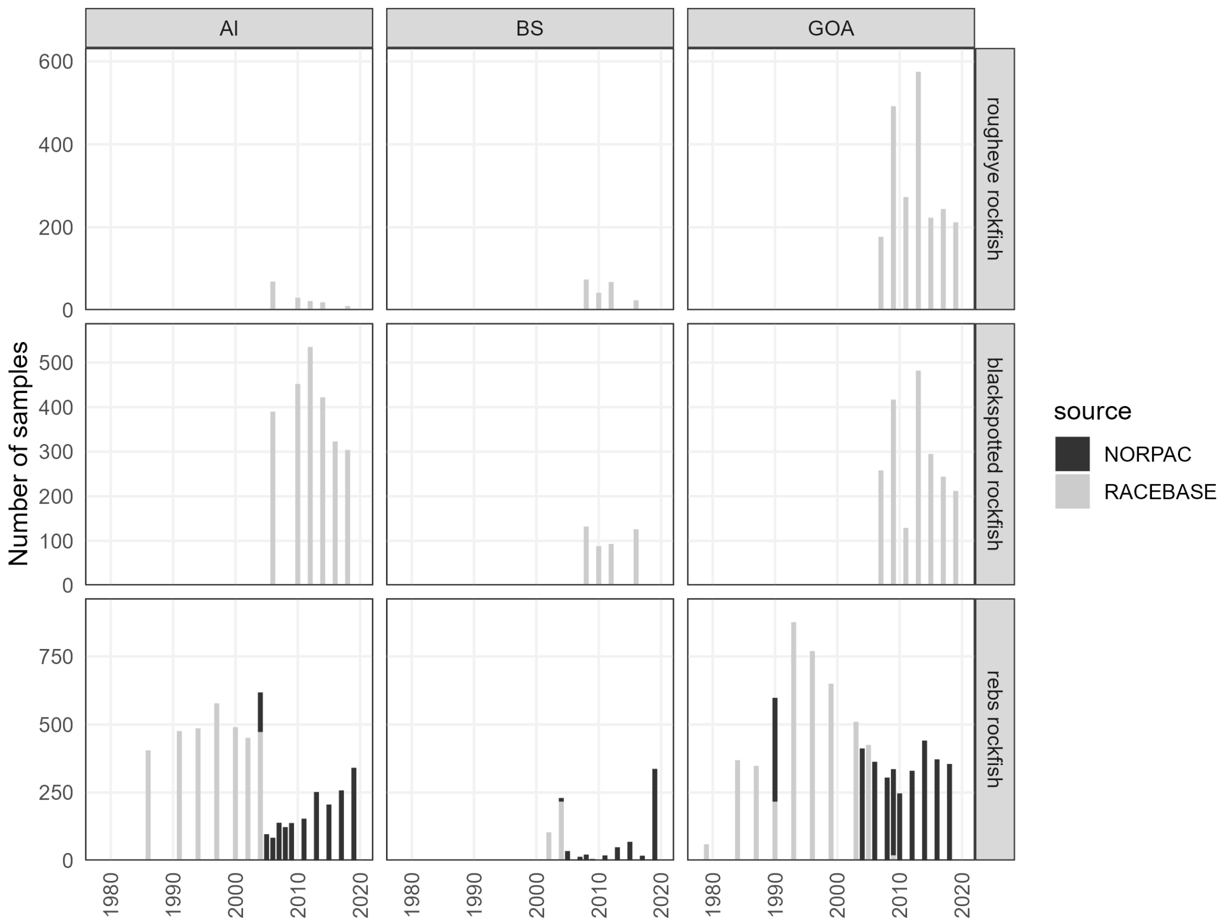

Figure 3. -- Annual sample sizes of rougheye, blackspotted, and unidentified rougheye/blackspotted ('rebs') rockfish ages in the Alaska Fisheries Science Center (AFSC) survey (RACEBASE) and fishery (NORPAC) databases in the Aleutian Islands (AI), Eastern Bering Sea (BS), and Gulf of Alaska (GOA). Note that rougheye and blackspotted rockfish are not identified to species in the fishery.

U.S. Secretary of Commerce
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