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ARTICLE

Data-limited fishery assessment methods shed light on the exploitation history and population dynamics of Endangered Species Act-listed Yelloweye Rockfish in Puget Sound, Washington

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Abstract

Objective: The distinct population segment (DPS) of Yelloweye Rockfish *Sebastes ruberrimus* inhabiting the Puget Sound/Georgia Basin was listed under the Endangered Species Act (ESA) in 2010, and a formal recovery plan for the DPS was published by National Oceanic and Atmospheric Administration Fisheries in 2017. In this recovery plan, the biological criteria for delisting or downlisting were specified as certain levels of spawning potential ratio (SPR), a commonly used metric of equilibrium stock status for commercially exploited fishes. Although this metric can be estimated from length compositions, the combination of length data with a catch history (which was not previously available for this DPS) improves our understanding of population dynamics over time and allows us to estimate a different measure of stock status, relative (to unfished) spawning stock biomass (SSB), rather than only SPR.

Methods: To estimate relative SSB and reconstruct the historical dynamics of this DPS, we reconstructed the catch history from fisheries records, collated length data from historical and contemporary hook-and-line surveys, and fitted a data-limited version of a statistical catch-at-age model.

Result: Despite a high level of uncertainty, we estimated that Yelloweye Rockfish in Puget Sound are above 25% of unfished biomass (a reference point detailed in the recovery criteria) under the assumption of deterministic recruitment, presenting the first direct estimates of Yelloweye Rockfish population status in Puget Sound.

Conclusion: However, as informed by recent genetic studies, the DPS boundaries of ESA-listed Yelloweye Rockfish extend from South Puget Sound to Queen Charlotte Strait in British Columbia. The Canadian portion of this population is managed separately and is currently estimated to be at 32% of unfished biomass (95% quantiles = 15%–68%). Thus, the disjunction between the biological boundaries of the population and the jurisdictional boundaries between Canada and the United States presents an additional source of uncertainty in assessing recovery that must be addressed to achieve DPS-wide recovery goals.

KEYWORDS

catch reconstruction, data-limited stock assessment, fisheries, management, population dynamics, threatened and endangered species

INTRODUCTION

For species of conservation concern, the data available for population viability analysis or status assessments can be severely lacking, often owing to limited agency resources and the rarity of listed species (Schwartz 2008). Nevertheless, Section 4(c)(2) of the U.S. Endangered Species Act (ESA) requires regulatory agencies to conduct a status review once every 5 years for any listed species, including demographically discrete and significant distinct population segments (DPSs). Therefore, because consequential changes in listing status (i.e., downlisting, delisting, or uplisting) and additional regulatory decisions are highly influenced by these 5-year reviews, quantitative analytical methods to assess population status and viability despite limited data are crucial for federal agencies to fulfill their mandates.

In the Pacific Northwest, two rockfish species have DPSs that are listed under the ESA: the Puget Sound/Georgia Basin (PSGB) DPS of Yelloweye Rockfish *Sebastes ruberrimus* is listed as threatened, while the PSGB DPS of Bocaccio *Sebastes paucispinis* is listed as endangered (Endangered and Threatened Wildlife and Plants 2010). Due to their extreme rarity within the DPS boundaries, data on Bocaccio since the time of listing have been very limited, precluding any quantitative analysis. In contrast, Yelloweye Rockfish have been sampled with comparative regularity, and recent genetic evidence has confirmed that Yelloweye Rockfish collected from Puget Sound, Washington, to Queen Charlotte Strait, British Columbia (Figure 1), are distinct from populations found on the outer coast (Andrews et al. 2018). The Yelloweye Rockfish is a deepwater rockfish with low productivity and episodic recruitment (Love et al. 2002), but given the species' longevity, these episodic recruitment events do not greatly affect population persistence. Yelloweye Rockfish have a maximum reported age of 147 years (Love 2011). Due to their late age at maturity and low productivity, many species of rockfish are highly vulnerable to fisheries exploitation (Parker et al. 2000; Williams et al. 2010). Yelloweye Rockfish have been heavily exploited throughout their range, which extends from California through the Gulf of Alaska (Gertseva and Cope 2017; Yamanaka et al. 2018; Wood et al. 2021). Within each area where Yelloweye Rockfish are currently fished commercially,

Impact statement

Yelloweye Rockfish in Puget Sound are listed under the Endangered Species Act, but monitoring their recovery is difficult due to a lack of data. In this study, we applied elements of historical ecology and data-limited fisheries stock assessment methods to estimate the status of this population for the first time, which will inform management actions to recover this species.

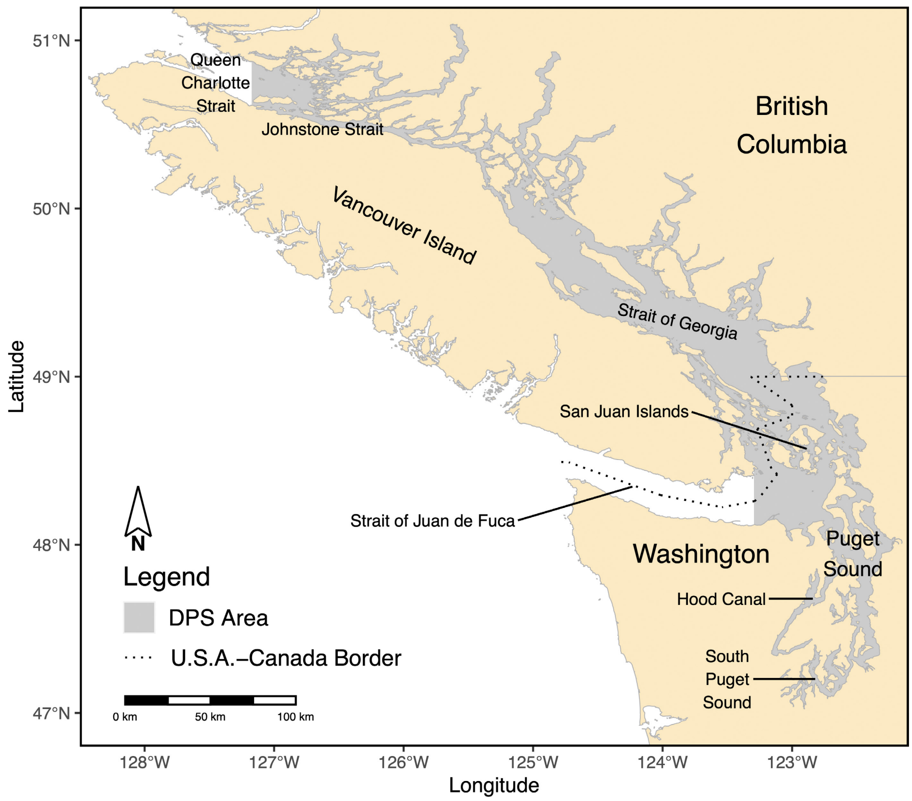

FIGURE 1 Boundaries of the Puget Sound/Georgia Basin Distinct Population Segment (DPS) of Yelloweye Rockfish.

the corresponding management agency (Department of Fisheries and Oceans Canada [DFO], National Marine Fisheries Service [NMFS], or Alaska Department of Fish and Game) conducts regular stock assessments, which integrate available fishery-independent and fishery-dependent data into a population model. The most recent status assessment for the West Coast stock estimated that it was at 28% of unfished biomass (Gertseva and Cope 2017), while the coastal British Columbia stock was estimated to be at 18% of unfished biomass (Yamanaka et al. 2018).

Prior to the 1960s, rockfishes in Puget Sound were not a primary target of commercial and recreational fisheries, and monitoring of individual rockfish species within catches was consequently not a priority for the Washington Department of Fisheries (WDF; DiDonato 1969; Palsson et al. 2009). However, new Puget Sound groundfish fisheries were developed in the 1970s, and these opportunities were promoted to commercial and recreational fishers that were displaced by the closure of Canadian waters to foreign fishing fleets and the 1974 United States v. Washington federal court ruling that reaffirmed treaty fishing rights and reduced the salmon quota for nontribal fishers (Palsson et al. 2009). The first Puget Sound groundfish management plan was later published in 1982, although the rapid development of these fisheries in the intervening years resulted in catch reporting and monitoring that were not comprehensive (Pedersen and DiDonato 1982; Palsson et al. 2009). As a result, abundance information on specific rockfish species in Puget Sound into the 1970s is severely lacking; when the original decision was made to list PSGB Yelloweye Rockfish under the ESA, trends in abundance were based on trends in total rockfishes, with proxy data (e.g., frequency of occurrence in recreational or commercial fishery surveys) used to provide species-specific information (Drake et al. 2010).

The lack of estimates for abundance or biological data (e.g., lengths or ages) has limited the ability to assess the status of ESA-listed rockfishes with respect to their species-specific recovery criteria based on spawning potential ratio (SPR; Tonnes et al. 2016; National Marine Fisheries Service 2017b). The SPR, which is defined as the proportion of the unfished reproductive potential remaining at a given level of fishing pressure (Hordyk et al. 2015), was chosen by the recovery team based on the ability to estimate it using limited data (National Marine Fisheries Service 2017b). However, data-limited methods capable of estimating SPR or other metrics of stock status from the sparse data available for rockfish species in Puget Sound were not yet well articulated at the time the listing decision was made in 2010 or during the first 5-year review after listing (Tonnes et al. 2016). This is because many data-limited assessment methods were developed in response to the 2006 amendments to the Magnuson–Stevens Fishery Conservation and Management Act (hereafter, Magnuson–Stevens Act [MSA]), which established legal mandates to identify annual catch limits for all stocks (Newman et al. 2015). While the MSA dictates how commercially exploited fish stocks are managed, the ESA relates to species threatened with extinction within a DPS. Thus, these recently developed methods to assess fish stocks managed under the MSA present an opportunity to provide new, species-specific insights into the dynamics of an ESA-listed species.

Earlier studies of rockfishes in Puget Sound strongly supported a significant decline in overall populations over the past 40 years (Palsson et al. 2009; Williams et al. 2010). A previous study of population trajectories of rockfishes in Puget Sound indicated an annual average decrease of 3.9% per year, translating to a 77% decline from 1977 to 2014 (Tolimieri et al. 2017). That study, which represented the best available science at the time of the last 5-year review in 2016, was based on two data sources: (1) catch per unit effort (CPUE) from recreational anglers, as determined via catch record cards, phone interviews, and creel surveys (e.g., Kraig and Scalici 2019); and (2) CPUE from a long-term, systematic trawl survey conducted by the Washington Department of Fish and Wildlife (WDFW; Quinnell and Schmitt 1991; Palsson et al. 2002; Blaine et al. 2020). However, the applicability of those data for informing the status of ESA-listed Yelloweye Rockfish was limited by the infrequency with which this species was detected by those methods (Tolimieri et al. 2017). In the case of the recreational fishery data, regulatory changes, which included reductions in bag limits starting in 1994 (Palsson et al. 2009), a prohibition on Yelloweye Rockfish retention in 2002, and a 36.576-m (120-ft) depth limit when targeting bottom fish in 2010, meant that this deepwater species was not well represented by the overall trends in rockfish abundance. In addition, the WDFW trawl survey, which mainly samples soft-bottom habitat, does not effectively sample Yelloweye Rockfish, as this species is typically associated with rocky habitat (O'Connell and Carlile 1993; Love et al. 2002; Pacunski et al. 2013, 2020). Therefore, to inform the status of this species with respect to recovery criteria, methods that disaggregate ESA-listed Yelloweye Rockfish from encounters with other rockfishes, are necessary.

Here, we present a case study of how methods that are typically applied to commercially exploited species can shed light on the status of ESA-listed Yelloweye Rockfish in PSGB when presented with only a catch history and limited length composition data. By using a modified version of Stock Synthesis (SS), a statistical age-structured population modeling framework (Methot and Wetzel 2013) used to assess other groundfish species in U.S. fisheries, with catch and length data only (Rudd et al. 2021), we generated quantitative estimates of population status that can be used to inform future conservation and management actions under the ESA framework.

METHODS

Catch reconstruction

Removal histories provide both magnitude and trend in fishing mortality rates, which can help to determine the conditions under which fishing mortality affects fish populations (Ralston et al. 2010). A catch reconstruction for Puget Sound Yelloweye Rockfish was completed for the first time in this study in order to develop hypotheses on which removal histories could lead to historically low abundance. This required a reconstruction of the two main fisheries for Yelloweye Rockfish in Puget Sound: the commercial and recreational fisheries.

Rockfish catches from commercial and recreational fisheries in Puget Sound were previously reported by Palsson et al. (2009); the recreational catches were reported from 1970 to 2007, and the commercial catches were reported from 1921 to 2007. Because of limited species composition data and often low confidence in species assignments, these catches were only reported at the genus (*Sebastes*) level (Palsson et al. 2009). In this study, we expanded the taxonomic and temporal resolution of this catch history, estimating the commercial catch of Yelloweye Rockfish from 1921 to 2020 and the recreational catch from 1938 to 2020.

To partition Yelloweye Rockfish catches from estimates of total rockfish catch, we applied the available species composition data (1970–present for commercial landings; 1965–1967 and 1980–present for recreational landings) to these catches and constructed alternative catch history scenarios using uncertainty in these catches. The catch scenarios incorporated spatially and temporally varying sources of uncertainty corresponding to the data sources and the primary associated uncertainty for each time period, an overview of which is presented in the following sections. Although there are still remaining sources of uncertainty that could not be addressed through our catch scenario approach, the bounding of uncertainty presented here gives a reasonable estimate of plausible removal histories sufficient for our modeling approach. Detailed information on the catch reconstruction and the creation of catch scenarios can be found in the Supplementary Methods (available separately online).

The resulting catch scenarios were as follows: a "medium" catch scenario, which served as the "most likely" estimate, coupled with "high" and "low" catch scenarios, which attempted to capture the upper and lower bounds of uncertainty. In accordance with a recent genetic study (Andrews et al. 2018) that showed differentiation between the Yelloweye Rockfish population in Hood Canal and the rest of PSGB, we excluded Hood Canal from the catch history we present for Yelloweye Rockfish in Puget Sound. Ecological conditions within Hood Canal—specifically, seasonal bouts of low dissolved oxygen—have also resulted in the application of a distinct fishery management regime to this area.

Commercial catch reconstruction

The reconstruction of commercial catches of Yelloweye Rockfish in Puget Sound was conducted in three general steps: (1) estimating catches of total rockfish from fisheries records; (2) estimating the proportion of total rockfish catch that was Yelloweye Rockfish; and (3) generating catch scenarios based on the sources of uncertainty associated with steps 1 and 2.

We estimated the total catch of rockfishes by using different data sources collected by the WDF and later the WDFW. Quantitative estimates of rockfish landings from the commercial fishery in Puget Sound began in 1921 based on receipts from taxes levied on the sale of various fish products (Nye 1982). This system of estimating landings, which had issues associated with the limited information gleaned from tax receipts (e.g., limited spatial resolution; origin of catch was sometimes unclear), was improved in 1935 with the advent of the fish ticket system (Nye 1982). This system required fishermen to report catches on standardized tickets that included fields for critical information, such as catch area and gear type. With slight improvements over time, such as the introduction of an interview system in the 1950s to gather additional information from fishing vessel captains (Alverson 1957), the fish ticket system remained in place for the majority of the history of the commercial bottom fish fishery in Puget Sound. Significant regulatory changes banned commercial bottom fish trawl, jig, and troll fishing throughout Puget Sound east of Neah Bay by the early 1990s (Palsson et al. 2009), and the remaining fisheries that employed gear with a risk of rockfish impacts were closed in 2010 (Washington Department of Fish and Wildlife 2010).

Species composition data from the commercial fishery that are necessary to prorate the catch of rockfishes into species are very limited. Prior to 1970, when the WDF began collecting field samples of commercial catches, there was no reliable species composition information for rockfishes. The only exception to this for Yelloweye Rockfish is that “Red Snapper” was a reporting category from 1955 to 1969 and was a common name used for Yelloweye Rockfish at the time (Kincaid 1919; Smith 1937). Therefore, for our catch reconstruction, when “Red Snapper” catch was reported during the period 1955–1969, “Red Snapper” landings were interpreted as the total Yelloweye Rockfish landings for the time period. In all other time periods prior to 1970, Yelloweye Rockfish landings were estimated by prorating total rockfish catch to individual species by using species composition data from WDFW commercial landings by gear type and region from 1970 to 1987 (the closest time period for which species composition data were available; Pedersen and Bargmann 1986; Schmitt et al. 1991). From 1970 onwards, field samples taken by the WDFW from commercial catches were used to prorate the catch of total rockfish into species from the same or similar time periods.

Recreational catch reconstruction

The recreational fishery for bottom fish in Puget Sound has been a significant monitoring challenge for the WDF/WDFW but is also responsible for the majority of the landings of PSGB Yelloweye Rockfish, which are associated with rocky habitats (Palsson et al. 2009). The estimates of recreational rockfish harvest from 1970 to 2007 (Palsson et al. 2009) formed the basis for our catch reconstruction. We expanded the temporal extent of this catch history back to 1938 using early reports by the WDF on the sport fishery, and we prorated all catch to species using (1) species composition data from the Marine Recreational Fisheries Statistical Survey, which collected data from 1980 to 2002; or (2) species composition estimates generated in early studies of the recreational bottom fish fishery (Buckley 1967, 1968; Buckley and Satterthwaite 1970).

Monitoring of recreational fisheries in Puget Sound was historically focused on salmon, with only sparse reports on bottom fish harvest until 1965 (DiDonato 1969). During this time, most bottom fish catch was bycatch from salmon anglers, whose effort and catch were much more closely monitored; thus, catch rates of bottom fish by salmon anglers were used to inform our estimates of Yelloweye Rockfish harvest from 1938 to 1965. From 1938 to 1941, the WDF attempted to estimate catches from the sport fishery for the first time, with inclusion of “rockfish” and “Red Snapper” as reporting categories. These reports, with adjustments made for underreporting, constitute the start of our time series of recreational catches. However, starting in 1942, the WDF abandoned attempts to report catches of all species and focused only on salmon and total angler effort. The CPUEs from the 1938–1941 reports were thus applied to estimates of total angler-days from the period 1942–1965 to estimate catches of rockfish.

In 1965, the WDF began an attempt to monitor the growing recreational fishery targeting bottom fish

(Buckley 1967). This initiated a series of reports on the bottom fish sport fishery for 1965–1973 (Buckley 1967, 1968; Buckley and Satterthwaite 1970; Bargmann 1977). In our catch reconstruction, the report from 1965 was omitted due to anomalies in data reporting, and catches from 1970 onwards were re-estimated by Palsson (1987); therefore, we only used the reports from the years 1966–1969.

From 1970 to 2003, the WDFW estimated catches from the recreational bottom fish fishery through a combination of catch records from salmon anglers and a dockside creel survey of hook-and-line anglers (Palsson et al. 2009). Salmon anglers were required to return catch record cards, from which the number of salmon trips was estimated. The creel survey was used to determine the bottom fish catch per trip, which was then multiplied by the number of trips per month and area to estimate the total number of bottom fish caught (Palsson 1987). An assumption inherent in these estimates is that dockside creel surveys, which sampled only a small fraction of angler trips, were representative with regard to the bottom fish encounter rate on a spatiotemporal scale that was fine enough to justify this expansion method. In addition, reliance on the salmon sport fishery to estimate bottom fish catches proved problematic after large-scale closures of salmon fisheries from 1994 to 2003 (see Supplementary Methods).

From 2003 to 2020, the WDFW conducted surveys of the recreational fishery through a telephone survey of licensed fishers to estimate fishing effort and through a dockside creel survey that estimated catch rates of specific species (e.g., Kraig and Scalici 2019). This new system removed the reliance on open salmon fisheries for bottom fish catch estimates and was deliberately designed to obtain data for all target species. Importantly, this reporting system also collected information on released rockfish, which was previously not obtained, thereby allowing separation of the encounter rate and the retention rate. This change was crucial to estimating fishery impacts after rockfish retention was banned across the whole of Puget Sound in 2010. We applied estimates of released rockfish mortality to this information to estimate total mortality. Although there are significant sources of uncertainty in catch estimates from the creel survey (e.g., possible underreporting, species misidentification, and inconsistent data weighting), fishery mortality from this time period was minor compared to preceding time periods, and this uncertainty is addressed in the catch scenarios (see Supplementary Methods).

Length composition data sources

Catch data alone are typically insufficient to determine stock status (Free et al. 2020; Ovando et al. 2021). Therefore, the second set of information needed to evaluate the status of Yelloweye Rockfish is the biological composition of the population. Age data are preferred because they give a direct measure of population age structure, but they are more difficult to obtain and the sampling of structures for age estimation is usually lethal, thus limiting the collection of age data for ESA-listed species. As a proxy for age data, we used length composition data from three hook-and-line research surveys (1974–1977, 2014–2015, and 2017–2019) that caught Yelloweye Rockfish in Puget Sound. Because of small sample sizes, data from the two recent surveys were combined, resulting in two distinct time periods of data (a historical sample and a contemporary sample). Each survey used recreational fishing methods to sample areas where anglers currently or historically targeted rockfish; thus, the length composition data were assumed to reflect the selectivity and encounter likelihood of the recreational fishery. Although the recreational fishery is now closed, the selectivity of the surveys during the time period after fishery closure is assumed to be the same as that of the open recreational fishery. This is an important assumption of the modeling framework (see Population dynamics model).

The best historical data available are from a hook-and-line survey of marine fishes (Washington et al. 1978). This survey covered the years 1974–1977 and was intended to gather information supporting the growth of a recreational rockfish fishery and to inform understanding of the biology and ecology of rockfish in Puget Sound (Browning 2014). The survey used a variety of recreational fishing methods (e.g., angling with bait such as herring, squid, jigs, or spinners) in 0–180 m of water; effort was focused primarily in Puget Sound proper (the marine waters extending eastward from the mouth of Admiralty Inlet) but also extended into the Strait of Juan de Fuca. The sampling area was divided into a grid of units of 3.43 km^2 (1 nautical mi^2) and sampling targeted areas of suspected rockfish habitat. Researchers departed from Seattle or Mukilteo, Washington, and targeted areas that had the characteristics of high-quality rockfish habitat: complex bottom structure, kelp beds, and areas of known rockfish abundance (Browning 2014). For this analysis, we used only the lengths of Yelloweye Rockfish that were caught within the PSGB DPS boundaries, excluding Hood Canal.

More contemporary length distribution data were gathered from two research projects focused specifically on ESA-listed rockfishes. First, we used length data collected by Andrews et al. (2018) in 2014 and 2015 for all individuals caught within the DPS boundaries, excluding Hood Canal ("ESA Genetics" study). That project used similarly common hook-and-line fishing methods as the Washington et al. (1978) study and typically fished at depths from 30 to 100 m. However, sampling effort for that study was not uniformly distributed; rather, it targeted sites where ESA-listed rockfish species were most likely to be found. Site selection was informed by consultation with recreational fishing guides, local fishing captains, local angler clubs, scientists, and managers, as well as recent and historical observations from recreational anglers, remotely operated vehicle (ROV) surveys (Pacunski et al. 2013, 2020; Lowry et al. 2022), scuba divers, and other research and monitoring surveys (e.g., Blaine et al. 2020). As a second contemporary source, we used length data collected during a research project studying the rates of rockfish bycatch and the effects of various bait types on rockfish bycatch in the Lingcod *Ophiodon elongatus* fishery in Puget Sound during 2017–2019 ("Lingcod Bycatch" study; K. Andrews, unpublished data). This study used three specific types of bait and targeted 12 sites in the main basin of Puget Sound and the San Juan Islands, where Lingcod were most prevalent during the ESA Genetics study.

Population dynamics model

The main objective of the population dynamics model was to gain insight into the relative stock status—calculated as the fraction of unfished population size—of the PSGB Yelloweye Rockfish DPS across significant sources of uncertainty. The lower end of the uncertainty interval is interpreted as the conservative estimate of population status as well as an indication of the risk of extinction. We also focus on relative stock size rather than absolute stock size, as the measure of absolute abundance is highly uncertain given the limited data. Measures of absolute abundance are only needed if setting catch limits under fisheries management frameworks, which is both outside the scope and capabilities of our analysis, whereas relative stock status offers a direct measure of population recovery within an ESA context.

The portion of the PSGB Yelloweye Rockfish DPS that occurs in U.S. waters is the only portion of the stock considered in this analysis. Although genetic research (Andrews et al. 2018) indicated that there is one panmictic Yelloweye Rockfish population (excluding Hood Canal) from South Puget Sound to Queen Charlotte Strait in British Columbia, the Canadian portion of the PSGB DPS was excluded from this analysis. We modeled the U.S. data separately for three reasons: DFO recently completed an assessment of Yelloweye Rockfish in British Columbia inside waters ("Inside" Yelloweye Rockfish), for which more data are available (Haggarty et al. 2021); the population size of Yelloweye Rockfish in Canadian waters is much higher than that in Puget Sound and would swamp any signal in the U.S. portion of the DPS; and data-driven recovery actions identified within U.S. waters of the DPS are under the regulatory authority of NMFS and the WDFW.

The population dynamics model used for this analysis was SS with catch and length compositions only (SS-CL; Rudd et al. 2021), and different model formulations were used to explore uncertainty. For each of the model formulations, length data from the hook-and-line research projects and the catch histories were the main data inputs into SS-CL. Stock Synthesis (Methot and Wetzel 2013) is an integrated stock assessment framework that provides for flexibility in data treatment, allowing it to be highly scalable to the amount of data available. The SS-CL model uses the SS framework but includes only catch and length data and usually fixes the values of life history parameters. The SS-CL formulation of SS has been demonstrated, through simulation testing and comparisons to full stock assessment results, to generate low-bias estimates of key population quantities (including stock status) when life history parameter values are reasonably specified and with as little as 1 year of length data, although performance improves with larger sample sizes and more years of length data (Rudd et al. 2021).

We explored uncertainty in our different model formulations by changing two major inputs: catch histories and the value of natural mortality (M). Exploration across possible Beverton–Holt steepness values (a measure of stock productivity; values searched ranged from 0.3 to 1.0, with the reference model at 0.72) was also performed, but it produced very limited model sensitivity; therefore, those results are not included here. Natural mortality is a common life history trait used to explore parameter uncertainty, as it is hard to estimate directly and is highly influential for estimates of stock status (Punt et al. 2021). The SS-CL model was run using three catch scenarios (high, medium, and low), each of which was also applied to a series of M-values. The series of M-values was based around a lognormal distribution with a mean of 0.044 (Gertseva and Cope 2017) and a standard deviation of 0.31, as suggested by Hamel and Cope (2022); this resulted in a series of explored M-values ranging from 0.024 (~2.5% quantile) to 0.081 (~97.5% quantile), with a step of 0.004.

Length data from the three research projects previously described (Length composition data sources) were the primary data sources for the SS-CL model. Although other length composition data were available from samples of recreational catch, they were not included in the final version of the SS-CL model because of their likely biased sampling of larger individuals, which did not reflect the selectivity of the fishery. When the SS-CL model was run with these length data included, the model was unable to fit due to the high number of very large individuals in the data set with lengths considerably higher than the average asymptotic length value. The anomalously high prevalence of very large individuals could be explained by known issues in catch reporting, such as high grading, whereby large individuals are overrepresented in the data (Ainsworth and Pitcher 2005). Therefore, length compositions from the two time periods described earlier (Length composition data sources) are the only length data included in the model and are assumed to represent the recreational fishery selectivity. In total, 28 Yelloweye Rockfish lengths were available from the 1970s, which were summarized into a single year (1975) due to small sample sizes, compared to 62 lengths from the surveys in the 2010s, which were similarly summarized into a single year (2015); the year 2015 was chosen because this was the mean catch year once all of the length samples from the contemporary surveys were aggregated. Given the long life span and relatively slow dynamics of Yelloweye Rockfish populations, this aggregation of lengths is reasonable. The length compositions are shown in Figure 2 for 1975 (Figure 2A) and 2015 (Figure 2B). Life history parameters for Yelloweye Rockfish were fixed at the values from the most recent stock assessment for the U.S. West Coast stock (Gertseva and Cope 2017) and are provided in Supplemental Table 1 (available separately online).

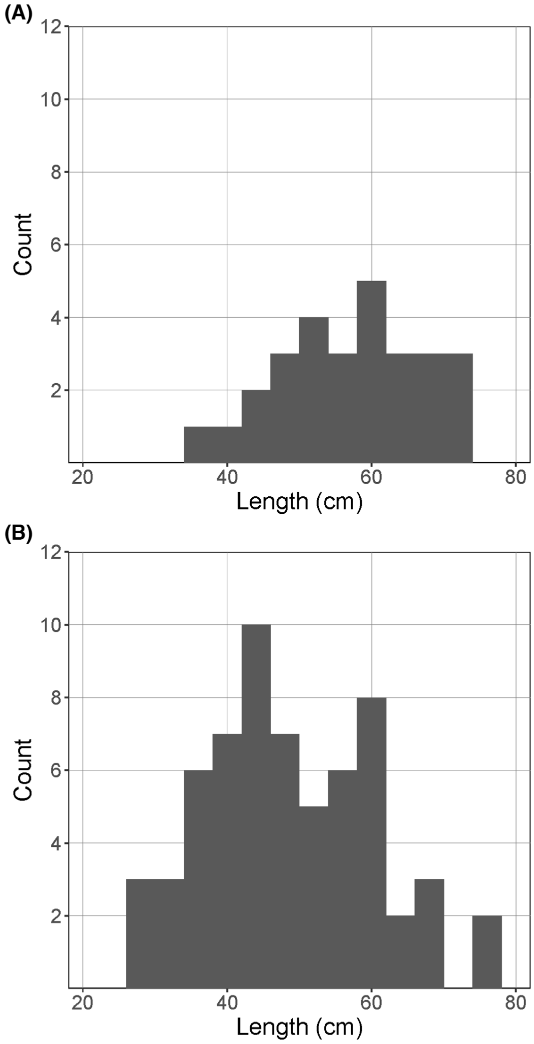

FIGURE 2 Length composition data included in the stock assessment model for Yelloweye Rockfish: (A) data from studies conducted in the 1970s, which were summarized into a single year (1975) for the model; and (B) data from studies from the 2010s, which were summarized into a single year (2015) for the model.

The SS-CL model estimates the initial recruitment size ($\ln R_0$) and the two logistic selectivity parameters while fitting the length composition data via maximum likelihood estimation and assuming that inputted catches are removed from the population without error. Within-model uncertainty is estimated using asymptotic variance. This variance estimation is influenced particularly by the low sample sizes of the length compositions (allowing for a broader fit to the length data) but may still be insufficient to capture the major sources of uncertainty caused by fixing certain model inputs. The Beverton–Holt stock–recruitment relationship was used in our assessment model, with steepness fixed at 0.72, a value that was derived from a meta-analysis of West Coast rockfishes with similar life histories (Thorson et al. 2019).

RESULTS

Catch reconstruction

Commercial catch of Yelloweye Rockfish began in the early 1920s and was relatively low until an increase in the mid-1940s, after which harvest declined steadily until 1970 (Figure 3A). Catches were then relatively high until the mid-1990s, when they dropped rapidly. The recreational catch of Yelloweye Rockfish showed a gradual increase in harvest through the first part of the time series, followed by maximum catches from about 1970 to 1990 and another decline over the subsequent two decades (Figure 3B). These fundamental patterns hold regardless of which catch scenario is considered, although the estimated uncertainty in the extent of the commercial data series is much larger. Overall, the recreational harvest was greater than the commercial harvest; in the base (medium) catch scenario, the total recreational catch represented approximately 60% of the total catch.

Population dynamics

Despite evaluating the sensitivity of model outputs to a wide range of uncertainty across catch histories and different values of M, the overall trend of the population was very similar (Figure 4). Puget Sound Yelloweye Rockfish declined in abundance starting in approximately 1970,

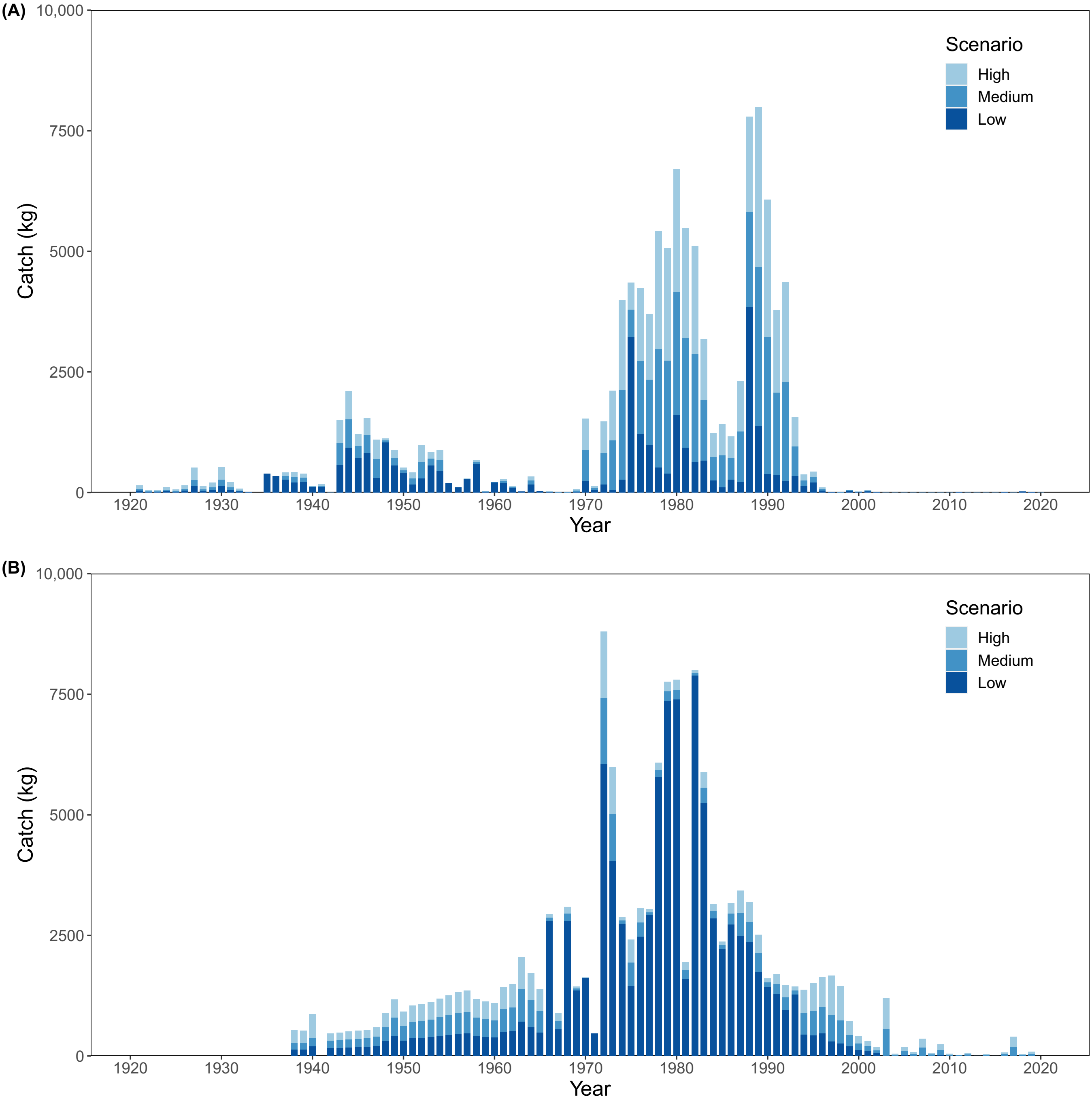

FIGURE 3 Catch reconstruction (kg) for Yelloweye Rockfish in Puget Sound (Hood Canal excluded), showing (A) the commercial catch reconstruction and (B) the recreational catch reconstruction.

with a minimum abundance in 1994 (for the high and medium catch scenarios) or 1992 (for the low catch scenario), consistent with the perception of possibly critically low stock size (thus the petition to list the DPS under the ESA). The population then increased in abundance over the past two decades in accordance with essentially no fishing mortality and deterministic recruitment. Relative spawning output showed similar temporal trends in the stock status and very high within-model uncertainty, with larger dips in the population during the 1990s with different catch and *M*-values. However, after this decline, significant restrictions in both the commercial and recreational fisheries led to very low fishery impacts for the past 25 years. With the deterministic recruitment assumed by the models (the same assumption used in the coastwide U.S. Yelloweye Rockfish stock assessment) and in the general absence of harvesting, the model suggested that the population has rebounded to over 40% of unfished spawning output even at the lowest *M*-values and to over 15% if considering the low 95% trajectory of those low-*M* runs.

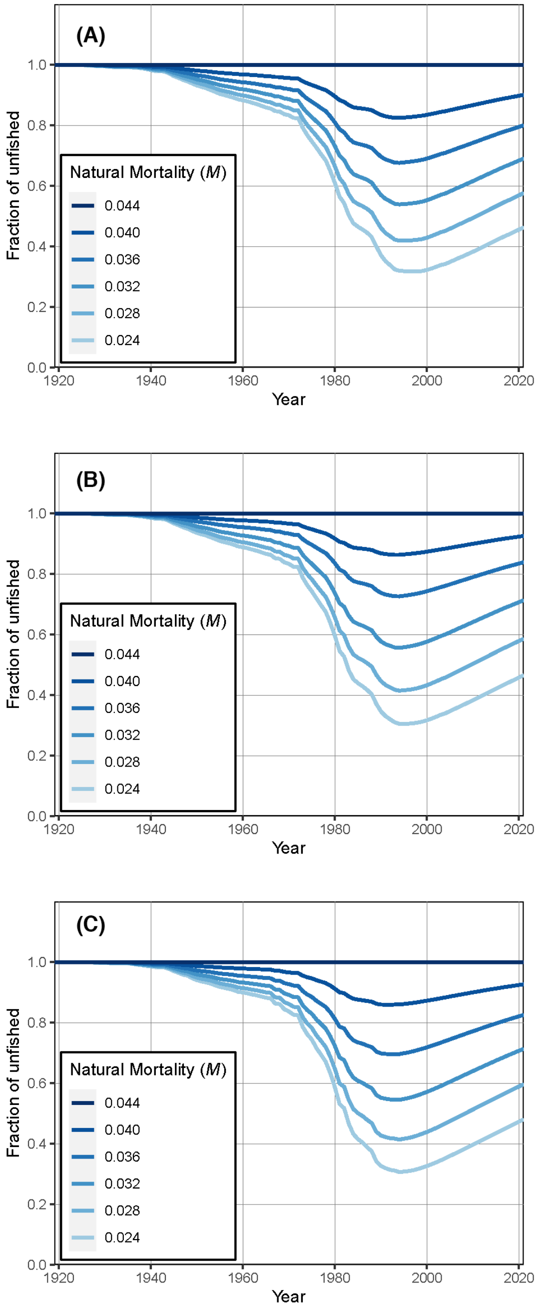

FIGURE 4 Relative stock size (fraction of unfished spawning output) of the U.S. portion of the Puget Sound/Georgia Basin Yelloweye Rockfish Distinct Population Segment (excluding Hood Canal), profiled over a range of natural mortality (*M*) values for the (A) high, (B) medium, and (C) low catch scenarios.

Considering the worst-case scenarios of low *M* across the catch scenarios, the lower limits of population status do include critically low relative population sizes (Figure 5). Thus, the model suggested that although this Yelloweye Rockfish stock possibly reached very low levels in the 1990s, the low removals for over two decades indicate that the population has increased considerably under the assumption of consistent productivity and no removals beyond natural causes.

DISCUSSION

The management of rare, threatened, and endangered species is often a difficult process that is plagued by uncertainty due to limited resources and data. The creative application of analytical tools is needed when presented with limited historical and contemporary data on species of conservation concern. In this study, we estimated a plausible range of population dynamics for ESA-listed Yelloweye Rockfish in Puget Sound by collating different sources of information to reconstruct likely removal histories and evaluate population scale and length composition data from two distinct periods, allowing us to estimate relative population size using a simple but integrated data-limited stock assessment model. We also explored a major source of possible model misspecification, the value of natural mortality, to obtain an expansive understanding of uncertainty in relative stock status. Previous assessments of the status of this population relied on proxy data from congenerics and often lacked species-specific insights (Drake et al. 2010; Tonnes et al. 2016), whereas the assessment model applied here provides the first estimates of Yelloweye Rockfish population status in Puget Sound for conservation purposes. The population trajectory, which showed a decline until the 1990s followed by an increase in the population size, is similar to the trajectory seen on the U.S. West Coast, as the coastwide assessment showed low relative stock sizes up through the early 2000s and then an increase to almost 30% of the unfished spawning output in 2017 (Gertseva and Cope 2017). Notably, the recovery of the population starting in the 1990s, as suggested by our model, is opposite the trend found by Tolimieri et al. (2017), who suggested a continuous decline through 2014 (the last year of their study). However, as noted previously, there were various management changes starting in the mid-1990s (prohibition on Yelloweye Rockfish retention, changes in depth limits for recreational fishing to protect ESA-listed Bocaccio and Yelloweye Rockfish) that limited how well the all-rockfish trends presented by Tolimieri et al. (2017) captured trends in Yelloweye Rockfish abundance.

As our analysis focused on evaluating the potential of low stock status, the highly risk-averse consideration of the 95% confidence interval under catch uncertainty and very low *M*-values still shows that the Puget Sound Yelloweye Rockfish population reflects a moderate stock status. In the most conservative (not most probable) estimate of stock status explored, using the lowest value for *M* and the highest catch scenario, the population was still estimated to have a 66% probability of being over 25% of the unfished population size, a key reference point in the recovery criteria (National Marine Fisheries Service 2017b). We also explored a length-only version

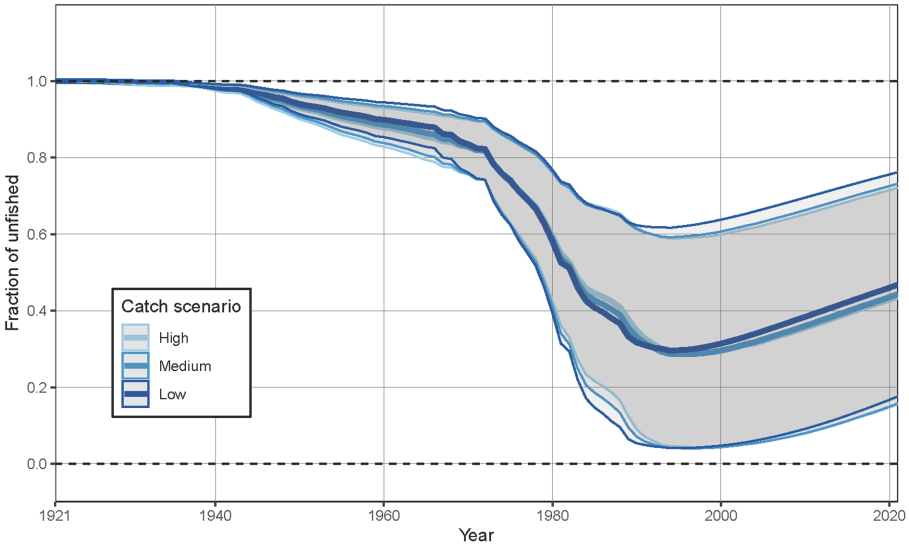

FIGURE 5 Relative stock size (fraction of unfished spawning output) of the U.S. portion of the Puget Sound/Georgia Basin Yelloweye Rockfish Distinct Population Segment (excluding Hood Canal), based on the lowest natural mortality ($M = 0.024$) scenario across the three catch scenarios. Shaded areas are the 95% confidence intervals.

of the model (length-based [LB]-SPR; i.e., dropping the catch history and only fitting the length data). Those models suggested that the current stock status is around 40% with the reference *M*-value and 15% with the lowest explored *M*-value. One critical difference between the LB-SPR model and the catch and length (SS-CL) model is that the LB-SPR model assumes that fishing mortality is still occurring (i.e., a constant fishing mortality throughout the time period; Hordyk et al. 2015). Thus, the LB-SPR model predicted lower relative stock sizes compared to the SS-CL model, which was able to incorporate the information that removals essentially stopped two decades ago. Despite that major assumption and the median result differences, the LB-SPR and SS-CL results still overlapped in the message that Yelloweye Rockfish have likely increased since the time of the perceived lowest population size. By applying elements of historical ecology, fisheries science, and conservation biology in a highly collaborative research effort, we collectively offer these results and management-relevant science that will be used to inform recovery efforts for this ESA-listed species.

Marine and anadromous fishes listed under the ESA each have unique recovery criteria tailored to their biology and available data, with a wide variety of monitoring and analytical methods needed to track progress toward meeting recovery goals based on these metrics. As Yelloweye Rockfish and Bocaccio are commercially exploited in other parts of their range, metrics typically used for harvested populations were selected as the biological recovery criteria for the PSGB DPSs (unique amongst ESA-listed species); thus, methods that are typically used for commercially exploited species were applicable. Many listed fish species tend to have relatively more data for tracking their recovery, as the amount of available data is often correlated with the ease of collecting data for these species based on their life history. Anadromous species, such as the Southern DPS of Green Sturgeon *Acipenser medirostris*, Gulf Sturgeon *A. oxyrinchus desotoi*, and the Southern DPS of Eulachon *Thaleichthys pacificus*, have recovery criteria based on abundance during the freshwater life history stage. Marine fishes, such as PSGB Yelloweye Rockfish, do not have population estimates that are as easily attainable. As of 2021, there are only seven nonforeign, strictly marine fishes listed under the ESA. Four are elasmobranchs: Giant Manta *Manta birostris* (throughout its range), Oceanic Whitetip Shark *Carcharhinus longimanus* (throughout its range), Scalloped Hammerhead *Sphyrna lewini* (Eastern Pacific DPS, Central and Southwest Atlantic DPS, and Indo-West Pacific DPS), and Smalltooth Sawfish *Pristis pectinata* (U.S. DPS). The other three are teleosts: Nassau Grouper *Epinephelus striatus* (throughout its range), Yelloweye Rockfish (PSGB DPS), and Bocaccio (PSGB DPS). Of these seven marine species, only PSGB Yelloweye Rockfish, PSGB Bocaccio, and the U.S. DPS of Smalltooth Sawfish have final recovery plans as of 2023. A draft recovery plan for the Oceanic Whitetip Shark was released in January 2023 and is currently under review (National Marine Fisheries Service 2023).

The Smalltooth Sawfish has the most data available of any ESA-listed marine species, and an element of its downlisting criteria is an annual rate of increase in relative abundance (National Marine Fisheries Service 2009). Progress toward meeting this goal is monitored via three fishery-independent surveys (Brame et al. 2019), which is unique among ESA-listed species. The WDFW has used ROV surveys of varying designs and spatial coverages to estimate Yelloweye Rockfish abundance in portions of the PSGB DPS (Pacunski et al. 2013, 2020; Lowry et al. 2022); however, a consistent sampling protocol that can track population abundance through time will be resource intensive and logistically complex and will require long-term, stable resources to implement. Thus, with unique recovery criteria and a paucity of data, the approach outlined in this study is an example of a creative application of quantitative ecological methods tailored to the recovery criteria, available data, and biology of this species. As recovery plans are developed for recently listed marine fishes and as more species continue to be listed, creative methods that borrow from similar (or different) fields will be central to efforts to track the status and recovery of these species in their remote habitats.

Other ESA-listed species are even more data limited than PSGB Yelloweye Rockfish. For example, the PSGB DPS of Bocaccio is listed as endangered under the ESA and individuals are rarely encountered in Puget Sound: between 1987, when consistent monitoring surveys in Puget Sound began, and 2021, research surveys have observed only 14 Bocaccio in Puget Sound within the DPS boundaries (Pacunski et al. 2013; Andrews et al. 2018; R. Pacunski and J. Blaine, unpublished data). This is despite trawl surveys that have been conducted since 1987 on an annual or biannual schedule (Quinnell and Schmitt 1991; Palsson et al. 1998, 2002, 2003; Blaine et al. 2020), multiple ROV surveys in the San Juan Islands and in Puget Sound proper (Pacunski et al. 2013, 2020; Lowry et al. 2022), and hook-and-line studies that have targeted Bocaccio (Andrews et al. 2018). The discreteness of PSGB Bocaccio as a DPS remains unresolved; at the time of listing, discreteness of this DPS was based on expert opinion (and was not unanimous among reviewers; Drake et al. 2010), and the subsequent genetic study that led to the delisting of Canary Rockfish *Sebastes pinniger* (and confirmed the discreteness of the PSGB Yelloweye Rockfish DPS) was unable to obtain enough Bocaccio samples to determine whether PSGB Bocaccio are distinct from Bocaccio on the U.S. West Coast (Andrews et al. 2018). With so few data points, even data-limited fisheries methods like the ones employed in this study are unable to give any insight into the dynamics of the PSGB Bocaccio population. Without the ability to estimate SPR, as is specified in the criteria, it is plausible that this DPS will exist in a sort of limbo, with no prospect for delisting because of extreme data deficiencies. However, efforts are underway to collect more information on the abundance, genetics, and population trends of Bocaccio in Puget Sound, which may improve the ability to assess their status in the future.

As is the case in population modeling, particularly in data-limited situations, there were considerable sources of uncertainty in our study that can be summarized into two general themes: data uncertainty and model uncertainty. Data uncertainty in this study comes from known sources, such as the catch reconstruction and the very low sample sizes and missing years for the length composition; general data representativeness of the underlying population structure; and unknown uncertainty sources from data unavailability (e.g., no abundance indices and age compositions). As is the case in catch reconstruction, many different approaches could have been taken to estimate historical removals, and the catch reconstruction presented here represents only one approach. In the case of our catch reconstruction, we attempted to summarize uncertainty in the three catch scenarios using time-varying sources of uncertainty, including alternative catch composition data, different treatment of data with poor geographic resolution, and varying estimates of postrelease mortality. However, our attempt to avoid using arbitrary, fixed factors to the extent possible when generating these catch scenarios likely underestimated the uncertainty in the data. For example, catch composition data in the commercial landings were only available beginning in the 1970s, but total rockfish landings were available from a half-century earlier in the 1920s. Thus, we applied the only available catch composition data to these landings in all catch scenarios despite the temporal gap, making the assumption that different rockfish species were at the same relative population level during these two time periods. The recreational fishery for bottom fish in Puget Sound has been notoriously difficult to monitor (Palsson et al. 2009); therefore, the estimates of catch that we incorporated into our research have an unknown degree of uncertainty that could not be estimated in our catch reconstruction. Additional sources of mortality in the catch reconstruction for which we could not account were discards in the commercial fishery (as commercial records only recorded landings delivered to processors; Williams et al. 2010) and postrelease mortality in the recreational fishery (as the WDFW only began estimating releases beginning in 2003). However, as seen in Figures 4 and 5, the different catch scenarios did not have a significant impact on stock status. Lastly, the length composition data were based on small numbers of fish and a limited number of years, which also increased the uncertainty in the estimation of stock status. Rudd et al. (2021) conducted simulation testing of the effect of length composition data availability for a species with life history characteristics similar to those of Yelloweye Rockfish (i.e., longer lived, slow growing). They found that with only 1 year of length composition data and only 50 samples (the most similar scenario to our study, which has 1 year of 62 length samples and 1 year of 28 length samples), the median absolute relative error of the fraction unfished was 0.4, with the 90th quantiles spanning values from −0.6 to 1.3. As such, the small sample sizes available for length compositions for this population suggested considerable uncertainty in the stock status. However, the model outputs do reflect some of this data uncertainty, as seen in the wide uncertainty intervals in relative stock biomass (Figure 5) and the extremely wide uncertainty intervals around absolute stock size (Supplemental Figure 1 available separately online). Although relative stock biomass (Figure 5) is more relevant to informing the recovery criteria for this DPS, absolute stock biomass would help to inform the resiliency of the DPS to fishing mortality. For example, based on in-season estimates of absolute biomass for the ESA-listed Southern DPS of Eulachon, the recreational and commercial fisheries may be opened (National Marine Fisheries Service 2017a). Retention of Yelloweye Rockfish is currently prohibited in Puget Sound, but some mortality does occur due to barotrauma when these fish are released (Hochhalter and Reed 2011), and a refined estimate of absolute biomass would inform the threat that this fishing mortality poses to the DPS.

Model uncertainty—or uncertainties about the structure of the model itself—can be more insidious than uncertainty in the data, as it can lead to bias and an underrepresentation of the true uncertainty in model predictions (Hill et al. 2007). In our case, we had to assume a deterministic stock–recruit relationship, as evidenced by the monotonic recovery of the population beginning in the 1990s with near-zero fishing pressure (Figure 5). Unlike data-rich fisheries that have estimates of year-class strength from recruitment surveys or age data, no estimates of recruitment exist for ESA-listed species, and existing surveys (e.g., ROV surveys) are currently limited to detecting rockfish >10 cm in length, when they are clearly visible to the primary data collection camera (Pacunski et al. 2013). Therefore, we cannot verify that the recruitment estimated by the model is occurring. Despite this simplifying assumption, the overall trend in the population, while lagged in time because of a different exploitation history, was similar to that seen in the stock assessment for the U.S. coastal population (Gertseva and Cope 2017), which also assumed deterministic recruitment, and the DFO assessment of the Inside Yelloweye Rockfish population (Haggarty et al. 2021). The most extreme recruitment case would be no recruitment over the past two decades—a scenario that would lead to a persistently decaying population over time. This scenario seems very unlikely given that smaller individuals were sampled relatively frequently in the population during the most recent time period (Figure 2). To bracket uncertainty in population production, the *M*-value was explored, with the most emphasis placed on very low *M*-values in order to highlight risk-averse model specifications given the recovery goals. Although these remaining uncertainties are significant, this coarse resolution is still informative for management given the aim of estimating population status in order to inform recovery criteria under the ESA listing.

A final consideration for the ability of this study to inform the status of PSGB Yelloweye Rockfish is that the model presented here only models the U.S. portion of the PSGB DPS; the Canadian portion, which is subject to commercial exploitation, was modeled by DFO (Haggarty et al. 2021). The model used for the Canadian portion of the DPS, which has considerably more data available (e.g., abundance indices through ongoing longline surveys), was implemented through the Data-Limited Methods Toolkit (DLMtool; Carruthers and Hordyk 2018, 2019) and DLMtool's companion software package, the Management Strategy Evaluation Toolkit (MSEtool; Huynh et al. 2019). Although the uncertainty around the absolute stock size of the Puget Sound portion of the DPS is very wide, the Canadian portion of the DPS is considerably larger than the Puget Sound portion (Supplemental Figure 1) and the relative stock status is currently estimated to be 32% of unfished (95% quantiles = 15–68%; Supplemental Figure 2). Historical removals from the Canadian part of the DPS were also over 20 times larger than removals from the U.S. portion, even when the high catch scenario is considered, providing further evidence of the relative size of these two portions of the DPS. The recent report on the Canadian PSGB Yelloweye Rockfish population concluded that it was not in imminent danger of extinction; however, the status of the designated unit was changed from special concern (a status conferred in 2008) to threatened (Committee on the Status of Endangered Wildlife in Canada 2020). This issue of transboundary fish populations is a common one; however, unlike other species in the region, such as the Pacific Halibut *Hippoglossus stenolepis*, which is managed by the International Halibut Commission (Sumaila et al. 2020), coordinated international management of Yelloweye Rockfish in the Salish Sea does not take place. Hence, these two models, which examine different portions of one genetically homogeneous stock, present an additional source of uncertainty in assessing the status of the PSGB Yelloweye Rockfish DPS.

In the United States, as in many other countries, separate laws are concerned with the treatment of species conservation versus fisheries management. For instance, the goals of conserving species within an ESA framework differ from the goals of a traditional fisheries management (e.g., MSA) framework. Despite different objectives, similar tools can still be used to evaluate metrics reflecting those objectives, with the specific modeling approach dependent on the available data and the question of interest. A continuum of methods exists to estimate the status of fish populations with varying degrees of data limitation; these tools can be implemented through the SS Data-Limited Tool (https://github.com/shcaba/SS-DL-tool). In the present case, SS-CL was selected, as it best leveraged the existing data, and it was coupled with the evaluation of multiple scenarios to examine uncertainty in relative population status. We evaluated highly risk-averse (i.e., low-probability events regarding smaller relative population sizes) scenarios to ensure DPS conservation rather than trying to pinpoint optimal yield under less risk-averse conditions. This work highlights the possibility of linking analytical frameworks to move a species from an ESA framework to a fisheries management framework within a common tool. Conservation biology and natural resource management have traditionally been treated as separate realms and discontinuous in interpretations, yet they share common metrics, such as stock status. The ESA listing of PSGB Yelloweye Rockfish offers an example in which a more continuous analytical spectrum that evolves as more data become available can be applied, allowing us to more explicitly build a bridge between ESA listings (conservation) and fisheries management (sustainable use).

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The code and data required to reproduce this analysis are available at https://github.com/markusmin/ESA_RF_2021.

ETHICS STATEMENT

No ethics approval was needed for this study, as no fish were collected solely for this research.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.