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A Tier 4 Toolkit for Alaska Groundfish Stocks: Methods, Diagnostics, and Examples

J. Y. Sullivan and K. L. Omori

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National Oceanic and Atmospheric Administration
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A Tier 4 Toolkit for Alaska Groundfish Stocks: Methods, Diagnostics, and Examples

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Abstract

Under the North Pacific Fishery Management Council's Fishery Management Plans for Alaska's groundfish, Tier 4 stock assessments integrate spawning potential ratio (SPR) based reference points of fishing mortality with a survey-based biomass dynamics model. Tier 4 is intended for stocks where biological information is sufficient to define SPR reference points, but available data do not support age-structured population models. In Tier 4 assessments, SPR-based fishing mortality reference points, such as $F_{40\%}$ and $F_{35\%}$, are derived from per-recruit calculations using life history schedules and fishery selectivity, while stock biomass and associated uncertainty are estimated using the same random effects, state-space random walk (REMA) model applied in Tier 5 assessments. To date, Tier 4 has only been applied to Gulf of Alaska (GOA) sharpchin rockfish, a component species in the GOA other rockfish stock complex. However, interest in Tier 4 applications is increasing as new species-specific biological information becomes available for data-limited stocks that remain constrained by sparse age data. In addition, confounding between survey catchability and recruitment estimation in assessments using statistical catch-at-age models can complicate inference on absolute biomass scale, motivating Tier 4 approaches that separate per-recruit reference point calculations from biomass estimation. This document details a standardized Tier 4 methodology for Alaska groundfish, describes recommended diagnostics and sensitivity analyses, and introduces an accompanying R package (*tier4tools*) that implements a consistent and reproducible workflow. The package is designed to support single-species stock and multispecies complexes, accommodate distinct life histories, and interface directly with the REMA framework used for Tier 4 and Tier 5 biomass estimation for groundfish stock assessments. We present two case studies, a single-species stock (GOA sharpchin rockfish) and a multispecies complex (GOA rougheye rockfish [*S. aleutianus*] and

blackspotted rockfish [*S. melanostictus*]), to illustrate the Tier 4 workflow and demonstrate how alternative biological assumptions influence reference points and resulting harvest recommendations.

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Introduction

Fisheries stock assessments for groundfish commonly rely on age-structured models to estimate population size, recruitment, fishing mortality, and biological reference points. However, many stocks do not have the age composition data, survey time series, or fishery sampling needed to support statistical catch-at-age assessments. Data-limited approaches therefore play a key role in providing management advice when information is sparse, uncertain, or inconsistent over time. In Alaska, the North Pacific Fishery Management Council's (NPFMC) groundfish Fishery Management Plans (FMPs) define a tier system for groundfish that links assessment methods and harvest control rules to the quantity and quality of available data (NPFMC 2024). Higher tiers (Tiers 1-3) rely on age-structured population models that jointly estimate recruitment, fishing mortality, and spawning biomass. Lower tiers (Tiers 4-6) are applied when key data inputs, particularly consistent age composition data or reliable estimates of fishing mortality, are unavailable or insufficient to support age-structured modeling.

Within the NPFMC framework, Tier 4 and Tier 5 groundfish assessments are designed for stocks where biomass must be estimated from survey indices rather than reconstructed from population dynamics. Both tiers estimate biomass using a state-space random walk (REMA) model applied to survey biomass estimates but differ in how fishing mortality reference points are defined. Tier 5 assessments define reference points as fixed fractions of assumed natural mortality (M), whereas Tier 4 assessments derive reference points from spawning potential ratio (SPR) analyses using species-specific biological information and fishery selectivity. Tier 4 SPR-based reference points use per-recruit calculations similar to those used in Tier 3; however, Tier 4 deliberately separates reference point calculations from recruitment and biomass estimation. This structure

avoids confounding between recruitment and survey catchability that can complicate inference in integrated age-structured models, while retaining survey-based biomass estimation through the same REMA framework used in Tier 5. As new biological information becomes available for stocks that remain constrained by sparse age data, or for stocks where statistical catch-at-age models are poorly supported due to model instability or data limitations, Tier 4 has emerged as a practical alternative to Tier 3 and Tier 5 approaches.

Despite its long-standing inclusion in the NPFMC tier system, Tier 4 has been applied only once to date, for Gulf of Alaska (GOA) sharpchin rockfish (*Sebastes zacentrus*), a component species within the GOA other rockfish complex (Omori et al. 2023). Implementation details for Tier 4 reference point calculations, including per-recruit equations, treatment of plus groups, sensitivity analyses, and diagnostics, have historically varied across assessments and analysts. For multispecies complexes, additional uncertainty arises from heterogeneity in life history traits and uncertainty in species composition.

This report documents a standardized Tier 4 framework for Alaska groundfish assessments, with a primary focus on SPR-based reference point calculations, diagnostics, and sensitivity analyses. We introduce an accompanying R package, *tier4tools*, that implements a consistent and reproducible workflow for Tier 4 reference point analysis (Sullivan and Omori, 2026). Biomass estimation using the REMA model is treated as an external component and follows established methods described in Sullivan et al. (2022a). Two case studies, a single-species stock (GOA sharpchin rockfish) and a multispecies complex (GOA rougheye rockfish [*S. aleutianus*] and blackspotted rockfish [*S. melanostictus*]), illustrate the standardized workflow and demonstrate how alternative biological assumptions and stock composition influence Tier 4 reference points. The primary objective is to establish a common, transparent workflow and code base for existing

and future Tier 4 assessments that is user-friendly, well-documented, and version-controlled, while remaining flexible enough to accommodate both single-species stocks and multispecies complexes with differing life histories. The framework is intended to make Tier 4 assessments more accessible to stock assessment scientists and to provide practical guidance for authors considering a transition to Tier 4 from either higher or lower tiers.

Methods

Tier 4 Assessment Framework

Tier 4 stock assessments consist of two linked components. First, per-recruit calculations are used to derive fishing mortality reference points based on SPR and yield per recruit (YPR). Second, stock biomass and its associated uncertainty are estimated using a survey-based biomass dynamics model (i.e., REMA). Fishing mortality reference points derived from the per-recruit analysis are applied to biomass estimates to compute overfishing limits (OFL) and acceptable biological catch (ABC).

This manuscript focuses on the derivation, diagnostics, and interpretation of SPR-based fishing mortality reference points within the Tier 4 framework. Biomass estimation is treated as an external component and follows established methods summarized below.

Biomass estimation in Tier 4 and Tier 5 assessments

Biomass dynamics in both Tier 4 and Tier 5 assessments are estimated using a state-space random walk model fit to one or more survey indices, as described in Sullivan et al. (2022a). In this framework, which is implemented using the *rema* R library, true biomass is treated as an unobserved latent state that evolves through time, with observation equations linking survey

indices to biomass via lognormal error. Observation uncertainty is informed by survey variance estimates, with optional estimation of additional observation errors when warranted.

Tier 4 does not modify the biomass estimation model used in Tier 5. Instead, Tier 4 alters how fishing mortality reference points are defined and applied. Biomass estimates produced by REMA are combined with SPR-based fishing mortality reference points to compute OFL and ABC in the same manner as in Tier 5 assessments. Details of REMA model structure are therefore not reproduced here, and readers are referred to Sullivan et al. (2022a) and Balstad et al. (2024) for a complete model description and diagnostics.

Fishing mortality reference points in Tier 4 and Tier 5

The primary distinction between Tier 4 and Tier 5 assessments lies in the definition of fishing mortality reference points. For Tier 5 stocks, the Alaska groundfish FMPs define F_{OFL} and F_{ABC} as fixed fractions of assumed natural mortality M, with $F_{OFL} = M$ and $F_{ABC} = 0.75M$ (NPFMC 2024). These reference points are applied uniformly across stocks in the absence of sufficient biological information to support per-recruit analyses.

For Tier 4 groundfish stocks, the NPFMC FMPs specify that $F_{OFL} = F_{35\%}$ and $F_{ABC} = F_{40\%}$, where $F_{x\%}$ is the fishing mortality that reduces SPR to $x\%$ of its unfished level. These Tier 4 SPR-based reference points replace the Tier 5 assumption that *M* serves as a proxy for fishing mortality targets. In the *tier4tools* framework, $F_{40\%}$ and $F_{35\%}$ are implemented as default SPR targets consistent with current FMP guidance, but users may specify alternative SPR targets for sensitivity analysis or alternative management applications.

Although Tier 4 reference points are based on per-recruit calculations similar to those used in Tier 3 assessments, Tier 4 deliberately separates reference point calculation from recruitment and biomass estimation. Recruitment is not estimated, and biomass scale is determined entirely by survey-based estimates from REMA. This separation allows biological information to directly inform fishing mortality targets without requiring a full age-structured model.

The sections below describe the per-recruit model used to compute SPR-based reference points for single-species stocks and extensions to multispecies stock complexes, as well as diagnostics and sensitivity analyses implemented in *tier4tools*. Figure 1 outlines the analytical workflow for Tier 4 per-recruit analyses in *tier4tools*, from input construction through reference point calculations and sensitivity evaluation. Table 1 summarizes the core functions supporting each stage, including their inputs, outputs, and intended sequencing within the analysis pipeline. Code and reproducible examples are available at https://noaa-afsc.github.io/tier4tools.

Per-recruit model structure and notation

Let age be indexed by $a = a_{min}, \ldots, a_{max}$. All calculations are performed on a per-recruit basis, with unfished equilibrium recruitment scaled to $R_0 = 1$. The following age-specific quantities are defined:

- m_a: maturity-at-age, representing the proportion of females contributing to spawning.
- s_a: fishery selectivity-at-age, scaled to a maximum value of one.
- w_a: female weight-at-age.
- M_a: natural mortality-at-age, which may be constant or age-specific.

- L_a: length-at-age, which follows a von Bertalanffy growth curve.
- F: fully selected fishing mortality.

Total mortality-at-age is given by

$$Z_a = M + F \cdot s_a, \tag{1}$$

where F is fishing mortality.

Growth and weight-at-age

Length-at-age may be specified using a parametric growth function or provided directly as an external vector defined over a_{min} to a_{max}. If an external length-at-age vector is not supplied, the default is using the von Bertalanffy growth as follows:

$$L_a = L_\infty\left(1 - e^{-k(a-t_0)}\right). \tag{2}$$

Weight-at-age may be derived from weight-length parameters using

$$w_a = \alpha {L_a}^{\beta}, \tag{3}$$

or supplied directly as a vector w_a spanning the full age range.

Maturity-at-age

Maturity can be provided as an external vector defined over a_{min} to a_{max}, for example, from external biological analyses. Alternatively, maturity may be parameterized using a logistic maturity function:

$$m_a = \frac{1}{1 + e^{\frac{a - A_{50}}{\delta}}}, \tag{4}$$

where A_{50} is the age at 50% maturity and δ controls the slope of the maturity curve.

Fishery selectivity-at-age

Three options are available for defining selectivity. First, selectivity may be provided directly as an external age-specific vector, s_a, from a_{min} to a_{max}, for example, derived from a previous assessment model or composition analysis.

Second, the user can define knife-edge selectivity, which assumes full selectivity above a specified age threshold over a_c and zero selectivity below that age,

$$s_a = \begin{cases} 0 & \text{if } a < a_c \\ 1 & \text{if } a \geq a_c \end{cases}. \tag{5}$$

This option is intended for cases where fishery selectivity information is limited or sensitivity analyses. Third, selectivity may also be parameterized using a logistic function with the same functional form as maturity:

$$s_a = \frac{1}{1 + e^{\frac{a - S_{50}}{\delta_s}}}, \tag{6}$$

where S_{50} is the age at 50% selection and δ_s controls the slope of the selectivity curve.

Extension to multiple fisheries

In cases where multiple fisheries operate on the stock with distinct selectivity patterns, the Tier 4 SPR framework allows fleet-specific selectivity curves to be specified. Let $s_{a,f}$ be the

selectivity-at-age for fleet f, and let λ_f be the proportion of total fishing mortality attributable to each fleet, where

$$\sum_f \lambda_f = 1. \tag{7}$$

The λ_f proportions are user-defined and may be informed by long-term average catch proportions, fleet-specific F estimates from a previous age-structured assessment, or other management-relevant summaries of fleet composition. For per-recruit calculations, fleet-specific selectivities are summarized into an effective selectivity-at-age vector,

$$s_a^* = \sum_f \lambda_f \, s_{a,f} \tag{8}$$

such that

$$F_a = F s_a^*. \tag{9}$$

All succeeding equations in the SPR analysis use s_a^*, and therefore produce reference points based on total fishing mortality across fleets.

Survivorship and numbers per recruit

Unfished numbers-at-age, N_a, are initialized as

$$N_a = \begin{cases} R_0 & \text{if } a = a_{min} \\ N_{a-1} e^{-M_{a-1}} & \text{if } a > a_{min} \end{cases}. \tag{10}$$

Fished numbers-at-age, N_a^F, are initialized as

$$N_a^F = \begin{cases} R_0 & \text{if } a = a_{min} \\ N_{a-1}^F e^{-Z_{a-1}} & \text{if } a > a_{min} \end{cases}. \quad (11)$$

Plus group option

When a plus group is assumed at age a_{max}, unfished numbers in the plus group are calculated as

$$N_{a_{max}} = \frac{N_{a_{max}-1} \cdot e^{-M_{a_{max}-1}}}{1 - e^{-M_{a_{max}}}}. \quad (12)$$

For fished numbers,

$$N_{a_{max}}^F = \frac{N_{a_{max}-1}^F \cdot e^{-Z_{a_{max}-1}}}{1 - e^{-Z_{a_{max}}}}. \quad (13)$$

When a plus group is used, diagnostics should report the fraction of spawning biomass per recruit (SBPR) attributable to the plus group (see the section on *Per-recruit diagnostics* below for more details). Highly influential plus groups may indicate sensitivity to the maximum age and mortality assumptions.

Spawning biomass per recruit

Unfished spawning biomass per recruit is

$$SBPR_0 = \sum_a^{a_{max}} N_{\mathrm{a}} \cdot w_a \cdot m_a. \quad (14)$$

Fished spawning biomass per recruit under fishing is

$$SBPR_F = \sum_{a}^{a_{max}} N_a^F \cdot w_a \cdot m_a \,. \tag{15}$$

Spawning potential ratio is defined as

$$SPR(F) = \frac{SBPR_F}{SBPR_0}. \tag{16}$$

Yield per recruit

Catch in numbers-at-age is computed using the Baranov catch equation:

$$C_a = \frac{F \cdot S_a}{Z_a} \cdot (1 - e^{-Z_a}) \cdot N_a^F. \tag{17}$$

Yield per recruit in weight is

$$YPR = \sum_{a}^{a_{max}} C_a \cdot w_a \,. \tag{18}$$

Estimation of SPR-based fishing mortality reference points

SPR-based fishing mortality (F_{SPR}) reference points are defined generically as the values of F that achieve specified target SPR levels. For a target SPR level x, the reference point F_x is defined as the solution to

$$SPR(F_x) = x. \tag{19}$$

In practice, F_x is obtained numerically by evaluating the function $SPR(F)$ over a dense grid of candidate F values and selecting the F that minimizes $|SPR(F) - x|$. Under the applicable

groundfish FMPs, $F_{40\%}$ and $F_{35\%}$ correspond to F_{ABC} and F_{OFL}, respectively, and are defined as the fishing mortalities at which SPR is reduced to 40% and 35% of the unfished levels (see the previous section on *Fishing mortality reference points in Tier 4 and Tier 5* for more details).

Extension to multispecies stock complexes

For a stock complex consisting of I species indexed by $i = 1, \ldots, I$, species-specific SBPR and YPR are computed using shared or species-specific biological schedules and fishery selectivity: $M_{a,i}$, $m_{a,i}$, $w_{a,i}$, and $s_{a,i}$, depending on available information. A single unit of unfished recruitment is assumed for the stock complex and is partitioned among species using fixed proportions p_i, such that $\sum_{i=1}^{I} p_i = 1$. These proportions are used to scale species-specific SBPR contributions when computing combined SPR for the stock complex. Species-specific unfished recruitment is therefore defined as $R_{0,i} = p_i$. These recruitment proportions determine the relative contribution of each species to complex-level SBPR.

Two alternative approaches are implemented for defining shared F_{SPR} reference points for multispecies complexes:

1. **Unconstrained complex-level reference points** are derived from a complex level SBPR, constructed by aggregating the species-specific SBPR across the complex. Let $SBPR_i(F)$ be the species-specific SBPR at a given F, which is scaled by $R_{0,i} = p_i$ through the per-recruit calculation. Fished ($SBPR_{complex}(F)$) and unfished ($SBPR_{complex,0}$) complex-level SBPR is computed as

$$SBPR_{complex}(F) = \sum_{i=1}^{I} SBPR_i(F) \text{ and } SBPR_{complex,0} = \sum_{i=1}^{I} SBPR_{i,0}\,. \qquad (20)$$

The complex-level SPR is then obtained by

$$SPR_{complex}(F) = \frac{SBPR_{complex}(F)}{SBPR_{complex,0}}. \quad (21)$$

In this formulation, species-specific SBPR is first aggregated to the complex level using recruitment proportions p_i, and the resulting complex-level SPR curve is used to define reference points. Notably, species-specific SPR curves are not averaged directly; instead, species-specific SBPR contributions are aggregated prior to computing the complex-level SPR.

Unconstrained reference points $F_x^{unconstrained}$ are defined as the fishing mortality values that satisfy

$$SPR_{complex}\left(F_x^{unconstrained}\right) = x. \quad (22)$$

2. **Constrained complex-level reference points** require that all species in the complex meet the SPR target. For each species *i*, the species-specific target fishing mortality $F_{x,i}$ is defined implicitly as the solution to

$$SPR_i\left(F_{x,i}\right) = x. \quad (23)$$

The constrained reference point for the complex is then defined as

$$F_x^{constrained} = \min_i F_{x,i}. \quad (24)$$

Under this approach, the species with the lowest productivity determines the allowable fishing mortality for the complex, regardless of its contribution to total SBPR.

Per-recruit model diagnostics

Tier 4 SPR calculations can be sensitive to assumptions about maturity schedules, fishery selectivity, weight-at-age, natural mortality, and the treatment of the plus group. To support standardized review, *tier4tools* generates a set of per-recruit diagnostics summarized in Table 1, including age-based SBPR decomposition plots and plus-group indicators. For each species, the model computes per-recruit survivorship-at-age under fished, $l_a(F)$, and unfished conditions, $l_a(0)$. Age-specific contributions to SBPR, $b_a(F)$, are then calculated as

$$b_a(F) = l_a(F) w_a m_a. \tag{25}$$

Contributions are evaluated at $F = 0$ and F at the selected target reference point (e.g., $F_{target} = F_{40\%}$) and plotted as a function of age to visualize how fishing changes the age distribution of reproductive output. An additional diagnostic quantifies the SBPR removed by fishing at each age, r_a, as

$$r_a = b_a(0) - b_a\left(F_{target}\right). \tag{26}$$

To facilitate comparison across species with differing total reproductive output within a stock complex, an additional diagnostic expresses age-specific removals as a proportion of total unfished SBPR. For each age, proportional SBPR removal is defined as

$$r_a^{prop} = \frac{b_a(0) - b_a\left(F_{target}\right)}{\sum_{a=1}^{A} b_a(0)}. \tag{27}$$

This diagnostic highlights the relative contribution of each age class to total reproductive losses under fishing and is particularly useful for multispecies complexes where species differ in longevity, maturity schedules, and total SBPR. Proportional removal plots complement absolute

removal diagnostics by separating the distribution of fishing impacts across ages from differences in total reproductive output.

Finally, survivorship curves of $l_a(0)$ and $l_a(F_{target})$ are plotted to show whether changes in SBPR are driven primarily by survivorship through fishing selectivity and mortality or through the species' age-specific natural mortality, maturity, and growth. Because the terminal age can be treated as a plus group, *tier4tools* reports the fraction of total SBPR contributed by the terminal age. For visualization, the terminal age is optionally omitted from contribution and removal plots to avoid plus group dominance, while its influence is retained in the reported plus group share diagnostic.

Sensitivity analysis of SPR reference points

To characterize uncertainty in SPR-based fishing mortality reference points arising from key biological and fishery assumptions, *tier4tools* provides functions to conduct a structured sensitivity analysis using the per-recruit framework described above. Sensitivity analyses were implemented using a standardized grid-based approach to ensure consistency across stocks and to facilitate transparent comparison among scenarios.

Sensitivity analyses focused on a limited set of influential inputs that are commonly uncertain in Tier 4 assessments and directly affect SBPR. We varied the scalar M applied uniformly across ages, the midpoint of the logistic maturity curve (A_{50}) while holding the slope parameter fixed, the age at full selection under a knife-edge selectivity assumption (a_c), and, for multispecies complexes, recruitment proportions. Sensitivities were restricted to M, maturity, and selectivity variations applied uniformly across species. Standardized sensitivities of recruitment proportion assumptions were limited to two-species stocks, recognizing that proportions must sum to one

and changing the recruitment share of one species automatically determined the share of the other. For complexes of three species or more, changing the recruitment allocation to one species affects all remaining species simultaneously, making it difficult to construct a simple, structured grid of recruitment scenarios. Larger complexes can instead be evaluated using case-specific recruitment scenarios.

All sensitivity scenarios were generated by modifying the baseline per-recruit inputs and re-evaluating SPR and YPR across a fixed grid of *F* values, with reference points derived using the same nearest-grid approach as the base case. For each scenario, we recorded reference points ($F_{40\%}$ and $F_{35\%}$), constrained combined reference points when applicable in multispecies mode, combined YPR evaluated at $F_{40\%}$, and species-specific plus group diagnostics describing the fraction of SBPR attributable to the terminal age under unfished conditions and at the diagnostic reference *F*.

Guidelines for interpreting sensitivity results

Sensitivity results are intended to support qualitative interpretation of how assumptions influence SPR-based reference points, rather than to define probabilistic uncertainty bounds. Changes in *M* and maturity primarily affect survivorship to older ages and the timing of reproductive output, while changes in fishery selectivity affect the ages at which fishing mortality is applied. Recruitment proportion sensitivities highlight how reference points for multispecies complexes depend on assumptions about species composition when life histories differ.

Plus group diagnostics are reported alongside reference points to identify scenarios in which SPR estimates are dominated by the terminal age. Scenarios with a high fraction of SBPR attributable

to the plus group may indicate sensitivity to assumptions about the plus group age or *M* and warrant additional scrutiny.

Case studies

In this section, we present the Tier 4 workflow using two case studies, a single-species stock (sharpchin rockfish) and a multispecies complex (rougheye and blackspotted rockfish). R code to reproduce the results from these analyses is available online at https://github.com/noaa-afsc/tier4techmemo.

Sharpchin Rockfish

Background and model inputs

GOA sharpchin rockfish was used as the single-species Tier 4 case study to demonstrate application of the per-recruit framework to a data-limited stock with sufficient biological information to support SPR-based reference points. Sharpchin rockfish are caught primarily as non-target bycatch in mixed-species rockfish fisheries and have limited fishery-dependent and age composition data. This species is currently a Tier 4 stock in Alaska and is assessed as a component of the Other Rockfish complex (Omori et al. 2023).

Per-recruit calculations were conducted for sharpchin rockfish using species-specific life history information compiled from prior studies. Input values for maturity-at-age, growth, weight-at-age, natural mortality, and fishery selectivity assumptions are summarized in Table 2 and illustrated in Figure 2. Maturity-at-age was parameterized using a logistic function with a_{50} maturity at 10.1 years (Heifetz et al. 1998). Weight-at-age was derived from von Bertalanffy growth and weight-length relationships reported in earlier studies (Malecha et al. 2007).

Given the limited biological and fishery information available for sharpchin rockfish, sensitivity analyses focused on two inputs known to strongly influence SPR-based reference points: *M* and fishery selectivity. The base-case value of $M = 0.059$ was derived using the Hoenig (1983) longevity estimator (Malecha et al. 2007), with alternative values spanning a biologically plausible range (0.05-0.12) informed using longevity estimators in the Natural Mortality Tool (Cope and Hamel 2022). Sharpchin rockfish lack sufficient data to estimate a continuous selectivity curve, so fishery selectivity was assumed to follow a knife-edge pattern with a_c at age-10 in the base case. Ages 5 through 15 were explored as alternative values for the full selectivity age in the sensitivity analysis.

Results

Under the base case assumptions for GOA sharpchin rockfish, the per-recruit analysis produced well-defined SPR-based fishing mortality reference points ($F_{40\%} = 0.066$ and $F_{35\%} = 0.080$). SPR declined rapidly at low to moderate *F*s and more gradually at higher values (Fig. 3), consistent with the strong contribution of older age classes to total SBPR.

Age-based decomposition of unfished SBPR confirmed that reproductive output is dominated by older ages, consistent with slow growth, delayed maturity, and low M (Fig. 4A). Contributions to SBPR increased steadily with age and remained substantial through the oldest ages included in the model. At $F_{40\%}$, fishery removals of SBPR were concentrated in older, fully selected age classes, with peak removals occurring at intermediate to older ages (20-40 years), rather than at the youngest or terminal ages (Fig. 4B). As expected, survivorship curves confirmed that *F* acted entirely on ages at and above the assumed knife-edge selectivity threshold, with little impact on immature or early maturing fish (Fig. 4C). As a result, fishing reduced lifetime reproductive

output mainly by shortening survival at older ages rather than by preventing recruitment into the spawning population.

Sensitivity analyses revealed that both *M* and knife-edge selectivity, defined by a_c, strongly influenced SPR-based reference points for sharpchin rockfish (Fig. 5A). Values of $F_{40\%}$ ranged from 0.042 to 0.400 across the evaluated parameter space. $F_{40\%}$ increased with increasing *M* and later selectivity, with the greatest sensitivity occurring when high *M* coincided with delayed exposure to the fishery. At low *M* values, including the base-case $M = 0.059$, and under early selectivity, $F_{40\%}$ remained low and relatively insensitive to either parameter. In contrast, at higher M and later selectivity, small changes in either assumption produced large shifts in $F_{40\%}$, indicating strong interaction effects between mortality and selectivity assumptions.

YPR evaluated at $F_{40\%}$ increased with later selectivity and decreased with higher *M* (Fig. 5B). Although this pattern may appear counterintuitive if earlier selectivity is expected to increase yield, YPR is evaluated at a reference point $F_{40\%}$ that varies across scenarios rather than at a fixed *F*. Earlier selectivity caused spawning potential to decline rapidly with increasing *F*, resulting in a lower $F_{40\%}$ and correspondingly lower YPR. In contrast, later selectivity protected younger fish, allowing substantially higher *F* at the SPR target, which increased YPR despite delayed entry into the fishery. Higher *M* reduced YPR at $F_{40\%}$ by decreasing survivorship prior to harvest and lowering the *F* associated with the target SPR.

Rougheye and Blackspotted Rockfish

Background and model inputs

The GOA rougheye and blackspotted rockfish complex was used as a multispecies Tier 4 case study to demonstrate application of the per-recruit framework to a multispecies stock with contrasting life histories. Since 2008, this complex has been assessed under Tier 3 using a statistical catch-at-age model that combined rougheye and blackspotted rockfish into a single assessment unit with shared growth, maturity, and fishery processes (Shotwell et al. 2007). Persistent issues related to model scale, retrospective patterns, and sensitivity to species composition highlighted limitations of this approach for reliably estimating productivity and reference points for this stock, motivating exploration of a Tier 4 alternative (Sullivan 2025).

Per-recruit calculations were conducted jointly for rougheye and blackspotted rockfish using species-specific biological schedules where available. Life history inputs, including maturity-at-age, weight-at-age, von Bertalanffy growth parameters, natural mortality, and fishery selectivity-at-age, are summarized in Table 3 and illustrated in Figure 6. Maturity schedules represent functional maturity and account for skipped spawning (Sullivan et al. in review). Natural mortality was fixed at a single complex-level value ($M = 0.042$) due to uncertainty in species-specific longevity estimates at older ages (Sullivan et al., 2022b). Fishery selectivity was assumed identical for both species and was taken from the most recent assessment model (Sullivan et al. 2023), with full selection occurring at approximately age 13. The base case assumed equal recruitment contributions from rougheye and blackspotted rockfish (50:50).

Complex-level reference points were computed using the constrained and unconstrained alternatives defined in the Methods section *Extension to multispecies stock complexes*. Age-

based decomposition plots of SBPR were used to aid interpretation of multispecies SPR dynamics and to identify age classes driving differences between species. Sensitivity of reference points and implied species-specific yield share to stock composition was evaluated by varying the recruitment proportion assigned to rougheye rockfish from 0.2 to 0.8, with corresponding adjustments to blackspotted recruitment.

Results

When complex-level reference points were defined using the combined SPR curve alone (unconstrained method), the resulting F_{SPR} reference points fell between the species-specific values ($F_{40\%}^{unconstrained} = 0.048$ and $F_{35\%}^{unconstrained} = 0.059$; Fig. 7A). In contrast, when complex-level reference points were constrained such that all species were required to meet the SPR target, the resulting *F* values were substantially lower and coincided with the blackspotted rockfish species-specific reference points ($F_{40\%}^{constrained} = 0.031$ and $F_{35\%}^{constrained} = 0.036$; Fig. 7A), indicating that blackspotted rockfish was consistently the limiting species. Under the constrained approach, the resulting reference points corresponded to higher effective SPR at the complex level, with equivalent complex SPRs of approximately 52% at $F_{40\%}^{constrained}$ and 48% at $F_{35\%}^{constrained}$. Rougheye rockfish exhibited higher SPR across *F* levels, whereas blackspotted rockfish showed a more rapid decline in SPR with increasing *F* (Fig. 7B). These differences reflect contrasting life history schedules (Fig. 6), particularly later maturation and slower accumulation of reproductive biomass in blackspotted rockfish.

Age-based decomposition of unfished SBPR revealed substantial differences in how reproductive output was distributed across ages for the two species (Fig. 8A). Under unfished conditions, rougheye rockfish contributed to SBPR earlier and across a broader age range,

whereas blackspotted rockfish contributed relatively little SBPR at younger ages and relied disproportionately on survival to older ages to generate reproductive output. At $F_{40\%}^{constrained}$, reductions in SBPR were driven primarily by losses in older age classes for both species, with proportionally greater impacts for blackspotted rockfish (Fig. 9). Survivorship curves were effectively identical between species at both F_0 and $F_{40\%}^{constrained}$ due to shared *M* and selectivity assumptions (Fig. 8B). As a result, the differences observed in SPR were not driven by differential fishing mortality or survival rates but instead reflected interactions between survivorship and species-specific maturity and weight-at-age schedules that amplified losses in reproductive output for blackspotted rockfish at older ages. Plus-group diagnostics indicated that a substantial fraction of blackspotted rockfish SBPR was generated in the terminal age under unfished conditions, and that this contribution declined sharply at the target fishing mortality. In contrast, rougheye rockfish distributed SBPR more evenly across ages, making it less sensitive to age truncation under the same fishing regime.

Unconstrained complex-level SPR reference points were sensitive to the assumed recruitment proportions between rougheye and blackspotted rockfish (Fig. 10A). As the proportion of recruitment assigned to rougheye rockfish increased, $F_{40\%}^{unconstrained}$ and $F_{35\%}^{unconstrained}$ increased, reflecting the greater per-recruit productivity of rougheye rockfish and its higher SPR at a given *F*. In contrast, constrained reference points were largely insensitive to recruitment proportion assumptions across the full range examined. Because constrained reference points require each species to meet the SPR target and species-specific SPR curves are computed independently of recruitment scaling, the limiting species determined the complex-level *F* regardless of how recruitment was partitioned. In this case, blackspotted rockfish remained limiting across all recruitment proportion scenarios. While unconstrained reference points

reflected uncertainty in stock composition, constrained reference points provided a precautionary upper bound on fishing mortality that was robust to recruitment proportion uncertainty.

YPR at the selected reference points varied substantially with recruitment proportions, even when constrained reference points were applied (Fig. 10B). Changes in recruitment partitioning altered the relative contribution of each species to total yield, with higher rougheye recruitment proportions leading to greater rougheye yield share. At the base case 50:50 recruitment assumption, the implied rougheye yield share was approximately 65%, and was similar across SPR targets and reference point methods. These results indicate that uncertainty in recruitment composition primarily affects expected yield composition rather than the complex-level F_{SPR} reference points themselves.

Discussion

This study presents a standardized and reproducible Tier 4 framework for Alaska groundfish stock assessments, implemented through the *tier4tools* R package. The framework formalizes per-recruit calculations for SPR and YPR, provides a consistent approach for defining fishing mortality reference points, and introduces a suite of diagnostics and sensitivity analyses intended to support transparent review and interpretation. By explicitly linking biological schedules to reference point calculations, the Tier 4 approach bridges data-limited and data-moderate assessments and preserves continuity with existing Tier 5 methods when used in conjunction with REMA for biomass estimation. Similarly, Tier 4 provides an alternative framework for existing Tier 3 stocks that have sufficient information to estimate F_{SPR} reference points but lack data to estimate absolute biomass or population age structure reliably.

The case studies demonstrate how a unified implementation of Tier 4 assessments improves comparability across stocks and facilitates structured exploration of biological and fishery uncertainty. In particular, the age-based SBPR decomposition and standardized sensitivity analyses provide diagnostics that clarify how and why reference points differ across scenarios. The GOA sharpchin rockfish case study illustrates the behavior of Tier 4 reference points for a single, non-target species with limited fishery information but sufficient biological data. Sensitivity analyses demonstrated that uncertainty in both fishery selectivity and *M* influenced SPR-based reference points across the evaluated parameter space. $F_{40\%}$ increased with later selectivity and higher *M*, with the greatest sensitivity occurring when delayed selection into the fishery coincided with elevated *M*. This pattern highlights the importance of evaluating selectivity and mortality assumptions jointly and demonstrates the value of structured sensitivity analyses for identifying regions of the parameter space where Tier 4 reference points are most sensitive to uncertainty, rather than relying on informal or one-off scenario testing.

The GOA rougheye and blackspotted rockfish case study demonstrates how the Tier 4 framework accommodates multispecies stock complexes with contrasting life histories. When complex-level F_{SPR} reference points were defined using the unconstrained approach (i.e., using the combined or complex-level SPR curve), resulting F_{SPR} values fell between the species-specific reference points and were sensitive to assumptions about recruitment proportions. In contrast, constrained reference points that required each species to meet the SPR target were consistently determined by blackspotted rockfish, the lower productivity species in the complex. Effective SPR for the full complex under the constrained approach was higher than 40%, reflecting the requirement that all species simultaneously satisfy the SPR target. Age-based decomposition revealed that differences in SPR responses were driven by species-specific

maturity and weight-at-age schedules rather than differences in fishing mortality or survivorship, which were shared across species. Blackspotted rockfish relied disproportionately on survival to older ages to generate reproductive output and exhibited greater sensitivity to age truncation, consistent with its role as the limiting species.

A key result from the multispecies analysis was the contrast between robustness of constrained reference points and sensitivity of yield species composition. While constrained F_{SPR} values were insensitive to recruitment proportion assumptions, YPR and implied yield shares varied substantially with recruitment allocation. At the base case assumption of equal recruitment, rougheye rockfish accounted for a disproportionate share of expected yield, reflecting higher per-recruit productivity even under a harvest strategy constrained by blackspotted rockfish. The results of the implied yield share analysis highlight an important distinction between the robustness of reference points and expected fishery outcomes. Constrained multispecies reference points provide a precautionary upper bound on F that is robust to uncertainty in species composition. However, uncertainty in recruitment proportions directly affected expected catch species composition and therefore the interpretation of realized yield under a shared harvest strategy. In complexes where species differ substantially in life history and productivity, improved species-level monitoring can enhance interpretation of catch composition and stock-specific performance, even when conservative reference points are applied. Genetic stock validation, expanded biological sampling, or improved species identification protocols may therefore be most valuable for evaluating realized yield and stock status trends, rather than for determining the appropriate constrained F_{SPR} reference points.

Together, these case studies demonstrate that Tier 4 assessments can provide biologically grounded and scientifically defensible advice for both single species and multispecies complexes

when age-structured models are infeasible. Reference points should be treated as static inputs informed by the best available biological information, analogous to Tier 5 reference points based on M, and revisited when new life history data, changes in fishery selectivity, or improved species identification warrant reassessment. Future extensions of the Tier 4 framework might include length-based SPR formulations (e.g., Hordyk et al., 2015) or formal evaluation of Tier 4 performance relative to higher and lower tiers through simulation. The examples also demonstrate the utility of a unified Tier 4 methods approach for the NPFMC groundfish stocks that can be applied to both single and multispecies cases. As new biological and monitoring data become available, a standardized Tier 4 workflow provides a transparent foundation for iterative improvement without requiring wholesale changes to assessment structure.

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Citations

Balstad, L.J., Sullivan, J., and Monnahan, C. 2024. A Plain Language Guide to Model Validation in REMA. Plan Team Report, Joint Groundfish Plan Teams, North Pacific Fishery Management Council. 605 W. 4th. Ave., Suite 306, Anchorage, AK 99501. Available through the Sept 2024 Joint GPT e-Agenda.

Cope, J.M., and Hamel, O.S. 2022. Upgrading from M version 0.2: An application-based method for practical estimation, evaluation and uncertainty characterization of natural mortality. Fisheries Research 256, p.106493. https://doi.org/10.1016/j.fishres.2022.106493.

Harris, J.P., Hutchinson, C., and Wildes, S. 2019. Using otolith morphometric analysis to improve species discrimination of blackspotted rockfish (*Sebastes melanostictus*) and rougheye rockfish (*S. aleutianus*). Fishery Bulletin, U.S. 117:234–244. https://doi.org/10.7755/FB.117.3.10.

Heifetz, J., Ianelli, J.N., and Clausen, D.M. 1998. Slope Rockfish, 281-321 p. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska. North Pacific Fishery Management Council, Anchorage, AK.

Hoenig, J.M., 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin, U.S. 82:898-903.

Hordyk, A.R., Ono, K., Sainsbury, K., Loneragan, N.R., and Prince, J. D. 2015. Some explorations of the life history ratios to describe length composition, spawning-per-recruit, and the spawning potential ratio. ICES Journal of Marine Science 72: 204–216.

Malecha, P.W., Hanselman, D.H., and Heifetz, J. 2007. Growth and mortality of rockfish (Scorpaenidae) from Alaska waters. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-172, 61 p.

NPFMC (North Pacific Fishery Management Council). 2024. Fishery management plan for the groundfish fisheries of the Gulf of Alaska, 145 p. North Pacific Fishery Management Council, Anchorage, AK. Available at https://files.npfmc.org/fmp/GOA/GOAfmp.pdf.

Omori, K.L., Tribuzio, C.A., and Ferriss, B. 2023. Assessment of other rockfish stock complex in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska. North Pacific Fishery Management Council, 605 W. 4th. Ave., Suite 306, Anchorage, AK 99501.

Sullivan, J., Monnahan, C., Hulson, P. Ianelli, J., Thorson, J. and Havron, A., 2022a. REMA: a consensus version of the random effects model for ABC apportionment and Tier 4/5 assessments. Plan Team Report, Joint Groundfish Plan Teams, North Pacific Fishery Management Council. 605 W. 4th. Ave., Suite 306, Anchorage, AK 99501. Available through the Sept 2022 Joint GPT e-Agenda.

Sullivan, J.Y., Tribuzio, C.A., and Echave, K.B. 2022b. A review of available life history data and updated estimates of natural mortality for several rockfish species in Alaska. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-443, 45 p.

Sullivan, J.Y., Zahner, J.A., Siple, M.C. and Ferriss, B.E. 2023. Assessment of rougheye and blackspotted rockfish stock in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska. North Pacific Fishery Management Council, 605 W. 4th. Avenue, Suite 306, Anchorage, AK 99501.

Sullivan, J.Y. 2025. A proposed Tier 4 approach to the rougheye and blackspotted rockfish complex in the Gulf of Alaska. Plan Team Report, Gulf of Alaska Groundfish Plan Team, North Pacific Fishery Management Council. 605 W. 4th. Ave., Suite 306, Anchorage, AK 99501. Available through the Sept 2025 Joint GPT e-Agenda.

Sullivan, J.Y. and Omori, K.L. 2026. tier4tools: Tier 4 Spawning Potential Ratio (SPR) Reference Points for NPFMC Groundfish Assessments. R package version 0.1.0. https://noaa-afsc.github.io/tier4tools/

Sullivan, J.Y., TenBrink, T.T., Gburski, C.M., and Adams, G.D. *In review.* When looks deceive: Impacts of species misidentification on estimates of maturity and stock productivity in a cryptic rockfish complex.

Shotwell, S.K., Hanselman, D., and Clausen, D. 2007. Assessment of rougheye and blackspotted rockfish in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska. North Pacific Fishery Management Council, 605 W. 4th. Ave., Suite 306, Anchorage, AK 99501-2252.

Table 1. -- Primary functions and analysis workflow implemented in *tier4tools* for Tier 4 spawning potential ratio (SPR) analyses. The table summarizes the sequence of core functions used to construct per-recruit inputs, compute $SPR(F)$ and yield per recruit curves, derive SPR-based fishing mortality reference points (e.g., $F_{40\%}$ and $F_{35\%}$), generate diagnostic outputs, and evaluate sensitivity to key biological and fishery assumptions. Functions are organized by analysis stage to illustrate the intended, reproducible workflow for both single-species stocks and multispecies stock complexes, including optional steps for constrained and unconstrained reference points.

Stage	**Function**	**What it does**	**Inputs**	**Output**	**Typical next step**
Build inputs	spr_input()	Validates and expands life history and fishery schedules across ages, supports single species or multispecies with recruitment proportions	Vector of ages, species-specific life history specifications (len, wt, maturity, selectivity, M), optional rec_prop (used for multispecies), R0	A standardized list object with species and age-specific vectors	plot_spr_inputs() for validating and visualizing inputs, then run_spr()
Visualize inputs	plot_spr_inputs()	Plots implied maturity-at-age, fishery selectivity-at-age, weight-at-age, optional length and *M*. Can compare multiple scenarios	spr_input object, optional compare list	List of ggplot objects	grid_spr_inputs() or proceed to run_spr()
Arrange input plots	grid_spr_inputs()	Combines input plots into a multi-panel layout using the *patchwork* library	list of plots from plot_spr_inputs()	One multi-panel figure	Save figure for report, then run_spr()
Run SPR engine	run_spr()	Computes SBPR, $SPR(F)$, $YPR(F)$, and SPR-based reference	spr_input object, F_vec, spr_targets, optional multispecies constraint,	A standardized list with	plot_spr_curves(), optionally plot_spr_decomp()

Stage	Function	What it does	Inputs	Output	Typical next step
		points (e.g., $F_{40\%}$, $F_{35\%}$), supports multispecies unconstrained and constrained reference points	option to output diagnostics	curves and reference points	
Plot SPR curves	plot_spr_curves()	Plots SPR(F) curve(s) and annotates reference points, handles single species and multispecies (species curves vs complex total, constrained vs unconstrained when present)	spr_out, which = "total"/"species" (for multispecies, plot SPR curves by species or for the full complex)	ggplot object	Use in methods/results, cross-check reference points
Diagnostic plots	plot_spr_decomp()	Age decompositions for SBPR contributions, removals, survivorship, compares F_0 vs F_{SPR}, includes plus-group diagnostics	spr_out (must have diagnostics = TRUE)	List of ggplot objects, plus an attached summary table	grid_spr_decomp() and add to appendix/diagnostics
Arrange diagnostics	grid_spr_decomp()	Combines decomposition plots into a multi-panel layout using the *patchwork* library	list from plot_spr_decomp()	One multi-panel figure	Save figure for report

Stage	Function	What it does	Inputs	Output	Typical next step
Sensitivity grid	spr_sensitivity()	Runs a gridded sweep over key uncertainties (*M*, maturity a_{50}, selectivity a_c, and for two-species, recruitment proportion), re-runs run_spr() per scenario, returns a tidy table	base spr_input, vectors for sensitivity analyses (e.g., vector of *M*, a_{50}, or prop), and multispecies_constraint= c("none", "all_species")	Data frame of reference points and diagnostics by scenario	plot_sensitivity_heat map(), or custom summaries
Sensitivity heatmap	plot_sensitivity_he atmap()	Heatmap for a two-parameter slice of the sensitivity table, optional base-case marker	Output from spr_sensitivity(), x, y (e.g., x="M", y="maturity_a50")	ggplot object	Use in results to show uncertainty patterns
Rec-prop sensitivity	plot_recprop_sensi tivity()	For two-species complexes, compares unconstrained vs constrained reference points across recruitment proportions, optional limiting-species and yield-share diagnostics (when available)	sens_uncon = output from spr_sensitivity(multispeci es_constraint=c("none"), sens_con = output from spr_sensitivity(multispeci es_constraint=c("all_spec ies"), include_yield_share	ggplot object or list of ggplot objects	Use when communicating multispecies complex tradeoffs

Table 2. -- Input values for Gulf of Alaska sharpchin rockfish case study, with details related to sensitivity analyses for natural mortality and fishery selectivity.

Input	**Value**	**Sensitivity Analysis**	**References**
Ages	1-100 years*		Heifetz et al. (1998)
Plus group calculations?	No		
Maturity $m_a(A_{50}, \delta)$	A_{50} = 10.06 y δ = -1.96		C. Lunsford, Alaska Fisheries Science Center, personal communication (1997); Heifetz et al. (1998)
von Bertalanffy growth (L_∞, t_0, k)	L_∞ = 35.02 cm t_0 = -0.75 k = 0.122		Malecha et al. (2007)
Weight-length (α, β)	α = 1.19e-5 β = 3.056		Trawl survey data
Natural mortality *M* (scalar)	0.059	*M* ranging from 0.05 - 0.12 based on maximum age estimators (Cope and Hamel, 2022)	Malecha et al. (2007) using Hoenig (1983) method based on maximum age of 58 y
Fishery selectivity s_a(knife-edge, a_c)	10	a_c ranging from 5-15 years	Limited fishery and survey data

* Age vector was extended to 100 years to account for all fish at ages past the estimated maximum age of 58 years.

Table 3. -- Input values for Gulf of Alaska rougheye and blackspotted rockfish case study.

Input	Rougheye	Blackspotted	Sensitivity Analysis	References
Ages	3-52			Sullivan et al. (2023)
Plus group calculations?	Yes (Plus group = 52)			Sullivan et al. (2023)
Recruitment proportions	0.5	0.5	Proportion rougheye: 0.2-0.8	
Maturity m_a (vector)	c(0.004, 0.003, 0.003, 0.003, 0.003, 0.004, 0.005, 0.009, 0.017, 0.037, 0.085, 0.175, 0.297, 0.412, 0.503, 0.569, 0.616, 0.649, 0.672, 0.688, 0.699, 0.705, 0.708, 0.708, 0.707, 0.705, 0.702, 0.698, 0.693, 0.688, 0.683, 0.677, 0.671, 0.664, 0.658, 0.651, 0.644, 0.637, 0.630, 0.622, 0.615, 0.607, 0.599, 0.591, 0.583, 0.575, 0.567, 0.559, 0.551, 0.543)	c(0.013, 0.013, 0.013, 0.013, 0.014, 0.014, 0.016, 0.018, 0.021, 0.024, 0.030, 0.037, 0.045, 0.054, 0.066, 0.079, 0.093, 0.108, 0.124, 0.139, 0.154, 0.169, 0.182, 0.195, 0.208, 0.220, 0.232, 0.243, 0.255, 0.266, 0.276, 0.286, 0.294, 0.302, 0.308, 0.314, 0.319, 0.323, 0.327, 0.331, 0.334, 0.338, 0.341, 0.345, 0.349, 0.353, 0.358, 0.364, 0.370, 0.370)		Sullivan et al. (in review)
von Bertalanffy growth (L_∞, t_0, k)	L_∞ = 54.4 t_0 = -0.36 k = 0.102	L_∞ = 52.6 t_0 = 0.20 k = 0.062		Harris et al. (2019)
Weight-length (α, β)	α = 1.14e-5 β = 3.098	α = 8.13e-6 β = 3.177		Sullivan et al. (in review)
Natural mortality M (scalar)	0.042			Sullivan et al. (2022b)
Fishery selectivity s_a(vector)	c(0.001, 0.001, 0.003, 0.007, 0.014, 0.028, 0.048, 0.066, 0.064, 0.057, 0.052, 0.076, 0.203, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1)			Sullivan et al. (2023)

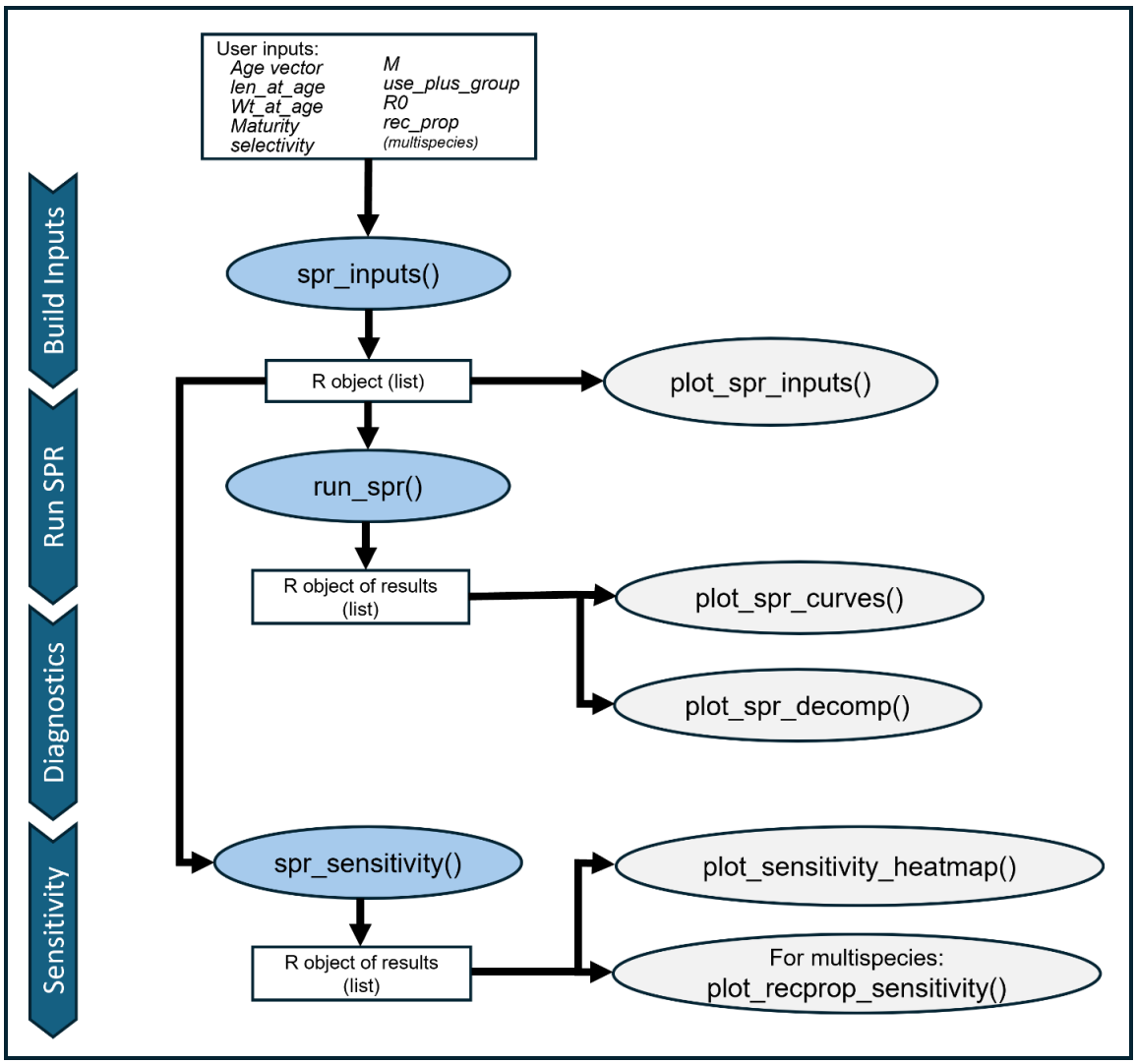


Figure 1. -- Workflow for Tier 4 per-recruit analyses implemented in *tier4tools*. User-specified biological and fishery inputs, including age vector, growth (both length-at-age or weight-at-age), maturity, fishery selectivity, natural mortality (*M*), equilibrium recruitment scaling (*R0*), and optional multispecies recruitment proportions, are first validated and expanded using spr_input(). The resulting input object can be inspected with plot_spr_inputs(). Per-recruit reference points are computed with run_spr(), producing results that can be visualized using plot_spr_curves(). Age-specific decompositions of spawning biomass per recruit can be visualized with plot_spr_decomp(). Sensitivity analyses are conducted with spr_sensitivity(), with outputs summarized using plot_sensitivity_heatmap() and, for multispecies applications, plot_recprop_sensitivity().

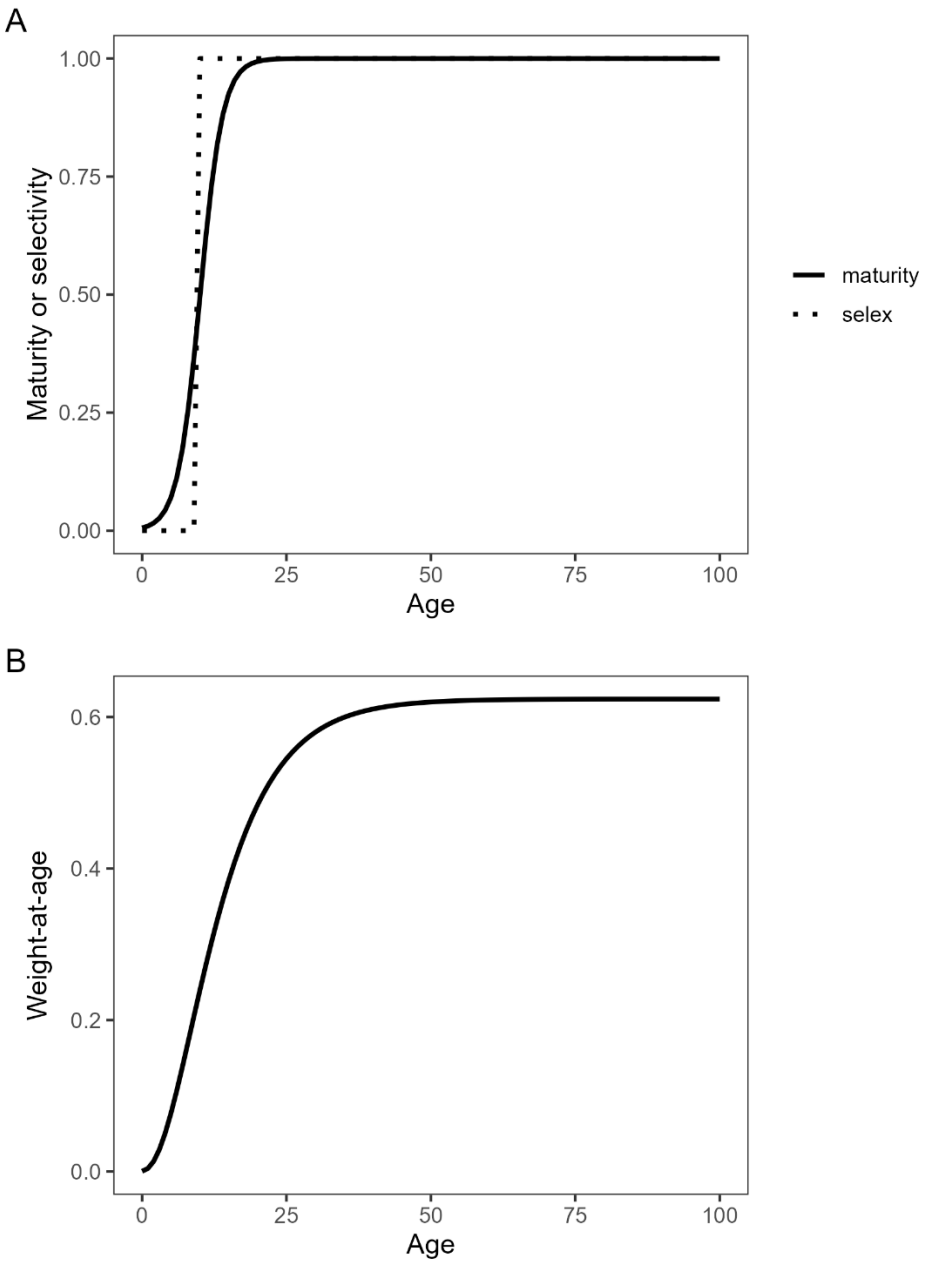


Figure 2. -- Life history schedules used in the Gulf of Alaska sharpchin rockfish case study, including (A) maturity-at-age and knife-edge fishery selectivity-at-age, and (B) weight-at-age (kg).

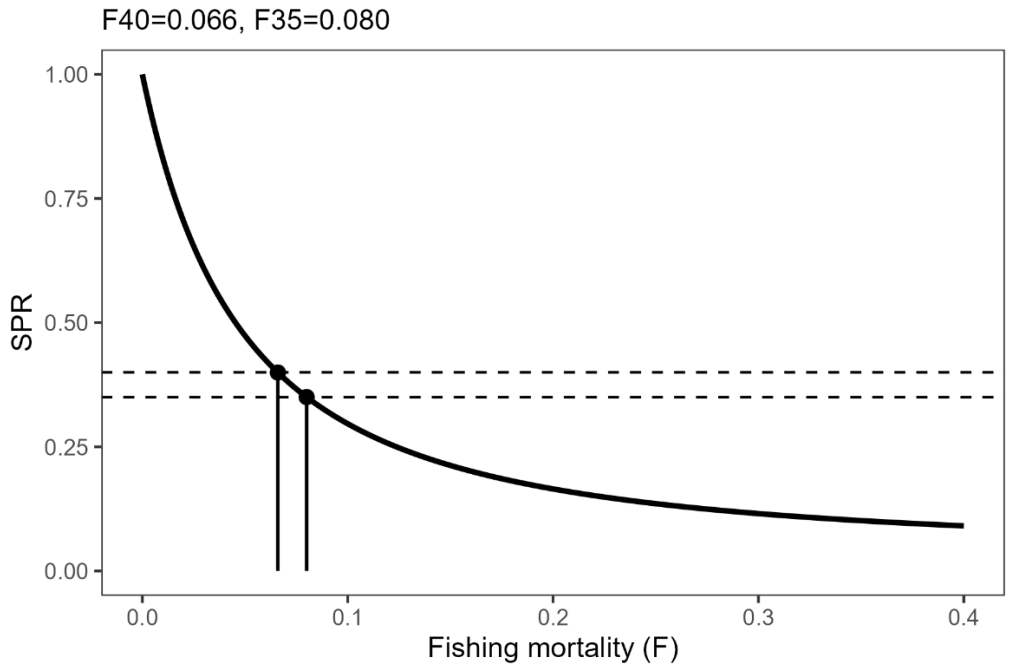


Figure 3. -- Spawning potential ratio (SPR) as a function of fishing mortality (F) for Gulf of Alaska sharpchin rockfish under base case assumptions. Horizontal dashed lines indicate SPR targets of 40% and 35%, with corresponding vertical lines and points denoting $F_{40\%}$ and $F_{35\%}$.

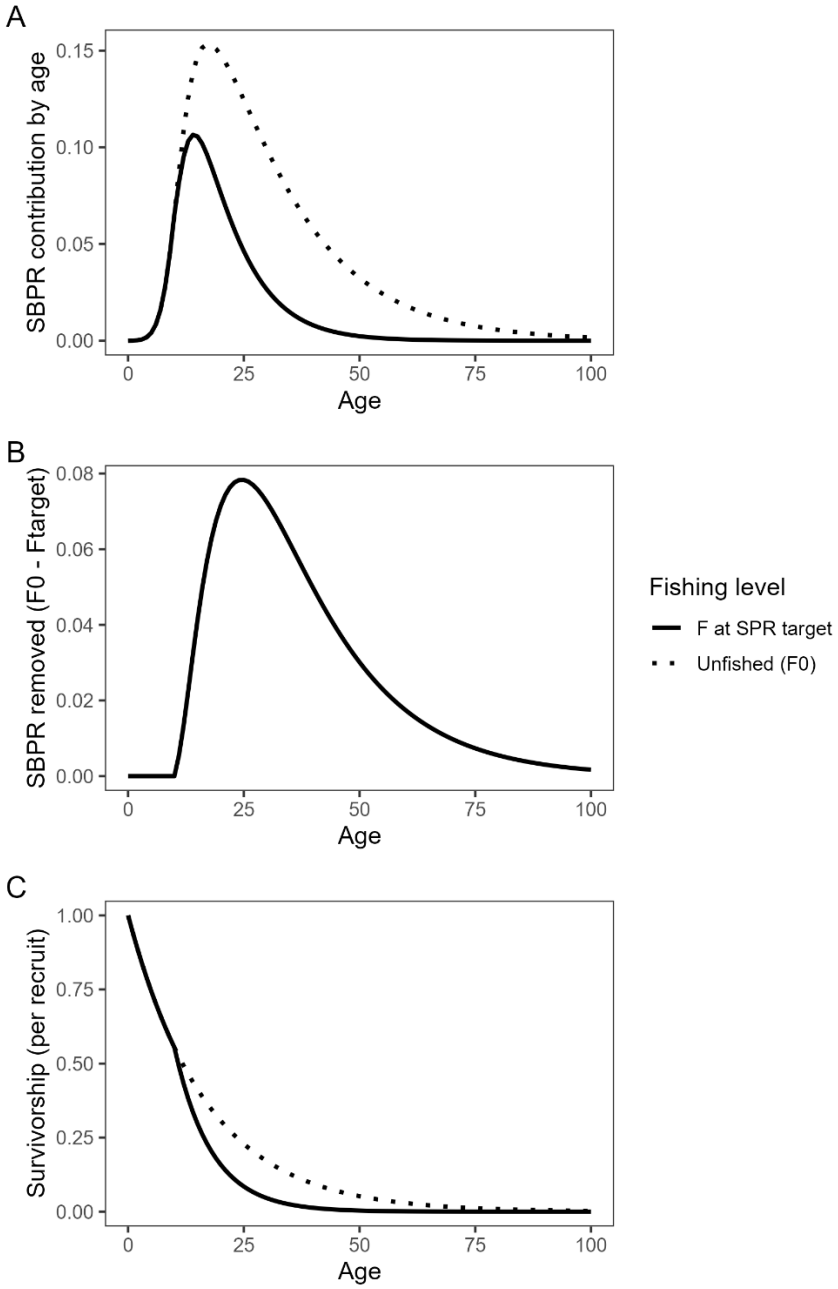


Figure 4. -- Age-based decomposition of spawning biomass per recruit (SBPR) for Gulf of Alaska sharpchin rockfish under base case assumptions: (A) contribution of each age to unfished SBPR (dashed line) and SBPR at the spawning potential ratio (SPR) target of $F_{40\%}$ (solid line); (B) SBPR removed by fishing at $F_{40\%}$ by age; and (C) survivorship per recruit under unfished conditions (dashed line) and at $F_{40\%}$ (solid line).

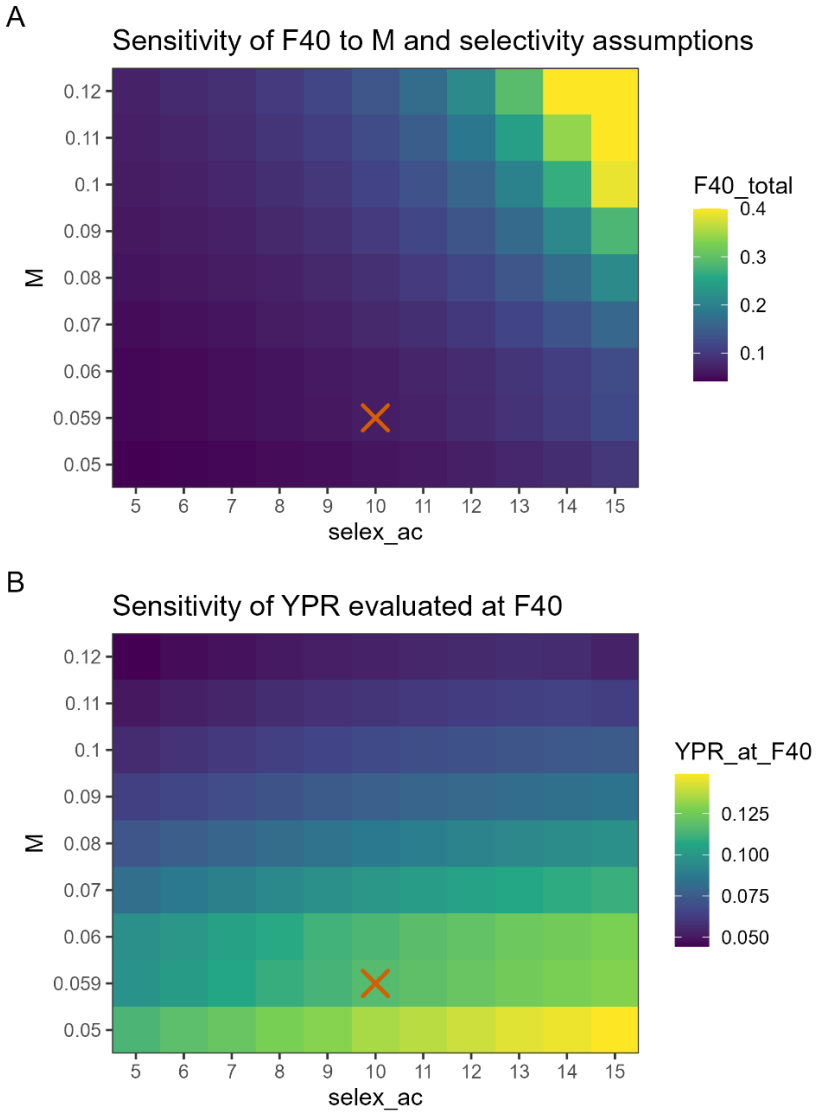


Figure 5. -- Sensitivity of (A) spawning potential ratio (SPR) target of $F_{40\%}$ and (B) yield per recruit (YPR) to natural mortality (M) and age at full selection into the fishery (selex_ac, a_c) for Gulf of Alaska sharpchin rockfish. The orange 'X' denotes results under the base-case assumptions.

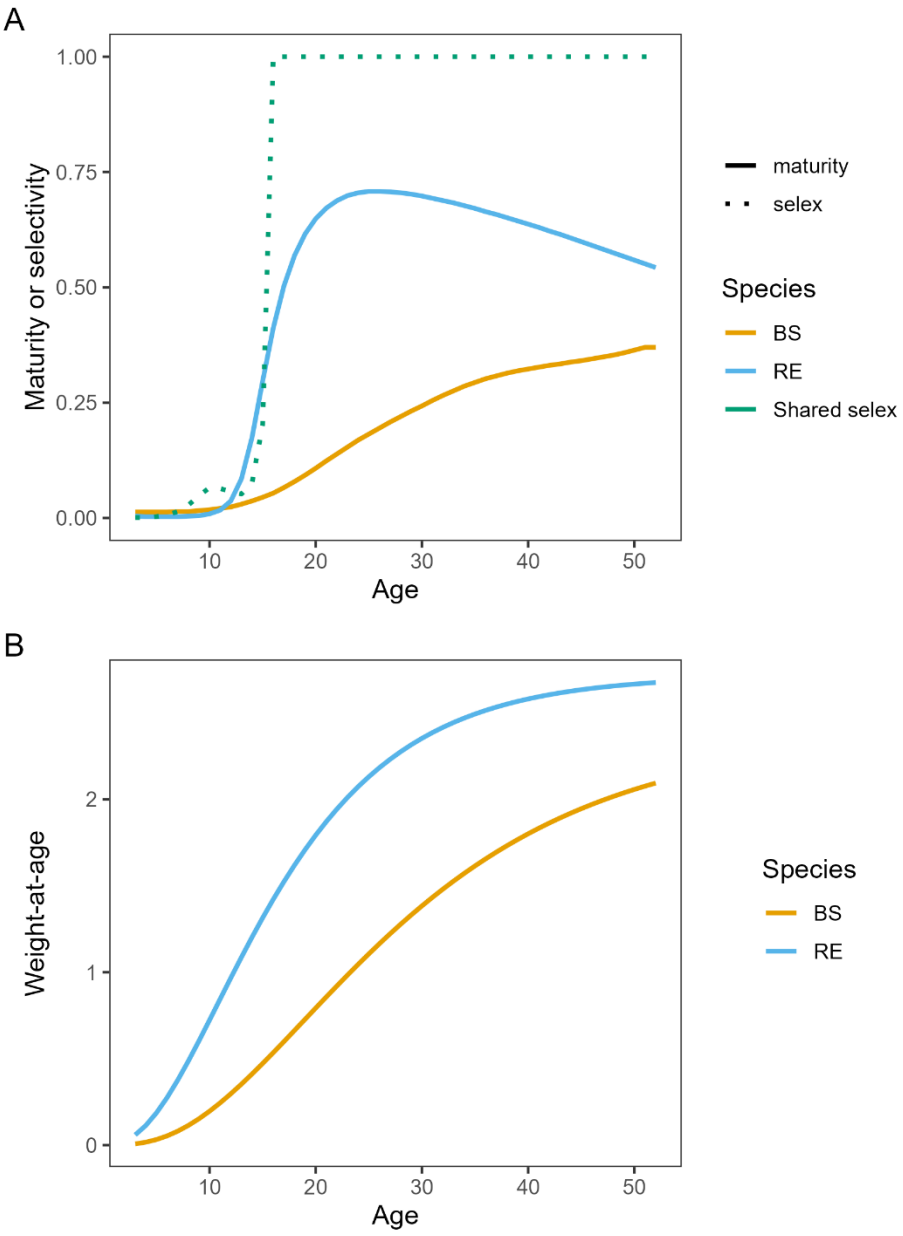


Figure 6. -- Life history schedules used in the Gulf of Alaska rougheye and blackspotted rockfish case study, including (A) maturity-at-age and knife-edge fishery selectivity-at-age, and (B) weight-at-age (kg).

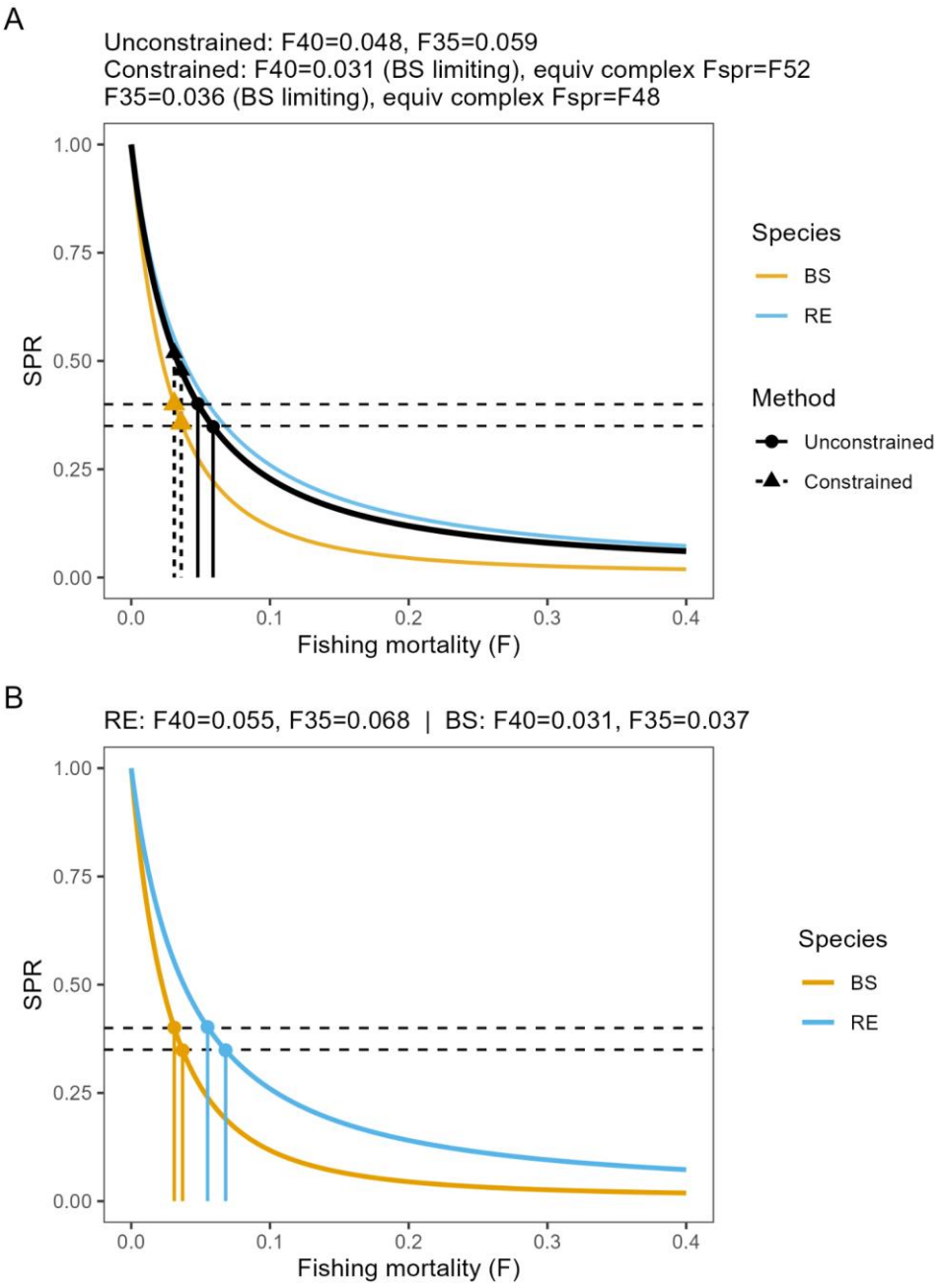


Figure 7. -- Spawning potential ratio (SPR) curves and reference points ($F_{40\%}$ and $F_{35\%}$) for the Gulf of Alaska rougheye and blackspotted rockfish complex case study. (A) Multispecies SPR curve (black line) under unconstrained (circles) and constrained (triangles) reference point calculations, with horizontal lines indicating SPR targets and vertical lines indicating corresponding fishing mortality reference points. The orange triangles on the blackspotted SPR curve highlight this species as the limiting species defining the constrained reference points. (B) Species-specific SPR curves and reference points for rougheye and blackspotted rockfish for comparison.

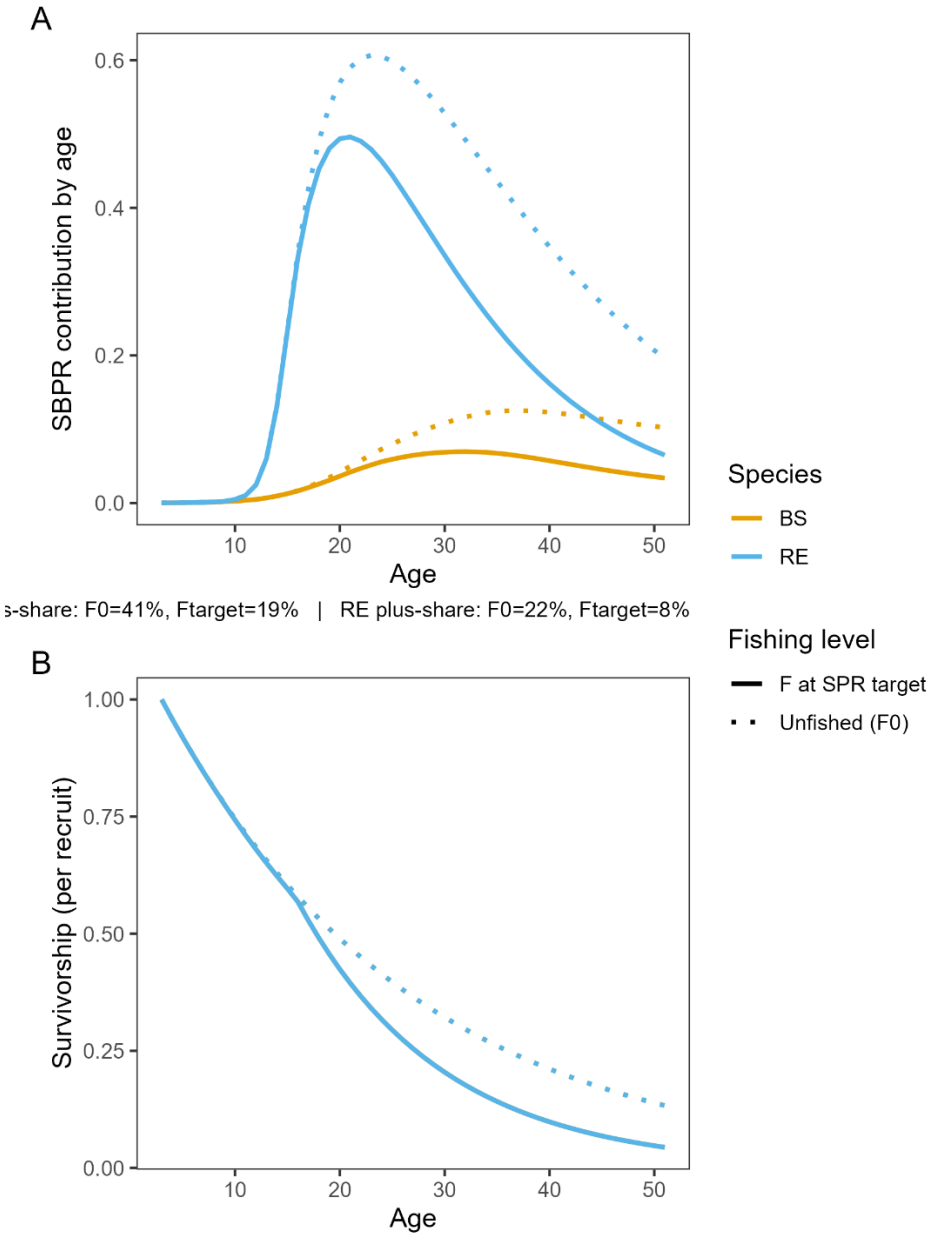


Figure 8. -- Age-based decomposition of spawning biomass per recruit (SBPR) for Gulf of Alaska rougheye and blackspotted rockfish complex under base case assumptions: (A) contribution of each age to unfished SBPR (dashed line) and SBPR at the spawning potential ratio (SPR) target of $F_{40\%}$ (solid line); and (B) survivorship per recruit under unfished conditions (dashed line) and at $F_{40\%}$ (solid line). Plus-group shares of SBPR under unfished and fished conditions are shown below panel A.

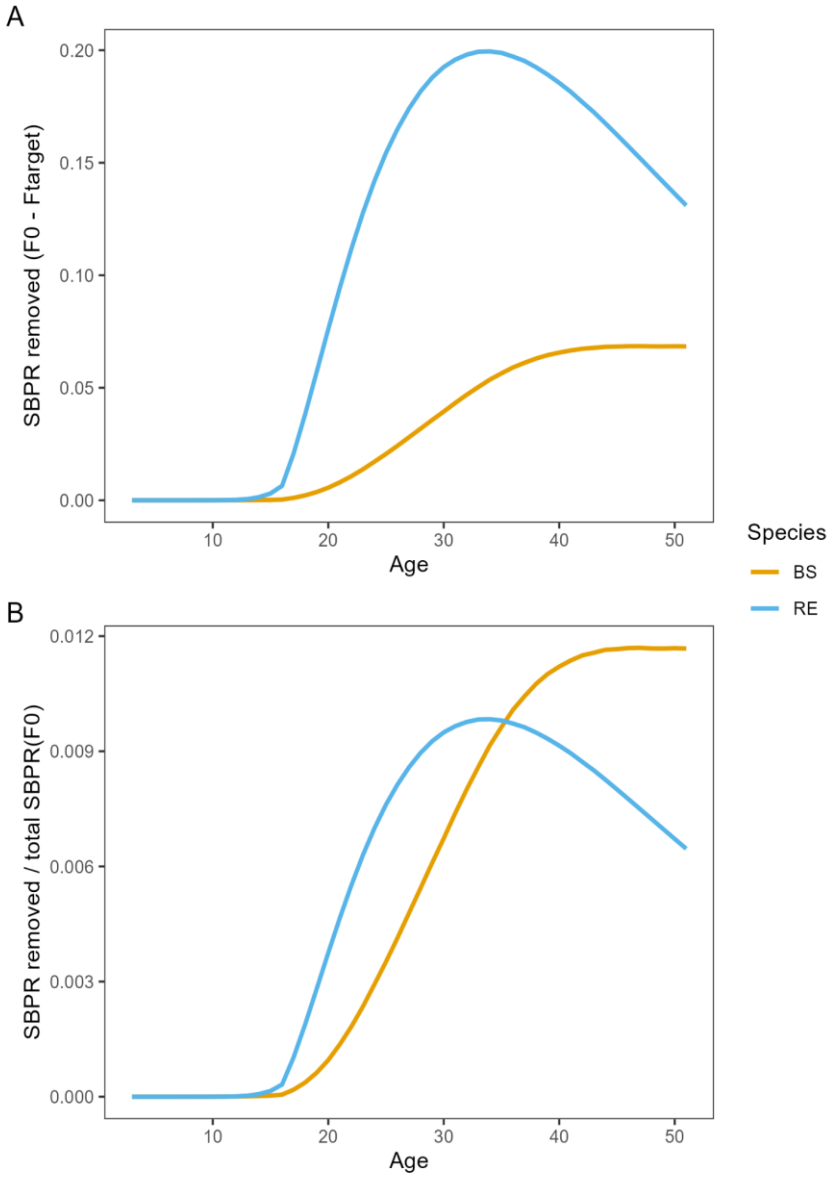


Figure 9. -- Age-based decomposition of spawning biomass per recruit (SBPR) for Gulf of Alaska rougheye and blackspotted rockfish complex under base case assumptions: (A) absolute SBPR removed by fishing at the SPR target of $F_{40\%}$ by age; and (B) SBPR removed by fishing expressed as a proportion of total unfished SBPR for each species.

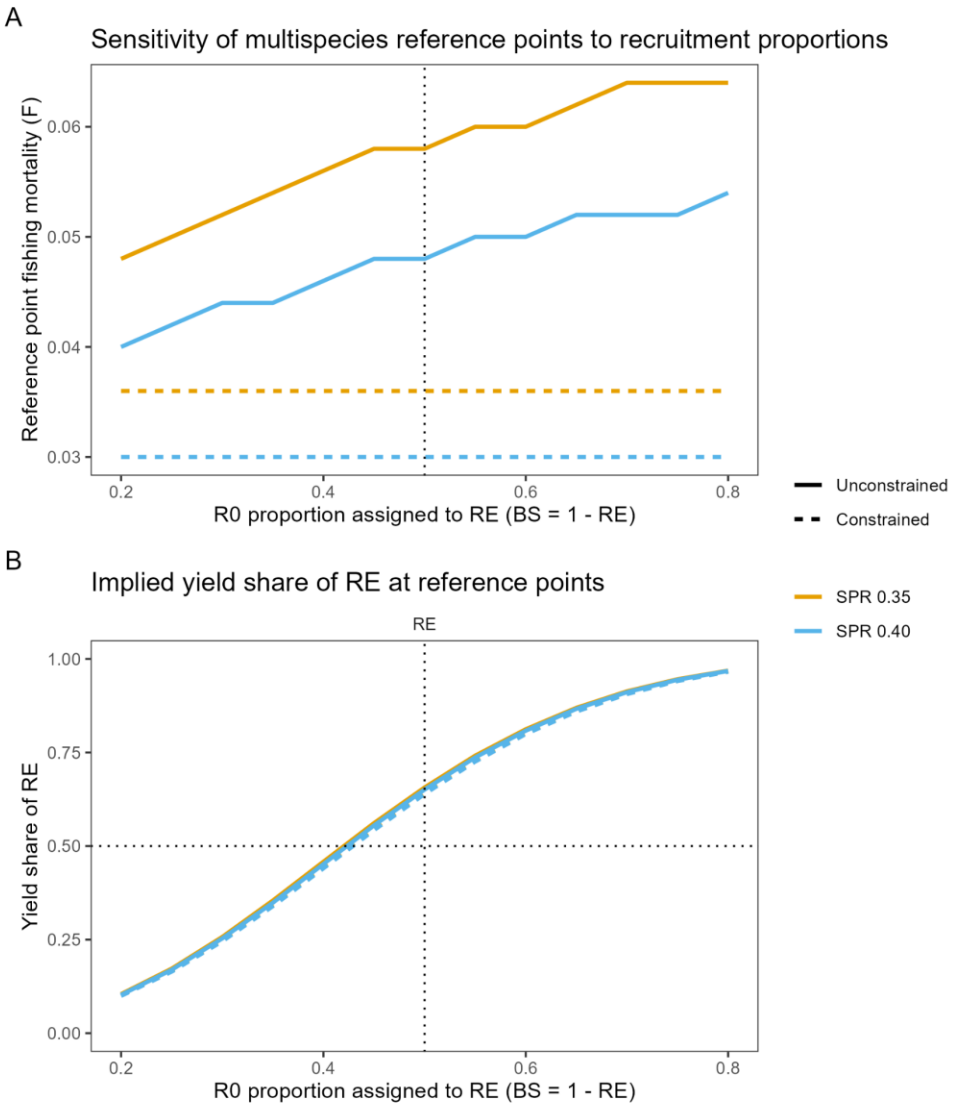


Figure 10. -- Sensitivity of multispecies reference points to recruitment allocation between Gulf of Alaska rougheye and blackspotted rockfish: (A) SPR-based fishing mortality reference points ($F_{40\%}$ and $F_{35\%}$) as a function of the proportion of unfished recruitment assigned to rougheye rockfish, with blackspotted recruitment equal to one minus this proportion; and (B) implied yield share of rougheye rockfish at the SPR 35% and 40% reference points across the same recruitment allocation gradient. Solid lines denote unconstrained reference points, and dashed lines denote constrained reference points with blackspotted rockfish as the limiting species defining constrained reference points. Vertical and horizontal reference lines denote equal recruitment and equal yield shares.



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