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Stock Assessment for Lingcod (*Ophiodon elongatus*) in the Strait of Georgia, British Columbia in 2014

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Foreword

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ABSTRACT

This stock assessment updates stock status for the inside Lingcod stock in the Strait of Georgia, British Columbia based on a range of hypotheses about uncertainties in Lingcod data and biology. Harvest advice for Strait of Georgia has not been requested at this time. Instead, this assessment focuses on characterizing how stock status has changed since the current management regime was introduced in 2006, as well as how current spawning biomass compares to biomass-based reference points. A two-sex statistical catch-at-age model in a Bayesian estimation framework was used to reconstruct abundance. The model was fit to catch data and two indices of abundance based on fishery catch-per-unit-effort (CPUE). Nine stock assessment scenarios were used to characterize a range of stock status estimates in 2014. For each scenario, two sets of reference points were used to characterize stock status: the reference points developed by the 2005 Lingcod Management Framework Committee and provisional reference points identified by the more recent DFO Decision-making Framework Incorporating the Precautionary Approach (DFO PA Framework).

In all scenarios, spawning biomass in 2014 was predicted with 100% certainty to be greater than spawning biomass at the start of the current management regime in 2006. The estimated magnitude of recovery however, was dependent on both the treatment of historical catch from the DBS District 1 (1927-1946) and the assumption made about density-dependent catchability. When the 2005 Lingcod Management Framework reference points were used to classify stock status, two scenarios predicted B_{2014} was most likely above the short-term recovery target of $0.25B_0$ but below the target of $0.40B_0$. The remaining seven scenarios predicted that B_{2014} was most likely above the limit reference point of 0.10 B_0, but below $0.25B_0$. A scenario-averaging approach to status estimation, in which the Bayesian posterior distributions from all nine scenarios were combined with equal weights, estimated a 71% probability that B_{2014} was between $0.10B_0$ and $0.25B_0$. When the B_{MSY}-based reference points from the DFO PA Framework were used to classify stock status, six scenarios predicted that B_{2014} was most likely in the cautious zone (between 0.4 B_{MSY} and 0.8 B_{MSY}) and three scenarios predicted that B_{2014} was most likely in the critical zone ($B_{2014} > 0.4$ B_{MSY}). The scenario-averaging approach estimated that B_{2014} had a 58% probability of being in the cautious zone, a 37% probability of being in the critical zone, and a 5% probability of being in the healthy zone (above $0.8B_{MSY}$).

Évaluation du stock de morues-lingues (*Ophiodon elongatus*) en 2014 dans le détroit de Georgie, Colombie-Britannique

RÉSUMÉ

La présente évaluation est une mise à jour de l'état du stock de morues-lingues en eaux intérieures dans le détroit de Georgie, en Colombie-Britannique, fondée sur une série d'hypothèses concernant les incertitudes liées aux données et aux cycles biologiques de la morue-lingue. Aucun avis sur les prélèvements de morues-lingues dans le détroit de Georgie n'a été demandé pour l'instant. La présente évaluation porte plutôt sur la caractérisation de la façon dont l'état du stock a évolué depuis l'introduction du régime de gestion actuel en 2006, ainsi que sur la façon dont la biomasse du stock reproducteur actuelle se compare aux points de référence fondés sur la biomasse. Un modèle des deux sexes fondé sur les prises selon l'âge et utilisé dans un cadre d'évaluation bayésienne a été employé pour reconstituer les données sur l'abondance. Le modèle a été adapté aux données sur les prises et à deux indices d'abondance basés sur le volume des prises par unité d'effort (PUE). En 2014, neuf scénarios d'évaluation du stock ont été utilisés pour caractériser diverses prévisions sur l'état du stock. Pour chaque scénario, deux ensembles de points de référence ont été utilisés pour caractériser l'état du stock : les points de référence élaborés par le Comité du cadre de gestion de la morue-lingue de 2005, et les points de référence provisoires du MPO figurant dans le plus récent cadre décisionnel pour les pêches intégrant l'approche de précaution (cadre de gestion du MPO pour l'approche de précaution).

Dans tous les scénarios, on a prédit avec une certitude totale que la biomasse du stock reproducteur sera plus importante en 2014 que celle du début du régime de gestion actuel en 2006. Toutefois, l'ampleur estimée du rétablissement dépendait à la fois du traitement des prises historiques dans le district 1 par le Bureau fédéral de la statistique (1927-1946) et des hypothèses émises par rapport à la capturabilité associée à la densité. Quand les points de référence de 2005 élaborés par le Comité du cadre de gestion de la morue-lingue étaient utilisés pour classifier l'état des stocks, deux scénarios ont permis de prévoir que B_{2014} excédait vraisemblablement la cible de rétablissement à court terme de 0,25B_0, mais était inférieur à la cible de 0,40B_0. Les sept autres scénarios ont permis de prévoir que B_{2014} excédait vraisemblablement le point de référence limite de 0,10B_0, mais était inférieur à 0,25B_0. Une approche de combinaison des scénarios visant à estimer l'état des stocks, dans laquelle les distributions bayésiennes a posteriori des neuf scénarios étaient combinées avec la même pondération, a permis d'estimer que B_{2014} avait une probabilité de 71 % de se trouver entre 0,10B_0 et 0,25B_0. Lorsqu'on a eu recours aux points de référence basés sur la B_{RMS} du cadre de l'approche de précaution du MPO pour classifier l'état du stock, six scénarios ont permis de prévoir que B_{2014} se trouvait vraisemblablement dans la zone de prudence (entre 0,4B_{RMS} et 0,8B_{RMS}), et trois scénarios ont permis de prévoir que B_{2014} se trouvait vraisemblablement dans la zone critique (B_{2014} > 0,4B_{RMS}). L'approche de combinaison des scénarios a permis d'estimer que B_{2014} avait une probabilité de 58 % de se trouver dans la zone de prudence, de 37 % de se trouver dans la zone critique et de 5 % de se trouver dans la zone saine (au-dessus de 0,8B_{RMS}).

1. INTRODUCTION

Lingcod (*Ophiodon elongatus*) in British Columbia are assessed and managed as five separate units based on Groundfish Management Areas. These units include one inside stock in the Strait of Georgia (Area 4B; minor Statistical Areas 13-19; 28 and 29 only) and four outside stocks: southwest Vancouver Island (Area 3C, and minor Statistical Area 20 from 4B), northwest Vancouver Island (Area 3D), Queen Charlotte Sound (Areas 5A and 5B, and minor Statistical Area 12 from 4B), and Hecate Strait and the west coast of Haida Gwaii (Areas 5C, 5D, and 5E).

The purpose of this stock assessment is to update stock status for the inside Lingcod stock in the Strait of Georgia (Figure 1), as requested by the Groundfish Management Unit (GMU). Large estimated declines in Lingcod abundance within the Strait of Georgia between 1927 and the late 1980s led to the closure of the commercial fishery in 1990 and a closure to Lingcod retention by the recreational fishery in 2002. Inside Lingcod were last assessed in 2005, at which time both the stock assessment and the development of management advice were overseen by a stakeholder committee and approved by the Canadian Science Advisory Pacific (CSAP) groundfish subcommittee. The assessment showed increased abundance in recent years, which led to the opening of limited recreational fishing opportunities in minor Statistical Areas 13-19. Harvest advice at that time was set below harvest control rule recommendations due to concerns about rockfish bycatch.

The current Request for Science Information / Advice submitted by GMU does not request harvest advice. Instead, it asks how stock status has changed since the current management regime was introduced in 2006. The focus of this assessment is therefore on updating the 2005 assessment framework with new data and characterizing stock status based on a range of hypotheses about uncertainties in Lingcod data and biology. In addition, we make recommendations for future assessment in support of developing harvest advice given ongoing data limitations for Strait of Georgia Lingcod.

1.1. LINGCOD BIOLOGY

Lingcod are unique to the west coast of North America, with a range extending from Baja, California to the Shumanagin Islands, Alaska. Adults typically inhabit nearshore waters. They can occur at depths ranging up to 450 m; however, they are most often found in rocky habitats between 10 to 100 m, especially during spawning season.

Lingcod are one of the few marine fish species in Canada that exhibit parental care for incubating eggs. Female Lingcod deposit eggs masses along rocky crevices or ledges in relatively shallow (< 100 m) nearshore waters each winter (Low and Beamish 1978). While females leave the nest site once the egg mass has been fertilized by one or more males, males will remain within 1 m of the nest for an average of 7 weeks until the eggs have hatched (Low and Beamish 1978, Withler et al. 2004). During this time, males display aggressive behaviour towards potential predators that feed on eggs and larvae. Their presence is believed to substantially reduce egg mortality (Low and Beamish 1978). In British Columbia waters, the spawning period extends from December until March, with peak spawning occurring in late January and early February (Cass et al. 1990). Once Lingcod larvae hatch in early March to April, they spend between 3 and 9 weeks as planktonic larvae (Phillips and Barraclough 1977, Marko et al. 2007). During this phase, movement is relatively passive with ocean currents affecting dispersion (Marko et al. 2007). Post-larval Lingcod settle on flat bottom habitats that contain some structural complexity such as eelgrass or kelp beds (Cass et al. 1990, Petrie and Ryer 2006). By age 2, individuals move into habitats of similar relief and substrate as adults.

Tagging studies in British Columbia have shown that once Lingcod reach maturity (approximately age 2 for males and age 4 for females), the majority of fish tend to stay close to the reef or rocky area to which they first recruited. A study on the outer coast of Vancouver Island found that 95% of fish tagged between 1978 and 1982 stayed within 10 km of the tagging location, and that only a few individuals migrated beyond 50 km (Cass et al. 1990). Similarly, a tagging study in the Strait of Georgia showed that 95% of Lingcod remained within 35 km of their tagging site within the first year of release (Smith et al. 1990). These two tagging studies did not observe any movement of adult Lingcod in and out of the Strait of Georgia (Cass et al. 1990, Smith et al. 1990); however, a genetic study would be the best approach to confirm that Strait of Georgia Lingcod do not mix with outside stocks. Similar results have been found from tagging studies in southeast Alaska, where 55% of fish stayed within 5 km of their tagging location and 83% stayed within 24 km (Stahl et al. 2014). An acoustic study of nine adult Lingcod in Puget Sound, Washington estimated the mean home range within which an individual spent 95% of its time to be 2820 m^2 in summer and 1139 m^2 in winter (Tolimieri et al. 2009).

While Lingcod are generally thought to display high site fidelity, some individuals do make frequent forays away from their home range for multiple days as a time (Starr et al. 2004, Stahl et al. 2014). A small proportion of tagged fish have been shown to make even longer-distance movements. Stahl et al. (2014) found that 5 of 453 tagged individuals travelled over 300 km and one individual traveled as far as 778 km (Stahl et al. 2014). Within the Strait of Georgia, the maximum distance a tagged Lingcod has been observed to travel is 99 km; this individual did not leave the Strait of Georgia (Smith et al. 1990).

Lingcod are also known to make seasonal movements on and off the spawning grounds (Cass et al. 1990; Martell et al. 2000). On the west coast of Vancouver Island, both male and female Lingcod are captured on nearshore trawling grounds between May and September. During the winter, trawl catches of male Lingcod drop steeply as individuals begin to aggregate inshore in October. Males disaggregate in April once they have finished guarding the nest. Females spend a shorter amount of time on the spawning grounds, and are more often encountered in trawl fisheries on the west coast during the winter than males (Cass et al. 1990). Directed studies at a smaller spatial scale have found that males display especially high site fidelity. Individuals often return to the same spawning grounds in subsequent years; and sometimes even return to the exact same nest site (King and Withler 2005). In comparison, females display lower site fidelity than males and are believed to disperse greater distances.

Lingcod are well-adapted predators with large mouth gapes that allow them to consume a wide range of prey species. In British Columbia waters, Lingcod are believed to feed heavily on Pacific Herring (*Clupea pallasii*) and Pacific hake (*Merluccius productus*); however, they have also been known to consume Sablefish (*Anoplopoma fimbria)*, Pacific Cod (*Gadus macrocephalus*), and various species of flatfish, rockfish, salmon, crabs, shrimp, squid, and octopus (Cass et al. 1990). In the San Juan Islands of Washington State, a recent study found that Lingcod diet composition was highly variable, with no single species dominating prey composition (Beaudreau and Essington 2007). An important finding of this study with implications for modelling Lingcod population dynamics is that Lingcod display cannibalism in the wild. For Lingcod larger than 30 cm, Lingcod made up 4.3% of their diet by weight (A. Beaudreau, pers. comm. cited in King et al. 2012). Once past their larval and early juvenile stages, marine mammals such as sea lions and harbour seals are likely the primary predators of Lingcod (Cass et al. 1990).

1.2. FISHERY & MANAGEMENT HISTORY

1.2.1. Commercial Fisheries

Commercial fishing for Lingcod in British Columbia began around 1860 (Cass et al. 1990). Between 1900 and the 1940s, Lingcod was ranked fourth in commercial importance in British Columbia after salmon, herring and sardines, and was the main source of fresh fish throughout the year (Wilby 1926; Cass et al. 1990). Prior to 1927, Lingcod landings were grouped with other groundfish species (Sablefish, rockfish, Pacific Cod, Pacific Hake and Pacific Tomcod) into a 'cod' category (Wilby 1937) though there is some suggestion that Lingcod comprised almost all of the catch (Ketchen et al. 1983).

Catches in the Strait of Georgia reached a historic high level in the 1930s and 1940s (Figure 2). Overall, the hook and line fishery accounted for over 80% of the Lingcod commercial catch in the Strait of Georgia. The hook and line catch in the Strait of Georgia averaged 2,800 tonnes in the 1930s and 1940s. Historic high landings of approximately 3,700 and 4,300 tonnes occurred in 1936 and 1944 respectively (Figure 2). By the 1950s, the hook and line catch had declined to an average of 1400 tonnes. The hook and line catch declined through to the early 1980s, when it reached an average of 280 tonnes, an approximate 80% decline from the catches in 1950s and a 90% decline from hook and line catches in the mid-1940s (Richards and Hand 1989).

During the 1920s, the commercial catch was almost exclusively taken by hook and line (mostly handline), but during the 1930s trawlers began to fish for Lingcod, and use of this gear to catch Lingcod in the Strait of Georgia increased during World War II (Chatwin 1958; Forrester and Ketchen 1963). Reliable trawl statistics for this period are not available, but Chatwin (1958) estimates that the proportion of Lingcod caught in the Strait of Georgia by trawl never exceeded 20% of average landings of 2789 tonnes. In 1947, large areas of the strait were closed to trawl gear and the proportion of the Lingcod catch by trawl dropped to about 3% (Chatwin 1958; Forrester and Ketchen 1963). These closures were in response to concerns that the rapidly developing fishery was conflicting with the long-established hook and line fishery for Lingcod and was having a negative impact on juvenile Lingcod (Forrester and Ketchen 1963). Investigations into trawl catch alleviated these concerns and by 1955, most fishing grounds were reopened to the trawl fishery (Forrester and Ketchen 1963). During the 1950s through 1970s, the proportion of Lingcod landed by trawl averaged 7%, and increased to 19% in the final ten years of the Strait of Georgia commercial fishery (1980-1989).

The handline fishery in the Strait of Georgia typically used live bait, usually herring or young rockfish or flatfish. Lingcod in the handline fishery were kept alive in live-wells onboard and then in submersed live-boxes until required for market (Wilby 1937). Lingcod were removed from the live-boxes and landed dressed (head off and gutted).

The commercial Lingcod fishery has been subject to a variety of management measures including size limits and seasonal closures (Table 1). In 1931, a winter closure (January and February) for Lingcod fishing was initiated to protect spawning fish and in 1946 this closure was extended to include December. In addition, a minimum weight limit of 3 pounds (approximately 58 cm, head-on) for retained Lingcod was applied to the commercial fishery in 1942. In 1979 the winter closure was extended for November 15 – April 15 and this was again extended in 1988 to November 15 – April 30. Since 1990, the retention of Lingcod by the commercial fishery in the Strait of Georgia (Minor Statistical Areas 13-19, 28 and 29) has been prohibited in response to conservation concerns (Richards and Hand 1989).

1.2.2. Recreational Fisheries

During the 1960s recreational fisheries in the Strait of Georgia underwent a rapid expansion. As the catch in the commercial fisheries declined in the 1980s, the recreational fishery accounted for a relatively large proportion (approximately 35%) of Lingcod landed in the Strait of Georgia. Most recreational fishing for Lingcod has been done via hook and line gear, although some recreational catch has been taken by spear fishing using SCUBA equipment. Recreational catch statistics are only available for hook and line gear. Despite recreational hook and line catches peaking during the 1980s with an average annual catch of 71,418 pieces, Lingcod have typically been a small component of the recreational catch of all species in the Strait of Georgia. The Lingcod recreational hook and line fishery has historically focused on Coho (*Oncorhynchus kisutch*) and Chinook (*O. tshawytscha*) salmon (English et al. 2002). Lingcod accounted for approximately 7% of the recreational catch in the 1980s, and only 1.5% of the total recreational catch in the 1990s as a result of increased restrictions on Lingcod retention (English et al. 2002).

The recreational fishery has undergone various changes in the timing of seasonal openings, bag limits, and minimum size limits since the 1980s (Table 2). In response to declining abundance of Lingcod in the 1980s, a winter closure (November 15 - April 15) for the recreational fishery was implemented in 1981, as was a voluntary size limit of 58 cm total length. With the closure of the commercial fishery in 1990, extended regulations were initiated in the Strait of Georgia recreational fishery for Lingcod. In 1991, a mandatory size limit of 65 cm was implemented, along with a reduced bag limit (from 3 to 1 fish per day), an annual limit (10 fish per year) and an extended winter closure (October 1 - May 31). Due to conservation concerns, the recreational fishery was closed for the retention of Lingcod in 2002.

Since 2002, the establishment of a network of Rockfish Conservation Areas (RCAs) in British Columbia has limited the geographic extent of Lingcod fishing within the Strait of Georgia. Within Areas 13-19, 28, and 29 of the Strait of Georgia, 95 RCAs have been established as a tool for inshore rockfish conservation, which represents almost 29% of rockfish habitat (DFO 2007, Yamanaka and Logan 2010). Within these areas, fishing activities encountering rockfish have been prohibited, including recreational and commercial hook and line fisheries.

In 2005, the development of assessment and management advice for Strait of Georgia Lingcod was overseen by a Lingcod Management Framework Committee (LMFC) that included representatives from multiple stakeholder groups (Logan et al. 2005; see next section for a summary of the process).

The LMFC recommended that a recreational fishery for Lingcod be continued in the Strait of Georgia but provided several recommendations for fishery management, including a total annual harvest of 5000 – 7000 pieces in minor Statistical Area 13-19, a minimum size limit of 65 cm, a limited fishing season of June to September, a daily limit of 1 Lingcod per person, an annual limit of 10 Lingcod per person, and no retention of Lingcod in minor Statistical Areas 28 and 29 (DFO 2005; Logan et al. 2005). Management decisions for Strait of Georgia Lingcod between 2006 and 2013 have closely followed the advice of the LMFC, with the exception of a brief decrease in the size limit to 60 cm during 2008 and 2009 and the fishing season starting in May since 2009 (Table 2). Minor Statistical Areas 28 and 29 have remained closed to Lingcod retention since 2002.

1.3. 2005 STOCK ASSESSMENT & MANAGEMENT FRAMEWORK

Assessment and management advice for Strait of Georgia Lingcod was last provided in 2005 (Logan et al. 2005). At this time, both the stock assessment and the development of management advice were overseen by a Lingcod Management Framework Committee (LMFC) that included representatives from DFO, the Province of British Columbia, the hook and line commercial fishery sector, the recreational fishery sector, plus environmental groups. The

LMFC developed a management procedure for Strait of Georgia Lingcod that consisted of three components:

1) the development of data inputs,
2) a stock assessment model that was fit to data, and
3) a harvest decision rule used to set catch based on assessment model outcomes.

Data inputs identified for the management procedure included landed catch from commercial (1927 to 1989) and recreational (1962 to 2002) fisheries and two indices of abundance: commercial CPUE (1962 -1989) and recreational CPUE (1982-2002).

The stock assessment component of the management procedure reconstructed stock dynamics from 1927 to 2003 using a catch-at-age population dynamics model fit to the data inputs. No age composition data were input to the model, although cohorts were tracked by the structural dynamics of the model.

To develop the preferred assessment model to be used as input to the harvest control rule, the committee proposed hypotheses to be tested in response to uncertainties about historical data, Lingcod population dynamics (including stock recruitment relationship, density-dependent growth, and density-dependent natural mortality), and the effects of climate change and seal predation (Table 3). The catch-at-age model was then used to evaluate how competing hypotheses affected characterization of stock status. Based on this evaluation, the committee selected a preferred model that was used as the basis for developing management advice. Limited data availability for this stock and large uncertainties about the reliability of landed catch and CPUE indices created a necessity for strong assumptions about the magnitude of historical landings and time-varying catchability. However, a comparison of results among competing hypotheses showed that only a few of these assumptions impacted perceptions of stock status. Those that did affect outcomes included the geographic definition of the Strait of Georgia and the inclusion of density-dependent growth and mortality.

As part of the harvest decision rule component of the management procedure, the 2005 LMFC proposed three reference points for classifying stock status and criteria were established for making harvest decisions based on stock status relative to these points (Logan et al. 2005). Reference points were expressed as a percentage of estimated unexploited spawning biomass, B_0, which can also be denoted as $B_{100\%.}$ These reference points were:

- $B_{10\%}$: a limit reference point below which fishing should not occur (i.e., $0.1B_0$);
- $B_{25\%}$: a short-term recovery target below which harvest is restricted (i.e., $0.25B_0$);
- $B_{40\%}$: a target reference point at which the stock is considered rebuilt (i.e., $0.4B_0$).

A limit on the acceptable probability of stock decline over the next 10 years was dependent on current stock biomass relative to these three reference points, and catch levels were set so that assessment model predictions showed that the specified probability would not be exceeded (Logan et al. 2005). In the end, the harvest decision rule component of the management procedure was not implemented in 2005. The total annual harvest was set lower than the harvest allowed under the harvest decision rule due to concerns about rockfish bycatch mortality from directed lingcod fishing.

Based on the assessment model formulation recommended by the LMFC and accepted by the CSAP groundfish subcommittee, spawning biomass in 2005 was estimated to be at 16% of unfished spawning biomass (DFO 2005, Logan et al. 2005).

1.4. DFO PRECAUTIONARY APPROACH FRAMEWORK

Since 2009, DFO policy has required fisheries to work towards implementing the Fishery Decision-Making Framework Incorporating the Precautionary Approach (DFO 2009, hereafter called simply the "DFO PA Framework"). The policy uses two biomass-based reference points to classify stock status into three stock status zones: (i) a limit reference point (LRP) and (ii) an upper stock reference point (USR). When a stock is below the LRP, it is in the critical zone, when a stock is between the LRP and the USR it is in the cautious zone, and when a stock is above the USR it is in the healthy zone.

The DFO PA Framework provides provisional values for the LRP and USR when there is insufficient information to estimate stock-specific MSY-based reference points. These are set relative to the spawning biomass associated with maximum sustainable yield, B_{MSY}, as follows:

- Limit Reference Point: $0.4B_{\text{MSY}}$
- Upper Stock Reference: $0.8B_{\text{MSY}}$

A target biomass reference point is not directly identified; however, the framework specifies that the reference removal rate should not exceed the fishing mortality associated with MSY, F_{MSY}, which implies a minimum target biomass of B_{MSY}.

- Target Reference Point: Biomass = B_{MSY}

The framework notes that actual reference points for a stock may be set lower or higher than these provisional reference points, but if so, should be clearly appropriate for the stock and consistent with the intent of the PA.

The DFO PA framework also provides guidance on how to scale fishery harvest relative to stock status within each of the three status zones; however, we do not describe this aspect of the framework here as harvest advice is not being provided.

1.5. 2014 STOCK ASSESSMENT

The current assessment maintains the first two components of the management procedure developed for Strait of Georgia Lingcod in 2005: the data inputs and the stock assessment model. A statistical catch-at-age model is used to characterize stock status, with many of the same assumptions and data sets used in 2005. The third component of the management procedure developed in 2005, the harvest decision rule, is not applied in 2014 as harvest advice has not been requested. A key different between the assessment approach taken in 2005 and the current assessment is that rather than focus on a single "preferred model" when formulating status advice, as was done in 2005, we present a range of plausible stock scenarios based on different hypotheses about Lingcod biology and data. We believe that this approach better represents structural uncertainty in assessment model outcomes.

For each scenario, two sets of reference points are used to characterize stock status (Table 4):

1) the reference points developed by the 2005 Lingcod Management Framework Committee, and
2) provisional BMSY-based reference points identified by the more recent DFO PA Framework.

Both sets of reference points are presented with equal weight when classifying stock status.

Through the inclusion of alternative model scenarios and a suite of reference points in our results, we highlight how model assumptions and reference points affect perceptions of Strait of Georgia Lingcod status. Based on this evaluation, we then provide a discussion of whether the assessment approach developed in 2005 should be used to provide future harvest advice in light of large uncertainties in the available Strait of Georgia Lingcod data. We also provide recommendations for future research and data collection that could improve stock assessment for this data-limited stock. Finally, we include recommendations for how the two sets of reference points presented in this assessment could be evaluated in the future to identify one set to be used for harvest advice.

2. MODEL INPUTS

Three types of inputs were required for the assessment model:

1) historical records of total landed catch,
2) relative abundance indices, and
3) biological parameters used to describe Lingcod growth and maturity.

For the most part, the data used in this assessment are the same as those used in the 2005 assessment (Logan et al. 2005), except where catch and index time series have been updated to 2014. We note any cases in which changes have been made to the data summary methods or data sources used in 2005.

2.1. CATCH DATA

Catch data used in the assessment model included commercial catch data (in biomass) and recreational catch data (in numbers). Lingcod have also been taken by Aboriginal fisheries within the Strait of Georgia; however, a time series of Lingcod catch for these fisheries is not available.

When presenting catch inputs, we group the nine minor statistical areas into four quadrants within the Strait of Georgia: the northwest quadrant (minor areas 13, 14), the northeast quadrant (minor areas 15, 16), the southwest quadrant (minor areas 17, 18, 19), and the southeast quadrant (minor areas 28, 29). These quadrants were developed as a basis for scenario-testing in the 2005 assessment, and we maintain them here when presenting data as some of our scenarios involve removing or adjusting catch from the southeast quadrant.

Discard mortality is not estimated in this assessment, which is the same approach taken in 2005. All released Lingcod are therefore assumed to survive. This choice is based on the lack of historical data on Lingcod discards prior to the 2000s in both the commercial and recreational fisheries, which is when the majority of Lingcod was landed. Available discard data from recent years are summarized in Appendix A; however, these data are not included in the current assessment as it would be inconsistent to account for recent discards while excluding historic ones. Furthermore, the proportion of Lingcod that survive capture and release from each fishery is uncertain. Future assessments should develop a method of including discard mortality into catch data (see discussion for more on this topic).

2.1.1. Commercial Catch

Commercial catch is summarized as annual reported landings for hook and line fisheries (longline and handline) and the trawl fishery combined. Catch records do not account for discard mortality. Data sources vary for three different time periods between 1927 and 1989, as described below. The start year for the time series, 1927, represents the first year that Lingcod catch records become available, rather than the first year of fishing. The end year, 1989, represents the last year of directed commercial fishing prior to the ban on Lingcod retention from commercial fishing.

1927 – 1946: Commercial landings of Lingcod between 1927 and 1946 were reported in annual Fisheries Statistics reports compiled by the Dominion Bureau of Statistics (DBS). Values for the four Strait of Georgia quadrants were previously summarized from these reports by Logan et al. (2005). Methods used to assign catches from DBS reporting units to the four Strait of Georgia quadrants for the current assessment were the same as those used in 2005; however, commercial landings for the years 1928 to 1930 have been revised due to a recently discovered inconsistency in the assignment of DBS reporting units to SoG quadrants. These revisions were minor, with adjustments to total Strait of Georgia landings of +12%, +2%, and –9% in 1928, 1929, and 1930, respectively. Catches were recorded in DBS reports as dressed weight in hundreds of tonnes. The same conversion factor that was applied by Logan et al. (2005) was used to convert dressed weight to round weight (factor = 1.39). The values used in this assessment and a description on the allocation of DBS units to each quadrant are provided in Table 5.

1947 – 1950: Commercial catches of Lingcod between 1947 and 1950 were only reported as coastwide totals. These are not suitable for modelling Strait of Georgia populations since there is no means to allocate catches to the Strait of Georgia. Annual catch values for each of the four quadrants were therefore infilled using linear interpolation between 1946 and 1951 catch values, as was done by Logan et al. (2005).

1951 – 1989: Starting in 1951, Lingcod catch statistics were reported by gear type and Pacific Fishery Management Council (PFMC) Statistical Area. Commercial catch in round tonnes for hook and line and trawl fisheries in the Strait of Georgia were previously compiled from DFO groundfish records and databases by Logan et al. (2005) for Statistical Areas 13-19. These 2005 values have been used for the current assessment (Table 6).

2.1.2. Recreational Catch

Recreational catch estimates (in numbers) between 1982 and 2013 were provided by the Strait of Georgia Creel Survey Program (Kris Hein, South Coast Area Database Coordinator, DFO, Nanaimo, BC, pers. comm.). The survey and analytical methodology of the creel program has been previously documented and peer-reviewed (Sturhahn and Nagtegaal 2001, English et al. 2002), with the most recent update available in Zetterberg et al. (2012). All recreational catch and recreational CPUE data used in this assessment comes from hook and line gear. Some recreational catch of Lingcod is taken by spear fishing; however, there are no official catch values for this fishery available at this time. The creel survey program does not cover spear-fishing locations.

Recreational catch estimates, by area, are summarized in Table 7. Catch values between 1982 and 1999 are the same as those used by Logan et al. (2005). Small changes were made to catch values in 2000 to 2002 as a result of creel catch data being finalized after the 2005 assessment for these years (changes = 0.6% to 3.8% of values used in the 2005 assessment).

Estimates of recreational catch are not available prior to 1982, so catch values were infilled to approximate a linear increase in recreational fishing effort between 1962 and 1982. While recreational fishing is also known to have occurred prior to 1962, recreational fishing in the Strait of Georgia underwent a rapid expansion during the 1960s. The choice of the initial year from which to interpolate recreational catches in unlikely to have an important effect on the results because recreational catches are expected to have been much smaller than commercial catches prior to the 1970s. A start year of 1962 was therefore selected for the development of the 2005 Lingcod Management Framework (Logan et al. 2005). Recent stock assessments for rockfish in the Strait of Georgia have selected 1945 as a start year based on informal interviews with the recreational sector that suggested recreational fishing effort increased after World War II (Yamanaka et al. 2012a, 2012b).

Starting in January 2011, the Strait of Georgia Creel Survey Program changed the boundaries used to define Statistical Areas to better align with Pacific Fishery Management Areas (Dave O'Brien, Fisheries and Oceans Canada, South Coast Region Salmon Stock Assessment, Nanaimo, BC, pers. comm.). In some cases, these changes resulted in fishing locations being re-assigned to different Statistical Areas (Appendix B). These changes are only relevant to scenarios in which data from the southeast quadrant of the Strait of Georgia was excluded. In these scenarios, minor sub-Areas 29-F and 29-G were included in Area 17 catch after 2011 to account for the re-assignment of areas that were formally in Area 17 to Area 29 under the new boundaries (Appendix B).

2.2. ABUNDANCE INDICES

Lingcod abundance data from fishery-independent research surveys within the Strait of Georgia is limited, with most abundance series having low or sporadic Lingcod catch, short time series, and / or limited geographic coverage (Appendix A). As a result, the two abundance indices used in this assessment are based on fishery catch-per-unit-effort (CPUE).

We provide abundance indices for two geographic units: the entire Strait of Georgia (SoG) and the Strait of Georgia with the southeast quadrant (PFMA areas 28 & 29) excluded (noSE). These two groupings correspond to alternative scenarios about the treatment of historic catch data from the Dominion Bureau of Statistic's "District 1" that were proposed in 2005 and are carried forward to this assessment. The reasoning behind these scenarios is described in more detail in the "Stock Assessment Scenarios" section (Section 4) of this document.

2.2.1. Commercial Fishery CPUE

Sales slip data with catch and effort information are available for 1967 to 1989. Since commercial trawl landings of Lingcod in the Strait of Georgia were typically small (Richards and Hand 1989), commercial CPUE was calculated using commercial hook and line catch and effort only. Historically, these fisheries targeted Lingcod only until the late 1970s when increased effort was directed on rockfish (Richards and Hand 1991). To avoid including directed rockfish effort in the Lingcod CPUE calculation, Richards and Hand (1991) suggested using only sales slips records with reported Lingcod catch of at least 100 kg. On average, the annual proportion of Strait of Georgia Lingcod catch that satisfied the qualification criteria was 83.5% with an overall decline of approximately 89% of the catch in 1967-1971 to approximately 71% of the catch in the final five years (Richards and Hand 1991). Annual CPUE values summarized by area in Table 8 and Figure 3 were taken from Richards and Hand (1991). When CPUE series for geographic areas made up of one or more statistical area were required (i.e., the entire Strait of Georgia as a single population), the mean CPUE for all statistical areas within the larger geographic area was used (Table 8). This approach assigns an equal weight to CPUE from each area, regardless of the magnitude of catch.

2.2.2. Recreational Fishery CPUE

Recreational catch and effort statistics collected from individual angler interviews between 1982 and 2013 were provided by the Strait of Georgia Creel Survey Program (Kris Hein, Fisheries and Oceans Canada, South Coast Region, Salmon Stock Assessment, pers. comm., September 2014). Each interview record contained information on the date, day type (weekday or weekend), time of day (morning, afternoon, evening), number of Lingcod retained, number of Lingcod released, total number of hours spent fishing, interview site, statistical area fished, sub-area fished, interviewer, and whether the trip was guided. The survey and analytical methodology of the Strait of Georgia creel program has been previously documented and peer-reviewed (Sturhahn and Nagtegaal 2001, English et al. 2002).

Lingcod CPUE was calculated as the total Lingcod encounters (retained and released fish) per 100 hours of fishing effort between May and September in Statistical Areas 13-19, 28, & 29 (Figure 1). Fishing effort included both targeted and non-targeted Lingcod fishing.

The method used to calculate an annual CPUE series from catch and effort data differs for this assessment compared to previous Lingcod assessments (Logan et al. 2005, King et al. 2003). In the past, catch and effort were summed for each Statistical Area, and an annual CPUE index was then calculated as the average CPUE over all Statistical Areas. This Area-based Average CPUE approach was deemed unsuitable for continued application due to changes in the boundaries used to define Statistical Areas in the creel data starting in 2011 and small sample sizes in some areas in recent years that resulted in outliers (Appendix B). Instead, an Interview-based Average method has been used for the current assessment in which a CPUE estimate is calculated for each individual interview, and the annual CPUE value for the entire Strait of Georgia is based on the average of estimates from each interview. A description and comparison of these two methods is presented in Appendix B. A generalized linear model (GLM) approach to estimating a standardized CPUE index was also considered; however, the approach was discarded due to poor model fits.

When calculating the 2014 Interview-based CPUE index, sampling effort that was directed at shellfishing only (as indicated in the interviewer comments) was excluded. Some interviews contained a single effort value, but noted that effort was directed at both finfish and shellfish (i.e., crabs or prawns). These records were included based on the assumption that the majority of effort was directed at line fishing, with only a small portion of the time spent setting and retrieving traps.

The final recreational CPUE index used as data input for the model is provided in Table 9 and Figure 3.

2.3. BIOLOGICAL PARAMETERS

Schedules describing length-at-age, weight-at-length, and proportion mature-at-age were calculated independent of the assessment model and were then input to the model as fixed values that were held constant over time (Figure 4). The equations used to model these schedules within the stock assessment model are provided in Appendix C, while the parameter values are given in Table 10. No new data were used to update these values for this assessment; the same parameters that were used for the 2005 assessment were applied. In the case of the maturity-at-age parameters, a slightly different parameterization of the relationship required the current parameters to approximate the relationship used for the 2005 assessment (Logan et al. 2005).

3. STOCK ASSESSMENT MODEL

3.1. OVERVIEW

A two-sex version of the statistical catch-at-age model iSCAM (Integrated Statistical Catch Age Model) was used for stock assessment modelling (Martell et al. 2012). A two-sex model was selected for Lingcod because of the large sexual dimorphism for this species. iSCAM is written in AD Model Builder (Fournier et al. 2012, Fournier 2013), and allows Bayesian estimation using the Markov Chain Monte Carlo (MCMC) method within AD Model Builder. The source code and documentation for the original iSCAM is available online.

The model structure used for this assessment is similar to that used for Pacific Herring and Pacific Cod stock assessments (Martell et al. 2012, Forrest et al. 2015), but has been adapted to model male and females separately. In addition, modifications to iSCAM have been made by the first author of this assessment to allow density-dependent mortality and non-linear catchability options. A description of the version of iSCAM used for this assessment, including model equations and prior distributions for Bayesian estimation, is provided in Appendix C.

iSCAM uses an errors-in-variables approach to fitting the data, in which a ratio parameter ρ is used to partition total model variance into observation error (abundance indices) and process error (recruitment deviations) components (Schnute and Richards 1995). The ρ parameter specifies the proportion of the total variance that is due to observation error. The equations used to specify this relationship are provided in Appendix C.

iSCAM allows for the weighting of each individual index observation relative to total observation error through user-specified relative weights. We assumed that all observations had the same variance by setting the relative weight parameter to 1.0 for each data point. This approach is the same as that used for the 2005 assessment (Logan et al. 2005). Attempts to estimate observation errors for each index point were not made for this assessment, but should be considered in the future.

Estimated model parameters included unfished equilibrium recruitment of age-1 fish (R_0), steepness for the Ricker stock recruitment curve (h), average recruitment ($\bar{R}$), a vector of instantaneous fishing mortality rates for each catch observation, annual log recruitment deviations from the underlying stock recruitment model, and a precision parameter that is the inverse of total variance. All estimated parameters had uninformative prior distributions (Appendix C). Fixed model parameters included natural mortality (M), fishery-specific selectivity parameters, and ρ.

The last assessment for Strait of Georgia Lingcod also used a statistical catch-at-age model, which was derived from a class library written in C++, called Fish++ (Logan et al. 2005). Several of the model assumptions that were used to model Strait of Georgia Lingcod in 2005 were incorporated into iSCAM in order to maintain consistency between assessments. A bridging analysis demonstrated that iSCAM could be configured to produce very similar results to the 2005 assessment model (Appendix C). These assumptions are described below.

Density-dependent Natural Mortality

As in 2005, the stock assessment model required a fixed value to be assumed for natural mortality (M) because there were insufficient data available to estimate this parameter. For most scenarios, an M value of 0.2 was used, which is the same value used for the 2005 assessment (Logan et al. 2005). Some scenarios assumed that natural mortality was a density-dependent process, with M decreasing linearly as abundance decreased (Appendix C). In this case, the maximum M was assumed to be 0.2 when the population was at unexploited abundance, decreasing to 0.18 when the stock was at zero abundance (Figure 5). This assumption was selected by the Lingcod Management Framework Committee in 2005 for inclusion in the recommended assessment model (Logan et al. 2005). The rationale for the relatively narrow range of M values at unfished abundance and zero abundance was not documented.

Selectivity Relationships

Selectivity relationships were modelled for three gear types:

(i) the commercial fishery (which includes catch data from hook & line and trawl fisheries, with the majority of the catch coming from hook & line),

(ii) the recreational fishery prior to 1991, during which time either no size limit or a voluntary minimum size limit of 58 cm total length (after 1981) was in place, and

(iii) the recreational fishery from 1991 onwards, during which time a minimum size limit of 65 cm was in place.

Recreational CPUE was modelled as a single abundance index that used the pre-1991 recreational selectivity relationship as the catch data used to estimate CPUE included retained and released lingcod, which means that the 65-cm size limit would not affect the index. Selectivity relationships for each of these three fisheries were fixed at values that were comparable to those assumed for the 2005 assessment (Logan et al. 2005; Table 11, Figure 6). Low sample sizes for available age composition data for this stock precludes the estimation of selectivity parameters.

Equal selectivity for the two types of commercial fishery gear (hook & line and trawl) was assumed both in the 2005 assessment and the current assessment. While the validity of this assumption is not fully known, it is retained in the current assessment due to data limitations and the small effect on assessment outcomes it is expected to have based on available information. Lingcod catch statistics between 1927 and 1951 were not reported by gear-type and attempts to partition catch during this period would be uncertain. The trawl fishery developed in the 1930s and was subject to a series of area-based closures between 1944 and 1953, so application of a single average "proportion trawl" value prior to 1952 would be unrealistic as the proportion was likely changing over time. Anecdotal information prior to 1954 and catch records between 1954 and 1989 show that the proportion of Lingcod caught by trawl fisheries in the Strait of Georgia has remained less than 20%, and has often been less than 10%. The selectivity functions for the two gears would therefore need to differ substantially to affect assessment outcomes. Available age composition from these two gear types between 1977 and 1983 suggests that selectivity for these two fisheries were similar (Figure 36 in Cass et al. 1990).

The commercial fishery and the pre-1991recreational fishery were modelled using an age-based logistic selectivity function, with the mean age of selectivity and the standard deviation of the mean age set at values that approximated the functions used in 2005. Age-based selectivities for males and females were assumed equal for these two gears. The recreational fishery post-1991 (i.e., minimum size limit = 65 cm total length) was modelled in iSCAM using a length-based logistic selectivity function centered on the minimum size limit (Table 11). This approach differed from the sex-specific age-based selectivity curves used for this fishery in 2005 (Logan et al. 2005). The length-based approach was necessary for this assessment however, because iSCAM is not currently configured to handle sex-specific age-based selectivity functions. The expected behaviour of the iSCAM and Fish++ approaches are similar: when a minimum size limit of 65 cm is in place, females will be vulnerable to fishing at a younger age than males (e.g., Figure 6, panel d).

Density-dependent CPUE Relationship

For scenarios that used density-dependent CPUE, commercial and recreational CPUE indices were modelled as a power function of vulnerable biomass (for commercial fishery) or vulnerable abundance (for recreational fishery), assuming the same degree of linearity between CPUE and vulnerable biomass (or abundance) that was estimated in 2005 (Figure 7). A mathematical description of the density-dependent CPUE relationship and assumed parameters values are provided in Appendix C.

Ricker Stock Recruitment

All scenarios considered in 2014 assumed a Ricker stock recruitment function, which is the same assumption that was made in the selected 2005 assessment model. Logan et al. (2005) also considered an alternative Beverton-Holt function, but found that the choice of stock recruitment function did not affect estimated stock status. The most recent assessment of the four outside Lingcod stocks in British Columbia also used a Ricker curve based on recent evidence that Lingcod display cannibalistic behaviour, which is better characterized by a Ricker model (King et al. 2012).

Unfished Equilibrium in 1927

The population was assumed to be at unfished equilibrium at the start of the available commercial catch series in 1927. This assumption was necessary to compensate for the lack of age composition data; however, it is known that some fishing occurred before 1927. Commercial fishing for Lingcod in the southern Strait of Georgia is reported to have started as early as the 1860s, with annual catches as high as 2500 tonnes per year by 1927 (Table 5). We discuss the potential implications of this assumption in the Discussion section.

3.2. ESTIMATION OF REFERENCE POINTS AND STOCK STATUS

iSCAM was used to approximate posterior distributions for B_0 and B_{MSY} (Appendix C), which served as a basis for deriving reference points for both the 2005 Lingcod Management Framework (reference points = $0.10B_0$, $0.25B_0$, and $0.40B_0$) and the DFO PA Framework (reference points = $0.40B_{MSY}$, $0.80B_{MSY}$, and B_{MSY}).

Stock status was quantified as the probability that spawning biomass in 2014, B_{2014}, exceeded each reference point. For each reference point, this probability was calculated as the proportion of MCMC samples for which B_{2014} exceeded the reference point estimate for that sample. The probability that B_{2014} was greater than spawning biomass in 2006, $Pr(B_{2014} > B_{2006})$, was also calculated to quantify the probability that spawning biomass had increased since the current management regime was introduced in 2006.

4. STOCK ASSESSMENT SCENARIOS

4.1. OVERVIEW

Twelve stock assessment scenarios are used to characterize a range of stock status estimates in 2014. These scenarios differ in

(i) their treatment of historic catch reported by the Dominion Bureau of Statistics between 1927 and 1946,

(ii) assumptions about density-dependent mortality and density-dependent catchability relationships, and

(iii) the natural mortality rate M.

An overview of all scenarios is presented in Table 12, and a more detailed description of each alternative hypothesis is described here.

4.1.2. District 1 Catches: 1927 – 1946

Between 1927 and 1946, catch statistics were reported by the Dominion Bureau of Statistics (DBS) using three Districts: District 1 (entrance to the Fraser River and Howe Sound), District 2 (northern British Columbia, typically from Prince Rupert to Smiths Inlet), and District 3 (southern British Columbia, including the west coast of Vancouver Island, Johnstone Strait, Strait of Georgia, and the Juan de Fuca Strait). Only District 1 and 3 landings are used in this assessment, with attempts made to allocate the appropriate levels of catch to each of the four quadrants used in this assessment (Table 5).

Uncertainty in the accuracy of District 1 catch values recorded by the DBS between 1927 and 1946 has previously been documented for both Lingcod and rockfish species in the Strait of Georgia (Logan et al. 2005, Yamanaka et al. 2012a, 2012b). The boundaries of District 1 approximate PFMC Areas 28 and 29 (Figure 1). Three hypotheses about potential discrepancies in District 1 catch were put forward by Logan et al. (2005):

1) District 1 catches between 1927 and 1946 could have included Lingcod caught in the Gulf Islands or elsewhere in the Strait of Georgia, but landed in Vancouver;
2) District 1 catches between 1927 and 1946 could have included Lingcod caught elsewhere in the Strait of Georgia that were landed and recorded in the area of capture, but then subsequently landed and recorded in District 1;
3) District 1 catches between 1927 and 1932 could have included Lingcod caught outside the Strait of Georgia (e.g., West Coast Vancouver Island or northern BC), but then landed in District 1.

Note that Hypothesis 3 does not apply past 1933 because the landings of Lingcod to District 1 were adjusted in 1933 to account for Lingcod caught outside the Strait of Georgia but landed in Vancouver (Logan et al. 2005).

The 2005 Lingcod stock assessment addressed uncertainties in District 1 catches in several ways. First, scenarios were considered in which all data were used as reported. The second approach considered scenarios that reduced District 1 catches between 1927 and 1933 by 10% to account for Hypothesis 3. Decreasing catch in this way has a relatively small effect on estimates of current stock status in 2003 (Logan et al. 2005). Preliminary investigation of this hypothesis for the current assessment also showed small differences in 2014 stock status (results not shown). A third approach to deal with uncertainties in District 1 catches was to exclude the entire southeast quadrant from the stock assessment (i.e., no data from this quadrant was used between 1927 and 2003). This third approach was selected as a basis for providing stock status and assessment advice in 2005.

For a recent assessment of Yelloweye Rockfish (*Sebastes ruberrimus*) in the Strait of Georgia, all data from District 1 was used as reported in the base case stock assessment model, and sensitivity analyses were used to characterize uncertainty in historical catch data by decreasing the entire catch series by 50% and increasing the entire catch time series by 150% (Yamanaka et al. 2012b).

In the current assessment, we use four "District 1 catch scenarios" to bracket a range of uncertainty around historical District 1 catches between 1927 and 1946:

noSE: Exclude Southeast quadrant from Strait of Georgia Population

The noSE scenario is the same as that used as a basis for stock status and harvest advice in 2005 (Logan et al. 2005), in which the southeast quadrants (PFMC Areas 28 and 29) are excluded from the stock assessment. As a result, Lingcod retention is currently prohibited in Areas 28 and 29. A limitation of this approach is that if District 1 Lingcod landings did include Lingcod caught elsewhere in the Strait of Georgia (i.e., Hypothesis 1 is correct), then the exclusion of these data when fitting the population model would underestimate historical biomass levels of Lingcod in the assessed Areas 13-19.

onlySEpre1947: Exclude all catch not from Southeast quadrant prior to 1947

In this scenario, only catch reported in the Southeast quadrant between 1927 and 1946 was included in estimates of total catch for the Strait of Georgia (i.e., catch from the other three quadrants were excluded). This scenario represents an extreme case of Hypothesis 2, e.g., 100% of catch from the southwest, northwest, and northeast quadrants were first landed in the area of capture, and then subsequently, landed and recorded again in District 1. Note that there are some years in which reported catch from the three excluded quadrants is greater than that reported in the Southeast quadrant, which suggests that <100% of catch from the excluded quadrants was likely double-counted. This scenario is meant to represent an extreme case however in order to bracket the range of uncertainty is historical catches, so we are not concerned with this relatively small discrepancy.

noSEpre1947: Exclude all catch from Southeast quadrant prior to 1947

This scenario was considered as a point of contrast to the onlySEpre1947 scenario. In this case, catch from the Southeast quadrant was excluded prior to 1947, but all other catch and CPUE statistics after 1947 included the southeast quadrant.

SoG: Use all catch data as recorded from the entire Strait of Georgia

The SoG scenario in which all catch from Areas 13-19, 28, and 29 are used as reported accommodates Hypothesis 1, in which District 1 catches between 1927 and 1946 included Lingcod caught in the Gulf Islands or elsewhere in the Strait of Georgia, but landed in Vancouver. Because the entire SoG (Areas 13-19, 28, 29) is assessed as a single pooled population, it does not matter whether catch was reported in the quadrant of capture, so long as it was reported in the Strait of Georgia. This approach assumes no double counting of catch occurred.

It is possible that none of these four District 1 catch scenarios provide an accurate representation of historical Lingcod catch from the Strait of Georgia between 1927 and 1946. The potential proportion of landings that were double counted is uncertain and it has been previously noted that the rate of double counting was likely variable between years (Yamanaka et al. 2012a, 2012b). These four scenarios are intended to bracket the range of uncertainty in these historic values however, and are therefore all presented with equal weight when characterizing stock status in the current assessment.

4.1.3. Density-dependent Effects

Density-dependent mortality and catchability

In these scenarios, the stock assessment model was configured using the relationships for density-dependent natural mortality and density-dependent catchability described in the Stock Assessment Model section (Section 3.1; see Figure 5 and Figure 7, as well as Appendix C for equations and assumed values). This configuration is also the same as Step5a of the bridging analysis presented in Appendix D.

When considering density-dependent catchability for the noSE and SoG models, the power exponent determining the degree of linearity between the abundance index and vulnerable biomass was held constant at the values estimated by Logan et al. (2005) for each of these scenarios, while the catchability coefficient q was estimated. For the onlySEpre1947 and noSEpre1947 catch scenarios, the power exponent was set at the values estimated for the SoG scenario by Logan et al. (2005) while q was estimated.

While estimates of the power exponent would likely change in 2014 due to 10 new years of data being added to the assessment models, we did not attempt to re-estimate these parameters for the current assessment.

These scenarios are denoted simply by the District 1 catch scenario name (e.g., noSE, SoG) in Table 12.

noDD: No density-dependent mortality and catchability

In the noDD scenarios, both the option to use density-dependent mortality and density-dependent catchability were turned off (i.e., both *M* and *q* were assumed constant over time). Preliminary analysis showed that turning off density-dependent mortality alone had a small effect on assessment results in 2014 (results not shown), so we do not present this step alone. Turning off density-dependent catchability had a larger effect on model results.

The suffix “noDD” added to a scenario ID denotes scenarios in which both density-dependent mortality and catchability were removed.

4.1.4. Natural Mortality (*M*)

M = 0.2

An *M* value of 0.2 was considered as this was the value selected by the Lingcod Management Framework Committee for inclusion in the 2005 assessment. When density-dependent mortality was used, the maximum *M* was assumed to be 0.2 when the population was at unexploited abundance, decreasing to 0.18 when the stock was at zero abundance (Figure 5). This assumption was selected by the Lingcod Management Framework Committee in 2005 for inclusion in the recommended assessment model (Logan et al. 2005).

highM: *M* = 0.3

A value of 0.3 was considered as an alternative hypothesis because it was within the range of Lingcod *M* values suggested by Jagielo and Wallace (2005) based on their analyses using the life history-based methods of Hoenig (1983), Alverson and Carney (1975), and Pauly (1980). Their range of estimated *M* values for males was 0.14 – 0.22, while the range for females was 0.26 – 0.38.

The suffix “highM” added to scenario IDs denotes scenarios in which *M* was set to 0.3 instead of 0.2. The case of highM with density-dependent mortality was not considered.

4.2. SELECTION OF SCENARIOS FOR CHARACTERIZING STOCK STATUS

Nine of the 12 stock assessment scenarios described above were used to characterize stock status in 2014 (Table 12). The three scenarios in which the southeast quadrant (PFMC Areas 28 and 29) were excluded from the Strait of Georgia stock (noSE, noSE_noDD, and noSE_noDD+highM) were not selected to represent stock status for several reasons. First, there is no biological basis for the assumption that recruitment in minor Statistical Areas 28 and 29 is separated from the rest of the Strait of Georgia. Second, if District 1 Lingcod landings did include Lingcod caught elsewhere in the Strait of Georgia (i.e., Hypothesis 1 in Section 4.1 is correct), then the exclusion of these data when fitting the population model would underestimate historical biomass levels of Lingcod in the assessed Areas 13-19. Finally, continued use of the noSE model precludes the provision of harvest advice for these areas. If re-opening minor Areas 28 and 29 to Lingcod retention is a goal for recreational and commercial fisheries within the Strait of Georgia, these areas should be included in a Strait of Georgia stock assessment. The inclusion of assessment scenarios that reduce Strait of Georgia catches between 1927 and 1946 is a better way to explore hypotheses related to catch misreporting during these years than simply eliminating the southeast quadrant from the stock.

While the three noSE scenarios are not considered plausible scenarios to characterize stock status, results from these scenarios are presented in this document to maintain consistency with the 2005 assessment. The noSE scenario was used a basis for stock status and harvest advice in 2005.

4.3. SCENARIO-AVERAGING

In addition to presenting results for each of the nine scenarios used to characterize stock status, we used a scenario-averaging approach (also called model-averaging) to represent structural uncertainty across scenarios. The nine scenarios used to create scenario-averaged results were: (i) onlySEpre1947, (ii) onlySEpre1947_noDD, (iii) onlySEpre1947_noDD+highM, (iv) noSEpre1947, (v) noSEpre1947_noDD, (vi) noSEpre1947_noDD+highM , (vii) SoG, (viii) SoG_noDD, and (ix) SoG_noDD+highM (Section 4.2; Table 12).

For each model parameter and derived reference point, vectors of 1,900 burned-in posterior samples from each of the nine scenarios were combined into a parameter vector of 17,100 samples. The probability of stock status in 2014 being above reference points was then calculated using the combined vectors of 17,100 samples. This approach assigned equal weight to all nine scenarios. Scenario-averaging such as this has been previously used to incorporate structural uncertainty in the assessment into harvest advice for Pacific Hake (Stewart et al. 2011) and Pacific Cod (Forrest et al. 2015).

5. RESULTS

Spawning biomass trajectories for each of the 12 scenarios are provided in Figure 8 - Figure 19, while summaries of posterior distributions for model parameters and management quantities are provided in Table 13 - Table 16. Comparisons of depletion trajectories (Spawning Biomass / Unfished equilibrium biomass) among scenarios are provided in Figure 20 - Figure 22. Estimates of fishery-specific fishing mortality over time are shown in Figure 24 - Figure 35.

All 12 scenarios show a similar spawning biomass trajectory since 1927, with a large decline in spawning biomass between 1927 and the late-1980s, followed by a gradual increase between the 1990s and 2014 (Figure 8 - Figure 19). The relative magnitude of the recent increase, however, is highly dependent on both the approach taken to deal with uncertainty in historical District 1 catches and the inclusion of density-dependent catchability relationships estimated by Logan et al. (2005), as described below. In the most optimistic scenario considered, the “noSE” scenario, the median posterior estimate of B_{2014} / B_0 was 0.463 while that of the lowest predicted year, 1988, was 0.032, indicating that spawning biomass has increased from 3.2% of B_0 in 1988 to 46.3% of B_0 in 2014 (Figure 8; Figure 20). In the most pessimistic scenario, the “SoG” scenario, the median posterior estimate of B_{2014} / B_0 was 0.138 while that of the lowest predicted year, 1989, was 0.057 (Figure 17; Figure 20).

Plots showing stock assessment model fits and properties of MCMC convergence are presented in Appendix E. Fits to the recreational CPUE index in the last four years of the time series were poor, with model predictions unable to capture the decline in recreational CPUE between 2010 and 2013 (Appendix E, Figures E.1 – E.12).

MCMC chains were slow to converge for all 12 assessment scenarios due to confounding among estimated parameters. Large thinning intervals were needed to achieve acceptable convergence in all cases (1 in 1000 runs to 1 in 2500 runs; Appendix E). MCMC convergence for all 12 scenarios was assessed based on a visual inspection of MCMC chains. Trace plots showed no trends, an inspection of the autocorrelation function for each estimated parameter showed that the maximum autocorrelation occurred at lag-1, and was always less than 0.25, and marginal posterior distributions for model parameters and derived MSY-based quantities were unimodal (Appendix E).

Parameter estimates of steepness (*h*) and unfished equilibrium recruitment (R_0) were negatively confounded in MCMC chains for all 12 scenarios (Appendix E). Estimated catchability coefficients for both the commercial and recreational CPUE series were confounded with each other, as well as average recruitment ($\bar{R}$), h, and to a lesser extent, R_0. Model parameters were also highly confounded with derived estimates of reference point quantities. Estimates of R_0 showed a high positive correlation with B_0 and B_{MSY}, while estimates of steepness showed a high positive correlation with F_{MSY} (Appendix E).

5.1. EFFECT OF HISTORICAL DISTRICT 1 CATCH DATA

When density-dependent catchability and density-dependent *M* effects were included in assessment models, the noSE scenario showed a much stronger rebound in spawning stock biomass between the late-1990s and 2014 compared to the other three approaches to dealing with uncertainty in District 1 catch (onlySEpre1947, noSEpre1947, SoG; Figure 20). The noSE model also had a much smaller estimate of unfished spawning stock biomass, B_0, and a higher estimate of steepness, h, compared to the other three catch scenarios when no density-dependent relationships were assumed (Table 13 - Table 16). For example, the median posterior estimate of B_0 (and 5^{th} to 95^{th} posterior percentile range; shown in brackets) for the noSE scenario was 18,135 tonnes (15,467 - 20,850), compared with median values of 31,172 tonnes (27,429 - 35,534), 37,915 tonnes (33,560 - 43,161), and 54,772 tonnes (46,520-64,081) for the noSEpre1947, onlySEpre1947, and SoG scenarios, respectively. Median steepness for the noSE scenario was 0.52, compared with values of 0.26-0.27 for the other three scenarios.

Catchability estimates for both the commercial and recreational CPUE series were also higher for the noSE scenario compared to the noSEpre1947, onlySEpre1947, and SoG scenarios. For example, the posterior median catchability estimate for the commercial fishery CPUE series (q_{cCPUE}) was 1.736 for the noSE scenario (Table 13), compared to 0.093 – 0.101 for the noSEpre1947, onlySEpre1947, and SoG scenarios (Table 14 - Table 16).

As a result of these differences, the estimated posterior distribution for the ratio B_{2104}/B_0 was substantially higher for the noSE scenario compared to the other three catch scenarios, with almost no overlap in posterior distributions. The posterior median (and 5^{th} - 95^{th} percentile range) for the noSE scenario was 0.463 (0.321 - 0.663), compared to estimates of 0.184 (0.144 - 0.235), 0.221(0.175 - 0.288), and 0.138(0.105 - 0.188) for the onlySEpre1947, noSEpre1947, and SoG scenarios, respectively.

5.2. EFFECT OF DENSITY-DEPENDENCE RELATIONSHIPS

Removing density-dependent catchability and density-dependent *M* effects from the model had an opposite effect on scale and productivity parameter estimates for the noSE District 1 catch scenario than it did for the other three catch scenarios. When density-dependence was removed from the noSE catch scenario, the estimated posterior distribution for steepness decreased while that of steepness increased (compare noSE and noSE_noDD scenarios in Table 13). Catchability estimates for both the commercial and recreational CPUE series also decreased when density-dependent effects were removed from the noSE catch scenario. The estimated posterior distribution for the ratio of B_{2014} / B_0 was lower for the noSE_noDD scenario compared to the noSE scenario, with the posterior median (and 5^{th} - 95^{th} percentiles) decreasing from 0.463 (0.321 - 0.663) for the noSE scenario to 0.286 (0.222 - 0.373) for the noSE_noDD scenario. The opposite pattern was seen for the other three catch scenarios, with B0 decreasing and steepness increasing when density-dependent effects were removed (Table 14 - Table 16).

The net effect of removing density-dependent relationships from all four catch scenarios was to more closely align the predicted spawning biomass trajectory from the noSE catch scenario with that of the other three scenarios (Table 13 - Table 16, Figure 21). Posterior estimates of B_0 and steepness were similar for the noSE_noDD, onlySEpre1947_noDD, noSEpre1947_noDD, and

SoG_noDD scenarios. The median posterior estimate for B_{2014} / B_0 ranged from 0.178 to 0.306 over these four scenarios.

An examination of the iterative difference from removing first density-dependent M effects and then density-dependent catchability showed that the difference in the estimated scale and productivity of the stock (i.e., B_0 and *h*) with and without density dependent effects was due to the removal of density-dependent catchability (results not shown).

5.3. EFFECT OF ASSUMED RATE OF M

Increasing the value of *M* assumed in the assessment model from 0.2 to 0.3 (when no density-dependent effects were assumed) had a smaller effect on model predictions than changing the treatment of District 1 catch or removing density-dependent effects. The direction and magnitude of change in parameter estimates and spawning biomass trajectories when *M* was reduced between the _noDD scenarios and the _noDD+highM scenarios was similar among all four catch scenarios (Table 13 - Table 16; Figure 22). Posterior distributions for *h*, B_0, and q_{rCPUE} all decreased, while the posterior distribution for q_{cCPUE} increased slightly. Decreases in the posterior distribution of B_{2014} / B_0 were seen in all four catch scenarios; however, the magnitude of this decline was small. For example, the posterior median (and 5^{th} – 95^{th} percentiles) of B_{2014} / B_0 for the noSE_noDD scenario was 0.286 (0.22 2 – 0.373), compared to 0.268 (0.203 - 0.353) for the noSE_noDD+highM scenario (Table 13).

5.4. STOCK STATUS IN 2014 RELATIVE TO REFERENCE POINTS

Stock status relative to reference points is only presented for the nine scenarios used to classify stock status in 2014, as well as for the scenario-average.

All nine assessment scenarios, as well as the scenario-average, predicted a continued increase in spawning stock biomass since the start of the current management regime, with a 100% probability that spawning biomass in 2014 was greater than spawning biomass in 2006 (Table 18).

When the 2005 Lingcod Management Framework reference points were used to classify stock status, none of the scenarios predicted that B_{2014} was most likely above the target biomass level of $0.40B_0$ (Table 18; Figure 36). Two scenarios predicted B_{2014} was most likely above the short-term recovery target of $0.25B_0$ but below the target of $0.40B_0$; both of these scenarios excluded catch data from the southeast quadrant prior to 1947 (noSEpre1947_noDD and noSEpre1947_noDD+highM). The remaining seven scenarios predicted that B_{2014} was most likely above the limit reference point of $0.10B_0$, but below $0.25B_0$. The SoG scenario predicted the lowest stock status in 2014, with a zero probability of $B_{2014} > 0.25B_0$. The scenario-averaging approach to status estimation estimated that B_{2014} was most likely between the limit reference point ($0.10B_0$) and the short-term recovery target ($0.25B_0$), with a 71% probability that B_{2014} was between these two points (Table 18).

When the B_{MSY}-based reference points from the DFO PA Framework were used to classify stock status, no scenarios produced a high probability that B_{2014} was in the healthy zone (i.e., B_{2014} > 0.8 $B_{MSY;}$ Table 18; Figure 36). Six of the nine scenarios predicted that B_{2014} was most likely in the cautious zone (between 0.4 B_{MSY} and 0.8 B_{MSY}). These scenarios included all three scenarios that excluded catch data from the southeast quadrant prior to 1947, two of the scenarios that only included catch from the southeast quadrant prior to 1947 (onlySEpre1947_noDD and onlySEpre1947_noDDM+highM) and one scenario that used all Strait of Georgia data as reported (SoG_noDD). The remaining three scenarios predicted that B_{2014} was most likely in the critical zone with a <50%probability that B_{2014} > 0.4 B_{MSY}. Once again, the SoG scenario predicted that lowest stock status in 2014 with a 1% chance that B_{2014}

> 0.40 B_{MSY}. The scenario-averaging approach estimated that B_{2014} had a 58% probability of being in the cautious zone, a 37% probability of being in the critical zone, and a 5% probability of being in the healthy zone (above 0.8B_{MSY}).

6. DISCUSSION

6.1. UPDATES FROM 2005 STOCK ASSESSMENT

All 12 stock assessment scenarios estimate a continued recovery in Strait of Georgia Lingcod spawning biomass to 2014 from historically low levels in the late 1980s. In all scenarios, spawning biomass in 2014 was predicted with 100% certainty to be greater than spawning biomass at the start of the current management regime in 2006. It should be noted however that the assessment modelling approach used for this assessment does not allow for much recruitment variation independent of spawning biomass, which means that the model is too constrained to fit to the drop in recreational CPUE in the last three years of the time series (2011 - 2013). As a result, the biomass prediction in 2014, as well as the predicted magnitude of recovery since 2006, may be optimistic.

The estimated magnitude of recovery is dependent on both the treatment of historical catch from the DBS District 1 (1927 - 1946) and the assumption made about density-dependent catchability. In the most optimistic scenario examined (noSE), the current model predicts that spawning biomass has increased from 3.2% of B_0 in 1988 to 46.3% of B_0 in 2014 based on posterior medians, while in the most pessimistic scenario (SoG), the current model estimates that spawning biomass has increased 5.7% of B_0 in 1988 to 13.8% of B_0 in 2014 based on posterior medians. All nine scenarios selected to characterize stock status in this assessment predicted spawning biomass in 2014 to be in either the cautious or critical zones (based on the DFO PA Framework categories) or somewhere below the target and/or short-term recovery limits (based on the 2005 Lingcod Framework).

Both the current assessment and the 2005 assessment predicted the Lingcod stock under the noSE scenario to be a smaller and more productive stock when compared to the SoG scenario. In addition, the noSE scenario showed a more rapid recovery from historically low levels of spawning biomass in 1988 - 1989 (Logan et al. 2005). For the noSE scenario, spawning biomass in 2003 was estimated at 15.99% of B_0, compared to an estimated low of 2.21% of B_0. In contrast, the SoG scenario indicated that spawning biomass in 2003 was 5.95% of B_0, compared to a predicted low of 1.62% of B_0 (Logan et al. 2005).

The effect of adding 11 years of new recreational catch and recreational CPUE data (2003 - 2013) was to increase the estimated scale of the population (B_0) and decrease the estimated productivity (steepness, h) for both the SoG and noSE catch scenarios. The bridging analysis we used to document the transition from the 2005 assessment to the current stock assessment shows that these differences are largely due to the inclusion of new data rather than a switch from the Fish++ to iSCAM modelling platforms (Appendix D). This result suggests that the relatively low estimates of steepness seen for many of the 2014 scenarios can be at least partly attributed to recent catch and CPUE data from the recreational fishery.

One possible explanation for the decrease in estimated productivity and increase in estimated B_0 with the addition of 2003 – 2013 data is that changes in the Strait of Georgia ecosystem have lowered Lingcod productivity. In fitting the 2014 data, the model had to account for why substantial reductions in catch in recent years did not result in a larger magnitude of stock increase than shown in recreational CPUE. Both unfished recruitment and steepness were assumed stationary over time within the assessment model, and M was assumed to decrease only slightly with increasing abundance. B_0 and h were negatively correlated within MCMC chains, so if productivity was decreasing over time, the model would be forced to decrease estimates of *h* while increasing estimates of B_0 to account for this slow rebuilding trend given assumptions of stationarity.

Alternatively, these changes in estimates of steepness could be due to recreational CPUE being a poor indicator of Lingcod abundance or inaccurate estimates of landed catch. Recreational CPUE is the only current data available to model from which it can infer productivity, so time-varying relationships in catchability or selectivity that are not captured in the assessment model formulation could also lead to a perceived decrease in productivity. We discuss the potential for changing productivity and the limitations of the CPUE indices and catch data in the "Assessment Limitations" section below.

6.2. DIFFERENCES BETWEEN SCENARIOS IN 2014

Key assumptions of the 12 assessment scenarios and posterior median estimates for B_0, *h*, and B_{2014} / B_0 are summarized in Table 19 for easy comparison when discussing differences among scenarios.

The results of our scenario analysis in 2014 shows that while the different approaches taken to address uncertainty in historical catch data from District 1 contribute to the wide range of stock status estimates seen over the 12 scenarios, the inclusion or exclusion of density-dependent catchability relationships had a larger effect. When density-dependent effects were removed, estimates of *h*, B_0, and B_{MSY} became much more similar among the four catch scenarios, as did estimates of B_{2014} relative to both sets of reference points. The different density-dependent catchability relationships used in this assessment are based on the relationships estimated in the last assessment (Logan et al. 2005). Future stock assessments for Strait of Georgia Lingcod that rely on fishery CPUE to index abundance should re-estimate these relationships using up-to-date data rather than continuing to use the relationships estimated by Logan et al. (2005).

Catch scenarios that included all historical Strait of Georgia catch data as reported (i.e., SoG, SoG_noDD, and SoG_noDD+highM) produced the highest estimates of B_0 and the lowest estimates of B_{2014} relative to reference points, regardless of whether density-dependent effects were included and the value of *M* assumed. This result occurs because the modelling approach we used allows limited recruitment variation independent of abundance, which means that the model cannot attribute high catches in early years to strong recruitment events. Instead, the model must predict a large initial abundance in 1927 to allow for the high annual catches removed during the 1930s and 1940s. When these initial high catch values were reduced in the onlySEpre1947 and noSEpre1947 catch scenarios, estimates of B_0 decreased and estimates of current stock status relative to reference points increased.

It is interesting to note that once density-dependent effects are removed, stock status predictions from the noSE_noDD scenario that excluded the southeast quadrant from the assessment altogether were comparable with those of the noSEpre1947_noDD scenario that only excluded catch data from the SE quadrant prior to 1947. This result is likely because fishery catches from the southeast quadrant were relatively small compared to other areas after 1951.

6.3. ASSESSMENT LIMITATIONS

Uncertainties in lead model parameters and derived management quantities were quantified in two ways. First, the sensitivity of the stock reconstruction to structural assumptions and data choices was examined by configuring the model into nine scenarios. Second, the modelled uncertainty within a scenario was represented by using a MCMC approximation to the posterior probability density. The nine alternative assessment scenarios bracket a range of hypotheses about historical District 1 catch data, density-dependent catchability in CPUE series, and the rate of natural mortality. We don't suggest the list of uncertainties represented in the nine scenarios is comprehensive however, so uncertainty is under-represented in this assessment. Additional uncertainties that were not addressed within our scenarios but that were identified for Lingcod in the 2005 assessment include the type of stock recruitment relationship, alternative forms of time-varying catchability, environmental effects, and changes over time in growth and natural mortality (Logan et al. 2005).

The use of fishery CPUE is a key source of uncertainty in this stock assessment. Recreational fishery CPUE is calculated based on total Lingcod catch (retained and released catch) and effort (including directed and non-directed effort) reported during creel survey interviews with anglers at the dock. If anglers are more likely to remember the number of fish retained than the number released, bias in CPUE estimates could vary among years due to varying rates of Lingcod retention under different size limits and bag limits (including years with no Lingcod retention). In addition, the amount of effort spent targeting Lingcod has changed over time in relation to salmon (*Oncorhynchus spp*.) and Pacific Halibut (*Hippoglossus stenolepis*) fishing opportunities. If Lingcod catchability is higher when Lingcod are targeted than when other species are targeted, changes in this proportion over time will bias the index.

Both commercial and recreational CPUE indices were calculated as a simple arithmetic average from available catch and effort observations in a given year (and in the case of commercial CPUE, within a given minor Statistical Area). Fishery CPUE indices are prone to time-varying catchability, which can bias CPUE indices. The use of arithmetic averages of qualified CPUE can be especially vulnerable to this effect. In the 2005 Strait of Georgia Lingcod assessment, Logan et al. (2005) attempted to account for this limitation by modelling CPUE as a function of biomass (i.e., density-dependent catchability), which we carry forward into some of the scenarios used in this assessment. Other scenarios, in which density-dependent effects are removed, assume that catchability is constant over time.

The potential for catchability to vary over time for fishery CPUE indices is well-documented (reviewed in Wilberg et al. 2010), and the density-dependent relationship considered here is just one option. Density-dependent catchability can result from decreases in the fraction of the area occupied by the stock as stock size decreases (i.e., range contraction) or fishing gear becoming saturated at high abundances (Hilborn and Walters 1992). Alternatively, catchability can gradually increase over time due to changes in fishing technology and fisher behaviour, which is sometimes referred to as technological creep (Pauly and Palomares 2010). Abrupt steps in catchability can also occur for several reasons including the rapid adoption of a more efficient technology or regulatory changes that affect fishing behaviour. All of these time-varying catchability relationships seem plausible hypotheses for fisheries in the Strait of Georgia given changes in recreational targeting behaviour between groundfish and salmon over time, changes in Lingcod management regulations and size limits, increased use of electronic downriggers in the recreational fishery, and the introduction of closed areas via rockfish RCAs. Given the strong effect that the assumption of density-dependent catchability had on results for this assessment, future stock assessments relying on recreational and commercial fishery CPUE should consider a more thorough investigation of these different types of time-varying catchability. For example, consultations with recreational fishers could be used to develop a list of plausible hypotheses, and a range of time-varying catchability scenarios could be considered to better characterize structural uncertainty arising from the relationship between Lingcod abundance and fishery CPUE.

In addition to directly modelling changes in catchability as described above, the development of standardized CPUE indices based on generalized linear models (GLM) could help account for changes in catchability. GLM methods standardize the CPUE series for measured covariates that are expected to cause changes in catch rates through time (Hilborn and Walters 1992, Quinn and Deriso 1999, Babcock and McAllister 2002). A GLM would allow us to account for temporal changes in fishing locations, depth, seasonality, and vessel. Standardized CPUE indices have been developed and input to stock assessments for several groundfish stocks in British Columbia, including outside Lingcod stocks (using bottom trawl fishery CPUE; King et al. 2012) and Yelloweye Rockfish in the Strait of Georgia (using hook and line fishery CPUE; Yamanaka et al. 2012b). Unfortunately, factors for which data are not readily available, such as technological advances and learning across years, cannot easily be accounted for. However, the development of GLM indices for Strait of Georgia Lingcod would still be an improvement over the current average-based method. Furthermore, GLM standardization allows estimation of year-specific coefficients of variation for index values, which could be input to iSCAM to assign weights to individual index observations.

While it is not clear whether the development of a standardized CPUE index would improve the reliability of commercial fishery CPUE, initial investigations into the development of a standardized CPUE index for the recreational fishery suggested that standardization may have few benefits (Appendix B). The set of explanatory variables considered in our initial analyses, including the year effect, accounted for less than 5% of the variation in CPUE estimates among interviews. These results led us to conclude that the set of GLM models we considered (which included a zero-inflated model that is expected to perform well for data sets with high proportions of zeros such as recreational CPUE data; Lecomte et al. 2013) could not reliably predict recreational fishery CPUE for Strait of Georgia Lingcod. These results raise concerns about the reliability of recreational CPUE as an indicator of abundance in this assessment. When combined with the downward trend in creel sampling effort in recent years and the strong effect that different assumptions about density-dependent catchability (hyperstability versus hyperdepletion) had on our assessment results, it appears that the reliability of the recreational CPUE index will continue to be a key uncertainty in future stock assessments. If stock assessment modelling is to be used in the long-term to provide harvest advice based on biomass estimates, the development of a fishery-independent abundance index for Strait of Georgia Lingcod should be a high priority. At present, estimates of increasing abundance for Strait of Georgia Lingcod are based solely on catch and CPUE estimates from the recreational fishery.

Another important source of uncertainty in this stock assessment is the assumption that all fishing mortality comes from landed catch. Release (or discard) mortality is not accounted for based on the lack of historical data on Lingcod discards prior to the 2000s, which is when the majority of Lingcod catch was taken. Changes in catch regulations throughout the course of commercial and recreational Lingcod fisheries complicate the estimation of fishery-specific release rates, as rates were likely affected by these changes. Furthermore, even for recent years in which estimates of Lingcod releases are known, considerable uncertainty exists in the proportion of released Lingcod that survive from different fishing methods. Trawl fisheries that retain lingcod on deck for 30 minutes before releasing can have mortality rates of 50%, while those that release Lingcod right after the codend is emptied can have mortality rates of zero (Parker et al. 2003). The DFO Groundfish Management Unit currently assumes a 4% release mortality rate for Lingcod releases by the recreational fishery (Rob Tadey, Hook and Line Coordinator, Groundfish Management Unit, DFO, Vancouver, BC, pers. comm.). This rate is similar to the 5% rate used for US recreational fisheries in the most recent West Coast US stock assessment (Hamel et al. 2009). A review of published literature showed no available estimates of discard mortality for Lingcod in hook and line fisheries. The potential effects on assessment outcomes of not including release mortality is hard to predict because it is not clear whether the proportional increase on total catch would be constant between 1927 and 2014 or change over time. The sensitivity of our current assessment results to the treatment of District 1 catch suggests that disproportionately increasing catch in one part of the time series (e.g., 1927 - 1946 in the District 1 catch scenario) can affect assessment outcomes. Future stock assessments for Strait of Georgia Lingcod should look for a method to incorporate discard mortality into catch data.

Catch from Aboriginal fisheries is also not accounted for in this assessment due to data limitations. Future assessments could explore an approach similar to that used for Yelloweye Rockfish (*Sebastes ruberrimus*) in the Strait of Georgia, in which a consumption rate taken from the literature was applied to population estimates for Aboriginal people who reside near, and have access to, the inside Yelloweye Rockfish population (Yamanaka et al. 2012b).

The assumption that the population was at unfished equilibrium in 1927 also introduces uncertainty to this assessment. This assumption was necessary to compensate for the lack of age composition data; however, it is known that some fishing occurred before 1927. Commercial fishing for Lingcod in the southern Strait of Georgia is reported to have started as early as the 1860s (Cass et al. 1990), with annual catches as high as 2500 tonnes per year by 1927. As a result, estimates of B_0 and B_{MSY} are expected to be underestimated by the assessment model. Future assessments of Strait of Georgia Lingcod should develop a method to reconstruct or interpolate historical Lingcod catches prior to 1927.

Both unfished recruitment and steepness were assumed stationary over time within the assessment model, and M was assumed to decrease only slightly with increasing abundance. However, as described in Section 6.1, one possible explanation for the decrease in estimated productivity and increase in estimated B_0 with the addition of 2003 – 2013 data is that changes in the Strait of Georgia ecosystem have lowered Lingcod productivity. While there are no directed research studies aimed at characterizing or explaining changes in Strait of Georgia Lingcod productivity, changes in the Strait of Georgia ecosystem since the 1990s have been well documented. The 1989 Pacific-basin regime shift (Hare and Mantua 2000; McFarlane et al. 2000) had a regional impact on the Strait of Georgia in the 1990s as observed in bio-physical and human indicators specific to the Strait (Perry and Masson 2013). Since the 1990s, there have been dramatic changes in the ecosystem of the Strait of Georgia, from physical forcing of lower trophic levels up through top predators. The spring freshet of the Fraser River, which initiates spring plankton bloom conditions, has moved to an earlier date (Morrison et al. 2002). This change in Fraser River input has been associated with very early plankton blooms that lead to large interannual differences in bloom times (Allen and Wolfe 2013). Larval and juvenile lingcod feed on copepods and euphausiids (Cass et al. 1990), both of which are the dominant zooplankton taxa in the Strait of Georgia (Mackas et al. 2013). Mackas et al. (2013) observed that earlier Fraser River freshets were associated with lower copepod biomass; they did not observe a significant association with euphausiids. Several fish species have had varying productivity responses since 1990, including decreased productivity for some salmon species (Coho - *Onchorhynchus kisutch*, Pink - *O. gorbuscha*, and Sockeye - *O. nerka*; Bradford and Irvine 2000, Beamish et al. 2004) and increased productivity for Pacific herring (*Clupea harengus*), which matched historic high spawning abundances in the 1990s (Schweigert 2004). Higher up the trophic scale, marine mammals such as harbour seals (*Phoca vitulina*) are at historic high abundance in the Strait of Georgia (Olesiuk 2010) and Steller sea lions (*Eumetopias jubatus*) have exponentially increased in abundance in British Columbia (Trites 2014; DFO 2010), with large numbers feeding in the Strait of Georgia in winter and early summer. Taken together, this information indicates that the population response of Lingcod in the Strait of Georgia to management measures will be confounded by environmental drivers, which may explain the slow rebuilding trend modeled in this stock assessment. It should be noted that changes in productivity over time will lead to biased estimates of reference points that are based on equilibrium assumptions, including B_{MSY}, F_{MSY}, and B_0.

6.4. SELECTION OF REFERENCE POINTS

Two types of reference points have been presented in this stock assessment with equal weight given to each set: (i) the B_0-based reference points developed by the 2005 Lingcod Management Framework and (ii) the B_{MSY}-based reference points suggested in the DFO PA Framework. Continued use of these two sets of reference points will be problematic for future assessments that provide harvest advice because this approach will require decision-makers to choose one or the other as a basis for harvest decisions. Simulations that include feedback control rules, sometimes called “Closed-loop” policy simulations, could be used to explore the performance of management procedures that use estimates of stock status relative to these two sets of reference points to set an allowable catch. Closed-loop policy simulations provide a means for examining trade-offs between conservation objectives and fishery catch objectives for a set of candidate management procedures (Walters 1986, de la Mare 1998, Cox and Kronlund 2008). This is done by simulating the entire management system by modelling data collection, stock assessment, the application of a harvest control rule based on assessment results, and the responses of fish populations to harvest. The simulation is driven by a mathematical-statistical model (called the “operating” model) that is assumed to represent the “true” state of nature as the system is projected forward in time. Observed monitoring data are generated with measurement error from this “true” fish population, and “current” population status (i.e., for the perceived population) is estimated by applying a stock assessment to observed data. Management decisions throughout the projection period are made based on the “perceived” state of the stock, which results in management actions (e.g., setting catch levels) that affect the “true” population in the underlying operating model. Performance measures that evaluate how the alternative management policies perform under these conditions are then calculated based on how they affect the state of the “true” population. Fishery objectives for the Strait of Georgia, including those previously identified by the 2005 Lingcod Management Framework Committee, could be incorporated into these performance measures to evaluate existing and alternative management procedures.

Additional issues that could be addressed within such a simulation framework include evaluating the management implications of failing to correctly account for changes in fishery CPUE within the assessment model, ignoring potential changes in Lingcod growth and productivity over time, and relying on only landed catch for assessment model fitting. A preferred management procedure would be one that was robust to these uncertainties, as demonstrated by including these effects in the operating model but not the management procedure.

Recommendations for Future Data Collection and Research

1) Development of a fishery-independent abundance index for Strait of Georgia Lingcod is needed if estimates of current biomass continue to be used as a basis for recommending a total allowable catch. Estimates of increased abundance in recent years based in the current assessment are informed solely by catch and CPUE data from the recreational fishery, which is undesirable given high uncertainty in the relationship between recreational CPUE and underlying Lingcod abundance.

2) In the absence of fishery-independent information, continued support of the Strait of Georgia Creel Survey program is strongly recommended. Catch and effort data from angler interviews and biological sampling are the primary source of information available at the present time. Continued reductions in sample size or coverage for the creel survey program will further hinder our ability to provide harvest advice for this stock.

3) Closed-loop policy simulations should be used to help identify an appropriate management procedure to be used as a basis for harvest advice in the future. This type of analysis could help identify a management procedure in which total allowable catch is set based on current biomass relative to either the DFO PA Framework reference points or the 2005 Lingcod Management Framework reference points, such that an acceptable trade-off between conservation and fishery catch objectives is achieved over a wide range of uncertain scenarios. Such work requires the development of clearly stated policy objectives for Strait of Georgia Lingcod.

4) Future stock assessments for Strait of Georgia Lingcod should incorporate discard mortality into catch data. The development of estimates of discard rates prior to the year 2000 for the different fisheries encountering Lingcod will be an extensive undertaking given multiple gear types (commercial hook and line, commercial trawl, recreational hook and line) and changes in management regulations (including size limits) through time.

5) Historic commercial fishery catches prior to 1927 should be reconstructed or interpolated to better represent the start of the fishery. Future assessments may also want to consider 1945 as a starting year for recreational fishing instead of 1962, as is done for Strait of Georgia rockfish species.

6) Life-history relationships for Strait of Georgia Lingcod should be updated using biological samples collected from the Strait of Georgia creel survey program. A comparison of these samples with existing data should be used to look for changes in growth and maturity over time.

7) GLM analyses should be used to develop standardized CPUE indices and associated coefficients of variation for annual observations.

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8. REFERENCES CITED

Allen, S.E., and Wolfe, M.A. 2013. Hindcast of the timing of the spring phytoplankton bloom in the Strait of Georgia, 1968-2010. *Prog. Oceangr*. 115: 6-13.

Alverson, D.L., and Carney, M.J. 1975. A graphical review of the growth and decay of population cohorts. *J. Cons. Int. Explor. Mer*. 36: 133-143.

Babcock, E.A., and McAllister, M.K. 2002. Bayesian methods for accounting for data contradictions in stock assessment of Atlantic white marlin. Col. Vol. Sci. Pap. ICCAT 55(2): 541-558 (SCRS/02/067).

Beamish, R.J., Schnute, J.T., Cass, A.J., Neville, C.M., and Sweeting, R.M. 2004. The influence of climate on the stock and recruitment of pink and sockeye salmon from the Fraser River, British Columbia, Canada. *Trans. Amer. Fish. Soc.* 133:1396–1412.

Beaudreau, A.H., and Essington, T.E. 2007. Spatial, temporal, and ontogenetic patterns of predation on rockfishes by lingcod. *Transactions of the American Fisheries Society,* 136: 1438–1452.

Bradford, M.J., and Irvine, J.R. 2000. Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. *Can. J. Fish. Aquat. Sci.* 57:13–16.

Cass, A.J., Beamish, R.J., and McFarlane, G.A. 1990. Lingcod (*Ophiodon elongatus*). Can. Spec. Pub. Fish. Aquat. Sci. 109: 40 p.

Chatwin, B.M. 1958. Mortality rates and estimates of theoretical yield in relation to minimum commercial size of Lingcod (*Ophiodon elongatus*) from the Strait of Georgia, British Columbia. J. Fish. Res. Bd. Canada 15: 831-849.

Cox, S.P., and Kronlund, A.R. 2008. Practical stakeholder-driven harvest policies for groundfish fisheries in British Columbia, Canada. Fisheries Research 94: 224–237

de la Mare, W.K. 1998. Tidier fisheries management requires a new MOP (management oriented paradigm). Reviews in Fish Biology and Fisheries 8: 349-356.

DFO. 2005. Strait of Georgia Lingcod (*Ophiodon elongatus*) Assessment and Advice for Fishery Management. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2005/042. (Accessed June 17, 2015)

DFO. 2007. Rockfish conservation areas: protecting British Columbia's rockfish. (Accessed June 17, 2015)

DFO. 2009. A Fishery Decision Making Framework Incorporating the Precautionary Approach. (Accessed June 17, 2015)

DFO. 2010. Management Plan for the Steller Sea Lion (*Eumetopias jubatus*) in Canada [Final]. Species at Risk Act Management Plan Series. Fisheries and Oceans Canada, Ottawa. vi + 69 pp. (Accessed June 17, 2015)

English, K., Searing, G.F., and Nagtegaal, D.A. 2002. Review of the Strait of Georgia Recreational Creel Survey, 1983-1999. Can. Tech. Rep. Fish. Aquat. Sci. 2414: 81 p.

Forrest, R.E., Rutherford, K.L, Lacko, L., Kronlund, A.R., Starr, P.J., and McClelland, E.K. 2015. Assessment of Pacific Cod (*Gadus macrocephalus*) for Hecate Strait (5CD) and Queen Charlotte Sound (5AB) in 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/052.

Forrester, C.R., and Ketchen, K.S. 1963. A review of the Strait of Georgia trawl fishery. Bull. Fish. Res. Bd. Canada No. 139, 81 p.

Fournier, D.A. 2013. An introduction to AD Model Builder for use nonlinear modeling and statistics. (Accessed June 17, 2015)

Fournier, D.A., Skaug, H.J., Ancheta, J., Ianelli, J., Magnusson, A., Maunder, M.N., Nielsen, A., and Sibert J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27: 233-249.

Hamel, O.S., Sethi, S.A., and Wadsworth, T.F. 2009. Status and future prospects for lingcod in waters off Washington, Oregon, and California as assessed in 2009. Status of the Pacific Coast Groundfish Fishery through 2009, Stock Assessment and Fishery Evaluation: Stock Assessments, STAR Panel Reports, and Rebuilding Analyses. Pacific Fishery Management Council, Portland, Oregon.

Hare, S. R. and Mantua, N. J. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progr. Ocean*. 47:103–146.

Hilborn, R., and Walters, C.J. 1992. Quantitative fisheries stock assessment. Choice, dynamics and uncertainty. Chapman and Hall, London, UK. 570 p.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Biol., US 82: 898-903.

Holt, K.R., Starr, P.J., Haigh, R., and Krishka, B. 2016. Stock Assessment and Harvest Advice for Rock Sole (*Lepidopsetta* spp.) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/009. ix + 256 p.

Jagielo, T.H., and Wallace, F. 2005. Assessment of Lingcod (*Ophiodon elongatus*) for the Pacific Fishery Management Council in 2005. *In* Pacific Fishery Management Council, 2005. Status of the Pacific Coast Groundfish Fishery Through 2005 and Recommended Acceptable Biological Catches for 2007-2008. Pacific Fishery Management Council, Portland, Oregon.

Ketchen, K.S., Bourne, N., and Butler, T.H. 1983. History and present status of fisheries for marine fishes and invertebrates in the Strait of Georgia, British Columbia. Can. J. Fish. Aquat. Sci. 40: 1095-1117.

King, J.R., McAllister, M., Holt, K.R., and Starr, P.J. 2012. Lingcod (*Ophiodon elongatus*) stock assessment and yield advice for outside stocks in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/124. viii + 177p. (Accessed June 17, 2015)

King, J.R., McFarlane, G.A., and Surry, A.M. 2003. Stock assessment framework for Strait of Georgia Lingcod. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/062: 63 p. (Accessed June 17, 2015)

King, J.R., and Withler, R.E. 2005. Male nest site fidelity and female serial polyandry in lingcod (*Ophiodon elongatus*, Hexagrammidae). *Molecular Ecology*, 14: 653-660.

Lochead, J.K., and Yamanaka, K.L. 2006. Summary report for the inshore rockfish (*Sebastes* spp.) longline survey conducted in Statistical Areas 12 and 13, August 24 – September 10, 2004. Can. Tech. Rep. Fish. Aquat. Sci. 2627: ix + 65 p.

Lochead, J.K., and Yamanaka, K.L. 2007. Summary report for the inshore rockfish (*Sebastes* spp.) longline survey conducted in Statistical Areas 14 to 20, 28 and 29, from August 11 to September 6, 2005. Can. Tech. Rep. Fish. Aquat. Sci. 2690: viii + 53 p.

Lecomte, J.-B., Benoît, H.P., Ancelet, S., Etienne, M.-P., Bel, L., and Parent, E. 2013. Compound Poisson-gamma vs. delta-gamma to handle zero-inflated continuous data under a variable sampling volume. Methods in Ecology and Evolution, 4(12): 1159-1166.

Logan, G., de la Mare, W., King, J., and Haggarty, D. 2005. Management Framework for Strait of Georgia Lingcod. DFO Can. Sci. Advis. Sec. Res. Doc. 2005/048. (Accessed June 17, 2015)

Low, C.J., and Beamish, R.J. 1978. A study of the nesting behaviour of lingcod (*Ophiodon elongates*) in the Strait of Georgia, British Columbia. *Fish. Mar. Serv. Tech. Rep.* 843: 27 p.

McFarlane, G.A., King, J.R., and Beamish, R.J. 2000. Have there been recent changes in climate? Ask the fish. *Prog. Oceanogr*. 47:147–169.

McPhie, R.P., and King, J.R. 2011. Lingcod (*Ophiodon elongatus*) egg mass and reef fish density SCUBA survey in the Strait of Georgia, February 15-25, 2010 and 2011. Can. Tech. Rep. Fish. Aquat. Sci. 2932: x + 33p.

Mackas, D.L., Galbraith, M., and Faust, D. 2013. Zooplankton time series from the Strait of Georgia: results from year-round sampling at deep water locations, 1990-2010. *Prog. Oceangr*. 115: 129-159.

Marko, P.B., Rogers-Bennett, L., and Dennis, A.B. 2007. MtDNA population structure and gene flow in lingcod (*Ophiodon elongatus*): limited connectivity despite long-lived pelagic larvae. Marine Biology 150: 1301-1311.

Martell, S., Schweigert, J., Cleary, J., and Haist, V. 2012. Moving towards the sustainable fisheries framework for Pacific herring: data, models, and alternative assumptions; Stock Assessment and Management Advice for the British Columbia Pacific Herring Stocks: 2011 Assessment and 2012 Forecasts. DFO Can. Sci. Advis. Sec. Res. Doc.2011/136: vi + 151 p. (Accessed June 17, 2015)

Martell, S.J.D., Walters, C.J., and Wallace, S.S. 2000. The use of marine protected areas for conservation of lingcod (*Ophiodon elongatus*). Bulletin of Marine Science 66: 729-743.

Morrison, J., Quick, M.C. and Foreman, M.G.G. 2002. Climate change in the Fraser watershed: flow and temperature predictions *J. Hydrology* 263: 230-244.

Olesiuk, P.F. 2010. An assessment of population trends and abundance of harbour seals (*Phoca vitulina*) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/105. . (Accessed June 17, 2015)

Parker, S.J., Rankin, P.S., Hannah, R.W., and Schreck, C.B. 2003. Discard mortality of trawl-caught lingcod in relation to tow duration and time on deck. North American Journal of Fisheries Management, 23: 530-542.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J. Cons. Int. Explor. Mer. 39: 175-192.

Pauly, D., and Palomares, M.L.D. 2010. An empirical equation to predict annual increases in fishing efficiency. Fisheries Centre Working Paper, 7. The University of British Columbia, Canada.

Perry, R.I., and Masson, D. 2013. An integrated analysis of the marine social-ecological system of the Strait of Georgia, Canada, over the past four decades, and development of a regime shift index. *Prog. Oceangr.* 115: 14-27.

Petrie, M.E., and Ryer, C.H. 2006. Laboratory and field evidence for structural affinity of young-of-the year lingcod. Transactions of the American Fisheries Society 135: 1622-1630.

Phillips, A.C., and Barraclough, W.E. 1977. On the early life-history of the lingcod (*Ophiodon elongatus*). Fish. Mar. Serv. Tech. Rep. 756: 35 p.

Quinn, T.J., and Deriso, R.B. 1999. Quantitative Fish Dynamics. Oxford University Press, New York, New York. 542 p.

R Development Core Team. 2012. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. (Accessed June 17, 2015)

Richards, L.J., and Hand, C.M. 1989. Lingcod. pp. 35-61. *In* Groundfish Stock Assessment for the West Coast of Canada in 1988 and Recommended Yield Options for 1989. Fargo, J., and Tyler, A.V. [eds.]. Can. Tech. Rep. Fish. Aquat. Sci. 1646: 294 p.

Richards, L.J., and Hand, C.M. 1991. Lingcod. *In* Fargo, J., and Leaman, B. M. [eds.]. 1991. Groundfish stock assessments for the west coast of Canada in 1990 and recommended yield options for 1991. Can. Tech. Rep. Fish. Aquat. Sci. 1778: 320 p.

Schnute, J., and Richards, L. 1995. Influence of error on population estimates from catch-age models. CJFAS 52:2063-2077.

Schweigert, J.F. 2004. Stock assessment for British Columbia herring in 2004 and forecasts of the potential catch in 2005. Can. Sci. Ad. Sec. Res. Doc. 2004/081. vii +95 p.

Smith, B.D., McFarlane G.A., and Cass A.J. 1990. Movements and mortality of tagged male and female lingcod in the Strait of Georgia, British Columbia. Trans. Am. Fish. Soc. 119: 813–824.

Stahl, J., Green, K., and Vaugh, M. 2014. Examination of lingcod, *Ophiodon elongatus*, movements in Southeast Alaska using traditional methods. Alaska Department of Fish and Game, Fishery Data Series No. 14-28, Anchorage.

Starr, R.M., O'Connell V., and Ralston, S. 2004. Movements of lingcod (*Ophiodon elongatus*) in southeast Alaska: potential for increased conservation and yield from marine reserves. Can. J. Fish. Aquat. Sci. 61:1083–1094.

Stewart, I.J., Forrest, R.E., Grandin, C., Hamel, O.S., Hicks, A.C., Martell, S.J.D., and Taylor, I.G. 2011. Status of the Pacific hake (whiting) stock in U.S. and Canadian waters in 2011. Final SAFE document. (Accessed June 17, 2015)

Sturhahn, J.C., and Nagtegaal, D.A. 2001. Proceedings of the 2000 creel workshop. Can. Manuscr. Rep. Fish. Aquat. Sci. 2558: 40 p.

Surry, A.M., King, J.R., and Haggarty, D.R. 2007. Bottom trawl survey of young-of-the-year lingcod (*Ophiodon elongatus*) in the Strait of Georgia, *CCGS Neocaligus*, July 28 – August 9, 2006. Can. Tech. Rep. Fish. Aquat. Sci. 2740: x + 50 p.

Tolimieri, N., Andrews, K., Williams, G., Katz, S., and Levin, P.S. 2009. Home range and patterns of space use by lingcod, copper rockfish, and quillback rockfish in relation to diel and tidal cycles. Mar. Ecol. Prog. Ser. 380: 229 – 243.

Trites, A. 2014. The Marine Mammals. Pp. 183-210 *In* The Sea Among Us: the Amazing Strait of Georgia, R.J. Beamish and G.A. McFarlane [eds.]. Harbour Publishing, Medeira Park, BC.

Walters, C.J. 1986. Adaptive Management of Renewable Resources. The Blackburn Press, New Jersey.

Walters, C., and Ludwig, D. 1994. Calculation of Bayes posterior probability distribution for key population parameters. Can. J. Fish. Aquat. Sci., 51: 713-722.

Wilberg, M.J., Thorson, J.T., Linton, B.C., and Berkson, J. 2010. Incorporating time-varying catchability in population dynamic stock assessment models. Reviews in Fisheries Science 18: 2-24.

Wilby, G.V. 1926. The ling cod, an important food fish. Canadian Fisherman 8(6): 183-202.

Wilby, G.V. 1937. The Lingcod, *Ophiodon elongatus* Girard. Bull. Fish. Res. Board Can. 54: 24 p.

Withler, R.E., King, J.R., Marliave, J.B., Beaith, B., Li, S., Supernault, K.J., and Miller, K.M. 2004. Polygamous mating and high levels of genetic variation in lingcod, *Ophiodon elongatus*, of the Strait of Georgia, British Columbia. Environmental Biology of Fishes 69: 345-357.

Yamanaka, K.L., and Logan, G. 2010. Developing British Columbia's Inshore Rockfish Conservation Strategy, Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 2: 28-46.

Yamanaka, K.L., McAllister, M.K., Etienne, M.-P., and Flemming, R. 2012a. Stock Assessment and Recovery Potential Assessment for Quillback Rockfish (*Sebastes maliger*) on the Pacific Coast of Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/135. vii + 151 p. . (Accessed June 17, 2015)

Yamanaka, K.L., McAllister, M.K., Olesiuk, P.F., Etienne, M.-P., Obradovich, S., and Haigh, R. 2012b. Stock Assessment for the inside population of yelloweye rockfish (*Sebastes ruberrimus*) in British Columbia, Canada for 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/129. xiv + 131 p. . (Accessed June 17, 2015)

Zetterberg, P.R., Watson, N.M., and O’Brien, D.S. 2012. Strait of Georgia recreational fishery statistics for salmon and groundfish, 2010. Can. Manuscr. Rep. Fish. Aquat. Sci. 3000: xii + 106 p.

9. TABLES

Table 1. Summary of management measures affecting Lingcod commercial fisheries in the Strait of Georgia between 1927 and 2013. Data sources used to compile table include Chatwin (1958), Forrester and Ketchen (1963), Richards and Hand (1989), and Cass et al. (1990).

Year	Description
1931	Winter closure in January - February for Lingcod fishing introduced
1942	Minimum size limit of 3 pounds (approx. 58 cm) applied to commercial fishery
1946	Winter closure extended to December - February
1944-1947	Large portions of Strait of Georgia fishing grounds closed to trawl gear, including Cape Mudge, Cape Lazo, Baynes Sound, Nanoose Bay, and southward from there along the east coast of Vancouver Island to Porlier Pass
1948 - 1953	Most Strait of Georgia trawl fishery closures removed
1979	Winter closure extended to November 15 – April 15
1988	Winter closure extended to November 15 – April 30
1990	Retention of Lingcod by all commercial fisheries in the Strait of Georgia prohibited

Table 2. Summary of management measures affecting Lingcod recreational fisheries in the Strait of Georgia up to 2013. Data sources used to compile table include English et al. (2002) and Rob Tadey (pers. comm., Hook and Line Coordinator, Groundfish Management Unit, DFO, Vancouver, BC).

Year	Description
Pre- 1981	Bag limit – 3 fish / day
1981	Winter closure introduced from November 15 – April 15 Voluntary size limit of 58 cm introduced
1991	Mandatory size limit of 65 cm introduced Bag limit reduced to 1 Lingcod per day and 10 Lingcod per year Winter closure extended to October 1 – May 31
1998	Retention of coho salmon by the recreational fishery prohibited; led to increased effort for other species including Lingcod
2002	Retention of Lingcod by recreational fishery prohibited in Areas 13 – 19, 28, and 29.
2006	Retention of Lingcod allowed in Areas 13 – 19, and 29-5. - Bag limit: 1 Lingcod per day, 10 per year - Lingcod retention permitted: June 1 – Sept 30 - Quota of 5000 Lingcod pieces Rockfish Conservation Areas established within SoG, within which all recreational line fishing is prohibited
2007	As 2006, except: - Lingcod retention permitted: June 15 – Sept 30 - Quota of 7000 Lingcod pieces
2008	As 2007, except: - Minimum size limit: 60 cm (decreased from 65 cm) - Lingcod retention permitted: June 1 – Sept 30 - Quota of 5000 Lingcod pieces
2009	As 2008, except: - Lingcod retention permitted: May 1– Sept 30 - Quota of 7000 Lingcod pieces
2010 - 2013	As 2009, except: - Minimum size limit: 65 cm

Table 3. Hypotheses suggested by the Lingcod Management Framework Committee as part of the 2005 assessment, as well as an indication (X) of whether the hypothesis was examined, whether it was deemed unlikely due to a lack of preliminary support from data, whether including it in the assessment model impacted assessment outcomes, and what assumption was made in the final assessment model put forward by the committee.

Hypothesis	**Not examined due to time constraints**	**No support from preliminary analysis**	**No impact on assessment outcomes**	**Assumption made in final model**
Uncertainties in catch data				
Do pre-1951 District 1 catches include transfers?	-	-	-	Exclude Southeast quadrant (District 1) from SoG population
Uncertain catch prior to 1927	X	-	-	Stock was at unfished equilibrium in 1927
Uncertainties in CPUE data	-	-	-	
Relationship between CPUE & abundance	-	-	-	Model CPUE as a power function of abundance
Recreational CPUE - directed, non-directed, or combined catch and effort?	X	-	-	Recreational CPUE based on combined directed and non-directed catch and effort
Uncertainties in demographic parameters				
Natural mortality (M = 0.2 or M = 0.4?)	-	-	-	Assume M = 0.2
Density-dependent growth & mortality	-	-	-	Assume density-dependent growth & mortality
Growth rates	X	-	-	Fix at previously estimated Lingcod values
Sex ratios in population	X	-	-	Asexual data; sex-specific growth & selectivity
Age-fecundity relationship	X	-	-	Fix at previously estimated Lingcod values
Uncertainties in ecosystem effects				
Predation proportional to seal abundance	-	X	-	No temporal variation in predation effects
Regime shifts with fixed effects	-	X	-	No regime shift effects
Regime shifts with time boundaries	X	-	-	No regime shift effects
Other environmental impacts	X	-	-	No temporal environmental effects
Forage species impacts (herring abundance)	X	-	-	No temporal variation in forage species effects
Stock recruitment relationship				
Beverton & Holt or Ricker?	-	-	X	Ricker relationship
Depensatory recruitment	-	-	X	No depensatory recruitment
Stock Structure / Geographic Boundaries				
Stock delineation (Single closed population vs. four-way division vs. two-way division)	-	-	-	SoG is a single closed population, excluding southeast quadrant (District 1)
Common recruitment & sedentary adults	-	-	-	SoG has a single recruitment function
Immigration / emigration	X	-	-	No immigration / emigration effects

Table 4. Two sets of reference points used to characterize stock status. The DFO PA Policy reference points are expressed as a fraction of the spawning stock biomass associated with maximum sustainable yield (B_{MSY}), while the 2005 Lingcod Management Framework reference points are expressed as a fraction of unfished spawning stock biomass (B_0).

DFO PA Policy	2005 Lingcod Framework
Limit Reference Point = 0.4 B_{MSY}	Limit Reference Point = 0.10 B_0
Upper Stock Reference = 0.8 B_{MSY}	Short-term Recovery Target = 0.25 B_0
Target Reference Point: B_{MSY}	Target Reference Point = 0.40 B_0

Table 5. Commercial catch (retained tonnes) of Lingcod in the Strait of Georgia 1927 – 1946 by geographic quadrant (Southeast = Statistical Areas 28-29, Northeast = Statistical Areas 15-16, Northwest = 13-14, Southwest = Statistical Areas 17-19). All data were obtained from annual Fisheries Statistics reports compiled by the Dominion Bureau of Statistics (1927-1946) and converted from dressed weight (hundred lbs) to round weight (tonnes). The allocation of catch areas used by the DBS to the four geographic areas is described in footnotes.

	Geographic Quadrant				
Year	**Southeast**	**Northeast**	**Northwest**	**Southwest**	**Total**
1927	1648.3[a]	229.1[b]	224.9[c]	449.5[d]	2551.9
1928	1378.6	512.1[e]	336.6[f]	621.4[g]	2848.8
1929	1718.9	343.2	359.5	401.6[g]	2823.2
1930	1735.9	176.5[h]	407.1[i]	393.4[j]	2712.9
1931	1669.9	185.7	459.1	638.6	2953.3
1932	1540.4	133.7	174.9	443.0	2292.0
1933	1439.7	105.2	257.5	465.4	2267.9
1934	1904.8	72.9	361.0	452.6	2791.3
1935	2426.4	104.2	450.5	598.0	3579.1
1936	2652.5	134.7	478.7	407.3	3673.3
1937	2273.1	12.9	30.5	189.0	2505.5
1938	1123.7	65.1	561.3	782.6	2532.7
1939	2253.5	119.2	89.5	208.3	2670.5
1940	439.5	201.5	720.1	699.6	2060.8
1941	1213.6	41.2	371.0	549.2	2175.0
1942	861.4	155.0	457.2	553.5	2027.2
1943	1059.8	179.4	605.5	477.1	2321.7
1944	2848.5	280.8	663.4	546.3	4339.0
1945	2113.1	205.0	579.7	636.7	3534.5
1946	1623.2	226.2	625.5	498.6	2973.6

[a] Catch from District 1 (1927 – 1946)

[b] 66% of catch from Gower Point to Bute Inlet

[c] 33% of catch from Cowichan Bay to Big Qualicum River; 66% of catch from Qualicum River to Oyster River; 33% of catch Bute Inlet to Gower Point

[d] 66% of catch from Big Qualicum River to Cowichan Bay; 66% catch from Cowichan Bay to San Juan Harbour

[e] Catch from Toba Inlet to Gower Point (1928-1929)

[f] Catch from Adam River to French Creek; 50% of catch from French Creek to Nanaimo (1928-1929)

[g] 50% of catch from French Creek to Nanaimo; catch from Nanaimo Victoria; 50% of catch from Victoria to San Juan Harbour (1928-1929)

[h] 66% of catch from George Point to Gower Point (1930 – 1946)

[i] Catch from Tuna Point to French Creek; 33% of catch from George Point to Gower Point (1930 – 1946)

[j] Catch from French Creek to Shoal Harbour; 50% of catch from Shoal Harbour to Sombrio Point (1930 – 1946)

Table 6. Commercial catch (retained tonnes) of Lingcod for hook & line and trawl fisheries in the Strait of Georgia, 1951 – 1989, by minor area and quadrant. Catch is reported by Minor Statistical Area (13-19, 28, 29) and assigned to geographic quadrants (Southeast, Northeast, Northwest, Southwest) as indicated in the table.

	Minor Statistical Area									
	Southeast		Northeast		Northwest		Southwest			Total
Year	28	29	15	16	13	14	17	18	19	
1951	2.0	3.5	46.3	99.3	398.9	102.0	369.5	263.5	32.7	1317.7
1952	7.0	5.7	73.2	169.7	441.2	95.0	452.9	244.7	29.2	1518.6
1953	4.4	2.6	46.1	166.2	346.5	96.0	293.4	186.3	39.0	1180.5
1954	4.8	7.6	21.5	244.9	437.5	186.9	368.6	184.7	35.1	1491.6
1955	0.0	6.5	64.7	243.0	330.0	88.8	344.1	135.2	44.7	1257.0
1956	1.2	10.1	60.6	235.0	564.8	108.0	407.8	113.9	45.4	1546.8
1957	0.3	8.7	107.3	288.4	542.5	96.4	371.0	104.7	54.4	1573.7
1958	0.6	6.2	79.3	229.7	502.1	114.9	358.9	97.8	76.6	1466.1
1959	0.7	19.9	31.4	167.8	339.2	89.6	352.6	90.1	402.9	1494.2
1960	1.3	7.0	47.1	174.7	340.1	114.7	388.2	100.9	205.5	1379.5
1961	7.7	11.7	45.6	186.4	393.7	106.8	305.3	78.5	93.2	1228.9
1962	8.9	9.8	60.4	139.0	412.5	122.8	244.5	67.1	102.9	1167.9
1963	0.1	2.8	30.5	159.6	301.6	73.3	254.6	50.1	64.8	937.4
1964	0.1	7.9	18.8	170.0	291.8	49.3	209.1	62.9	73.2	883.1
1965	0.0	7.8	6.6	135.8	303.2	61.5	172.3	61.5	74.0	822.7
1966	1.1	2.5	28.7	125.7	299.5	71.7	146.3	72.3	35.4	783.2
1967	0.0	2.7	19.8	133.3	335.2	66.6	117.6	75.9	21.3	772.4
1968	0.0	3.5	22.0	104.7	273.6	79.3	176.5	61.9	32.6	754.1
1969	0.0	7.3	56.0	109.5	228.2	87.0	158.9	63.9	41.0	751.8
1970	0.0	3.3	84.7	85.7	226.1	44.3	281.4	51.3	30.6	807.4
1971	0.1	2.2	66.8	89.7	119.3	32.9	211.0	36.7	34.3	593.0
1972	0.0	4.7	43.6	81.3	152.3	27.2	138.3	26.3	41.8	515.5
1973	0.6	2.4	62.0	38.2	85.9	9.2	130.2	37.9	27.7	394.1
1974	0.0	0.6	25.2	24.4	133.6	16.3	130.2	25.8	46.3	402.4
1975	0.0	1.4	76.0	26.5	96.2	16.4	124.7	15.5	24.5	381.2
1976	5.7	1.2	74.9	17.2	98.1	13.5	85.1	15.6	37.1	348.4
1977	2.2	0.4	63.4	19.0	128.0	34.3	109.4	44.0	28.9	429.6
1978	0.2	2.5	48.3	18.4	158.0	28.2	147.3	43.0	64.0	509.9
1979	8.6	2.0	28.9	15.7	217.1	39.7	161.8	31.7	44.9	550.4
1980	6.7	0.7	26.4	6.8	138.2	20.2	104.0	27.2	42.1	372.3
1981	0.3	0.7	34.7	15.6	138.4	29.7	84.5	23.1	68.4	395.4
1982	0.5	1.1	50.7	7.7	177.8	15.3	66.6	28.8	52.5	401.0
1983	0.3	0.7	33.0	19.6	112.6	19.6	58.6	27.2	78.5	350.1
1984	0.0	0.3	4.0	5.2	65.6	7.6	50.6	35.9	32.8	202.0
1985	0.0	0.3	4.2	0.5	46.0	8.6	34.3	18.7	21.4	134.0
1986	0.0	0.5	0.5	4.0	20.2	16.9	18.4	16.3	44.5	121.3
1987	6.7	0.0	0.9	0.1	22.6	2.6	11.7	9.4	17.6	71.6
1988	1.6	1.1	0.1	0.2	12.1	2.6	7.2	5.4	16.9	47.2
1989	0.0	0.0	0.3	0.9	12.9	5.3	4.7	5.3	14.6	44.0

Table 7. Estimated recreational Lingcod landings (pieces) from the Strait of Georgia Recreational Creel Survey. Catch is reported by Statistical Area (13-19, 28, 29) and assigned to geographic quadrants (Southeast, Northeast, Northwest, Southwest) as indicated in the table.

	Minor Statistical Area									
	Southeast		Northeast		Northwest		Southwest			
Year	**28**	**29**	**15**	**16**	**13**	**14**	**17**	**18**	**19**	**Total**
1982	6126	3656	1285	17618	15004	5724	8886	6019	8986	73304
1983	5965	3636	1036	17263	14119	2137	5123	5621	4910	59810
1984	8854	8101	1668	28706	39719	11435	16405	7148	9761	131797
1985	3068	2669	858	13985	23177	6194	8863	5283	9008	73105
1986	1885	1562	1272	9366	25788	9714	6332	4250	6611	66780
1987	794	797	1432	8100	23494	10288	6916	3029	5426	60276
1988	727	1697	1285	9802	22580	11540	5796	3479	3734	60640
1989	319	755	799	7455	20905	8630	4764	2991	5714	52332
1990	146	327	458	4993	13297	4763	2298	1002	1727	29011
1991	177	266	51	976	2509	1153	1569	278	681	7660
1992	303	234	24	1026	1635	468	1121	204	397	5412
1993	191	382	53	2325	973	489	964	206	734	6317
1994	249	333	85	2091	1427	758	939	462	259	6603
1995	47	153	14	1124	843	662	977	314	260	4394
1996	145	63	61	274	1232	76	619	387	468	3325
1997	302	237	107	384	1035	324	289	554	273	3505
1998	182	50	24	550	514	227	602	250	519	2918
1999	155	47	25	197	1372	71	536	103	409	2915
2000	351	130	23	1243	986	926	1097	202	204	5162
2001	251	109	124	1932	1462	1195	2163	587	574	8397
2002	237	227	0	2620	73	9	291	38	116	3611
2003	77	2	0	21	0	32	329	3	21	485
2004	18	1	0	0	45	0	210	9	53	336
2005	56	1	0	0	0	0	53	0	27	137
2006	0	0	53	130	414	162	1444	812	562	3577
2007	0	0	9	503	985	37	602	245	184	2565
2008	100	2	149	673	762	202	386	193	291	2758
2009	4	0	93	340	900	308	835	223	388	3091
2010	14	11	18	419	310	206	999	300	361	2638
2011	35	121	334	291	552	675	1644	631	238	4521
2012	14	139	128	460	2101	447	2441	766	400	6896
2013	0	0	0	0	2577	740	1311	445	438	5511

Table 8. Lingcod qualified catch-per-unit-effort (kg/d) by Statistical Area from commercial hook and line sales slip data. Catch per unit effort is determined for landings with at least 100 kg of Lingcod. Missing data denotes years with no qualified landings. Data from Richards and Hand (1991).

	Minor Statistical Area								Average, Strait of Georgia	Average, excluding Southeast
	Southeast	Northeast		Northwest		Southwest				
Year	28 & 29	15	16	13	14	17	18	19		
1967	87	314	213	301	236	127	124	164	195.8	211.3
1968	227	375	194	318	179	127	110	168	212.3	210.1
1969	--	438	213	272	168	136	129	292	235.4	235.4
1970	257	351	196	254	168	175	154	228	222.9	218.0
1971	25	267	196	266	171	166	113	217	177.6	199.4
1972	147	283	178	301	201	143	150	191	199.3	206.7
1973	119	264	185	287	132	167	150	207	188.9	198.9
1974	327	269	135	312	253	139	135	170	217.5	201.9
1975	46	242	194	312	160	171	189	193	188.4	208.7
1976	140	250	123	275	150	174	126	128	170.8	175.1
1977	115	256	222	200	192	148	125	131	173.6	182.0
1978	210	206	278	192	126	155	105	132	175.5	170.6
1979	163	270	184	198	144	224	116	124	177.9	180.0
1980	119	220	92	274	87	167	95	101	144.4	148.0
1981	46	194	129	177	90	148	87	94	120.6	131.3
1982	55	152	83	189	85	129	130	96	114.9	123.4
1983	51	235	127	138	118	144	95	93	125.1	135.7
1984	36	99	126	74	80	95	159	124	99.1	108.1
1985	96	104	156	107	90	132	71	191	118.4	121.6
1986	35	175	119	53	131	103	87	114	102.1	111.7
1987	213	93	--	32	44	84	87	53	86.6	65.5
1988	96	--	--	31	19	80	84	59	61.5	54.6
1989	--	--	--	44	--	114	61	56	68.8	68.8

Table 9. Interview-based Average CPUE index calculated using Method 2 for the entire Strait of Georgia (SoG; Areas 13-19, 28, 29) and the Strait of Georgia with the southeast quadrant excluded (noSE; Areas 13-19).

Year	SoG	noSE
1982	4.91	4.89
1983	5.48	5.51
1984	8.98	9.17
1985	4.72	5.14
1986	5.29	5.93
1987	4.95	5.49
1988	4.61	5.12
1989	3.80	4.24
1990	4.44	5.09
1991	6.26	7.26
1992	5.59	5.97
1993	3.72	3.96
1994	4.30	5.01
1995	3.89	4.40
1996	7.56	8.23
1997	7.17	7.78
1998	8.32	9.46
1999	6.88	7.24
2000	9.86	10.37
2001	13.03	13.86
2002	11.55	12.42
2003	9.92	11.15
2004	7.95	9.24
2005	8.82	9.93
2006	11.57	13.27
2007	10.39	11.53
2008	13.28	14.68
2009	11.70	13.31
2010	19.59	21.92
2011	15.38	17.18
2012	12.59	14.04
2013	9.75	10.25

Table 10. Biological parameters assumed when fitting the stock assessment model to data. The notation shown matches the notation used when describing the assessment model in Appendix C.

Parameter description	Notation	Females	Males
Maximum age	A	20	20
von Bertalanffy rate parameter	k	0.2	0.2
von Bertalanffy asymptotic length (mm)	L_∞	1040	900
Weight-at-length scale parameter	$\acute{a}$	1.26 x 10^{-6}	1.26 x 10^{-6}
Weight-at-length exponent parameter	$\acute{b}$	3.329	3.329
Age at 50% maturity	$\dot{a}$	5.0	2.0
Standard deviation of age at 50% maturity	$\dot{\gamma}$	0.35	0.001

Table 11. Description of assumed selectivity relationships.

Fishery	Selectivity Type	Parameters (mean, sd)
Commercial Fishery	Age-based logistic	(4.45, 0.2)
Recreational Fishery; pre-1991 (voluntary size limit ≤ 58 cm)	Age-based logistic	(2.0, 0.2)
Recreational Fishery; 1991+ (size limit = 65 cm)	Length-based logistic	(650, 15)

Table 12. Description of stock assessment scenarios used to explore uncertainties in stock status in 2014. The three scenarios highlighted with shading were not selected to characterize stock status in 2014 (see Section 4.2). The remaining 9 scenarios were all equally weighted when characterizing stock status.

Scenario ID	Approach to District 1 Catch	DD M?	DD q?	M
noSE	Exclude SE from model	Yes	Yes	0.2
noSE_noDD	Exclude SE from model	No	No	0.2
noSE_noDD+highM	Exclude SE from model	No	No	0.3
onlySEpre1947	Only SE catch < 1947	Yes	Yes	0.2
onlySEpre1947_noDD	Only SE catch < 1947	No	No	0.2
onlySEpre1947_noDD+highM	Only SE catch < 1947	No	No	0.3
noSEpre1947	Exclude SE catch < 1947	Yes	Yes	0.2
noSEpre1947_noDD	Exclude SE catch < 1947	No	No	0.2
noSEpre1947_noDD+highM	Exclude SE catch < 1947	No	No	0.3
SoG	Use all catch as recorded	Yes	Yes	0.2
SoG_noDD	Use all catch as recorded	No	No	0.2
SoG_noDD+highM	Use all catch as recorded	No	No	0.3

Table 13. The 5th, 50th, and 95th percentiles of MCMC posterior distributions for model parameters and associated quantities for the three "noSE" assessment scenarios (see Section 4 text and Table 12 for a description of scenarios). Posterior medians (50th percentiles) are highlighted in bold font.

	noSE			noSE_noDD			noSE_noDD+highM		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
Model Estimated Parameters									
R_0	119,660	**140,302**	161,302	170,719	**193,159**	218,412	359,783	**413,901**	477,224
$\bar{R}$	56,504	**63,014**	70,015	66,762	**74,320**	84,302	123,845	**139,282**	159,251
H	0.44	**0.52**	0.61	0.34	**0.37**	0.41	0.3	**0.32**	0.35
q_{cCPUE}	1.444	**1.736**	2.121	0.054	**0.069**	0.087	0.072	**0.094**	0.122
q_{rCPUE}	6.92 x^{-3}	**7.99 x^{-3}**	9.32 x^{-3}	5.69 x^{-5}	**7.14 x^{-5}**	8.89 x^{-5}	4.99 x^{-5}	**6.36 x^{-5}**	7.99 x^{-5}
ϑ^2	10.51	**14.92**	20.57	10.56	**14.79**	20.22	9.97	**14.06**	19.2
Derived Quantities									
B_{2014}	6,294	**8,414**	11,036	5,727	**7,151**	9,014	4,526	**5,724**	7,345
B_0	15,467	**18,135**	20,850	22,067	**24,967**	28,232	18,686	**21,497**	24,786
B_{2014} / B_0	0.321	**0.463**	0.663	0.222	**0.286**	0.373	0.203	**0.268**	0.353
0.1 B_0	1,547	**1,814**	2,085	2,207	**2,497**	2,823	1,869	**2,150**	2,479
0.25 B_0	3,867	**4,534**	5,212	5,517	**6,242**	7,058	4,672	**5,374**	6,196
0.4 B_0	6,187	**7,254**	8,340	8,827	**9,987**	11,293	7,475	**8,599**	9,914
B_{MSY}	6,123	**7,716**	9,369	8,964	**10,451**	12,098	8,021	**9,396**	11,055
B_{2014}/B_{MSY}	0.724	**1.087**	1.658	0.524	**0.684**	0.906	0.46	**0.612**	0.812
0.4 B_{MSY}	2,449	**3,086**	3,748	3,586	**4,180**	4,839	3,209	**3,759**	4,422
0.8 B_{MSY}	4,899	**6,172**	7,495	7,172	**8,361**	9,679	6,417	**7,517**	8,844
B_{MSY} / B_0	0.391	**0.426**	0.453	0.405	**0.419**	0.432	0.425	**0.437**	0.448
F_{MSY}	0.118	**0.156**	0.215	0.072	**0.089**	0.11	0.09	**0.115**	0.143
MSY	768	**854**	942	619	**696**	777	602	**688**	772

Table 14. The 5th, 50th, and 95th percentiles of MCMC posterior distributions for model parameters and associated quantities for the three "onlySEpre1947" assessment scenarios (see Section 4 text and Table 12 for a description of scenarios). Posterior medians (50th percentiles) are highlighted in bold font.

	onlySEpre1947			**onlySEpre1947_noDD**			**onlySEpre1947_noDD+ highM**		
	5%	**50%**	**95%**	**5%**	**50%**	**95%**	**5%**	**50%**	**95%**
Model Estimated Parameters									
R_0	259,634	**293,330**	333,916	214,439	**246,508**	279,978	458,455	**526,690**	610,519
$\bar{R}$	72,702	**83,129**	96,431	72,846	**81,883**	93,563	132,884	**151,481**	175,110
H	0.25	**0.26**	0.28	0.33	**0.36**	0.39	0.3	**0.32**	0.35
q_{cCPUE}	0.082	**0.101**	0.123	0.047	**0.061**	0.077	0.065	**0.085**	0.11
q_{rCPUE}	4.28 x^{-9}	**6.69 x^{-9}**	1.01 x^{-8}	4.64 x^{-5}	**5.93 x^{-5}**	7.36 x^{-5}	4.17 x^{-5}	**5.37 x^{-5}**	6.76 x^{-5}
ϑ^2	11.00	**15.37**	21.25	12.05	**16.81**	22.96	11.55	**16.3**	22.18
Derived Quantities									
B_{2014}	5,511	**6,926**	8,926	6,200	**7,782**	9,945	4,836	**6,185**	7,889
B_0	33,560	**37,915**	43,161	27,718	**31,863**	36,190	23,811	**27,355**	31,709
B_{2014} / B_0	0.144	**0.184**	0.235	0.188	**0.245**	0.326	0.17	**0.225**	0.298
0.1 B_0	3,356	**3,792**	4,316	2,772	**3,186**	3,619	2,381	**2,736**	3,171
0.25 B_0	8,390	**9,479**	10,790	6,930	**7,966**	9,047	5,953	**6,839**	7,927
0.4 B_0	13,424	**15,166**	17,265	11,087	**12,745**	14,476	9,524	**10,942**	12,684
B_{MSY}	17,720	**20,324**	23,460	11,445	**13,445**	15,497	10,300	**12,009**	14,049
B_{2014}/B_{MSY}	0.267	**0.341**	0.444	0.44	**0.579**	0.778	0.385	**0.513**	0.684
0.4 B_{MSY}	7,088	**8,130**	9,384	4,578	**5,378**	6,199	4,120	**4,804**	5,619
0.8 B_{MSY}	14,176	**16,259**	18,768	9,156	**10,756**	12,398	8,240	**9,607**	11,239
B_{MSY} / B_0	0.526	**0.537**	0.546	0.409	**0.422**	0.434	0.428	**0.439**	0.449
F_{MSY}	0.024	**0.032**	0.041	0.069	**0.085**	0.103	0.089	**0.111**	0.136
MSY	419	**526**	635	752	**855**	972	741	**852**	981

Table 15. The 5th, 50th, and 95th percentiles of MCMC posterior distributions for model parameters and associated quantities for the three "noSEpre1947" assessment scenarios (see Section 4 text and Table 12 for a description of scenarios). Posterior medians (50th percentiles) are highlighted in bold font.

	noSEpre1947			**noSEpre1947_noDD**			**noSEpre1947_noDD + highM**		
	5%	**50%**	**95%**	**5%**	**50%**	**95%**	**5%**	**50%**	**95%**
Model Estimated Parameters									
R_0	212,206	**241,161**	274,905	171,365	**197,727**	227,539	364,426	**423,371**	490,464
$\bar{R}$	70927	**81319**	94308	70361	**79476**	90107	128871	**147316**	169445
h	0.25	**0.27**	0.29	0.34	**0.37**	0.41	0.3	**0.32**	0.35
q_{cCPUE}	0.083	**0.101**	0.124	0.048	**0.061**	0.077	0.065	**0.086**	0.112
q_{rCPUE}	$4.23 \times^{-9}$	**$6.73 \times^{-9}$**	$1.01 \times^{-8}$	$4.70 \times^{-5}$	**$5.91 \times^{-5}$**	$7.32 \times^{-5}$	$4.16 \times^{-5}$	**$5.37 \times^{-5}$**	$6.79 \times^{-5}$
ϑ^2	11.06	**15.47**	21.45	12.07	**16.99**	23.45	11.56	**16.36**	22.00
Derived Quantities									
B_{2014}	5,480	**6,895**	8,936	6,218	**7,793**	9,806	4,870	**6,127**	7,868
B_0	27,429	**31,172**	35,534	22,150	**25,558**	29,411	18,927	**21,989**	25,474
B_{2014} / B_0	0.175	**0.221**	0.288	0.231	**0.306**	0.398	0.213	**0.279**	0.371
$0.1\ B_0$	2,743	**3,117**	3,553	2,215	**2,556**	2,941	1,893	**2,199**	2,547
$0.25\ B_0$	6,857	**7,793**	8,883	5,538	**6,389**	7,353	4,732	**5,497**	6,368
$0.4\ B_0$	10,972	**12,469**	14,213	8,860	**10,223**	11,765	7,571	**8,796**	10,189
B_{MSY}	14,277	**16,452**	19,042	9,054	**10,700**	12,581	8,087	**9,601**	11,323
B_{2014}/B_{MSY}	0.33	**0.42**	0.552	0.545	**0.728**	0.968	0.483	**0.638**	0.858
$0.4\ B_{MSY}$	5,711	**6,581**	7,617	3,622	**4,280**	5,033	3,235	**3,840**	4,529
$0.8\ B_{MSY}$	11,421	**13,161**	15,234	7,243	**8,560**	10,065	6,470	**7,681**	9,059
B_{MSY} / B_0	0.517	**0.528**	0.539	0.405	**0.419**	0.431	0.425	**0.437**	0.448
F_{MSY}	0.025	**0.034**	0.044	0.073	**0.089**	0.11	0.091	**0.115**	0.144
MSY	362	**452**	539	634	**714**	807	612	**707**	805

Table 16. The 5th, 50th, and 95th percentiles of MCMC posterior distributions for model parameters and associated quantities for the three "SoG" assessment scenarios (see Section 4 text and Table 12 for a description of scenarios). Posterior medians (50th percentiles) are highlighted in bold font.

	SoG			SoG_noDD			SoG_noDD + highM		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
Model Estimated Parameters									
R_0	359,901	**423,741**	495,758	308,915	**363,984**	435,201	656,440	**778,950**	930,256
$\bar{R}$	80,450	**93,817**	111,247	80,426	**92,687**	107,485	146,268	**170,675**	201,225
h	0.24	**0.26**	0.28	0.33	**0.35**	0.39	0.29	**0.32**	0.34
q_{cCPUE}	0.074	**0.093**	0.116	0.043	**0.056**	0.073	0.059	**0.079**	0.104
q_{rCPUE}	$3.48x^{-9}$	**$5.79\ x^{-9}$**	$9.20\ x^{-9}$	$4.28\ x^{-5}$	**$5.52\ x^{-5}$**	$7.07\ x^{-5}$	$3.80\ x^{-5}$	**$4.96\ x^{-5}$**	$6.46\ x^{-5}$
ϑ^2	11.29	**15.27**	21.12	11.98	**16.92**	23.6	11.59	**16.67**	23.02
Derived Quantities									
B_{2014}	5,759	**7,553**	10,057	6,491	**8,365**	10,739	5,053	**6,675**	8,776
B_0	46,520	**54,772**	64,081	39,930	**47,048**	56,253	34,094	**40,457**	48,315
B_{2014} / B_0	0.105	**0.138**	0.188	0.13	**0.178**	0.24	0.121	**0.166**	0.226
0.1 B_0	4,652	**5,477**	6,408	3,993	**4705**	5625	3,409	**4,046**	4,832
0.25 B_0	11,630	**13,693**	16,020	9,982	**11,762**	14,063	8,523	**10,114**	12,079
0.4 B_0	18,608	**21,909**	25,632	15,972	**18,819**	22,501	13,638	**16,183**	19,326
B_{MSY}	25092	**29,820**	35,312	16,659	**19,961**	24,151	14,859	**17,793**	21,527
B_{2014}/B_{MSY}	0.191	**0.254**	0.347	0.306	**0.418**	0.572	0.272	**0.375**	0.519
0.4 B_{MSY}	10,037	**11,928**	14,125	6,664	**7,984**	9,661	5,944	**7,117**	8,611
0.8 B_{MSY}	20,073	**23,856**	28,250	13,327	**15,968**	19,321	11,887	**14,234**	17,222
B_{MSY} / B_0	0.535	**0.545**	0.555	0.412	**0.425**	0.436	0.430	**0.440**	0.451
F_{MSY}	0.022	**0.03**	0.039	0.066	**0.082**	0.099	0.085	**0.108**	0.131
MSY	555	**721**	902	1,029	**1,219**	1,471	1,021	**1,231**	1,485

Table 17. The 5th, 50th, and 95th percentiles for the scenario-average distribution, which was made by combining samples from the posterior distributions of the nine scenarios selected to characterize stock status. Medians (50th percentiles) are highlighted in bold font.

	Scenario-average		
	5%	**50%**	**95%**
Model Estimated Parameters			
R_0	195,791	**357,528**	789,970
$\bar{R}$	73,888	**91,545**	175,538
h	0.25	**0.32**	0.38
q_{cCPUE}	0.051	**0.081**	0.115
q_{rCPUE}	4.73x^{-9}	**4.94 x^{-9}**	6.86 x^{-9}
ϑ^2	11.51	**16.24**	22.32
Derived Quantities			
B_{2014}	4,836	**6,185**	7,889
B_0	23,811	**27,355**	31,709
B_{2014} / B_0	0.170	**0.225**	0.298
0.1 B_0	2,381	**2,736**	3,171
0.25 B_0	5,953	**6,839**	7,927
0.4 B_0	9,524	**10,942**	12,684
B_{MSY}	10,300	**12,009**	14,049
B_{2014}/B_{MSY}	0.385	**0.513**	0.684
0.4 B_{MSY}	4,120	**4,804**	5,619
0.8 B_{MSY}	8,240	**9,607**	11,239
B_{MSY} / B_0	0.428	**0.439**	0.449
F_{MSY}	0.027	**0.084**	0.127
MSY	434	**763**	1332

Table 18. Stock status in 2014 relative to reference points for the nine stock assessment scenarios selected to characterize stock status (see Section 4.2), as well as the scenario-average in which all scenarios are combined with equal weight. For each scenario (i.e., row), values are the probability that spawning biomass in 2014, B_{2014}, is greater than the reference point specified in the column header.

		2005 Management Framework			DFO PA Framework		
Scenario ID	$P(B_{2014} > B_{2006})$	$P(B_{2014} > 0.10B_0)$	$P(B_{2014} > 0.25B_0)$	$P(B_{2014} > 0.40B_0)$	$P(B_{2014} > 0.40B_{MSY})$	$P(B_{2014} > 0.80B_{MSY})$	$P(B_{2014} > B_{MSY})$
onlySEpre1947	1.00	1.00	0.03	0.00	0.16	0.00	0.00
onlySEpre1947_noDD	1.00	1.00	0.45	0.00	0.99	0.04	0.00
onlySEpre1947_noDD+highM	1.00	1.00	0.26	0.00	0.92	0.01	0.00
noSEpre1947	1.00	1.00	0.21	0.00	0.62	0.00	0.00
noSEpre1947_noDD	1.00	1.00	0.89	0.05	1.00	0.29	0.03
noSEpre1947_noDD+highM	1.00	1.00	0.75	0.02	1.00	0.10	0.01
SoG	1.00	0.97	0.00	0.00	0.01	0.00	0.00
SoG_noDD	1.00	1.00	0.03	0.00	0.60	0.00	0.00
SoG_noDD+highM	1.00	0.99	0.01	0.00	0.36	0.00	0.00
Scenario-average	1.00	1.00	0.29	0.01	0.63	0.05	0.00

Table 19. Summary of differing assumptions for the 12 assessment scenarios, as well as posterior median estimates of unfished equilibrium biomass (B_0), steepness (h), and the ratio of B_{2014} / B_0. The "DD M?" column indicates whether density-dependent mortality was assumed, the "Commercial CPUE Relationship" and "Recreational CPUE Relationship" columns indicate whether the CPUE index was constant, assumed hyperstability in density-dependence, or hyperdepletion in density-dependence, and the M column indicates the assumed rate of natural mortality.

	Assumptions							
Scenario ID	**Approach to District 1 Catch**	**Commercial CPUE Relationship**	**Recreational CPUE Relationship**	**DD M?**	***M***	B_0	***h***	B_{2014} / B_0
noSE	Exclude SE from model	Hyperstable	Hyperstable	Yes	0.2	18,135	0.52	0.46
noSE_noDD	Exclude SE from model	Constant	Constant	No	0.2	24,967	0.37	0.29
noSE_noDD+highM	Exclude SE from model	Constant	Constant	No	0.3	21,497	0.32	0.27
onlySEpre1947	Only SE catch < 1947	Hyperstable	Hyperdepleted	Yes	0.2	37,915	0.26	0.18
onlySEpre1947_noDD	Only SE catch < 1947	Constant	Constant	No	0.2	31,863	0.36	0.25
onlySEpre1947_noDD+highM	Only SE catch < 1947	Constant	Constant	No	0.3	27,355	0.32	0.23
noSEpre1947	Exclude SE catch < 1947	Hyperstable	Hyperdepleted	Yes	0.2	31,172	0.27	0.22
noSEpre1947_noDD	Exclude SE catch < 1947	Constant	Constant	No	0.2	25,558	0.37	0.31
noSEpre1947_noDD+highM	Exclude SE catch < 1947	Constant	Constant	No	0.3	21,989	0.32	0.28
SoG	Use all catch as recorded	Hyperstable	Hyperdepleted	Yes	0.2	54,772	0.26	0.14
SoG_noDD	Use all catch as recorded	Constant	Constant	No	0.2	47,048	0.35	0.18
SoG_noDD+highM	Use all catch as recorded	Constant	Constant	No	0.3	40,457	0.32	0.17

10.FIGURES

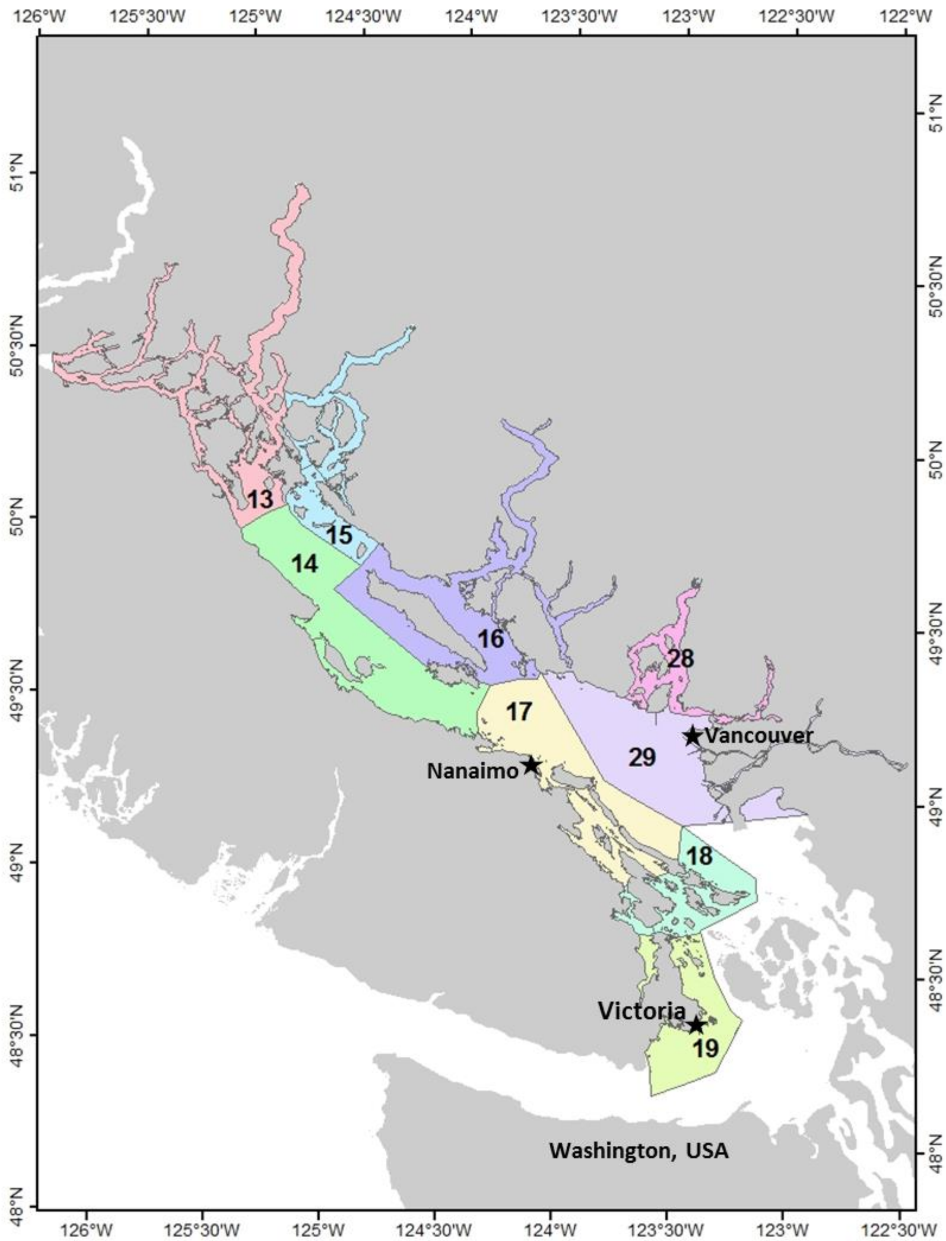


Figure 1. Minor Statistical Areas used to define the Strait of Georgia Lingcod stock for this assessment.

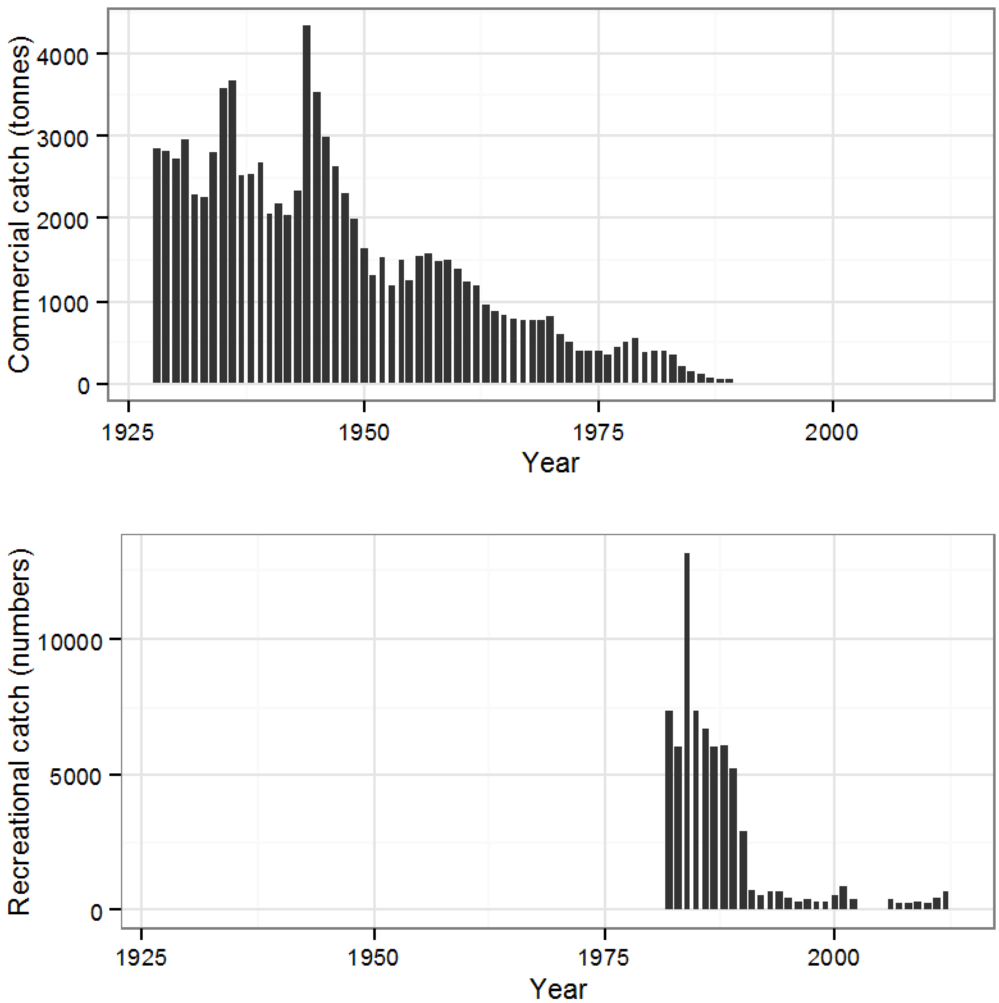


Figure 2. Available catch data from directed Lingcod commercial (hook & line and trawl gear combined) and recreational fisheries in the Strait of Georgia (defined as minor Statistical Areas 13-19, 28, 29).

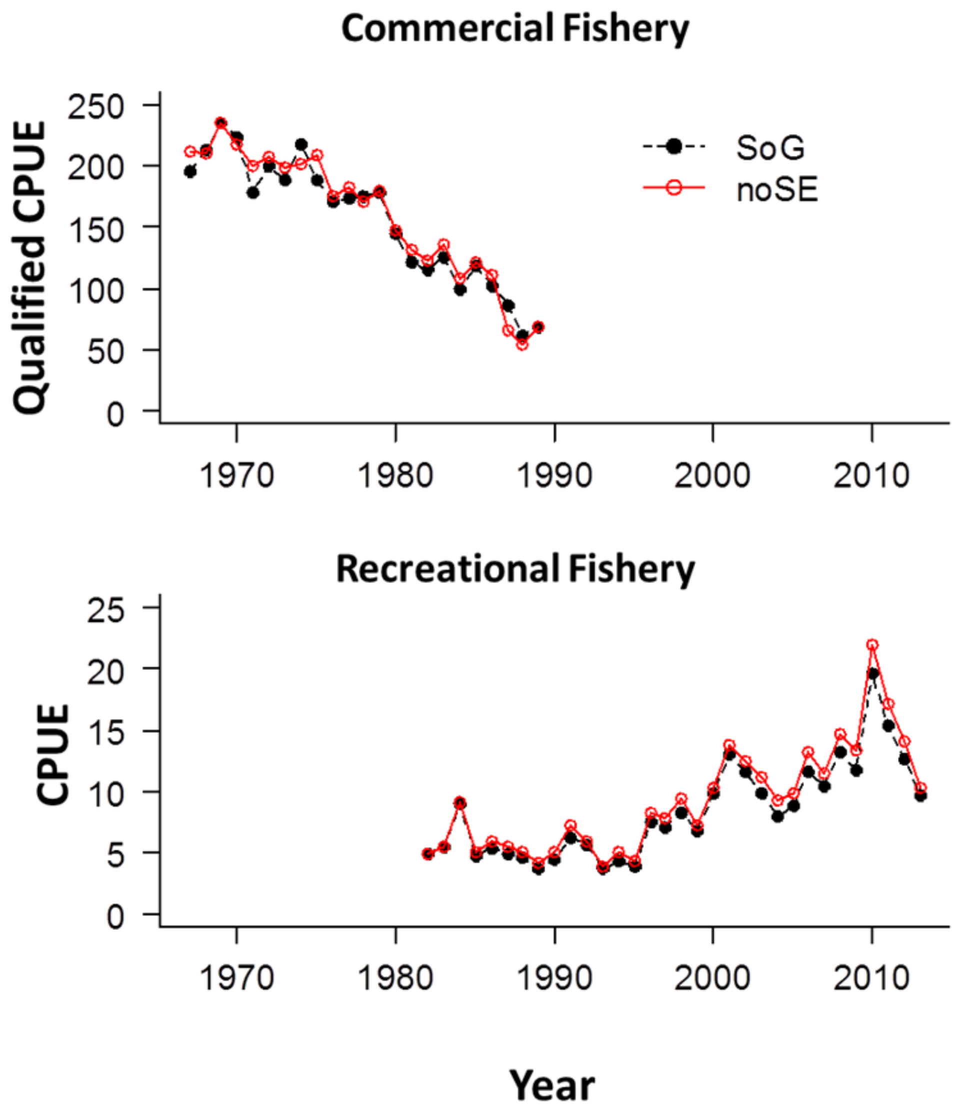


Figure 3. Commercial (top) and recreational (bottom) CPUE indices used as relative abundance indices when fitting the stock assessment model to data. The black solid circles show indices used for scenarios that modelled the whole Strait of Georgia, while the open red circles show indices used for scenarios that excluded the southeast quadrant. See text for a description of CPUE calculation for each fishery.

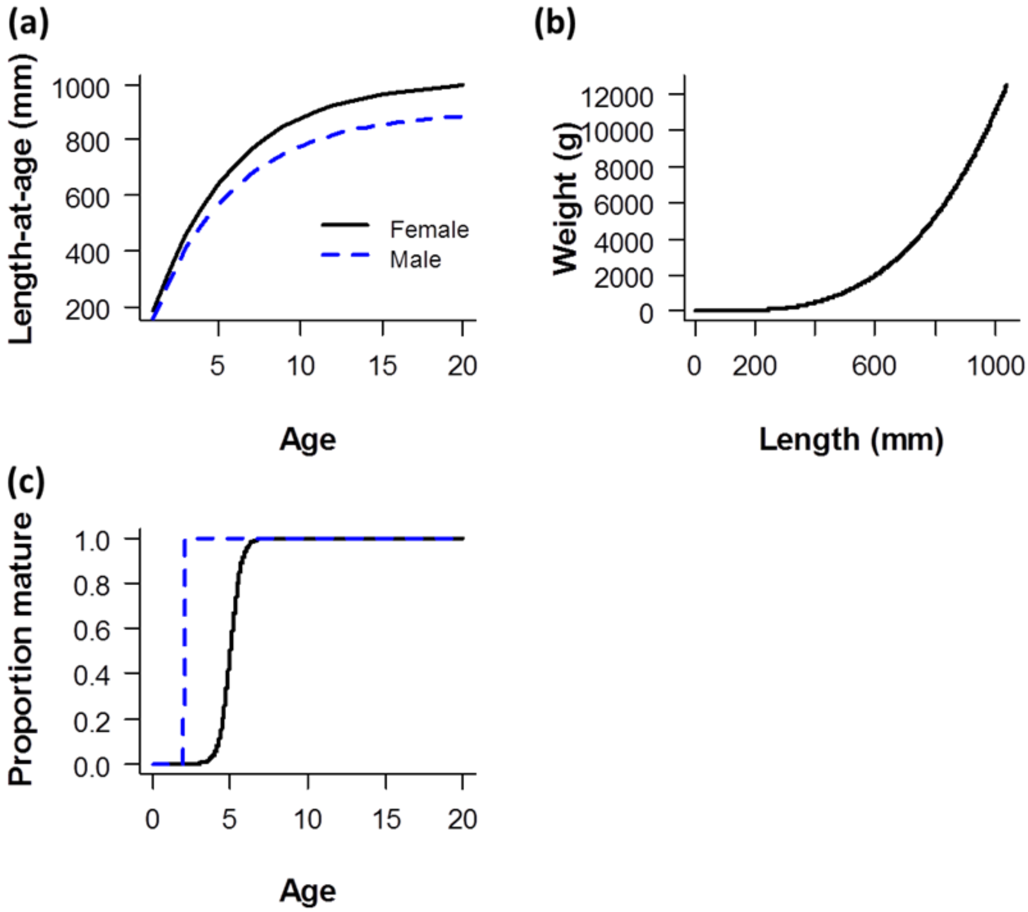


Figure 4. Biological relationships used as input to the stock assessment model. Panel a: Length-at-age by sex (females = solid black, males = dashed blue). Panel b: Weight at length for both sexes. Panel c: Proportion mature at age by sex (females = solid black, males = dashed blue).

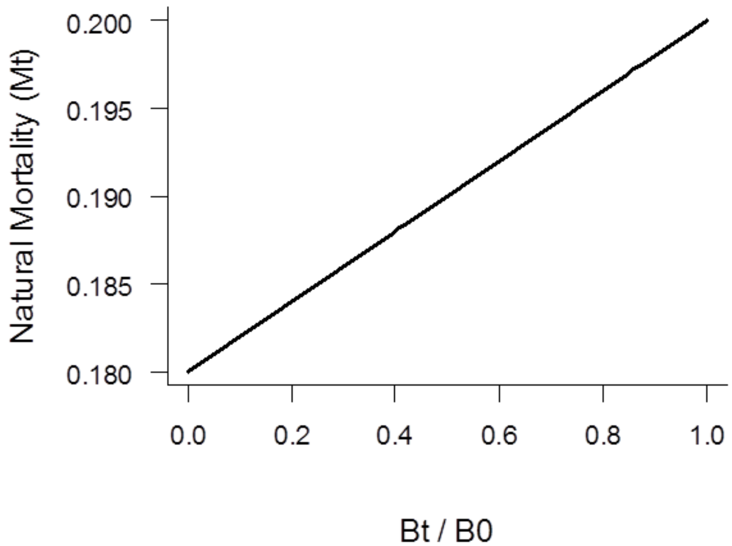


Figure 5. Relationship used to describe natural mortality in year t (M_t) as a function of the ratio between biomass in year t (B_t) and unfished equilibrium biomass (B_0) for scenarios in which density-dependent mortality was assumed with M_0 = 0.2 and M_1 = 0.18.

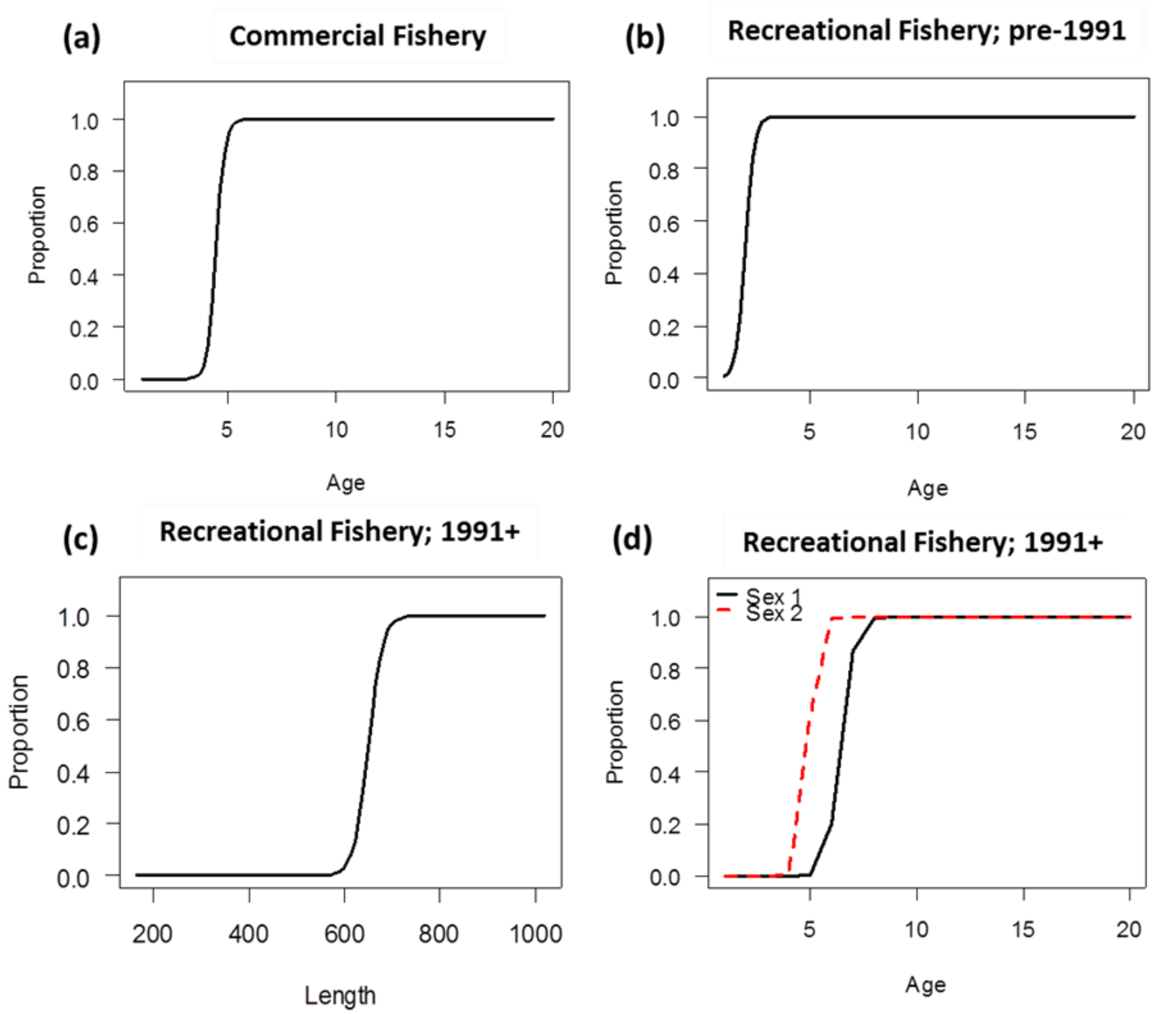


Figure 6. Assumed selectivity relationships showing the proportion of fish vulnerable to fisheries for the commercial fishery (panel a), the recreational fishery prior to 1991 (panel b), and the recreational fishery from 1991 onwards (panel c). Panel d shows the realized age-based selectivity for the 1991+ recreational fishery based on the assumed selectivity relationship in panel c and sex-specific length-at-age (sex 1 = males, sex 2 = females).

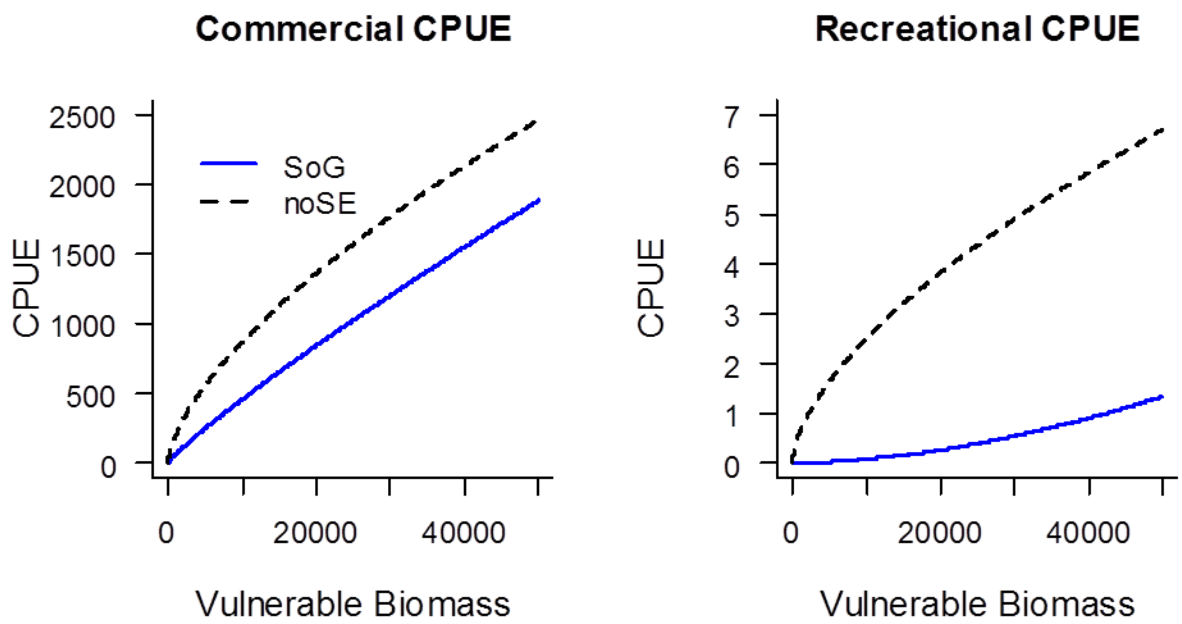


Figure 7. Density-dependent catchability relationships estimated by Logan et al. (2005) for commercial CPUE (left panel; CPUE = kilogram / day) and recreational CPUE (right panel; CPUE = lingcod encountered / 100 hours fishing effort) in the SoG and noSE models. For 2014 assessment scenarios with density-dependent CPUE, the power exponent determining the degree of linearity between the abundance index and vulnerable biomass was held constant at the values estimated by Logan et al. (2005), while the catchability coefficient q was estimated.

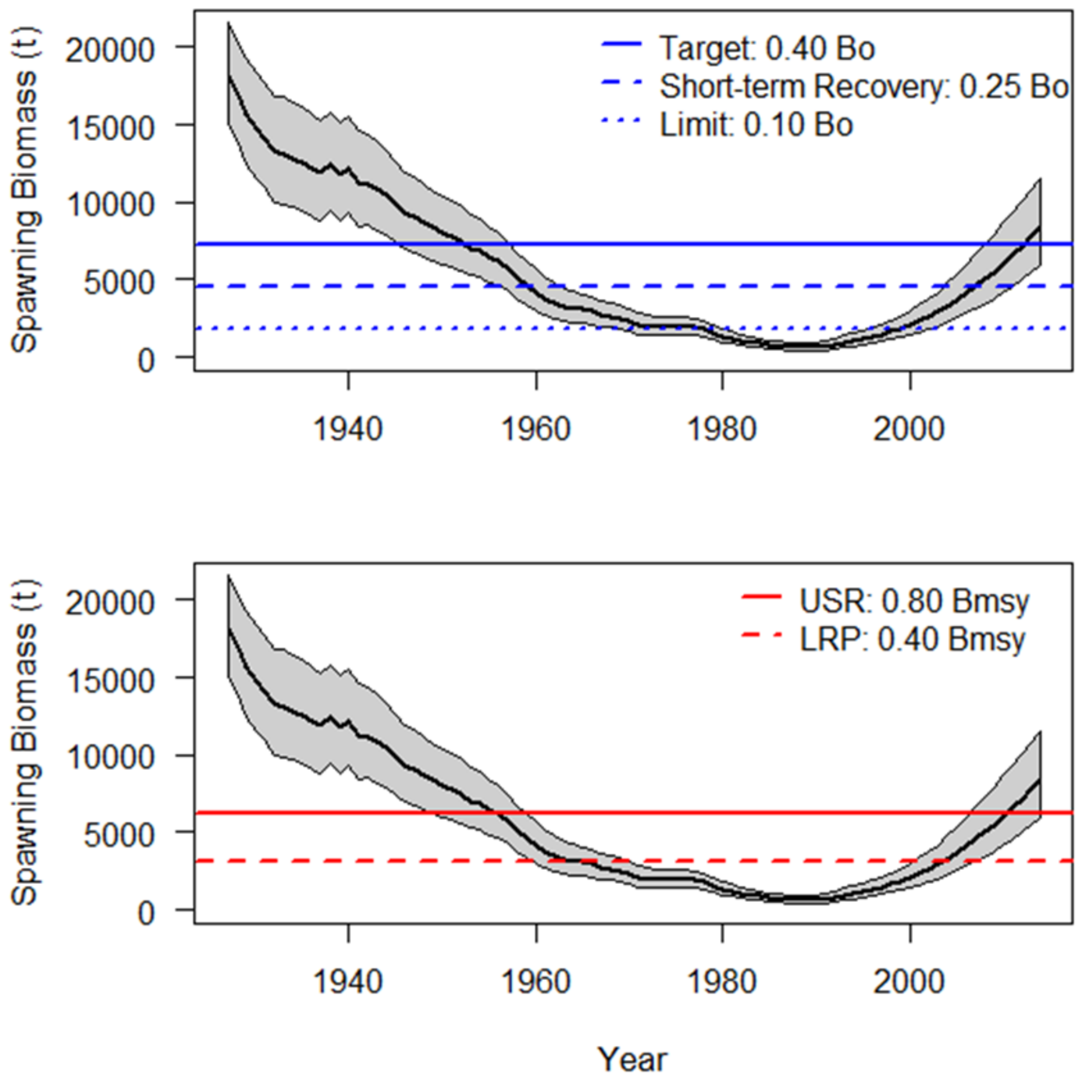


Figure 8. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the noSE scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

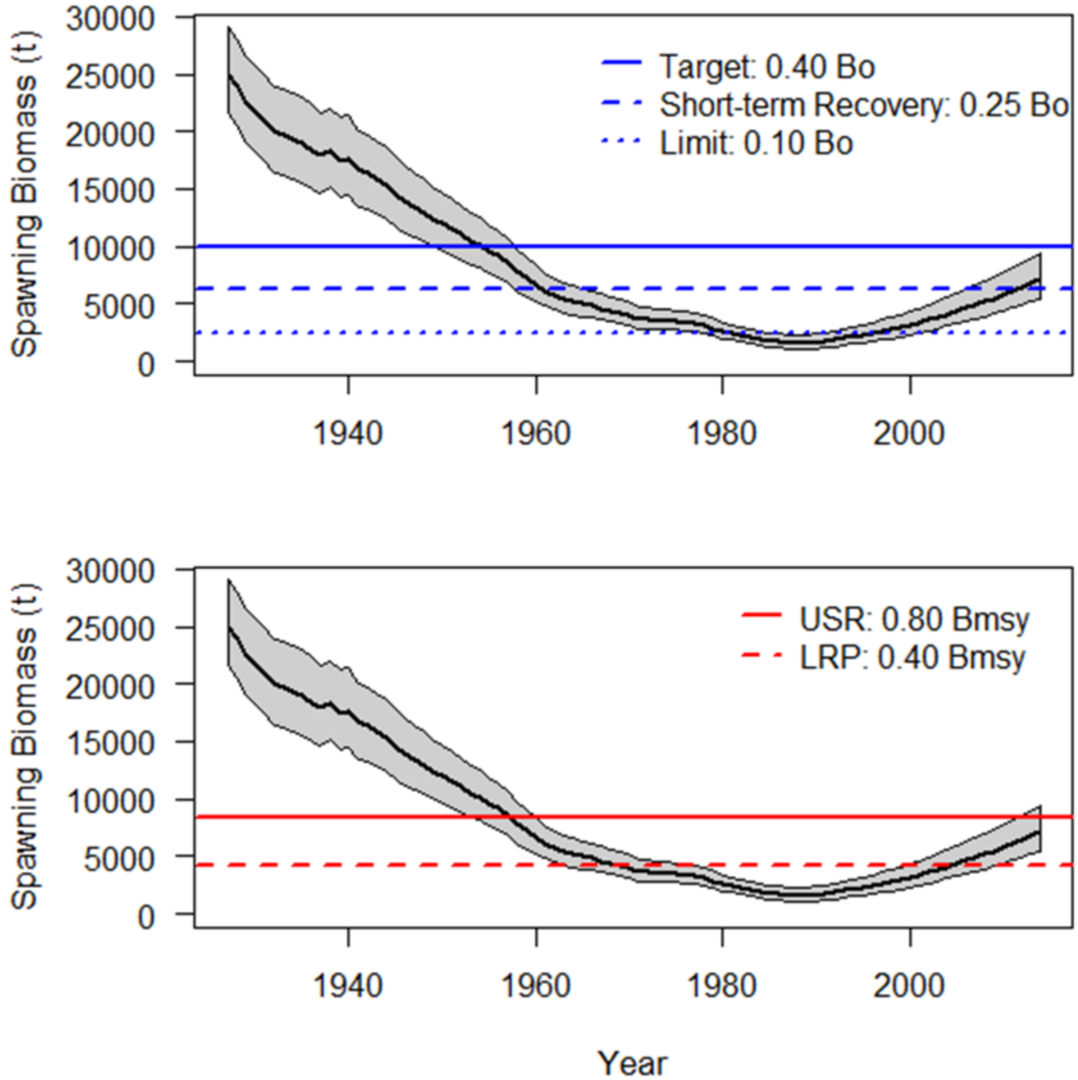


Figure 9. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the noSE_noDD scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

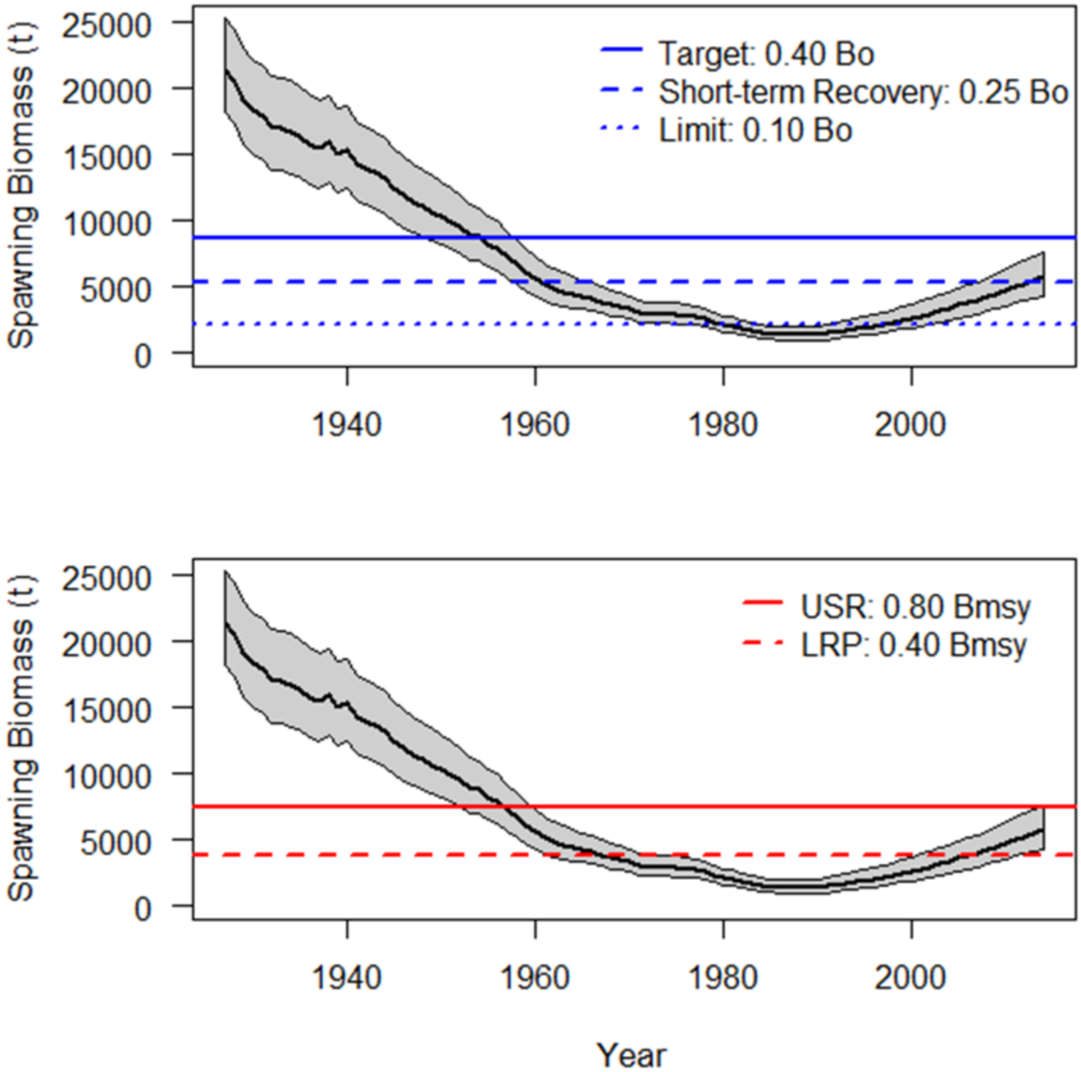


Figure 10. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the noSE_noDD+highM scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

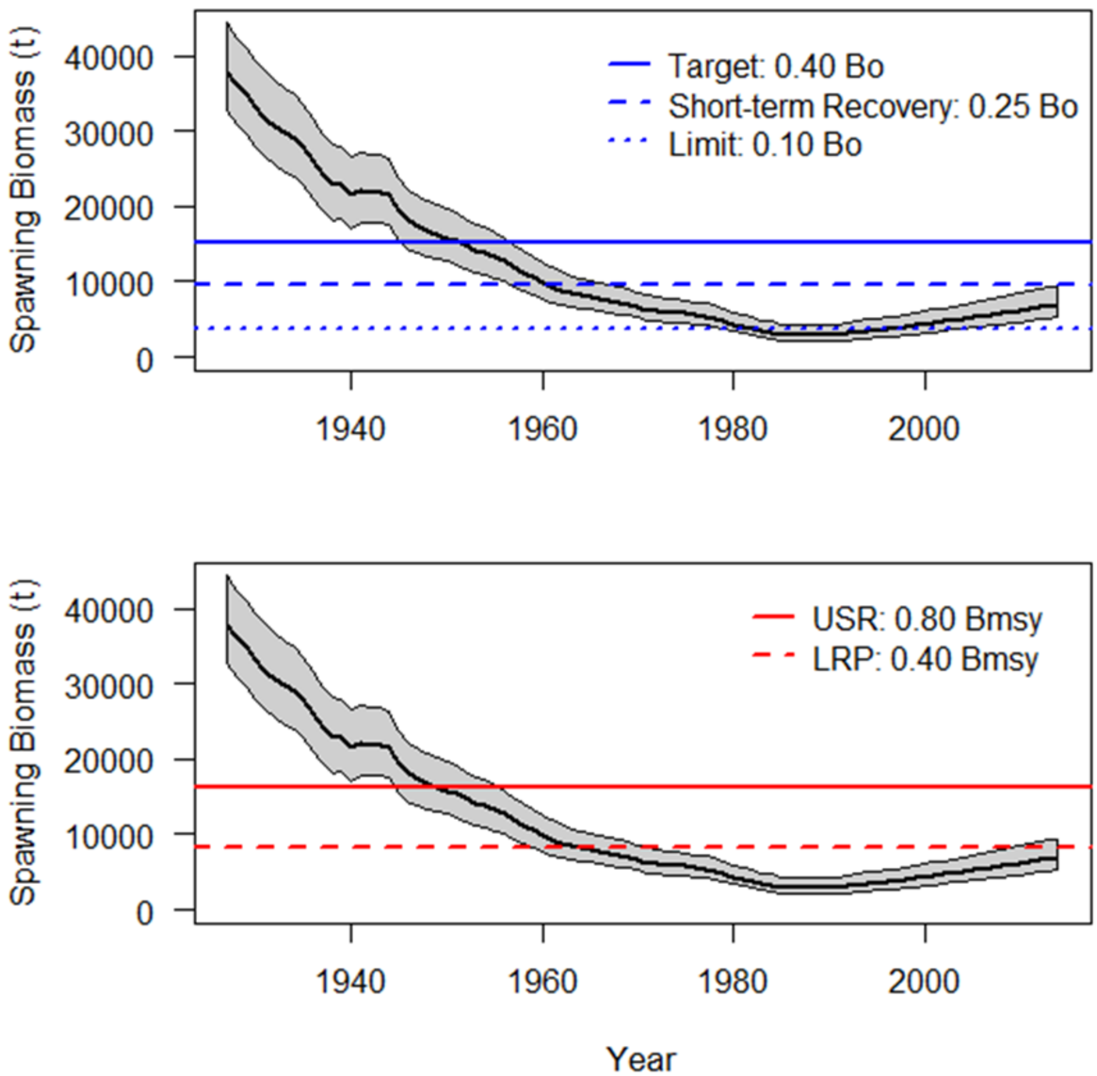


Figure 11. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the onlySEpre1947 scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

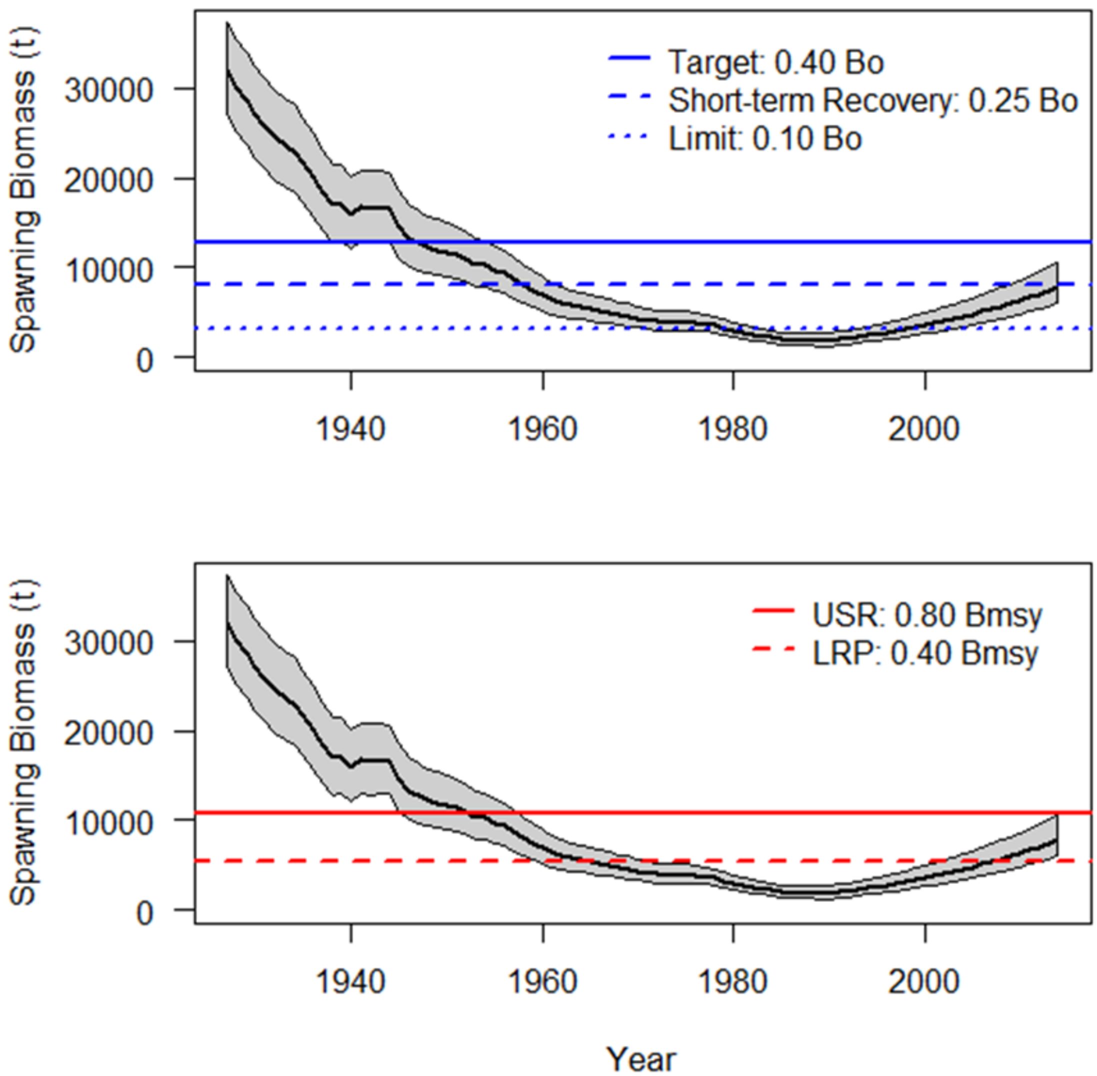


Figure 12. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the onlySEpre1947_noDD scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

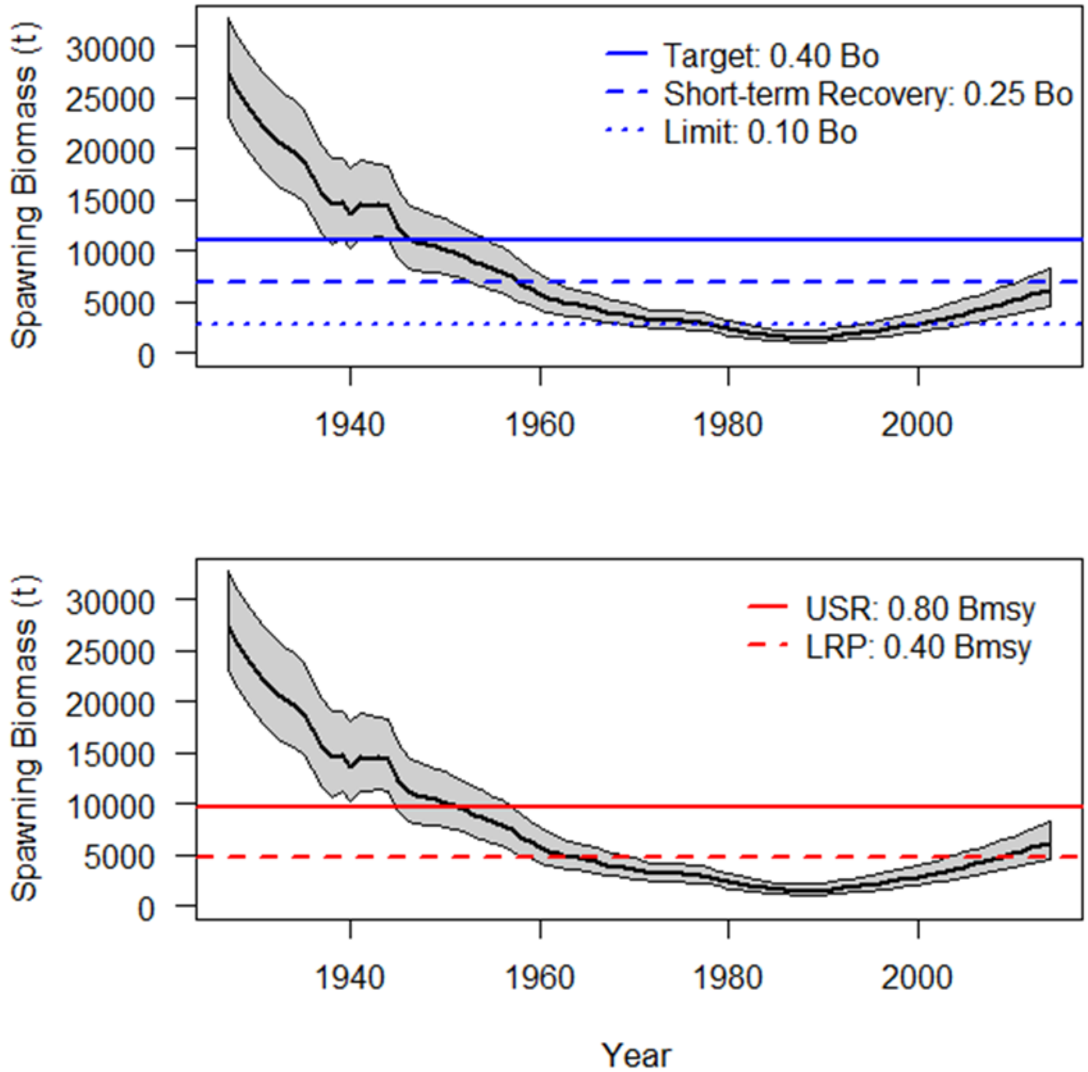


Figure 13. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the onlySEpre1947_noDD+highM scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

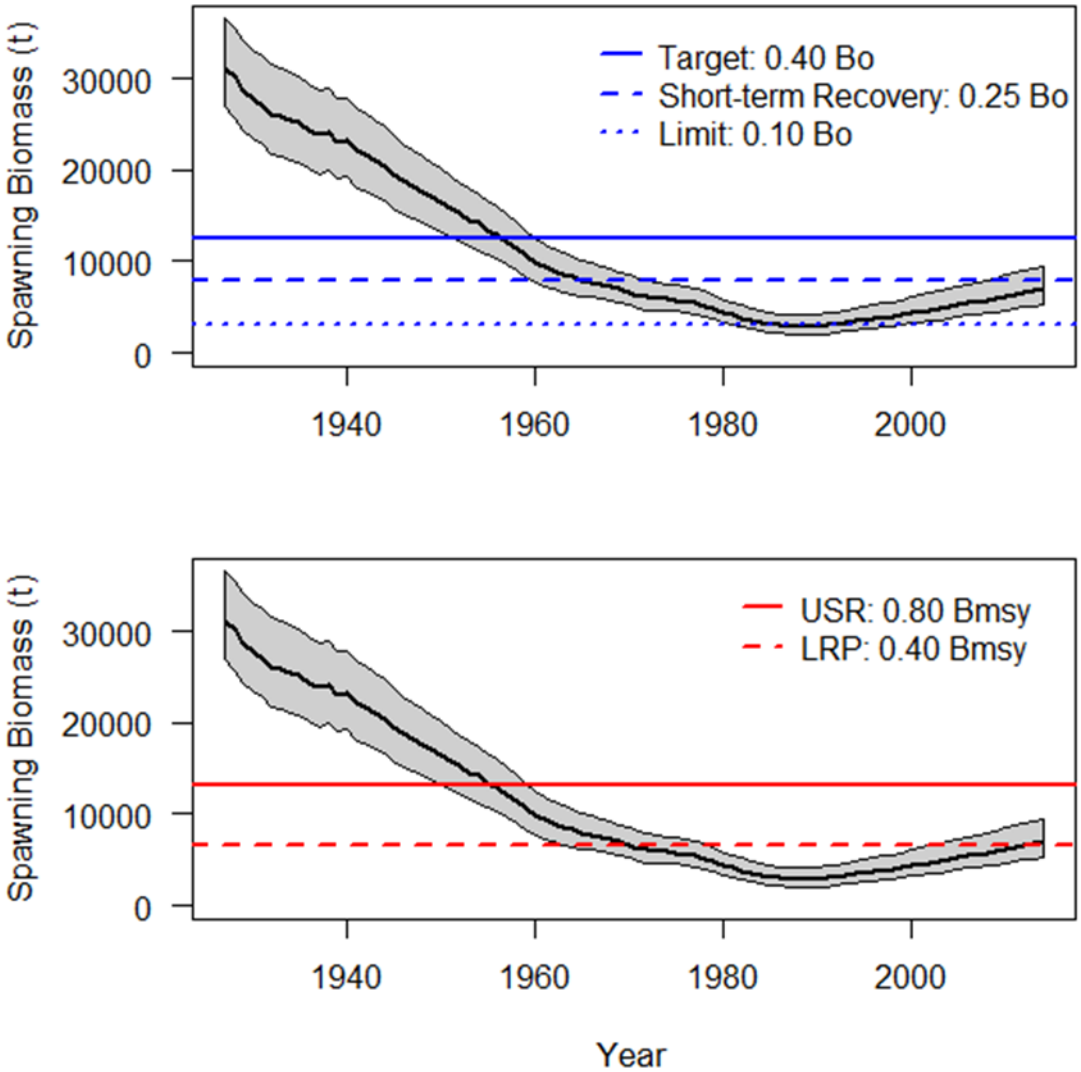


Figure 14. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the noSEpre1947 scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5^th and 95^th percentiles. Reference points are presented as posterior median estimates.

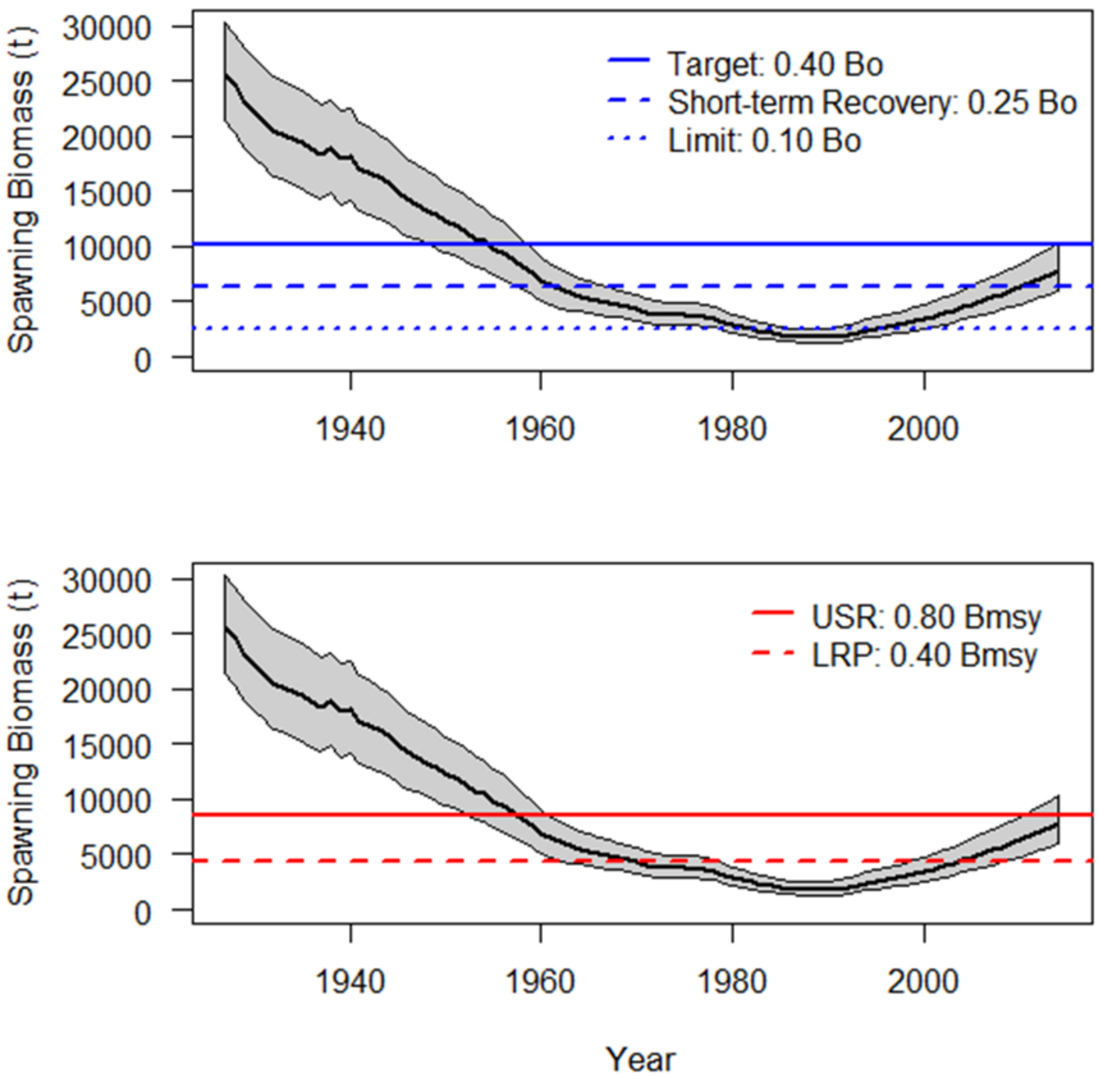


Figure 15. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the noSEpre1947_noDD scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

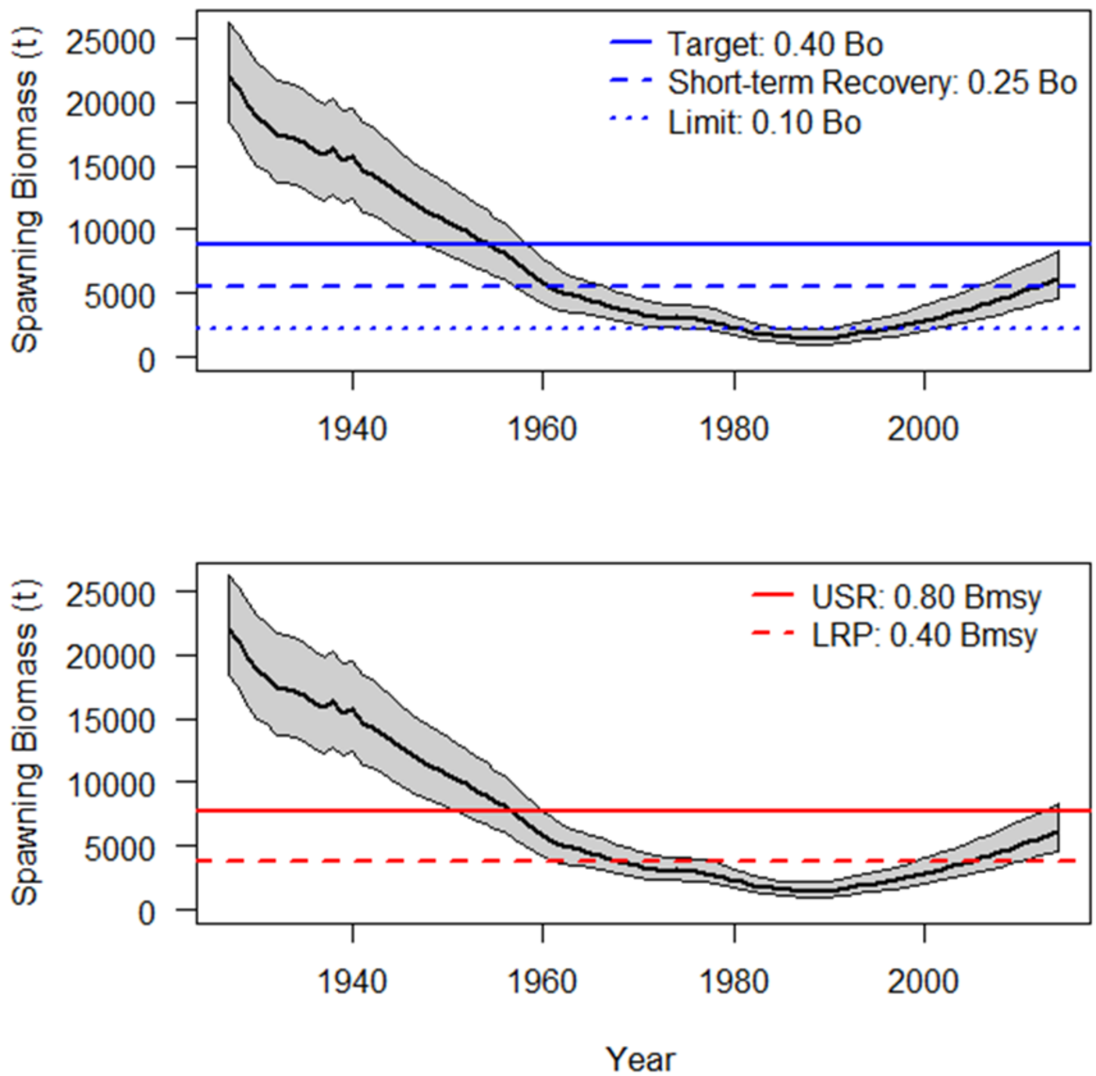


Figure 16. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the noSEpre1947_noDD+highM scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

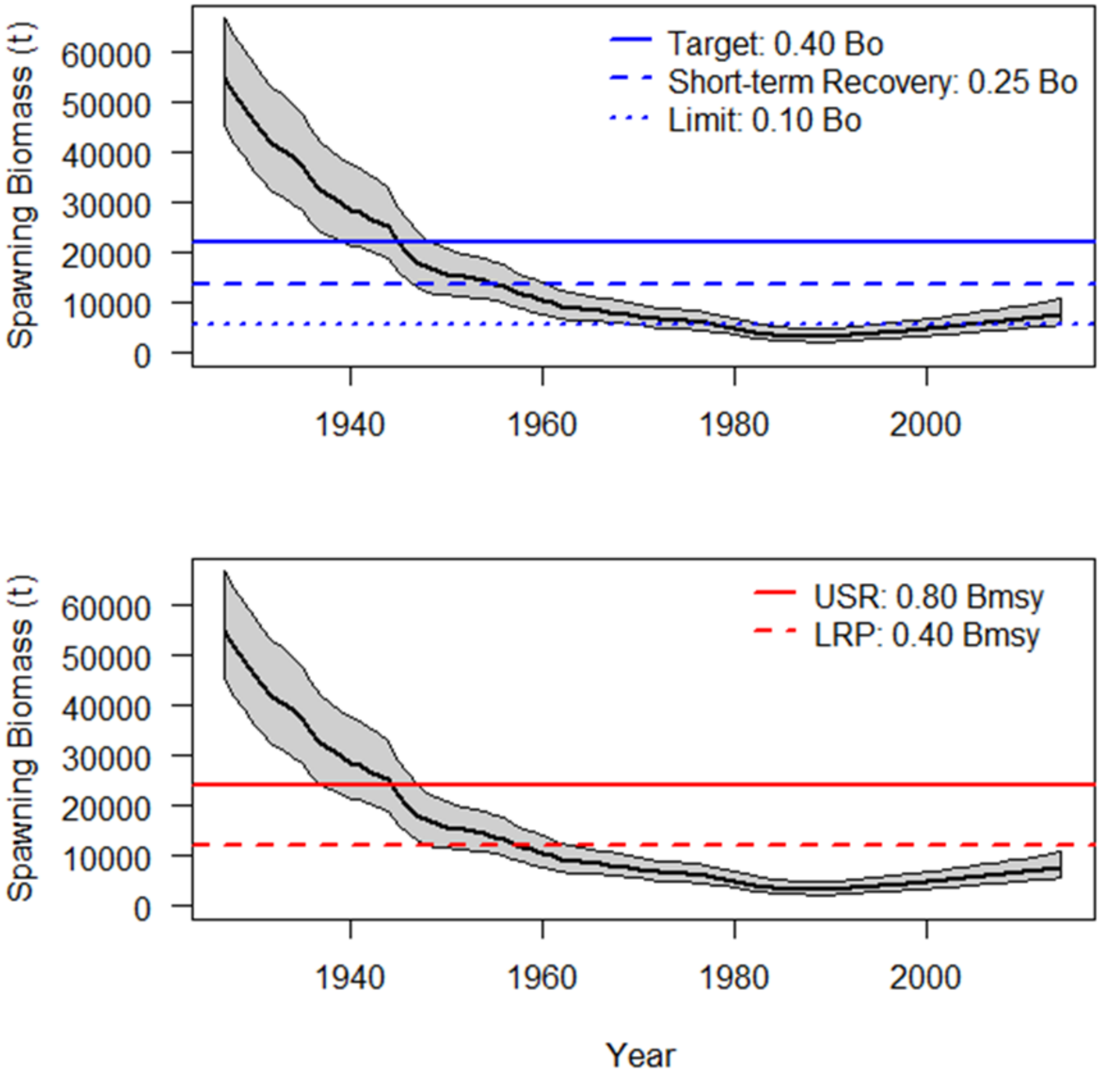


Figure 17. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the SoG scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

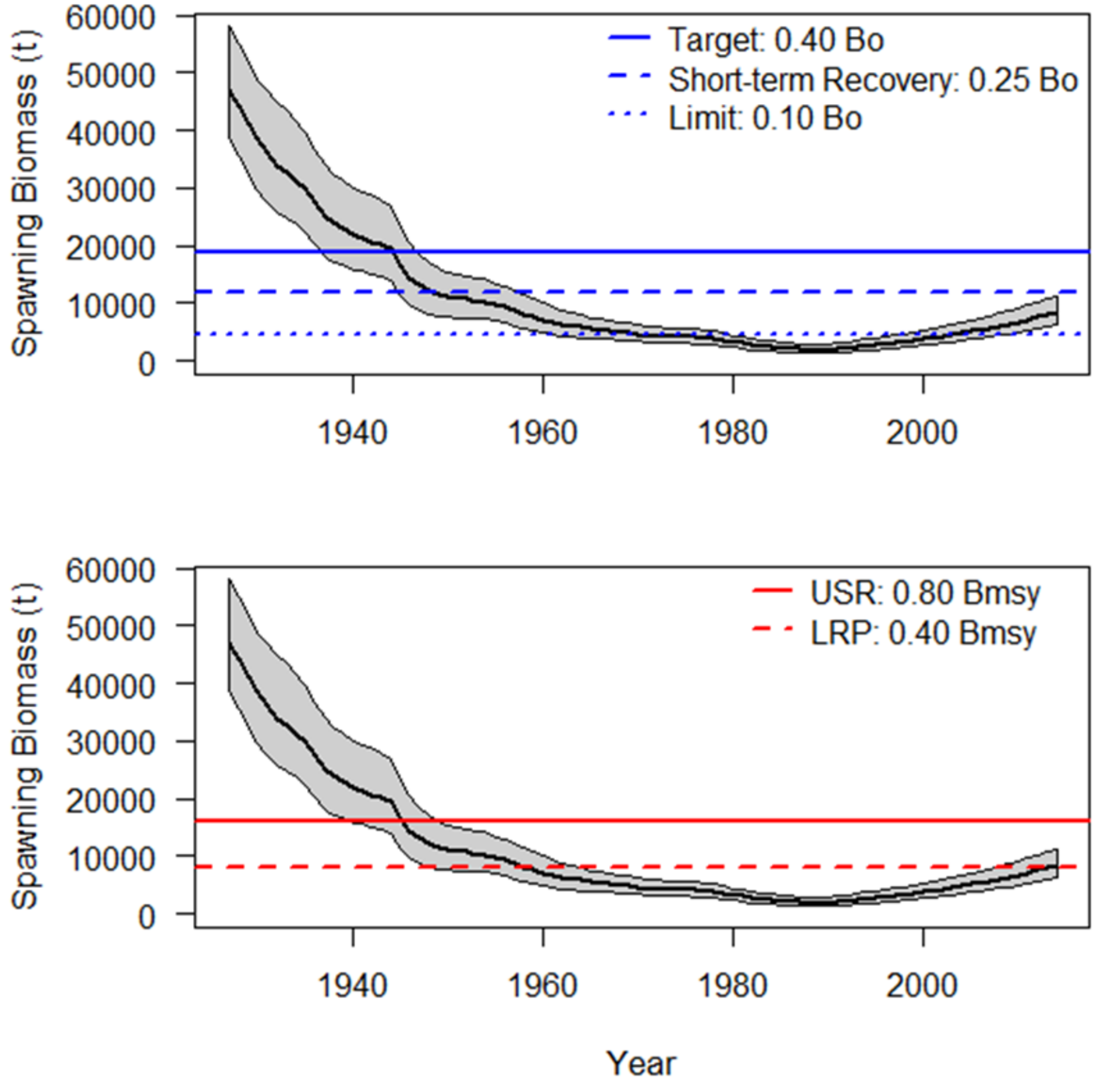


Figure 18. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the SoG_noDD scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5^{th} and 95^{th} percentiles. Reference points are presented as posterior median estimates.

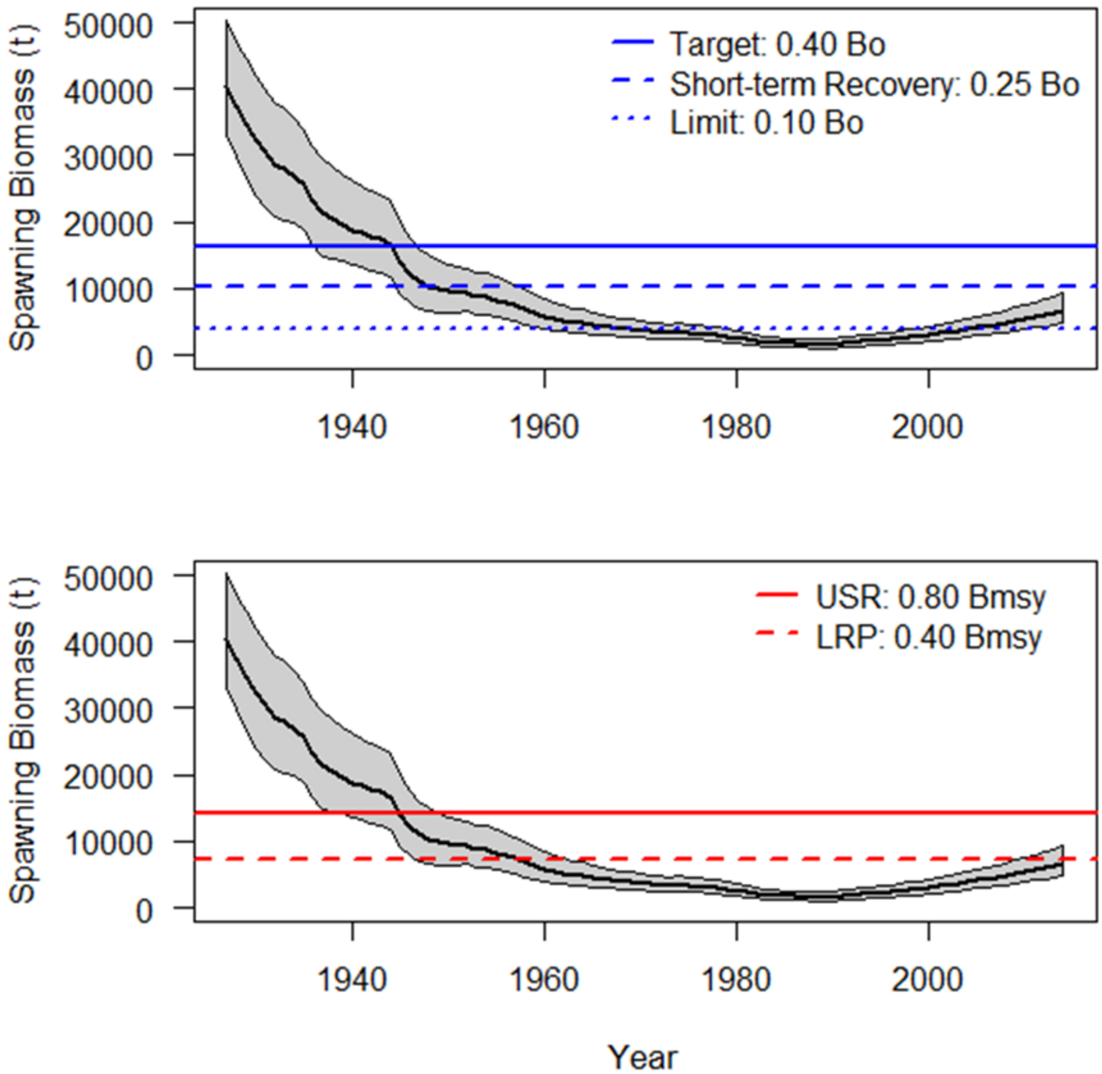


Figure 19. Estimated spawning biomass (in tonnes) over time relative to the 2005 Lingcod Management Framework reference points (Target, Short-term recovery target, and Limit reference points in top panel) and the DFO PA Framework reference points (Upper Stock Reference (USR) and Limit Reference Point (LRP) in bottom panel) for the SoG_noDD+highM scenario. In each panel, the thick black line shows the median from posterior distributions of spawning biomass approximated via the MCMC method, while the grey shading shows the 5th and 95th percentiles. Reference points are presented as posterior median estimates.

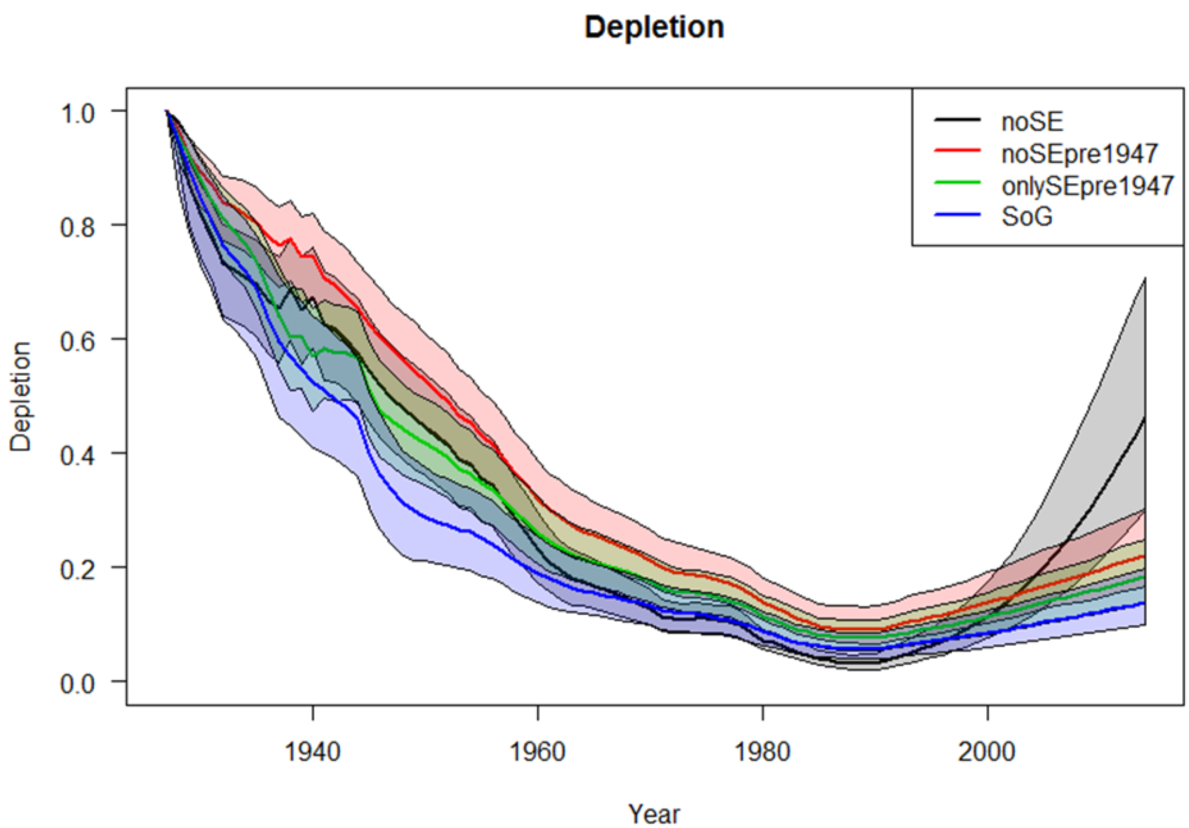


Figure 20. Comparison of depletion trajectories (Spawning Biomass / Unfished equilibrium biomass) for the four scenarios that used density-dependent mortality and density-dependent catchability.

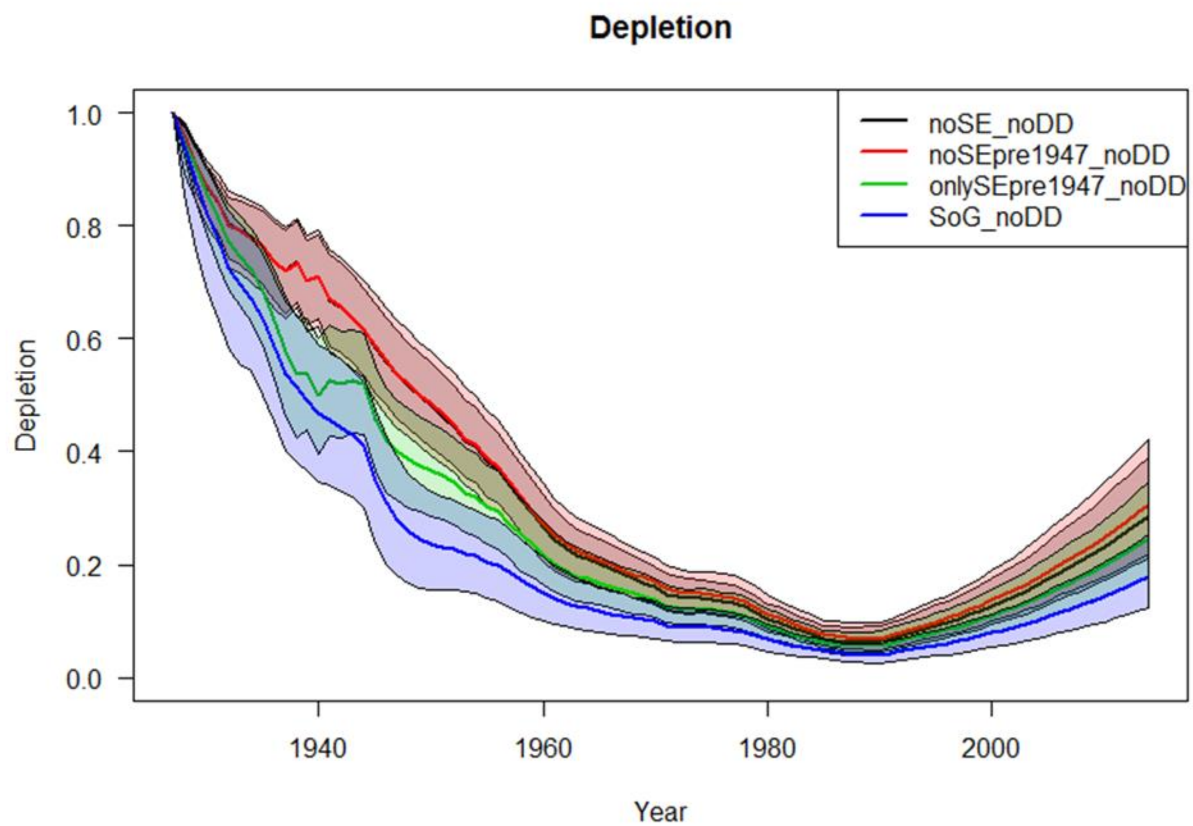


Figure 21. Comparison of depletion trajectories (Spawning Biomass / Unfished equilibrium biomass) for the four scenarios that assumed constant natural mortality and catchability over time, and assumed a natural mortality rate of M=0.2.

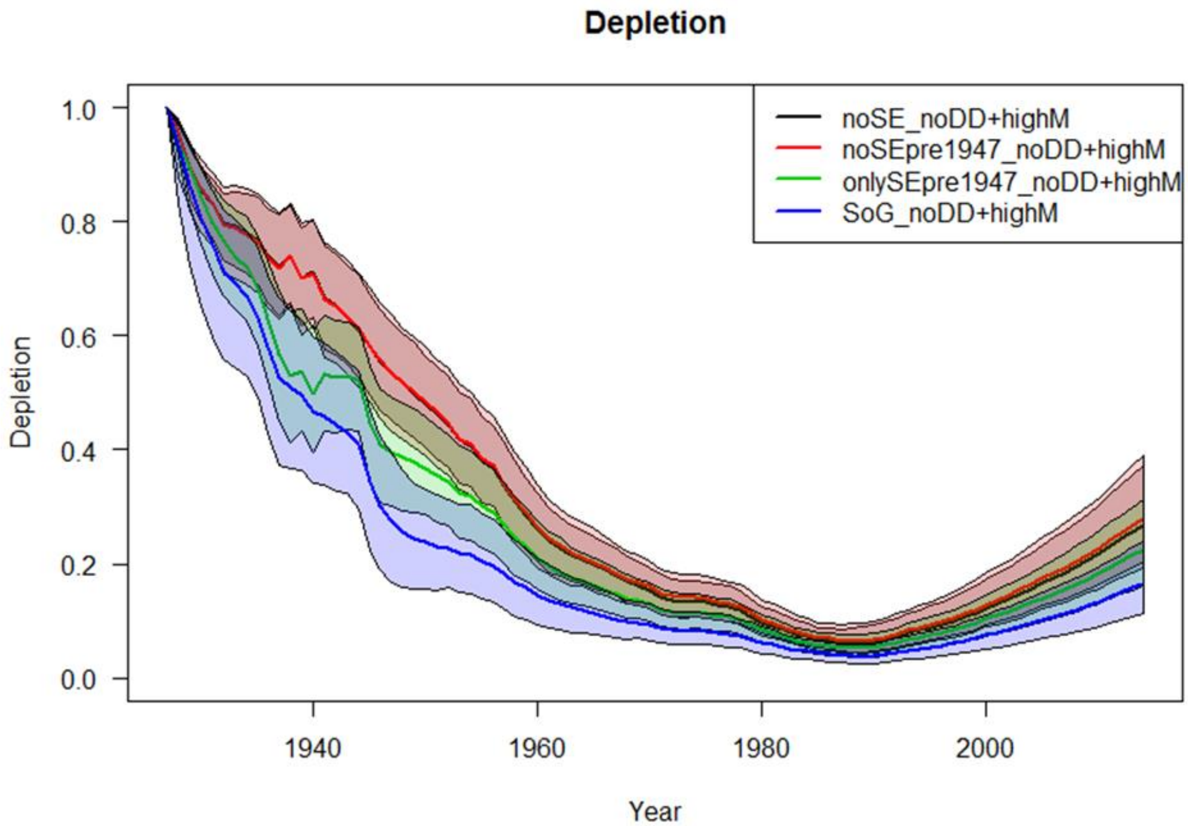


Figure 22. Comparison of depletion trajectories (Spawning Biomass / Unfished equilibrium biomass) for the four scenarios that assumed constant natural mortality and catchability over time, and assumed a natural mortality rate of M=0.3.

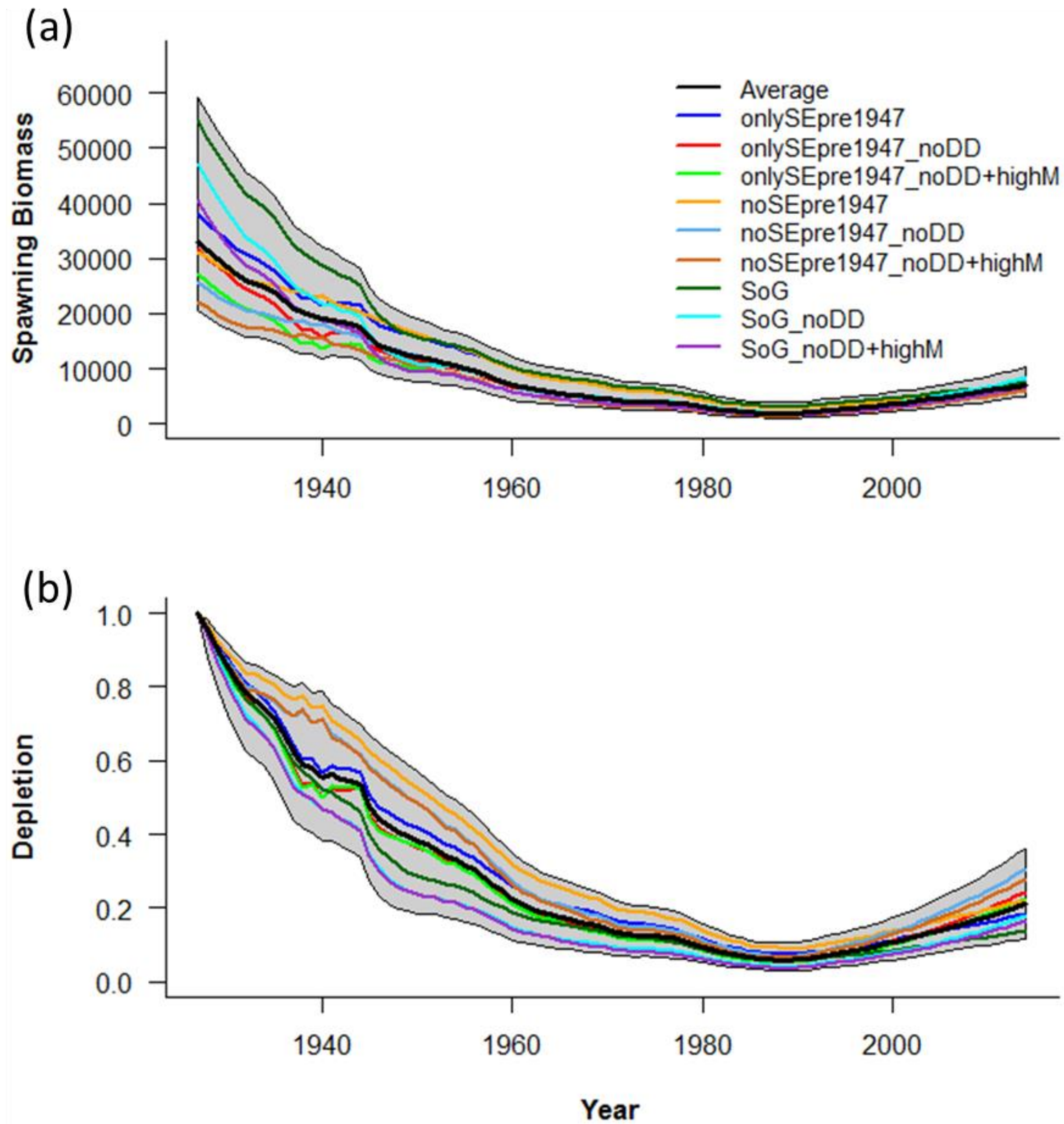


Figure 23. Panel a: Posterior median estimates of spawning biomass (in tonnes) over time for the scenario-averaging approach (solid black line). Grey shading shows the 5th and 95th percentiles of the scenario-averaged trajectory, while the multi-coloured solid lines show the posterior median estimates from each of the nine individual scenarios used to create the scenario-average. Panel b: Posterior median estimates of depletion (B_{2014} / B_0) over time for the scenario-averaging approach (solid black line). Grey shading and multi-coloured lines are the same as panel a.

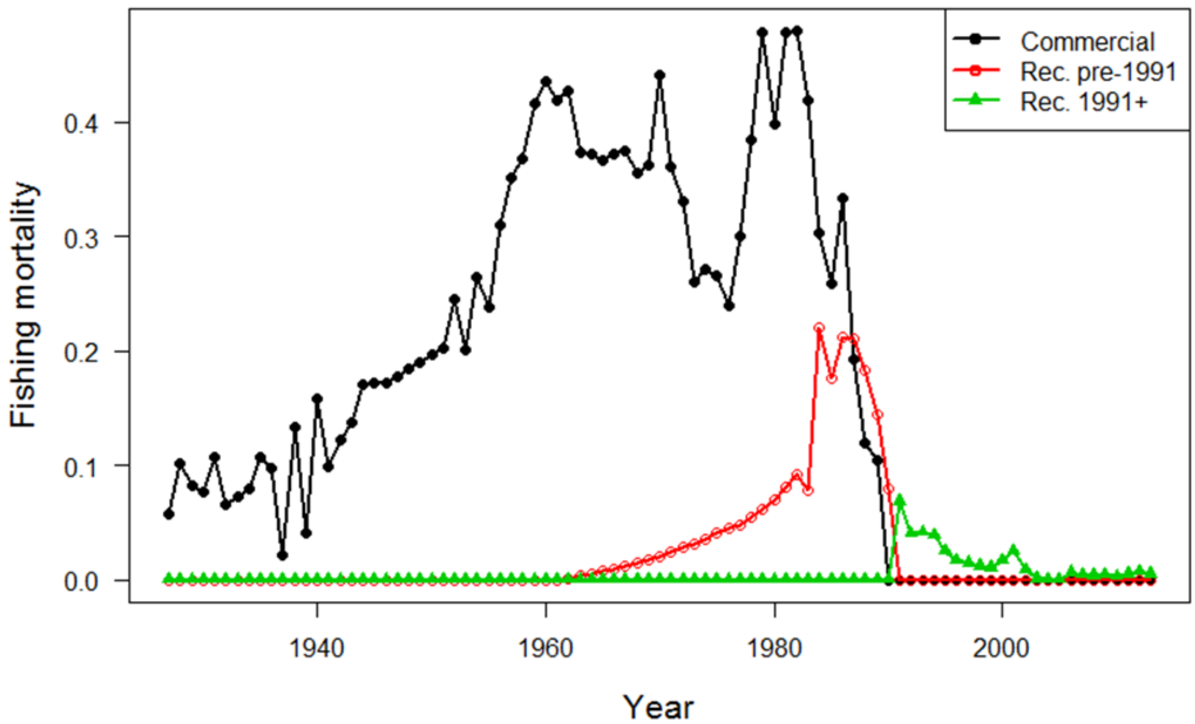


Figure 24. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the noSE scenario.

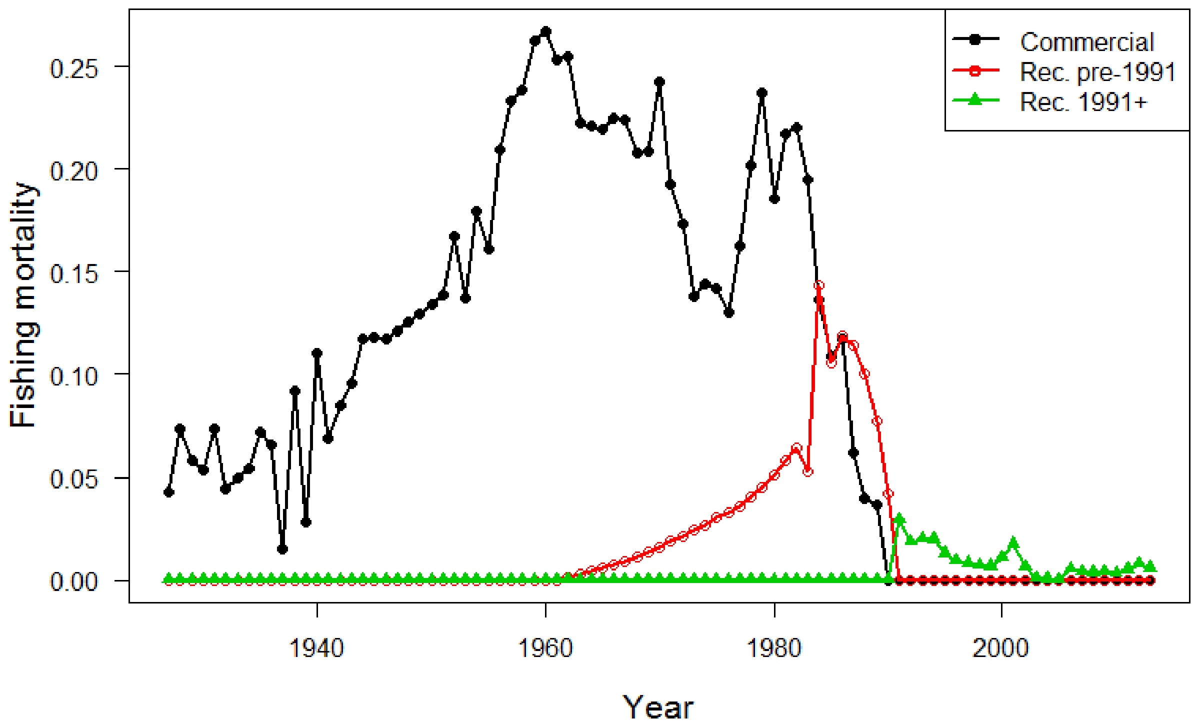


Figure 25. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the noSE_noDD scenario.

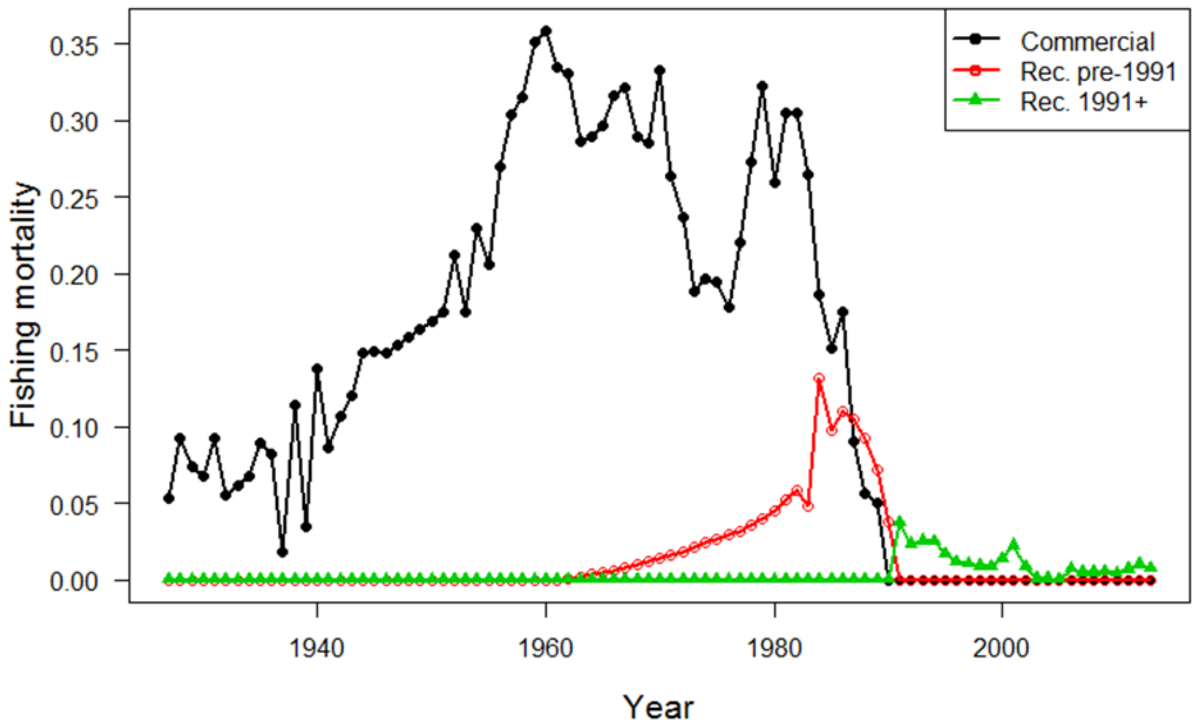


Figure 26. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the noSE_noDD+highM scenario.

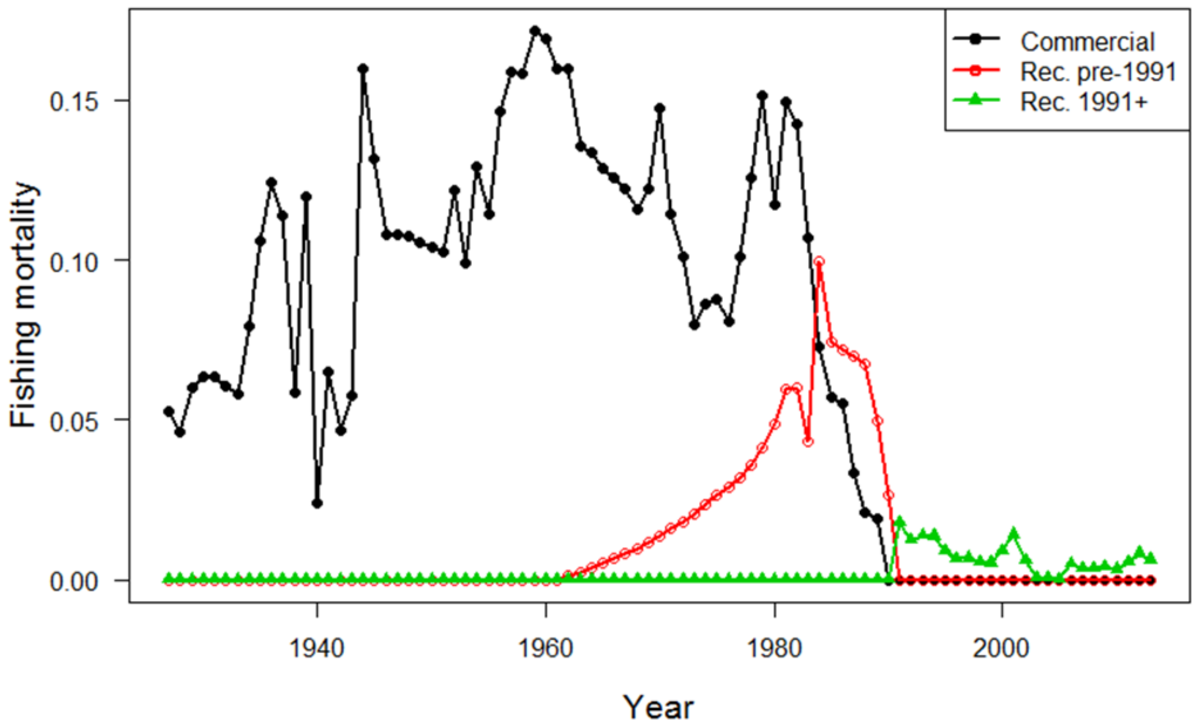


Figure 27. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the onlySEpre1947 scenario.

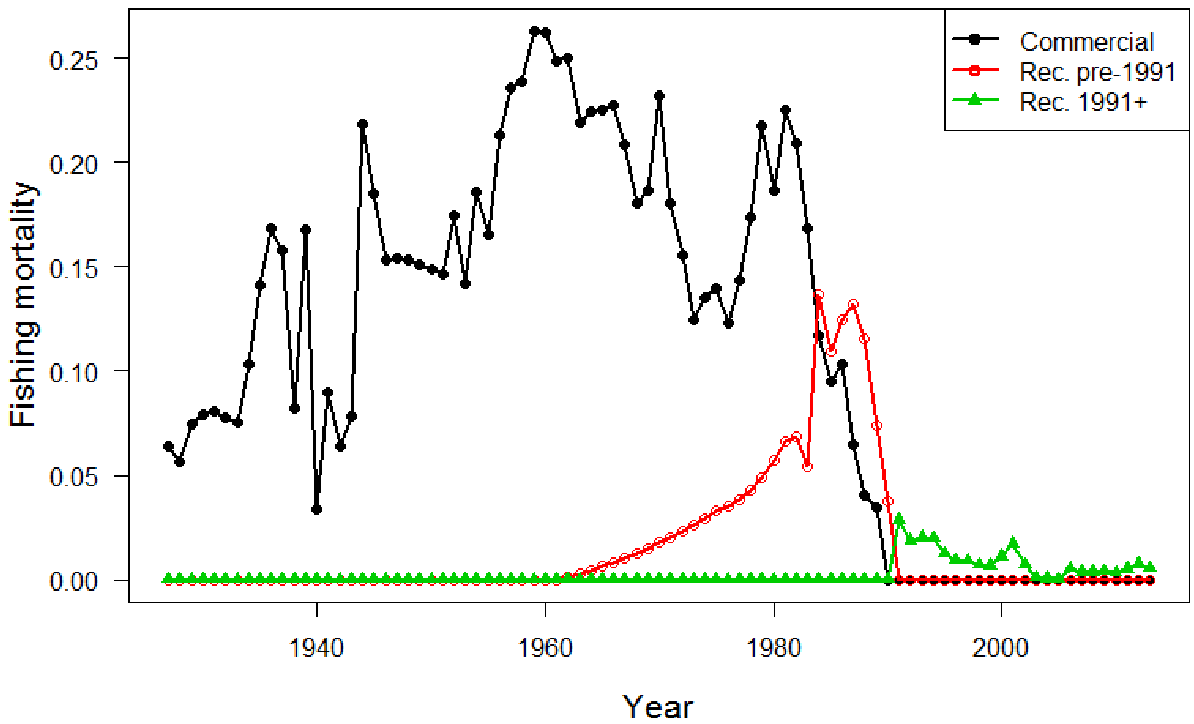


Figure 28. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the onlySEpre1947_noDD scenario.

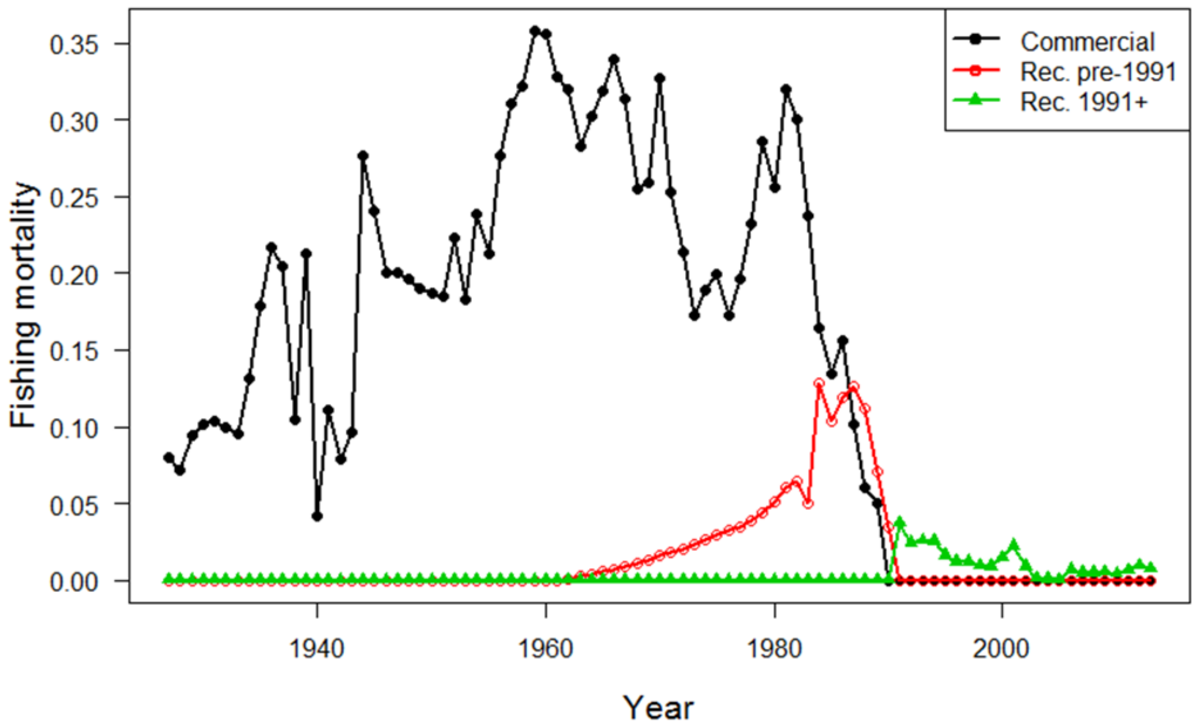


Figure 29. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the onlySEpre1947_noDD+highM scenario.

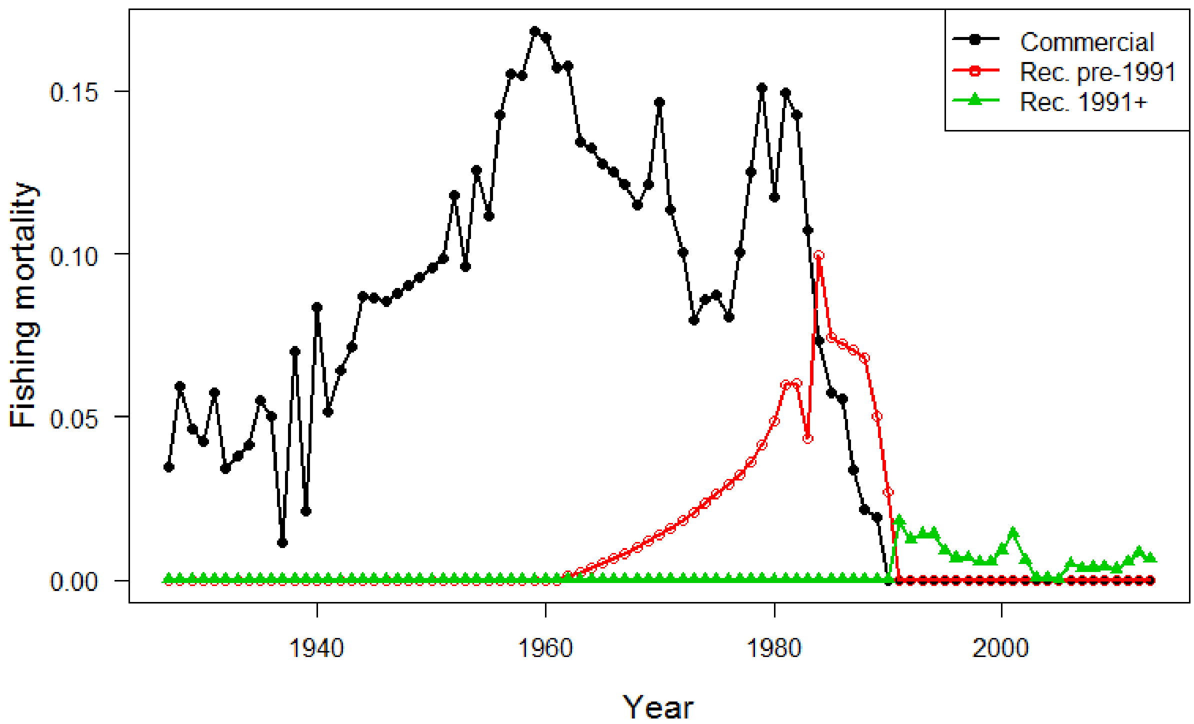


Figure 30. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the noSEpre1947 scenario.

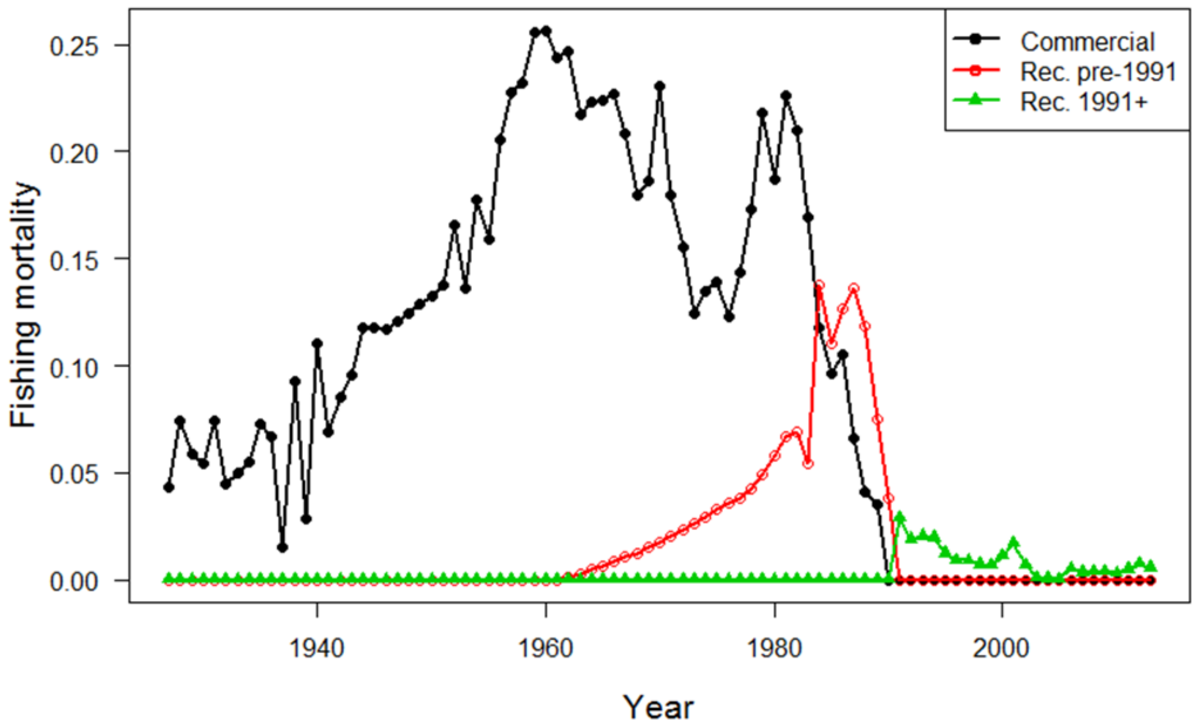


Figure 31. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the noSEpre1947_noDD scenario.

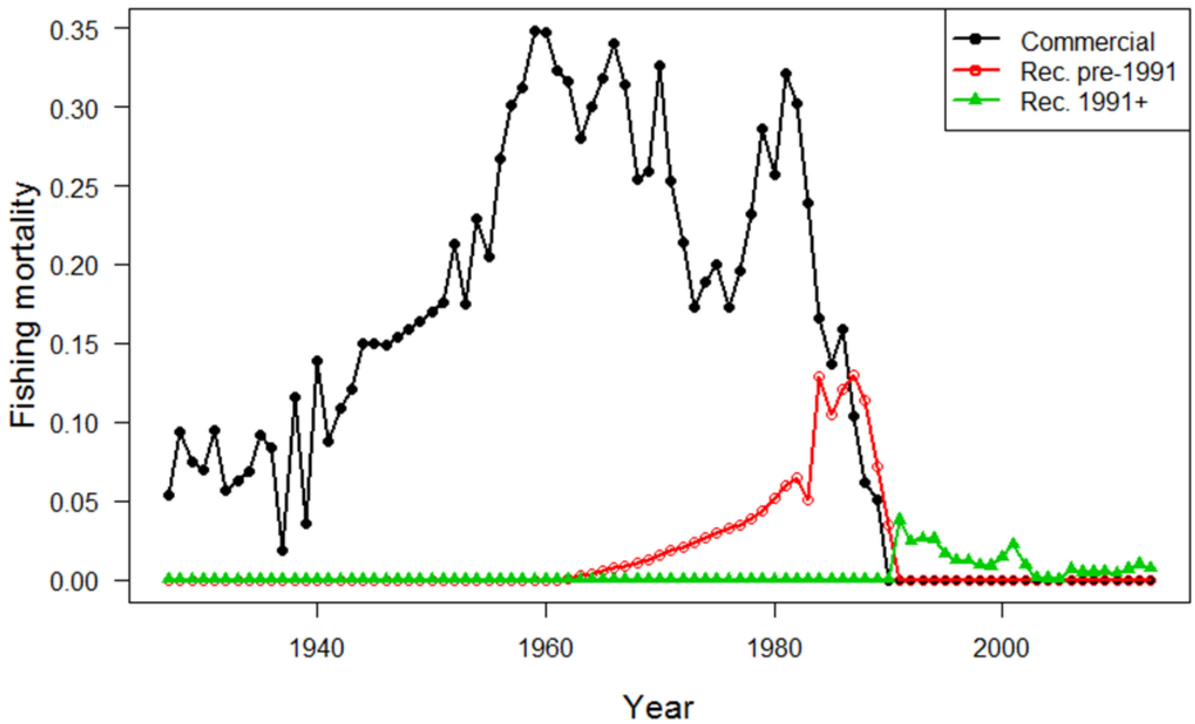


Figure 32. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the noSEpre1947_noDD+highM scenario.

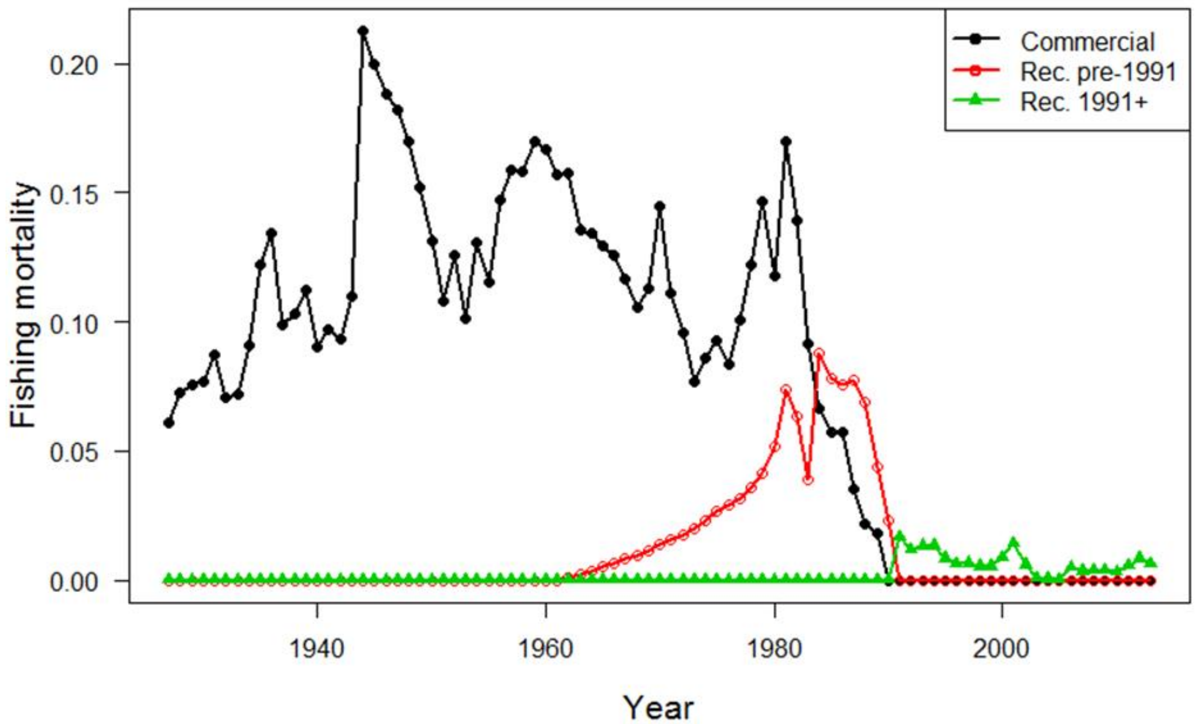


Figure 33. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the SoG scenario.

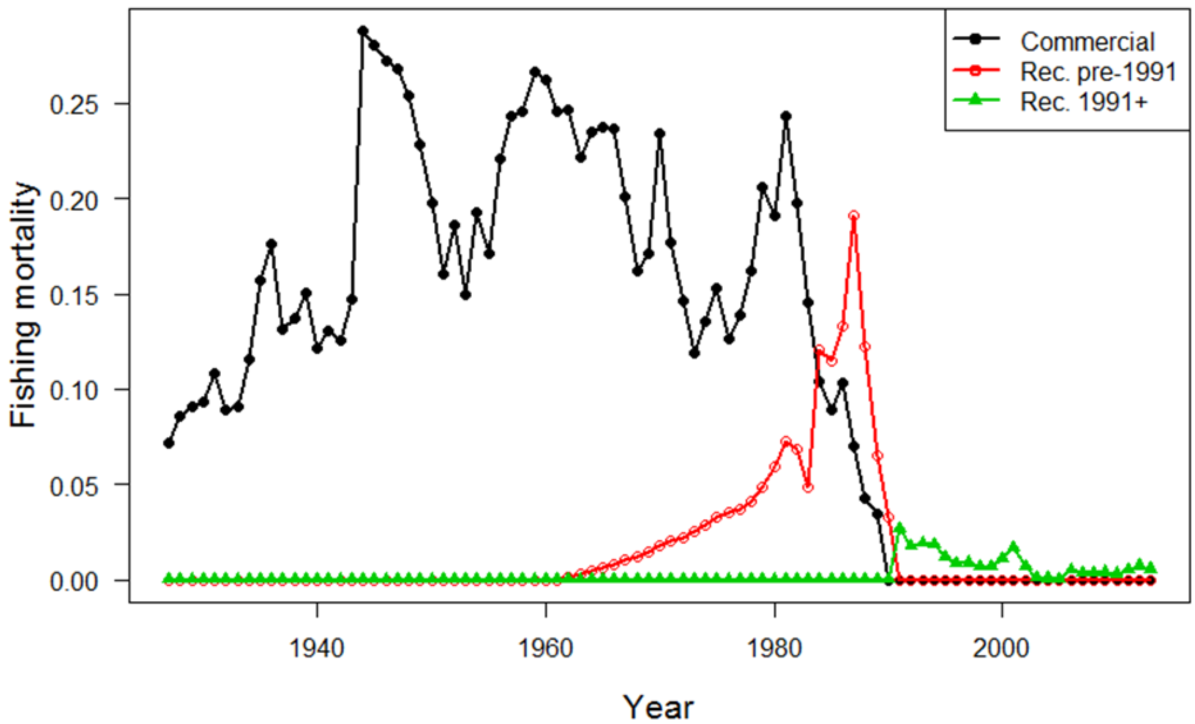


Figure 34. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the SoG_noDD scenario.

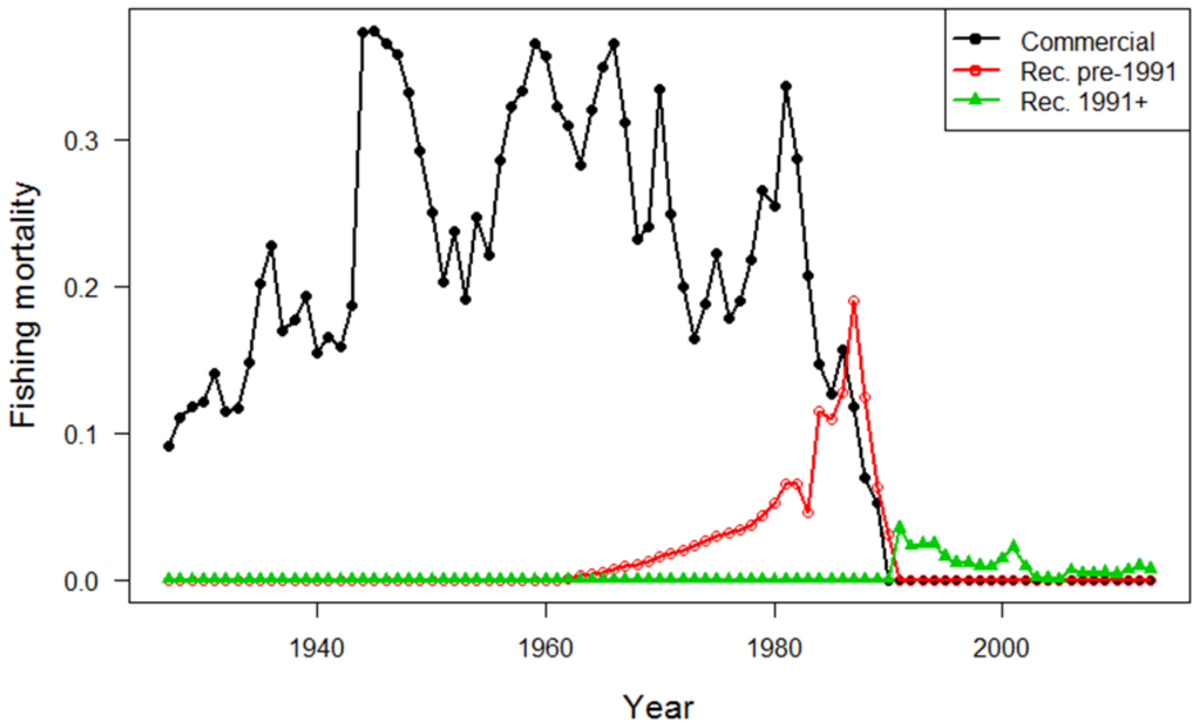


Figure 35. Maximum posterior density estimates of instantaneous rate of fishing mortality over time for three gear types (Commercial fishery, recreational fishery prior to 1991, and recreational fishery from 1991 onwards) in the SoG_noDD+highM scenario.

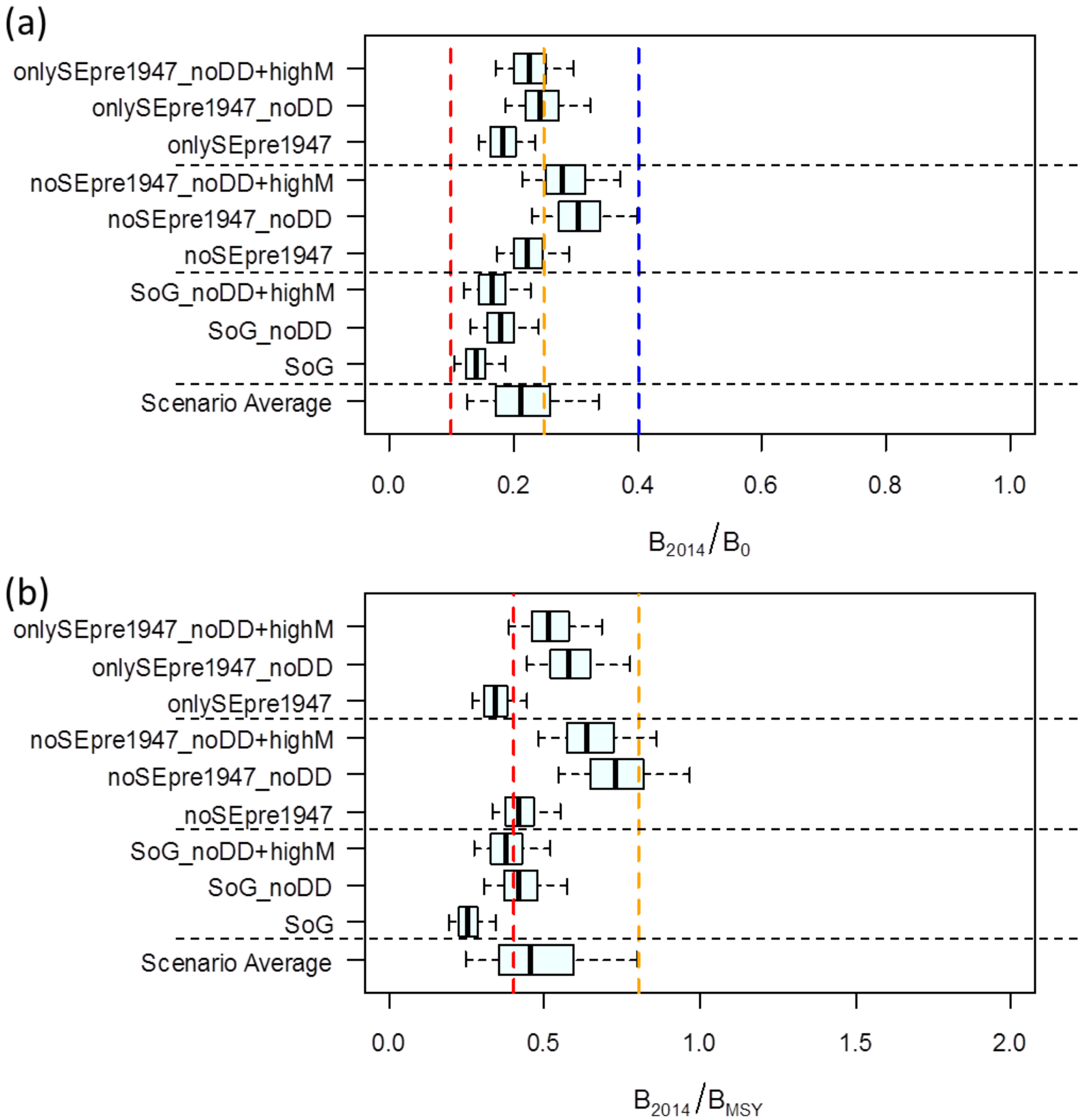


Figure 36. Panel a: Current stock status (represented as the ratio of B_{2014} to B_0) relative to the reference points recommended by the 2005 Lingcod Assessment and Management Framework for each of the nine assessment scenarios selected to characterize stock status, as well as the scenario-average case (red vertical dashed line = limit reference point of $0.1B_0$, orange vertical dashed line = short-term recovery target of $0.25B_0$, blue vertical dashed line = long-term recovery target of $0.4B_0$). Panel b: Current stock status (represented as the ratio of B_{2014} to B_{MSY}) relative to the provisional reference points recommended by the DFO PA Framework for each of the nine assessment scenarios as well as the scenario-average case (red vertical dashed line = limit reference point of $0.4B_{MSY}$, orange vertical dashed line = upper stock reference at $0.80B_{MSY}$). Boxplots show the 5, 25, 50, 75, and 95 percentiles from the MCMC results.

APPENDIX A: DATA AVAILABILITY

We summarize availability for three types of Strait of Georgia Lingcod data in this appendix:

1) fishery-independent indices of abundance from research surveys,

2) biological samples from the recreational fishery, and

3) fishery discards.

FISHERY INDEPENDENT ABUNDANCE INDICES

Table A.1 briefly summarizes research surveys carried out partially or totally within the Strait of Georgia that captured Lingcod as part of the overall catch. Data are summarized only for valid sets from Statistical Areas 13 through 19, 28 and 29. None of these survey series were considered for 2014 assessment modelling scenarios due to concerns about short time series, low lingcod catch and/or poor geographic coverage.

The 2012 Synoptic Trawl survey and the 2003-2014 Inshore Rockfish (IRF) Longline Surveys are both new series that have been initiated since the 2005 Lingcod assessment was prepared (Logan et al. 2005). The 2012 Synoptic trawl survey is currently only one data point, so cannot yet be used to develop a relative index of abundance. The IRF survey has low annual catches of Lingcod (Table A.1), and does not target a portion of the Lingcod depth distribution shallower than 41 meters (Lochead and Yamanaka 2007). Estimates of coefficients of variation for Lingcod biomass estimates from the IRF survey between 2003 and 2005 range from 2.36 to 3.39 (Lochead and Yamanaka 2006, Lochead and Yamanaka 2007). Neither the Synoptic bottom trawl survey nor the inshore rockfish survey provide suitable abundance indices at this time; however, they should be re-visited for future stock assessments. Options to expand existing survey designs and account for habitat-based stratification of biomass estimates could also be explored to reduce uncertainty in the IRF survey.

Over the course of the six years in which the Spiny Dogfish longline survey in the Strait of Georgia has been conducted, only 19 of the 288 survey sets caught Lingcod.

The Lingcod young-of-the-year (YOY) trawl survey series contains only five data points. An initial examination of the relative abundance estimates over these five years showed no trend (Surry et al. 2007), so the effect of adding the index to the current assessment was not expected to have much effect on assessment outcomes. Furthermore, including an age-zero abundance index in the assessment model would have required modifications to the iSCAM assessment model that were considered beyond the scope of this assessment.

The Lingcod Egg Mass survey provides a relatively long time series of diving observations; however, the geographic coverage of this survey is limited largely to a single reef near Snake Island within the Strait of Georgia, which raises concerns about its ability to track basin-wide trends. Additional sites from the local area near Nanaimo were occasionally surveyed some years. Dive depths were restricted to 20m or less, restricting observations to a limited portion of depths inhabited by Lingcod (McPhie and King 2011).

Table A.1. Summary of research surveys in the Strait of Georgia having caught or observed Lingcod. Table values reflect data from usable sets within the area of interest (Strait of Georgia - Statistical Areas 13 to 19, 28 and 29). Surveys conducted in 2014 for the Spiny Dogfish Longline and Northern portion of the Inshore Rockfish Longline are not included in this table. The 5th and 95th percentiles for depths from valid sets indicate the general depth range covered by each survey series. Mean Lingcod catch in numbers/set are given for positive catches (Pos) and for all usable sets including zero catches (Incl zero).

		Survey Years			Sets w. Lingcod/	Mean Lingcod No. / Set		Valid Set Depth (m)	
Survey Series	**Gear**	**First**	**Last**	**Total**	**Total Usable Sets**	**Pos**	**Incl zero**	**5%**	**95%**
Spiny Dogfish Longline	longline	1986	2011	6	19 / 288	3.11	0.20	27	272
Inshore Rockfish Longline (North)	longline	2003	2012	6	65 / 175	2.46	0.91	28	131
Inshore Rockfish Longline (South)	longline	2005	2013	4	50 / 251	1.72	0.34	34	112
Lingcod Hook & Line (Jig)	handline	1985	2005	5	272 / 569	3.96	1.89	5	50
Lingcod YOY Trawl	bottom trawl	1991	2006	5	260 / 347	13.47	10.1	16	58
Reef-fish Jig	handline	1985	1988	4	156 / 376	1.86	0.77	8	100
Lingcod Egg Mass	scuba	1990	2012	13	NA	NA	NA	5	20
Strait of Georgia Synoptic	bottom trawl	2012	2012	1	5 / 51	19.8	1.94	75	391

BIOLOGICAL DATA FROM RECREATIONAL FISHERY

Biological samples from recreational catch are available from the Strait of Georgia creel program starting in 2000. These data were extracted from the creel database by Kris Hein (Kris Hein, South Coast Area Database Coordinator, DFO, Nanaimo, BC, pers. comm.) Table A.2 summarizes available length and sex information annually, along with the number of Lingcod fins collected for ageing. Data were filtered to include records from Statistical Areas 13 to 19 plus 28 and 29. Note that Lingcod retention from recreational fisheries was not permitted during 2002 - 2005 in the Strait of Georgia, which accounts for small sample sizes during this period.

After ignoring the limited numbers of 2003 - 2005 samples, an average of 117 Lingcod were measured annually during creel interviews. Females comprised 59% of the 959 Lingcod that were positively sexed. Mean length of the 1201 total specimens was 758 mm, after including unsexed Lingcod. Fins were collected from 908 Lingcod for ageing but none have been aged so far. They are stored with DFO's Sclerochronology Lab at the Pacific Biological Station in Nanaimo, BC for future consideration.

Table A.2. Summary of Lingcod biological data collected by the Strait of Georgia creel survey program.

		Length (mm)			No.	No.	No.	
Year	**Records**	**N**	**Mean**	**SD**	**Fins***	**Aged**	**Sexed**	**% Female**
2000	165	163	738	117	159	0	93	0.43
2001	174	171	750	97	168	0	124	0.60
2002*	28	26	762	245	20	0	11	0.64
2003*	3	3	-	-	-	-	-	-
2004*	1	1	-	-	-	-	-	-
2005*	7	5	-	-	-	-	-	-
2006	145	121	759	97	68	0	84	0.52
2007	99	91	789	119	54	0	54	0.65
2008	139	129	746	119	98	0	115	0.65
2009	122	116	734	108	82	0	101	0.61
2010	106	96	764	107	56	0	95	0.55
2011	116	108	744	102	87	0	111	0.64
2012	134	132	776	110	90	0	124	0.64
2013	55	48	773	120	26	0	47	0.60

* No Lingcod retention was allowed in the sport fishery

Biological data for Lingcod are also provided from selected survey series within Table A.1. DFO's GFBio database has not archived the 2014 surveys (northern IRF longline, Spiny Dogfish longline) and a variety of older surveys are currently absent from the database even though reports are available with summary information.

DISCARD RATES AND DISCARD MORTALITY

For commercial groundfish fisheries in the Strait of Georgia, reliable release estimates become available starting around 2006 – 2007, which is well after the ban on Lingcod retention from commercial fisheries starting in 1990.

For the recreational fishery, estimates of Lingcod releases become available from the creel survey program starting in 2000. The average annual estimate of recreational Lingcod releases (sub-legal and legal combined) between 2000 and 2013 is 25,615 fish, with a range of 11,976 to 59,997 fish per year (based on data provided by Kris Hein, South Coast Area Database Coordinator, DFO, Nanaimo, BC, pers. comm.; Table A.3). The DFO Groundfish Management Unit currently assumes a 4% discard mortality rate for Lingcod releases by the recreational hook and line fishery (Rob Tadey, Hook and Line Coordinator, Groundfish Management Unit, DFO, Vancouver, BC, pers. comm.). Applying this rate to available release estimates results in an average annual discard mortality of 1,025 fish per year between 2000 and 2013 (range = 479 – 2,400 fish per year).

Lingcod are currently encountered as bycatch in three commercial groundfish fisheries in the Strait of Georgia: the groundfish trawl fishery (under trawl licence option B), the rockfish hook and line fishery (ZN licence), and the Spiny Dogfish hook and line fishery. Due to the closure of commercial fisheries to Lingcod retention within Minor Areas 13-19, 28, and 29 of Area 4B, 100% of this bycatch is released. Data on Lingcod releases from these fisheries were extracted from the DFO Pacific Region Groundfish Database GFFOS. For the ZN rockfish and Spiny Dogfish fisheries, reliable release estimates become available at the start of the 2006 - 2007 fishing year, which was the first year of 100% electronic monitoring for hook and line fisheries. For the Option B trawl fishery, 100% electronic monitoring started August 1, 2007. Release numbers provided in Table A.3 from these three fisheries are based on fisher logbooks. A review of 10% of the video recorded from the two hook and line fisheries suggests that logbooks annually reported from 83% to 101% of Lingcod numbers predicted by electronic monitoring, with an 8-year average of 93% (Kate Rutherford, Groundfish Statistics Coordinator, Groundfish Section, DFO, Nanaimo, BC, pers. comm.). Estimates of release mortality for these fisheries are not available; however, it is likely that release mortality is less than 100%. A study of trawl fishery discard mortality in Oregon found that Lingcod mortality was 0% for animals discarded immediately after the cod end was emptied on deck, and increased to 50% after 30 minutes on deck (Parker et al. 2003).

Table A.3. Available data on Lingcod releases from current fisheries in the Strait of Georgia. The numbers shown in brackets in the Recreational Hook and Line (H&L) fishery column shows estimates of discard mortality from this fishery if a 4% mortality estimate was applied to annual releases.

Fishing Year	**Fishery**				
	Recreational H&L; in numbers (x 4% mortality)		Option B trawl; in tonnes	ZN Rockfish; in numbers	Spiny Dogfish; in numbers
2000/2001	32,768	(1311)	-	-	-
2001/2002	59,997	(2400)	-	-	-
2002/2003	56,857	(2274)	-	-	-
2003/2004	31,205	(1248)	-	-	-
2004/2005	20,996	(840)	-	-	-
2005/2006	14,183	(567)	-	-	-
2006/2007	15,917	(637)	-	201	41
2007/2008	12,022	(481)	0.68	1149	81
2008/2009	11,976	(479)	0.42	519	175
2009/2010	19,607	(784)	0.46	2053	25
2010/2011	27,096	(1084)	0.43	489	44
2011/2012	21,715	(869)	0.36	342	5
2012/2013	18,587	(743)	0.61	915	121
2013/2014	15,679	(627)	0.46	1477	27

APPENDIX B: RECREATIONAL CPUE

This appendix describes the steps and rationale used to develop a relative abundance index based on recreational catch-per-unit-effort (CPUE). A description of the data set used for these analyses is provided in Section 2.2.2 of the main assessment document. The final recreational CPUE index used for input into the stock assessment model is based on the Interview-based average method (Method 2) described in this appendix.

In previous Lingcod assessments (Logan et al. 2005, King et al. 2003), an annual CPUE index was calculated as the average CPUE over all Statistical Areas as follows:

METHOD 1: AREA-BASED AVERAGE CPUE

1) Sum catches and effort from individual interviews, *i*, for each Statistical Area, *a*:

$$Catch_a = \sum_{i}^{n_i} Catch_i$$

$$Effort_a = \sum_{i}^{n_i} Effort_i$$

where n_i represents the total number of interviews conducted in Statistical Area *a* between May and September in a given year.

2) Calculate CPUE for each Statistical Area, *a*:

$$CPUE_a = \frac{Catch_a}{Effort_a}$$

3) Calculate CPUE for entire Strait of Georgia as the average CPUE over all areas:

$$CPUE_{SoG} = \frac{\sum_a^{n_a} CPUE_a}{n_a}$$

where n_a represents the number of Areas within the Strait of Georgia.

This method assigns an equal weight to CPUE from each Statistical Area. For combinations of Statistical Area and year in which a CPUE value was not available, the average CPUE from the previous three years in that Area were used (excluding values that had already been infilled). The Average CPUE index in each Area up to 2010 is shown in Table B.1.

The “Area-based average” method of CPUE calculation was deemed unsuitable for continued application past 2010 for two reasons. First, reductions in sampling effort in recent years have led to some apparent outliers in area-specific CPUE values in recent years. For example, an examination of area-specific CPUE values showed that the large annual increases in CPUE in some years were due to unusually large CPUE values in one area that coincided with reduced sampling effort (e.g., see Area 14 in 2004, Area 29 in 2008, and Area 16 in 2010 in Table B.1). In 2004, only 256 hours of fishing were sampled in Area 14, which was a substantial drop compared to previous years which sampled 1,456 – 16,095 hours. In 2008, only 5.5 hours of fishing were sampled in Area 29. These outliers highlight the limitations of using the Average-based method that assumes representative sampling at the Area-scale in each year.

The second reason for discontinuing the Area-based average method is a recent change in the boundaries used to define Statistical Areas in the creel interview data set. Starting in January

2011, the Strait of Georgia Creel Survey Program changed the boundaries used to define Statistical Areas to better align with Pacific Fishery Management Areas (Dave O'Brien, Fisheries and Oceans Canada, South Coast Region, Salmon Stock Assessment, pers. comm.; Figure B.1). In some cases, these changes resulted in fishing locations being re-assigned to entirely different Statistical Areas (Figure B.1). For example, the southeast portion of Area 17 was re-assigned to Area 29, while the northwest portion of Area 16 was divided between Areas 14 and 15. As a result, the equal weights assigned to each Area up to 2010 cannot be consistently applied after 2010 because boundary definitions have changed.

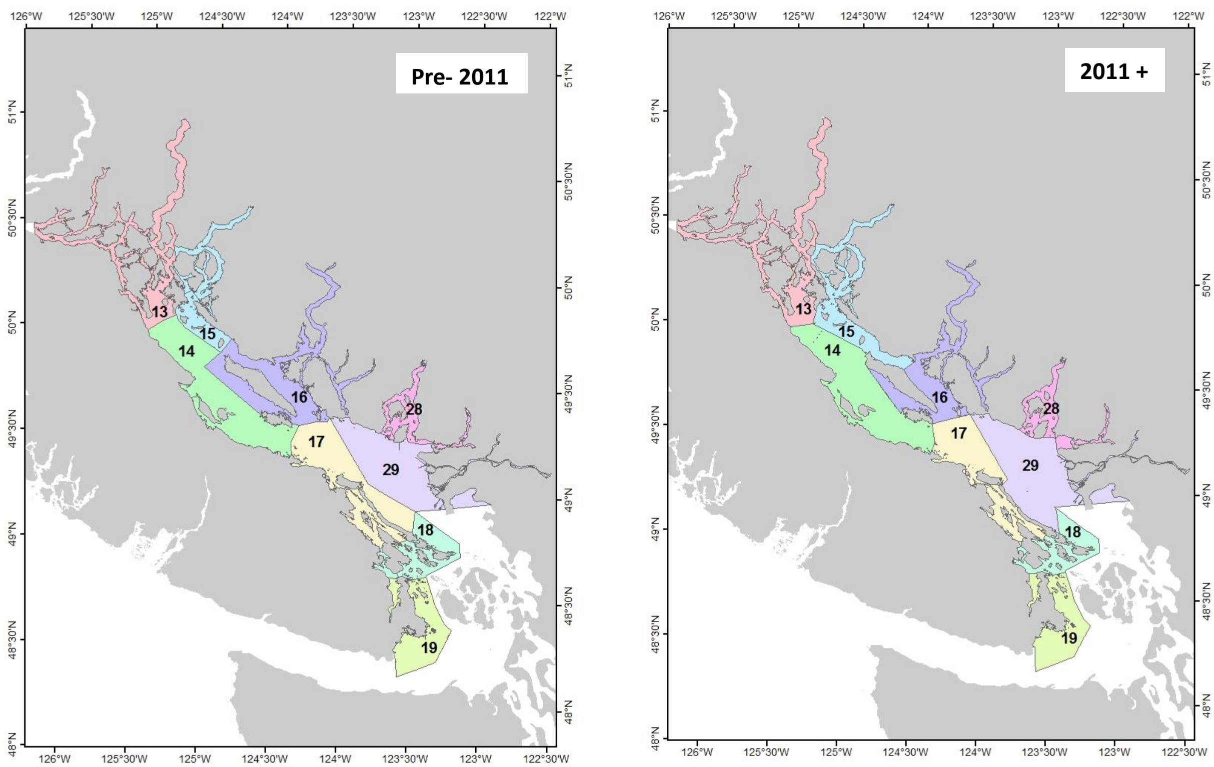


Figure B.1. Creel survey boundaries used to define Statistical Areas 13-19, 28, and 29 prior to 2011 (left) and from 2011 onwards (right).

Table B.1. Area-specific CPUE estimates calculated as Step 2 in Method 1, as well as the final Area-based Average CPUE index for the entire Strait of Georgia (SoG; Areas 13-19, 28, 29) and the Strait of Georgia with the southeast quadrant excluded (noSE; Areas 13-19). Infilled values are indicated with grey highlighting.

	Statistical Area										
Year	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**28**	**29**	**SoG Average**	**noSE Average**
1982	5.96	2.27	4.56	10.60	7.86	4.95	4.22	4.64	3.14	5.36	5.77
1983	7.49	1.69	5.01	6.32	3.81	7.60	7.51	4.76	6.10	5.59	5.63
1984	12.07	4.89	4.47	9.36	7.45	7.13	10.89	10.21	3.28	7.75	8.04
1985	6.25	2.05	2.96	6.16	4.24	7.08	6.52	3.93	1.83	4.56	5.04
1986	7.25	4.13	3.47	5.34	4.11	8.38	5.63	2.5	1.18	4.67	5.47
1987	6.82	2.87	3.82	6.44	2.87	3.36	5.73	1.97	0.97	3.87	4.56
1988	7.15	2.15	3.95	5.47	2.79	4.02	4.15	1.30	1.50	3.61	4.24
1989	7.03	2.37	2.95	5.85	2.66	2.63	3.11	1.61	1.46	3.30	3.80
1990	8.34	2.50	2.99	5.23	2.66	4.05	5.54	1.17	0.37	3.65	4.47
1991	13.46	3.58	4.11	5.83	4.01	4.05	4.00	1.71	0.93	4.63	5.58
1992	9.17	2.45	3.57	4.62	4.49	5.60	12.06	1.99	1.47	5.05	5.99
1993	6.77	1.96	1.64	5.76	3.05	3.31	6.65	1.82	2.07	3.67	4.16
1994	6.67	3.94	1.82	7.36	3.71	10.97	6.89	1.20	4.54	5.23	5.91
1995	6.87	5.09	2.36	2.59	3.39	4.26	3.17	0.81	3.39	3.55	3.96
1996	10.74	3.03	4.56	3.54	4.55	6.30	24.45	2.19	5.19	7.17	8.17
1997	9.32	5.00	6.83	15.61	6.14	7.52	10.35	2.97	13.59	8.59	8.68
1998	10.66	5.48	12.90	13.00	8.47	5.47	13.73	1.37	1.79	8.10	9.96
1999	9.00	1.53	5.78	5.58	3.89	4.52	13.01	3.55	4.28	5.68	6.19
2000	7.10	4.17	7.93	17.75	11.16	6.03	17.42	4.13	26.36	11.34	10.22
2001	8.23	6.21	7.51	17.97	14.62	8.19	32.39	4.75	2.28	11.35	13.59
2002	8.40	4.46	15.24	20.22	15.87	7.86	22.47	5.65	5.04	11.69	13.50
2003	4.41	6.73	16.32	13	16.6	3.61	12.39	4.65	11.23	9.88	10.44
2004	3.63	26.33	16.37	11.27	8.57	15.92	13.06	2.43	9.52	11.90	13.59
2005	3.62	5.51	8.56	16.49	11.57	12.35	14.93	3.66	2.92	8.85	10.43
2006	4.54	8.67	17.74	18.72	23.31	21.69	12.55	3.58	6.22	13.00	15.32
2007	3.63	6.47	4.73	25.39	16.31	35.90	13.42	0.65	6.22	12.52	15.12
2008	4.12	15.91	18.21	32.89	20.8	18.74	11.45	4.84	54.55	20.17	17.45
2009	5.35	7.66	24.85	37.91	16.71	20.83	8.29	1.57	1.62	13.87	17.37
2010	3.7	14.69	7.5	95.49	29.72	17.41	18.01	0.66	1.47	20.96	26.65

An alternative method of calculating a Strait of Georgia CPUE index that can be applied consistently before and after 2011 is an Interview-based average CPUE. This approach uses the mean CPUE over all interviews conducted each year within the Strait of Georgia, thereby applying an equal weight to each interview conducted in a given year.

METHOD 2: INTERVIEW-BASED AVERAGE CPUE

1) For each interview, *i*, conducted in the Strait of Georgia in a given year, calculate an interview-specific CPUE value:

$$CPUE_i = \frac{Catch_i}{Effort_i}$$

2) Calculate a CPUE index for that year as the average of all interview-specific CPUE values:

$$CPUE_{SoG} = \frac{\sum_i^{n_i} CPUE_i}{n_i}$$

where n_i represents the total number of interviews conducted in the Strait of Georgia that year.

The Interview-based CPUE index between 1982 and 2013 is shown in Table 9 of the main assessment document. For scenarios in which Statistical Areas 28 and 29 were excluded from the entire Strait of Georgia, sub-Areas 29-F and 29-G from the post-2010 boundaries were included in Area 17 when calculating CPUE. This adjustment was necessary to deal with the re-assignment of portions that were formally part of Area 17 to Area 29 under the new boundaries (Figure B.1).

OTHER METHODS: GENERALIZED LINEAR MODELLING

The number of creel survey interviews conducted annually has declined between 1982 and 2013 (Table B.2). As a result, not all Areas have been sampled in all months in recent years (K. Hein, DFO Strait of Georgia Creel Survey Program, pers. comm.). This reduction in sampling effort could bias average CPUE trends if effort reductions were disproportionately focused on low CPUE months or locations. To investigate whether changes over time in interview site, month, and other extraneous variables had an effect on catch rates, we considered several different generalized linear models (GLM). In each case, a stepwise GLM procedure was used to estimate a time series of relative annual changes in catch-per-unit-effort (CPUE) based on the relationship between CPUE and available predictive variables (factors).

Table B.2. Number of creel survey interviews conducted in the Strait of Georgia (Statistical Areas 13-19, 28, and 29) between 1982 and 2013, as well as the number of hours of fishing that were sampled by the creel program. Interviews and sampling effort directed at only shellfish are excluded.

Year	Number of Interviews	Number of Hours Sampled
1982	13,621	52,519
1983	12,582	46,626
1984	24,273	93,767
1985	29,444	113,471
1986	21,150	81,376
1987	17,605	67,582
1988	20,980	75,995
1989	16,551	61,059
1990	17,290	62,212
1991	13,339	48,405
1992	19,992	71,912
1993	16,910	58,410
1994	13,486	49,243
1995	10,094	35,932
1996	11,134	38,774
1997	8,513	30,317
1998	5,888	20,591
1999	7,648	27,622
2000	9,002	32,583
2001	7,650	27,814
2002	4,625	16,795
2003	4,597	17,587
2004	3,204	12,415
2005	2,717	10,559
2006	2,737	10,826
2007	3,124	12,195
2008	3,057	12,036
2009	3,504	14,267
2010	2,923	11,719
2011	2,676	10,942
2012	2,962	11,403
2013	3,601	14,281

Three different types of distributions were considered for GLM modelling: Lognormal, Binomial, and Compound Poisson-gamma. Six predictor variables were used to define the maximum model: Year, Month, Landing Site (a unique code for each site within the Strait of Georgia), Day Type (weekday or weekend), Time of Day (Morning, Evening, or Weekend), and whether the fishing trip was guided (Guided = Yes or No). The stepwise procedure used to fit the lognormal and binomial models has been previously described when calculating commercial CPUE indices for other British Columbia groundfish stocks (e.g., King et al. 2012, Holt et al. 2016); while the Compound Poisson-gamma model has been described in Lecomte et al. (2013). We do not describe the method further in this appendix as none of the GLM models were used for stock assessment modelling.

A lognormal GLM model was determined unsuitable for the Lingcod creel dataset. Lognormal GLMs are confined to positive catch observations because the logarithm of zero is undefined. Therefore, only interviews with non-zero Lingcod catch could be included. This approach would have resulted in 91% of the interview data being excluded from the model.

A GLM with a binomial distribution was considered because it allows zero catch events to be included. In this case, the response variable was the presence or absence of a Lingcod in the catch, which means that the probability of encountering a Lingcod was used to represent abundance trends. A stepwise model selection procedure was used to find the most parsimonious combination of factors using Akaike's Information Criterion (AIC). Year was forced as the first variable within the stepwise procedure. The final binomial GLM model fit from the stepwise procedure included Year and Landing Site as predictor variables. The R^2 value of the final model fit was small (0.06), indicating that the explanatory variables considered, including year, had little effect on the predicted index. Explanatory variables only explained 6% of the variance in the presence/absence data.

Finally, a zero-inflated GLM was considered. Data with high proportions of zeros can be handled with zero-inflated models, such as the Compound Poisson-gamma GLM model proposed in Lecomte et al. (2013). An attempt to fit this model to the Lingcod creel dataset showed that the explanatory variables considered had little effect on model results (Pers. comm. Jean-Baptiste Lecomte). As with the binomial model, the variance explained by the model was small (R^2=0.03).

The small R^2 values for both the binomial and compound Poisson-gamma models led us to conclude that these models should not be used to explain or predict recreational fishing CPUE for Strait of Georgia Lingcod. We do not present any further results for these methods.

CPUE METHOD FOR 2014

We selected the Interview-based average approach to develop a CPUE index for the current 2014 assessment (Table 9 of main assessment document). Comparisons of the Area-based average CPUE method used for previous assessments and Interview-based CPUE are shown for the entire Strait of Georgia (Figure B.2) and the Strait of Georgia with the southeast quadrant excluded (Figure B.3). Calculation of the Area-based CPUE after 2010 is not possible due to concerns about outliers due to reduced sample sizes in recent years and a change in the Area boundaries in 2011.

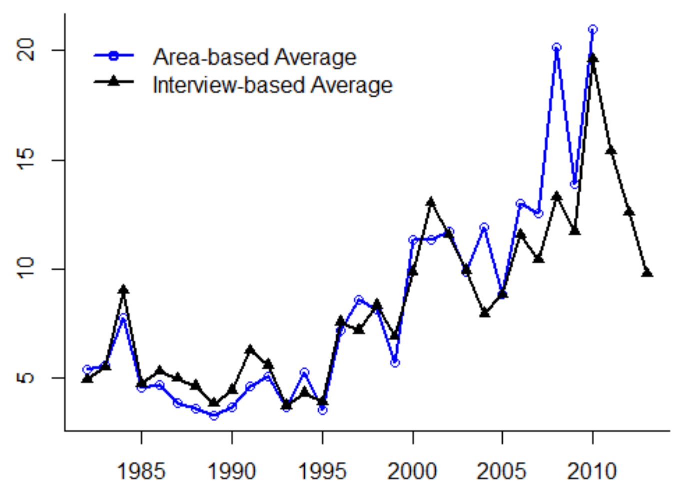


Figure B.2. Comparison of recreational CPUE indices for the erntire Strait of Georgia (SoG; Areas 13-19, 28, 29) calculated using the Area-based method and the Interview-based method.

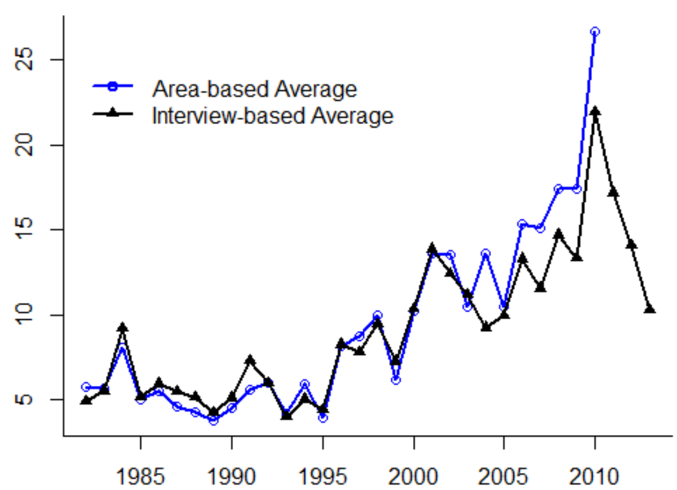


Figure B.3. Comparison of recreational CPUE indices for the Strait of Georgia with the southeast quadrant excluded (noSE; Areas 13-19) calculated using the Area-based method and the Interview-based method.

APPENDIX C. MODEL EQUATIONS

INTRODUCTION

Stock Assessment modelling was conducted using the Integrated Statistical Catch Age Model (iSCAM), developed by Steven J.D. Martell (Martell et al. 2011). iSCAM is written in AD Model Builder and the source code and documentation for the original iSCAM are available online. iSCAM uses a statistical catch-at-age model implemented in a Bayesian estimation framework.

The version of iSCAM used for this assessment is based on a more recent IPHC-developers version, also developed by S. Martell, that models males and females separately and includes a length-based option for modelling selectivity. Further modifications to the IPHC-developers version have been made by the first author of this assessment (K.R. Holt) to allow density-dependent natural mortality and density-dependent catchability options for Strait of Georgia Lingcod.

Running of iSCAM and compilation of results figures was streamlined using the iscam-gui software package developed by Chris Grandin (pers. comm., Pacific Biological Station, Fisheries and Oceans Canada). iscam-gui is written in R (R Development Core Team, 2012), and provides an R gui interface that allows users to run and show output of multiple iSCAM model runs next to each other.

This appendix contains the documentation in mathematical form of the underlying iSCAM age-structured model, its steady-state version that is used to calculate reference points, the observation models used in predicting observations, and the components that formulate the objective function that is used to estimate model parameters. All of the model equations are laid out in tables and are intended to represent the order of operations, or pseudocode, in which to implement the model. A documented list of symbols used in model equations is given in Table C.1. The documentation presented here is a revised version of the iSCAM user-guide written by S. Martell. Much of the text and equations have been taken directly from the original user guide, with modifications by K.R. Holt to describe the expansion to a two-sex model and the additional Lingcod options.

ANALYTIC METHODS: EQUILIBRIUM CONSIDERATIONS

A Steady-State Age-Structured Model

For the steady-state conditions represented in Table C.2, we assume the parameter vector Θ in (C.1) is unknown and would eventually be estimated by fitting iSCAM to data. For a given set of sex-specific growth parameters and maturity-at-age parameters defined by (C.2), growth is assumed to follow the von Bertalanffy relationship (C.3), mean weight-at-age is given by the allometric relationship in (C.4), and the age- and sex-specific vulnerability is given by a length-based logistic function (C.5). Note, there are alternative selectivity functions implemented in iSCAM; the length-based logistic function is shown here because it is used to model selectivity to the only current lingcod fishery in the Strait of Georgia (the recreational fishery with a 65cm minimum size limit). Mean fecundity-at-age by sex (C.6) is assumed to be proportional to the mean weight-at-age of mature fish, where maturity at age is specified by the sex-specific parameters $\dot{a}_s$ and $\dot{\gamma}_s$ for the logistic function.

Table C 1. A list of symbols, constants and variable descriptions for variables used in iSCAM.

Symbol	Value	Description
Indexes		
s		Index for sex
a		Index for age
t		Index for year
k		Index for gear
Model dimensions		
S	2	Number of sexes
$\acute{a}, A$	1, 20	Youngest and oldest age class (A is a plus group)
$\acute{t}, T$	1927, 2013	First and last year of catch data
K	3	Number of gears including survey gears
Observations (data)		
$C_{k,t}$		catch in weight by gear k in year t
$I_{k,t}$		relative abundance index for gear k in year t
Fixed parameters		
M	0.20	Instantaneous natural mortality rate
ρ	0.70	Fraction of the total variance associated with observation error
$\hat{a}_k, \hat{\gamma}_k$	See Table C.4	Selectivity parameters for gear k
Estimated parameters		
R_o		Age-$\acute{a}$ recruits in unfished conditions
κ		Recruitment compensation
$\bar{R}$		Average age-$\acute{a}$ recruitment from year $\acute{t}$ to T
ϑ		Total precision (inverse of variance) of the total error
$\Gamma_{k,t}$		Logarithm of the instantaneous fishing mortality for gear k in year t
ω_t		Age-$\acute{a}$ deviates from R for years $\acute{t}$ to T
Standard deviations		
σ		Standard deviation for observation errors in survey index
τ		Standard deviation in process errors (recruitment deviations)
σ_C	0.25	Standard deviation in observed catch by gear
Residuals		
δ_t		Annual recruitment residual
η_t		Residual error in predicted catch
Growth & maturity parameters		
$l_{\infty s}$	900 / 1040	Asymptotic length in mm for males / females
$\dot{k}_s$	0.20 / 0.20	Brody growth coefficient for males / females
t_{os}	-0.001 / -0.001	Theoretical age at zero length for males / females
$\acute{a}_s$	1.13e-11 / 1.13e-11	Scaler in length-weight allometry (mm to 100's of kg)
$\acute{b}_s$	3.329 / 3.329	Power parameter in length-weight allometry for males / females
$\dot{a}_s$	2.0 / 5.0	Age at 50% maturity for males / females
$\acute{\gamma}_s$	0.001 / 0.35	Standard deviation at 50% maturity for males / females

Table C 2. Steady-state age-structured model assuming unequal vulnerability-at-age, age-specific fecundity and Ricker type recruitment.

Parameters

$$\Theta = (B_o, \kappa); \quad B_o > 0; \kappa > 1 \tag{C.1}$$

$$\Phi = (l_{\infty s}, \acute{k}_s, t_{os}, \acute{a}_s, \acute{b}_s, \dot{a}_s, \dot{\gamma}_s, \hat{a}, \hat{\gamma}, M) \tag{C.2}$$

Age-scheduled information

$$l_{a,s} = l(1 - \exp(-k_s(a - t_{os}))) \tag{C.3}$$

$$w_{a,s} = \acute{a}_s(l_{a,s})^{\acute{b}_s} \tag{C.4}$$

$$v_{a,s} = (1 + \exp(-(\hat{a} - l_{a,s})/\hat{\gamma}))^{-1} \tag{C.5}$$

$$f_{a,s} = w_{a,s}(1 + \exp(-(\dot{a}_s - a)/\dot{\gamma}_s))^{-1} \tag{C.6}$$

Survivorship

$$\iota_a = \begin{cases} 1/S, & a = 1 \\ \iota_{a-1}e^{-M}, & a > 1 \\ \iota_{a-1}/(1 - e^{-M}), & a = A \end{cases} \tag{C.7}$$

$$\hat{\iota}_{a,s} = \begin{cases} 1/S, & a = 1 \\ \hat{\iota}_{a-1,s}e^{-M-F_e v_{a-1,s}}, & a > 1 \\ \hat{\iota}_{a-1,s}e^{-M-F_e v_{a-1,s}}/(1 - e^{-M-F_e v_{a,s}}), & a = A \end{cases} \tag{C.8}$$

Incidence functions

$$\phi_E = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \iota_a f_{a,s}, \quad \phi_e = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \hat{\iota}_{a,s} f_{a,s} \tag{C.9}$$

$$\phi_B = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \iota_a w_{a,s} v_{a,s}, \quad \phi_b = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \hat{\iota}_{as} w_{a,s} v_{a,s} \tag{C.10}$$

$$\phi_q = \sum_{s=1}^{S}\sum_{a=1}^{\infty} \frac{\hat{\iota}_{a,s} w_{a,s} v_{a,s}}{M + F_e v_{a,s}} \left(1 - e^{(-M-F_e v_{a,s})}\right) \tag{C.11}$$

Steady-state conditions

$$R_o = B_o/\phi_B \tag{C.12}$$

$$R_e = R_o \frac{\ln(\kappa) - \ln(\phi_E/\phi_e)}{\ln(\kappa)} \tag{C.13}$$

$$C_e = F_e R_e \phi_q \tag{C.14}$$

Survivorship for unfished and fished populations is defined by (C.7) and (C.8), respectively. Note that fished survivorship is sex-specific to allow for sex-specific $v_{a,s}$ when the length-based logistic function is used to model vulnerability. It is assumed that all individuals ages A and older (i.e., the plus group) have the same total mortality rate. The incidence functions refer to the life-time or per-recruit quantities such as spawning biomass per recruit (ϕ_E) or vulnerable biomass per recruit (ϕ_B). Upper and lower case subscripts on incidence functions denote unfished and fished conditions, respectively. Spawning biomass per recruit is given by (C.9), the vulnerable biomass per recruit is given by (C.10), and the per-recruit yield to the fishery is given by (C.11). Unfished recruitment is given by (C.12) and the steady-state equilibrium recruitment for a given fishing mortality rate F_e is given by (C.13). Note that in (C.13) we assume that recruitment follows a Ricker stock recruitment model of the form:

$$R_e = s_o R_e \phi_e \exp(-\beta R_e \phi_e)$$

where the maximum juvenile survival rate is given by:

$$s_o = \kappa/\phi_E,$$

and the density-dependent term is given by:

$$\beta = \frac{\ln(\kappa)}{R_0 \phi E}$$

which simplifies to (C.13).

The equilibrium yield for a given fishing mortality rate is (C.14). These steady-state conditions are critical for determining various reference points such as F_{MSY} and B_{MSY}.

MSY-based Reference Points

When defining reference points for this assessment, only the current recreational fishery (with a 65-cm size limit) was used to calculate MSY quantities.

A special class library has been added to iSCAM to calculate MSY-based reference points. For single gear fisheries, F_{MSY} is determined by finding the equilibrium value of F, F_e, that results in the zero derivative of (C.14) using a Newton-Raphson method. Given an estimate of F_{MSY}, other reference points such as MSY are calculated using the equations in Table C 2. This procedure has not yet been implemented for the Ricker stock recruitment relationship however, so was not readily available for this assessment. Instead, a grid-search over a range of F_e values (0.001 to 0.40 in increments of 0.001) was used, and F_{MSY} was identified as the value of F_e producing the highest long-term equilibrium catch using (C.14).

ANALYTIC METHODS: STATE DYNAMICS

The estimated parameter vector in iSCAM is defined in (C.15) of Table C 3. The unknown parameters R_0 and κ, as well as the fixed parameter M, are the leading population parameters that define the overall population scale. The total variance ϑ^2 is estimated, while the proportion of the total variance that is associated with observation errors ρ is assumed fixed. The total variance is partitioned into observation errors (σ^2) and process errors (τ^2) using (C.16).

The unobserved state variables (C.17) include the numbers-at-age in year t of sex s ($N_{t,a,s}$), the spawning stock biomass in year t of sex s ($B_{t,s}$), and the total age- and sex-specific total mortality rate ($Z_{t,a,s}$).

Table C 3.Statistical catch-age model using the Baranov catch.

Estimated parameters

$$\Theta = (R_0, \kappa, \bar{R}, \vartheta^2, \Gamma_{k,t}, \{\omega_t\}_{t=1-A}^{t=T}) \quad \text{(C.15)}$$

$$\sigma^2 = \rho/\vartheta^2, \quad \tau^2 = (1-\rho)/\vartheta^2 \quad \text{(C.16)}$$

Unobserved states

$$N_{t,a}, \ B_{t,s}, \ Z_{t,a} \quad \text{(C.17)}$$

Initial states

$$N_{t,a,s} = \frac{1}{S}\bar{R}e^{\omega_{t-a}} \exp(-M)^{(a-1)}; \quad t=1; 2 \le a \le A \quad \text{(C.18)}$$

$$N_{t,a,s} = \frac{1}{S}\bar{R}e^{\omega_t}; \quad 1 \le t \le T; a = 1 \quad \text{(C.19)}$$

$$v_{k,a,s} = \frac{1}{1 + exp(-(l_{a,s} - \hat{a}_k)/\hat{\gamma}_k)} \quad \text{(C.20)}$$

$$F_{k,t} = \exp(\Gamma_{k,t}) \quad \text{(C.21)}$$

State dynamics (t > 1)

$$B_{t,s} = \sum_a N_{t,a,s} f_{a,s} \quad \text{(C.22)}$$

$$Z_{t,a,s} = M + \sum_k F_{k,t} v_{k,t,a,s} \quad \text{(C.23)}$$

$$\hat{C}_{k,t} = \sum_s \sum_a \frac{N_{t,a,s} w_{a,s} F_{k,t} v_{k,t,a,s} \left(1 - e^{-Z_{t,a,s}}\right)^{\eta_t}}{Z_{t,a,s}} \quad \text{(C.24)}$$

$$N_{t,a,s} = \begin{cases} N_{t-1,a-1,s} \exp(-Z_{t-1,a-1,s}) & a > 1 \\ N_{t-1,a,s} \exp(-Z_{t-1,a,s}) & a = A \end{cases} \quad \text{(C.25)}$$

Recruitment model

$$R_t = s_o B_{t-k} e^{-\beta B_{t-k} + \delta_t - 0.5\tau^2} \quad \text{(C.26)}$$

Table C 4. Definition of datasets denoted by gear index k in Tables C.1 - C.3. Note that the recreational fishery was modelled using two different gear types to account for the introduction of a 65cm minimum size limit in 1991. The recreational CPUE index was modelled using gear 2 because the catch component included both retained and discarded catch, which means that the introduction of a 65-cm size limit would not be expected to affect selectivity.

k	Dataset	Years with Catch Data	Years with CPUE Index	Selectivity Type	Selectivity Parameters($\hat{a}, \hat{\gamma}$)
1	Commercial fishery	1927-1989	1962-1989	Age-based	(4.45, 0.2)
2	Rec. fishery; limit ≤ 580mm	1962-1990	1982-2013	Age-based	(2.00, 0.2)
3	Rec. fishery; limit = 650mm	1991-2013	-	Length-based	(650, 15)

The initial numbers-at-age in the first year (C.18) and the annual recruits (C.19) are treated as estimated parameters and used to initialize the numbers-at-age array. Recruitment at age-1 is assumed to be 50% males and 50% females. When a length-based selectivity function is used (i.e. for the Strait of Georgia Lingcod Recreational Fishery with a 65-cm size limit; Table C.4), age- and sex-specific selectivity for gear type k is a function of the selectivity parameters (a_k and γ_k, which represent length at 50% selectivity and the associated standard deviation, respectively) and the sex-specific length-at-age a, $l_{a,s}$, as shown in (C.20). For the two Strait of Georgia Lingcod fisheries modelled using age-based logistic selectivity (Table C 4), the $l_{a,s}$ variable in equation (C.20) is replaced with age a, and the selectivity parameters(a_k and γ_k) would be based on mean age of selectivity and the associated standard deviation. In this latter case, vulnerability at age for these gears would be the same for males and females. The annual fishing mortality for each gear k in year t is the exponent of the estimated vector $\Gamma_{k,t}$ (C.21). The vector of log fishing mortality rate parameters $\Gamma_{k,t}$ is a bounded vector with a minimum value of -30 and an upper bound of 3.0. In arithmetic space this corresponds to a minimum value of 9.36e^{-14} and a maximum value of 20.01 for annual fishing mortality rates. In years where there are 0 reported catches for a given fleet, no corresponding fishing mortality rate parameter is estimated and the implicit assumption is there was no fishery in that year.

State variables in each year are updated using equations C.22–C.25, where the spawning biomass is the product of the numbers-at-age and the mature biomass-at-age (C.22). The total mortality rate is given by (C.23), and the total catch (in weight) for each gear is given by (C.24), assuming that both natural and fishing mortality occur simultaneously throughout the year. In cases in which catch data is available in numbered instead of weight (as specified by the user), the w_{as} term is omitted from (C.24). Lingcod catch was not differentiated by sex, so both sexes were combined to calculate a total catch in (C.24). The sex-specific numbers-at-age are propagated over time using (C.25), where members of the plus group (age A) are all assumed to have the same total mortality rate.

Recruitment to age k is assumed to follow a Ricker model for Strait of Georgia Lingcod (C.26) where the maximum juvenile survival rate (s_o) is defined by $s_o = \kappa/\phi_E$. For the Ricker model, β is derived by solving (C.26) for β conditional on estimates of κ and R_o:

$$\beta = \frac{\ln(\kappa)}{R_0 \phi E}$$

Option for Density-Dependent Natural Mortality

The option to specify density-dependent mortality was added to the version of iSCAM used for this assessment to allow replication of the 2005 assessment. Density-dependent mortality was implemented in the same way as the 2005 assessment (Logan et al. 2005):

$$M_t = M_0 + (M_1 - M_0)\left(1 - \frac{B_t}{B_0}\right)$$

where, B_t is total biomass (males and females combined) in year t, M_t is the natural mortality at stock biomass B_t, M_0 is natural mortality at unfished biomass (i.e., carrying capacity), and M_1 is natural mortality at negligible stock size. Both M_0 and M_1 were fixed at the same parameter values assumed by Logan et al. (2005). M_0 was set at 0.2 and M_1 was set at 0.18.

In the case of density-dependent mortality, an additional step was required when calculating reference points to determine the rate of natural mortality at equilibrium, M_e, conditional on each F_e value used in the grid search. Based on the above density-dependent equation:

$$M_e = M_0 + (M_1 - M_0)\left(1 - \frac{B_e}{B_0}\right)$$

where B_e is total biomass at equilibrium. Note that there is a circular relationship between M_e and B_e because calculation of M_e requires a value for B_e and vice versa. To deal with this circularity, it was necessary to use a numerical algorithm that iteratively found the level of depletion at equilibrium (i.e., B_e / B_0) conditional on F_e before solving M_e. Once M_e conditional on F_e was determined, other equilibrium quantities were determined as described in the reference point section of this appendix by replacing M with M_e in Table C 2.

RESIDUALS, LIKELIHOODS, AND OBJECTIVE FUNCTION VALUE COMPONENTS

There are three major components to the overall objective function that are minimized while iSCAM is performing maximum likelihood estimation. These components consist of the likelihood of the data, prior distributions, and penalty functions that are invoked to regularize the solution during intermediate phases of the non-linear parameter estimation. This section discusses each of these in turn, starting first with the residuals between observed and predicted states followed by the negative loglikelihood that is minimized.

Catch Data

It is assumed that the measurement errors in the catch observations are log-normally distributed, and the residuals given by:

$$\eta_{k,t} = \ln(C_{k,t} + o) - \ln(\hat{C}_{k,t} + o), \tag{C.27}$$

where o is a small constant (1.e-10) to ensure the residual is defined in the case of a zero catch observation. The residuals are assumed to be normally distributed with a user-specified standard deviation σ_C. At present, it is assumed within iSCAM that observed catches for each gear k have the same standard deviation. The negative loglikelihood (ignoring the scaling constant) for the catch data is given by:

$$\ell_C = \sum_k \left[T_k \ln(\sigma_C) + \frac{\sum_t (\eta_{k,t})^2}{2\sigma_C^2}\right], \tag{C.28}$$

where T_k is the total number of catch observations for gear type k.

Commercial fishery catch data for Area 4B Lingcod are available in biomass units (tonnes), while catch from recreational fisheries are reported as numbers (pieces). iSCAM allows users to specify catch units as biomass or numbers; however, to accommodate the constraint that catches from all gears have the same standard deviation, we re-scaled recreational catch to 10's of pieces so that it would be on the same scale as catch in tonnes from the commercial fishery.

This re-scaling required us to specify the parameters for the allometric weight-length relationship in (C.4) in units of mm to 100's of kg.

Relative Abundance Data

In the absence of density-dependent catchability, the relative abundance data are assumed to be proportional to the biomass that is vulnerable to the sampling gear:

$$V_{k,t} = \sum_s \sum_a N_{t,a,s} e^{-\lambda_{k,t} Z_{t,a,s}} v_{k,a,s} w_{a,s}, \tag{C.29}$$

where $v_{k,a,s}$ is the sex- and age-specific selectivity of gear k, and $w_{a,s}$ is the mean-weight-at-age for sex s. A user-specified fraction of the total mortality $\lambda_{k,t}$ adjusts the numbers-at-age to correct for survey timing. We set $\lambda_{k,t}$ to 0.5 for all index observations in the commercial and recreational CPUE indices since fishery catch and the collection of CPUE data are the same process, and natural mortality occurs throughout the fishing season.

The residuals between the observed and predicted relative abundance index is given by:

$$\epsilon_{k,t} = \ln(I_{k,t}) - \ln(q_k) + \ln(V_{k,t}), \tag{C.30}$$

where $I_{k,t}$ is the observed relative abundance index, q_k is the catchability coefficient for index k, and $V_{k,t}$ is the predicted vulnerable biomass at the time of sampling. The catchability coefficient q_k is evaluated at its conditional maximum likelihood estimate:

$$q_k = \frac{1}{N_k} \sum_{t \epsilon I_{k,t}} \ln(I_{k,t}) - \ln(V_{k,t})$$

where N_k is the number of relative abundance observations for index k (see Walters and Ludwig 1994 for more information). The negative loglikelihood for relative abundance data is given by:

$$\ell_I = \sum_k \sum_{t \in I_{k,t}} \ln(\sigma_{k,t}) + \frac{\epsilon_{k,t}^2}{2\sigma_{k,t}^2} \tag{C.31}$$

where,

$$\sigma_{\kappa,t} = \frac{\rho\varphi^2}{\bar{\omega}_{k\,t}},$$

where $\rho\varphi^2$ is the proportion of the total error that is associated with observation errors, and $\omega_{k,t}$ is a user specified relative weight for observation t from gear k. The $\bar{\omega}_{k,t}$ terms allow each observation to be weighted relative to the total error $\rho\varphi^2$; for example, to omit a particular observation, set $\bar{\omega}_{k,t} = 0$, or to give 2 times the weight, then set $\bar{\omega}_{k,t} = 2.0$. For the current assessment, we assumed all observations have the same variance by setting $\bar{\omega}_{k,t} = 1$.

Table C 5. Fixed values used for exponent determining degree of linearity between vulnerable biomass and commercial CPUE (cCPUE) or recreational CPUE (rCPUE) series (ψ_k in (C.32)) when density-dependent catchability is selected. Values are given for four different scenarios about the treatment of historical catch values from District 1 (i.e., the southeast quadrant).

Scenario	ψ_{cCPUE}	ψ_{rCPUE}
SoG	0.878	1.759
noSE	0.646	0.611
onlySEpre1947	0.878	1.759
noSEpre1947	0.878	1.759

Option for Density-dependent Catchability

The option to model relative abundance indices as a power function of vulnerable biomass was added to the version of iSCAM used for this assessment to allow replication of the approach taken in the last Strait of Georgia Lingcod assessment (Logan et al. 2005). This approach was taken in 2005 because the qualified commercial CPUE index used as an abundance index was not expected to be linearly related to abundance. In this case, (C.29) is replaced by:

$$V_{k,t} = (\sum_{s}\sum_{a} N_{t,a,s}e^{-\lambda_{k,t}Z_{t,a,s}}v_{k,a,s}w_{a,s})^{\psi_k} \tag{C.32}$$

where ψ_k is an exponent determining the degree of linearity between the CPUE series from gear k and the vulnerable biomass available to gear k in year t, $V_{k,t}$. When ψ_k is less than 1, a given change in CPUE implies a greater relative change in exploitable abundance (hyperstability); when ψ_k = 1, CPUE is proportional to abundance; and when ψ_k is greater than 1, a given change in CPUE implies a lesser relative chance in abundance (hyperdepletion). The ψ_k parameters for each gear k used to develop a CPUE index (k = 1 or 2) were estimated by Logan et al. (2005); however, we did not attempt to estimate these in our analyses due to time constraints. Instead, ψ_k was fixed at the values estimated by Logan et al. (2005) in scenarios that used density-dependent catchability (Table C 5).

Stock-Recruitment

Annual recruitment and the initial age-composition are treated as latent variables in iSCAM. Residuals between estimated recruits and the deterministic stock-recruitment models are used to estimate unfished spawning stock biomass and recruitment compensation. The residuals between the estimated and predicted recruits is given by

$$\delta_t = \ln(\bar{R}e^{w_t}) - f(B_{t-y}) \tag{C.33}$$

where $f(B_{t-y})$ is given by (C.26), and y is the age at recruitment, which is set to 1 for this assessment. Note that a bias correction term for the lognormal process errors is included in (C.26).

The negative log likelihood for the recruitment deviations is given by the normal density (ignoring the scaling constant):

$$\ell_\delta = n\ln(\tau) + \frac{\sum_{t=1+k}^{T}\delta_t^2}{2\tau^2} \tag{C.34}$$

Equations (C.33) and (C.34) are key for estimating unfished spawning stock biomass and recruitment compensation via the recruitment models. The relationship between (s_o, β) and (B_o, κ) for the Ricker stock recruitment model is defined as:

$$s_o = \kappa / \phi_E \quad \text{(C.35)}$$

$$\beta = \frac{\ln(\kappa)}{B_o} \quad \text{(C.36)}$$

where s_o is the maximum juvenile survival rate, and β is the density effect on recruitment.

BAYESIAN ANALYSIS OF MODEL PARAMETERS & POLICY PARAMETERS

Bayesian estimation was done using the Markov Chain Monte Carlo (MCMC) method to approximate posterior distributions for estimated parameters. Marginal posterior distributions of each model parameter were constructed by using the metropolis algorithm built into ADMB to sample from the joint posterior distribution. This was accomplished by running iSCAM in -mcmc mode followed by the -mceval option. Prior distributions, estimation bounds, and initial values for the MCMC procedure are shown in Table C 6. Marginal posterior densities were also produced for derived quantities such as MSY-based reference points using the steady-state age structured model described in Table C 2 and the associated text above.

The number of MCMC samples used for each of the 12 Lingcod assessment scenarios is given in Appendix E. All MCMC sequences had an initial burn-in period removed from the sequence to eliminate the effects of starting values on posterior distributions. Thinning was also used to reduce autocorrelation among draws. Burn-in periods and thinning intervals for each scenario are also summarized in Appendix E.

Table C 6. Details for estimation of parameters, including prior distributions with corresponding means and standard deviations, bounds between which parameters are constrained, and initial values. Note that the uninformative prior for ϑ was Gamma(0.001, 0.001), which results in the mean and standard deviation (sd) values provided.

Parameter	Prior distribution	Mean, standard deviation	Bounds	Initial value
SoG				
R_0	Uniform	–	[0.007, 3,269,017]	22,026
h	Normal	1.2, 10	[0.2, 208]	0.70
$\bar{R}$	Uniform	–	[0.5, 3,300,000]	89,000
ϑ	Gamma	20, 10	[0.01, 100]	2
noSE				
R_0	Uniform	–	[0.007, 3,269,017]	148
h	Normal	1.2, 10	[0.2, 208]	0.70
$\bar{R}$	Uniform	–	[0.5, 3,300,000]	89,000
ϑ	Gamma	20, 10	[0.01, 100]	2
onlySEpre1947				
R_0	Uniform	–	[0.007, 3,269,017]	22,026
h	Normal	1.2, 10	[0.2, 208]	0.70
$\bar{R}$	Uniform	–	[0.5, 3,300,000]	89,000
ϑ	Gamma	20, 10	[0.01, 100]	2
noSEpre1947				
R_0	Uniform	–	[0.007, 3,269,017]	22,026
h	Normal	1.2, 10	[0.2, 208]	0.70
$\bar{R}$	Uniform	–	[0.5, 3,300,000]	89,000
ϑ	Gamma	20, 10	[0.01, 100]	2

APPENDIX D: BRIDGING ANALYSIS TO 2005 ASSESSMENT

The bridging analysis presented in this appendix examines how switching modelling platforms in 2014, changing the method of CPUE calculation, and updating data sets to 2013 have changed reconstructed biomass estimates compared to the 2005 assessment model. This bridging analysis is intended to document the transition from the 2005 assessment model endorsed by the Lingcod Management Framework Committee (Logan et al. 2005) to the model scenarios used in this assessment. The following steps iteratively describe each change, and show the impact of each change on reconstructed biomass and depletion trajectories using maximum posterior density estimates. Each step builds on the previous step, which means that the Step 2 model includes the changes made during Step 1, the Step 3 model includes the changes made during Steps 1 and 2, and so on. An overview of each step is provided in Table D.1 and incremental changes in reconstructed spawning biomass and parameters estimates from each step are shown in Figure D.1 - Figure D.2 and Table D.2, respectively.

The bridging analysis was applied to two scenarios for dealing with uncertainty in historic District 1 catches that were considered in 2005. District 1 is a catch reporting unit used by the Dominion Bureau of Statistics (DBS) prior to 1947, which coincides with Statistical Areas 28 and 29 under the Pacific Fishery Management Council (PFMC) boundaries. This area was also labelled the Southeast (SE) quadrant for the 2005 stock assessment. A description of the sources of uncertainty in District 1 catches is provided in Section 4 of the main assessment document. The two scenarios related to District 1 catches in 2005 were:

1) use all data as recorded from the Strait of Georgia (SoG), defined as Statistical Areas 13-19, 28, and 29 and
2) exclude data from the SE quadrant, and only fit the assessment model to data from Statistical Areas 13-19.

The final model selected by the Lingcod Management Framework Committee in 2005 excluded all data from the SE quadrant; however, we present the bridging analysis for both scenarios.

We do not present Markov Chain Monte Carlo (MCMC) results or model fit diagnostics for Steps 1 to 3 of the Bridging Analysis; only maximum posterior density estimates are provided in this appendix. MCMC diagnostics and model fits for Step 5a are included in Appendix F because this bridging step was used to characterize stock status in 2014.

STEP 1: APPLY ISCAM TO 2002 DATASETS

The last assessment for Strait of Georgia Lingcod was reviewed by CSAP in 2005, using data up to the end of 2002 (Logan et al. 2005). The population dynamics model used at that time was derived from a class library written in C++, called Fish++. For the 2014 assessment, the modelling platform switched to the Integrated Statistical Age-structured Model (iSCAM), which is written in AD Model Builder (Appendix C).

The first step of the bridging analysis examined how the change in assessment model affected reconstructed biomass trajectories by fitting iSCAM to the data sets used as input to the 2005 assessment model. iSCAM was configured to match the Fish++ model used in 2005 as follows:

- Density-dependent mortality was included in iSCAM, using the same equation and parameter values assumed in 2005 (Figure 7 in main assessment document).
- Commercial and recreational CPUE indices were modelled as a power function of vulnerable biomass, assuming the same parameters that were estimated in 2005 (Table C 5 in Appendix C).

- Variance parameters ϑ^2 (total variance) and ρ (the proportion of total variance associated with observation error) were fixed at values that approximated the variance structure of the 2005 assessment model. The ρ parameter was set to 0.98 to match the assumption used by Logan et al. (2005) when fitting the model to data that all deviations between observed and predicted data arose from observation error (i.e., the model fitted to the data is assumed to have no variability in recruitment). The total variance parameter was then set to produce a standard deviation in observation errors for abundance indices (σ in Appendix C) that was the mean of the standard deviations in recreational and commercial CPUE estimated by Logan et al. (2005). The mean of the two CPUE standard deviations was 0.17 for the SoG model and 0.20 for the noSE model. When combined with the assumption that ρ=0.98, these values resulted in ϑ^2 values of 33.87 and 25.11 for the SoG and noSE models, respectively. The corresponding assumed standard deviation in recruitment (process error) was 0.025 for both SoG and noSE models.
- Selectivity options for iSCAM were set to mimic the age-dependent selectivity functions assumed for the 2005 assessment model. The first two gear-types, the commercial fishery and the recreational fishery prior to 1992 (i.e., size limit ≤ 58 cm), were modelled in iSCAM using an age-based logistic selectivity function, with the mean age of selectivity and the standard deviation of the mean age set at values that approximated the functions used in 2005 (Appendix C). Age-based selectivities for males and females were assumed equal for these two gears, as was done in 2005. The recreational fishery post-1992 (i.e., minimum size limit = 65 cm) was modelled in iSCAM using a length-based logistic selectivity function centered on the minimum size limit. This approach differed from the sex-specific age-based selectivity curves used for this fishery in 2005 in which females were exposed to the fishery at a younger age than males. The length-based approach was necessary in iSCAM however, because it is not currently configured to handle sex-specific age-based selectivity functions. The expected behaviour of the iSCAM and Fish++ approaches are similar: when a minimum size limit of 65 cm is in place, females will be vulnerable to fishing at a younger age than males.

The results of this step show that the iSCAM assessment model used in this assessment can be configured to closely match the reconstructed biomass trajectory and parameter estimates of the Fish++ model used in 2005 (Figure D.1). The SoG Fish++_2002 and iSCAM_2002 models have almost identical spawning biomass trajectories between 1927 and 2003, with the iSCAM model having a slightly higher estimate of unfished equilibrium spawning biomass in 1927 (B_0) and a slightly lower steepness (*h*; Figure D.2). Estimates of the ratio of spawning biomass in 2003 to B_0 (B_{T+1} / B_0 in Figure D.2) were essentially the same. The noSE Fish++_2002 and iSCAM_2002 models also produced similar spawning biomass trajectories; however the difference was larger than the SoG model fits. The noSE iSCAM_2002 model estimated a higher biomass level throughout the time series, and a higher B_{T+1} / B_0 ratio (0.160 for Fish++_2002 compared to 0.205 for iSCAM_2002; Figure D.2).

The only assumption used in the 2005 assessment model that was not modelled in iSCAM was density-dependent growth (Logan et al. 2005). The addition of this type of process into iSCAM and the calculation of MSY-based reference points when density-dependent growth is present, would have been time-consuming and was deemed not warranted based on the close approximation of the existing iSCAM configuration to the 2005 assessment results (Figure D.1).

Table D.1. Description of steps taken in bridging analysis. Each step was applied to two approaches for dealing with uncertainty in historical catch from the Dominion Bureau of Statistics District 1. Values for ρ (the proportion of total variance associated with observation error variance parameters) were fixed as shown in the table, and ϑ2 (total variance) were either fixed or estimated. See text of this appendix for additional information on each step taken.

Bridging Step	**Run ID**	**Approach to District 1 Catch**	**Data Source**	**Recreational CPUE Index**	ρ	ϑ^2
Step 1	SoG_iSCAM_2002_Bridge	SoG: Areas 13-19, 28, 29	2002 input files	Area-based	0.98	33.87
	noSE_iSCAM_2002_Bridge	noSE: Areas 13-19	2002 input files	Area-based	0.98	25.11
Step 2	SoG_ iSCAM_2002_Updated	SoG: Areas 13-19, 28, 29	Updated 2002 data	Area-based	0.98	33.87
	noSE_ iSCAM_2002_Updated	noSE: Areas 13-19	Updated 2002 data	Area-based	0.98	25.11
Step 3	SoG_ iSCAM_2002_IntvCPUE	SoG: Areas 13-19, 28, 29	Updated 2002 data	Interview-based	0.98	33.87
	noSE_ iSCAM_2002_IntvCPUE	noSE: Areas 13-19	Updated 2002 data	Interview-based	0.98	25.11
Step 4	SoG_iSCAM_2014_fixVar	SoG: Areas 13-19, 28, 29	Data updated to 2013	Interview-based	0.98	33.87
	noSE_iSCAM_2014_fixVar	noSE: Areas 13-19	Data updated to 2013	Interview-based	0.98	25.11
Step 5a	SoG_iSCAM_2014_estVarRho0.7	SoG: Areas 13-19, 28, 29	Data updated to 2013	Interview-based	0.70	Estimated
	noSE_iSCAM_2014_estVarRho0.7	noSE: Areas 13-19	Data updated to 2013	Interview-based	0.70	Estimated
Step 5b	SoG_iSCAM_2014_estVarRho0.7	SoG: Areas 13-19, 28, 29	Data updated to 2013	Interview-based	0.30	Estimated
	noSE_iSCAM_2014_estVarRho0.3	noSE: Areas 13-19	Data updated to 2013	Interview-based	0.30	Estimated

Table D.2. Parameters estimates from the 2005 assessment model (labelled Fish++_2002 to reflect that 2002 was the last year of data) compared with estimates from each step of the bridging analysis. Parameter notation is as follows: B_0 = unfished spawning stock biomass in 1927, h = stock recruitment steepness, q_{rCPUE} = catchability coefficient for the recreational fishery CPUE series, q_{cCPUE} = catchability coefficient for the commercial fishery CPUE series, ϑ^2 = total variance, σ = standard deviation of the observation errors in relative abundance indices, τ = standard deviation of the process error in recruitment deviations, and B_{T+1} = spawning biomass in the final year of model prediction. Shading indicates that a parameter (or derived parameter) was fixed at an assumed value.

Step	Run ID	B_0	h	q_{rCPUE}	q_{cCPUE}	ϑ^2	σ	τ	B_{T+1}	B_{T+1}/B_0
Strait of Georgia (SoG)										
Fish ++	SoG_Fish++_2002	43,355	0.34	1.18×10^{-10}	0.137	-	0.126, 0.215	0	3990	0.092
Step 1	SoG_iSCAM_2002_Bridge	45,255	0.32	8.18×10^{-9}	0.149	33.87	0.170	0.025	4241	0.094
Step 2	SoG_ iSCAM_2002_Updated	39,992	0.35	1.25×10^{-8}	0.175	33.87	0.170	0.025	3369	0.084
Step 3	SoG_ iSCAM_2002_IntvCPUE	41,278	0.33	1.24×10^{-8}	0.160	33.87	0.170	0.025	3728	0.090
Step 4	SoG_iSCAM_2014_fixVar	44,523	0.27	6.76×10^{-9}	0.104	33.87	0.170	0.025	7125	0.160
Step 5a	SoG_iSCAM_2014_estVarRho0.7	48,731	0.26	7.40×10^{-9}	0.103	43.12	0.127	0.083	6525	0.134
Step 5b	SoG_iSCAM_2014_estVarRho0.3	49,092	0.26	7.99×10^{-9}	0.106	22.81	0.115	0.175	6192	0.126
Exclude SE Quadrant (noSE)										
Fish ++	noSE_Fish++_2002	13,898	0.72	0.002	2.038	-	0.179, 0.217	0	2222	0.160
Step 1	noSE_iSCAM_2002_Bridge	14,844	0.67	0.009	2.520	25.11	0.198	0.025	3040	0.205
Step 2	noSE _ iSCAM_2002_Updated	14,356	0.71	0.009	2.573	25.11	0.198	0.025	2893	0.201
Step 3	noSE _ iSCAM_2002_IntvCPUE	15,342	0.64	0.009	2.288	25.11	0.198	0.025	2767	0.180
Step 4	noSE _iSCAM_2014_fixVar	18,229	0.49	0.008	1.700	25.11	0.198	0.025	7676	0.421
Step 5a	noSE _iSCAM_2014_estVarRho0.7	17,999	0.50	0.008	1.719	43.60	0.127	0.083	7485	0.416
Step 5b	noSE _iSCAM_2014_estVarRho0.3	18,086	0.50	0.008	1.703	19.87	0.122	0.188	7407	0.410

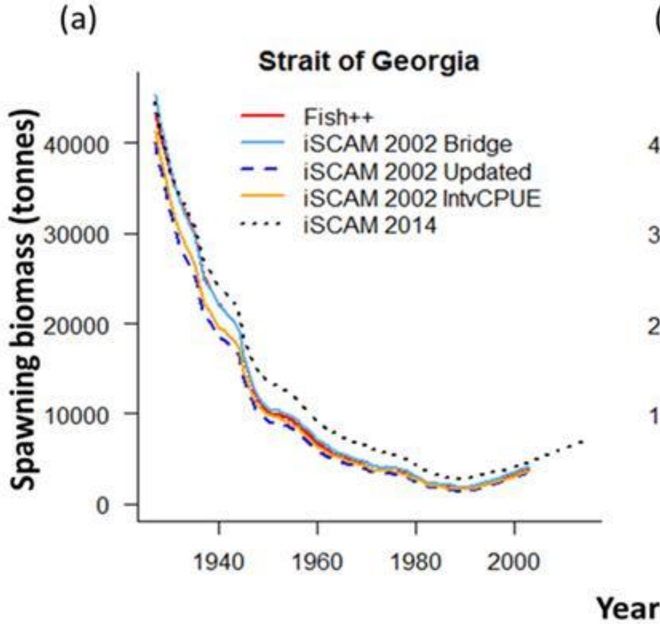


Figure D.1. Maximum posterior density estimates of spawning biomass (in tonnes) for steps 1 – 4 in the bridging analysis. Results are shown for the Strait of Georgia (SoG) scenario in panel a and for the 'Exclude SE quadrant' (noSE) scenario on panel b. See text and Table D.1 for a description of each step.

STEP 2: UPDATE 2002 DATASETS USING INFORMATION AVAILABLE IN 2014

Relatively small changes were made to some pre-2003 data inputs in the 2014 assessment due to new information becoming available, the finalization of catch values, and / or inconsistencies in the 2002 data sets. The purpose of this step is to show the extent to which the 2005 assessment results would have changed if these updated datasets had been used.

Updates to pre-2003 data made in 2014 include:

- Commercial landings for the years 1928 to 1930 have been revised due to a recently discovered inconsistency in the assignment of DBS reporting units to SoG quadrants. These revisions were minor, with adjustments to total SoG landings of +12%, +2%, and –9% in 1928, 1929, and 1930, respectively (see Table 5. Commercial catch (retained tonnes) of Lingcod in the Strait of Georgia 1927 – 1946 by geographic quadrant (Southeast = Statistical Areas 28-29, Northeast = Statistical Areas 15-16, Northwest = 13-14, Southwest = Statistical Areas 17-19). All data were obtained from annual Fisheries Statistics reports compiled by the Dominion Bureau of Statistics (1927-1946) and converted from dressed weight (hundred lbs) to round weight (tonnes). The allocation of catch areas used by the DBS to the four geographic areas is described in footnotes.Table 5 for 2014 values and a description of allocation of DBS reporting unit to PFMC Statistical Areas).
- Small changes were made to recreational catch values in 2000 to 2002 as a result of creel catch data being finalized after the 2005 assessment for these years (changes = 0.6% to 3.8% of values used in the 2005 assessment; see Table 5 for 2014 values).
- Commercial fishery CPUE values used as input to the 2005 assessment were replaced with values reported by Richards and Hand (1991) for the years 1979 to 1989. This change was made due to an inconsistency in the input data files for the 2005

assessment model and the catch tables reported in the document (Logan et al. 2005). The commercial CPUE values reported in the assessment document (Table C3 in Logan et al. 2005) match those of Richards and Hand (1991). The data in the 2005 input files differs from these values, but appears to be the same as was used to show model fit diagnostics in Figure 5. The source of this difference was not documented, so we have chosen to revert back to the Richards and Hand (1991) values for this assessment since these values are documented.

The results of this step show that the effect of updating these datasets prior to 2002 had small effects on predicted stock trajectories and parameter estimates. For the SoG models, the scale of the biomass trajectory dropped slightly compared to those from the Fish++ model and Step 1. Both B_0 and B_{T+1} / B_0 were smaller for the Step 2 model, but these differences were relatively small (e.g., B_{T+1} / B_0 was 0.084 for iSCAM_2002_Updated compared to 0.094 and 0.092 for Fish++ and iSCAM_2002; Table D.2). For the noSE models, Step 2 produced a trajectory that was similar to the Fish++ trajectory, but with a slightly higher estimate of B_{T+1} / B_0 compared to Fish++ (Table D.2).

STEP 3: USE AN INTERVIEW-BASED AVERAGE TO CALCULATE RECREATIONAL CPUE

Step 3 shows the effect of switching from an area-based average to an interview-based average when calculating recreational CPUE. The rationale for switching to an interview-based average in 2014 and a comparison of the indices produced by the two methods are provided in Appendix C.

Results from this step of the bridging analysis show that switching the method of CPUE calculation had opposite effects on reconstructed biomass trajectories in SoG and noSE scenarios, but that overall differences were small (Figure D.1). For SoG, switching CPUE method caused a slight increase in both B_0 and B_{T+1} / B_0, while for noSE, switching CPUE method caused a slight decrease in these parameters (Table D.2).

Based on the results of the first 3 bridging analysis steps, we conclude that the switch in stock assessment model (Fish++ vs. iSCAM) and subsequent changes to pre-2003 data made for this assessment do not have large effects on model results. We therefore proceeded with updating the configuration of iSCAM described in Step 3 for assessment scenarios in 2014.

STEP 4: UPDATE DATA TO THE END OF 2013

In this step, recreational catch and CPUE values (based on Interview-based averages) were updated to the end of 2013. Updating data to 2013 had similar effects in both SoG and noSE scenarios. Model results with updated 2013 data suggest a larger, less productive stock in each scenario. Estimates of stock productivity (i.e., steepness parameter *h*) have decreased, while estimates of B_0 have increased (Table D.2).

In both cases, spawning biomass is estimated to have continually increased since the last assessment (Figure D.1). This increase has been larger for noSE (B_{T+1} / B_0 = 0.421 in 2014 compared to B_{T+1} / B_0 = 0.180 in 2003) than for SoG (B_{T+1} / B_0 = 0.160 in 2014 compared to B_{T+1} / B_0 = 0.090 in 2003).

STEP 5: ALLOW FOR PROCESS ERROR IN RECRUITMENT AND ESTIMATE TOTAL VARIANCE

Finally, in Steps 5a and 5b, the assumption that 98% of the deviation between observed and predicted data arose from observation error was relaxed. iSCAM uses an errors-in-variables approach when fitting the model to data, which requires an assumption to be made about variance ratio relating process error in recruitment to observation error in the abundance index (ρ). In step 5, the value of ρ was reduced from the value of 0.98 used in previous bridging steps to a value of 0.7 (step 5a) or 0.3 (step 5b). At the same time, total variance was allowed to be estimated rather than assumed fixed.

Allowing increased process error had a small effect on reconstructed estimates of spawning stock biomass (Figure D.2). For the SoG models, there was a slight increase in biomass estimates from the early portion of the time series when process error was increased by setting ρ = 0.7 (step 5a). This corresponded with a larger estimated catchability coefficient for the commercial CPUE series and a smaller estimate of B_{T+1} / B_0 compared to the iSCAM 2014 scenario (Figure D.2, Table D.2). Decreasing ρ to 0.3 (step 5b) made no additional difference (Figure D.2, Table D.2). For the noSE models, there was almost no difference between Steps 4, 5a, and 5b (Figure D.2, Table D.2).

Based on the results of this bridging analysis, Step 5a was selected as a starting point for the 2014 assessment scenarios used to characterize stock status in the main assessment document. Step 5a was selected over Step 5b because MCMC analyses showed poor convergence diagnostics when ρ was set at values below 0.5 (results not shown).

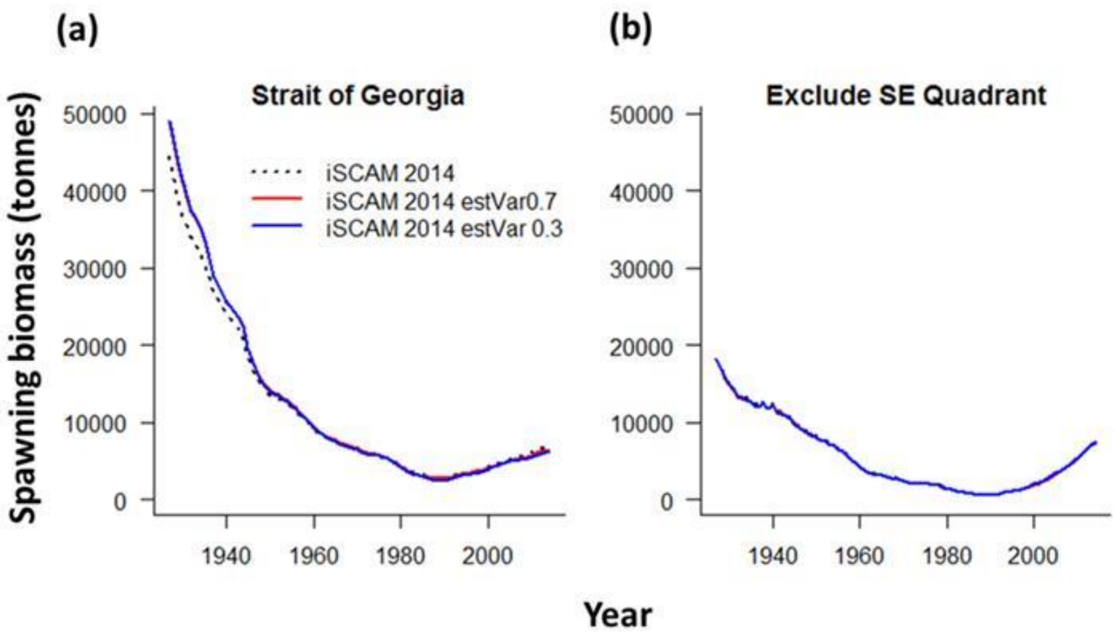


Figure D.2. Maximum posterior density estimates of spawning biomass (in tonnes) for steps 4-5 in the bridging analysis. Results are shown for the Strait of Georgia (SoG) scenario in panel a and for the 'Exclude SE quadrant' (noSE) scenario on panel b. See text and Table D.1 for a description of each step.

APPENDIX E: MODEL FIT DIAGNOSTICS

This Appendix contains figures that show properties of the model fit to data as well as diagnostics of the Markov Chain Monte Carlo (MCMC) estimation for the 12 assessment scenarios considered in 2014.

A summary of the estimation of MCMC chains from each scenario is shown in Table E.1.

Table E.1. Number of MCMC posterior samples (N), number of samples removed from chain for initial burn-in period, and thinning interval used on the chain for the 12 stock assessment scenarios.

Scneario ID	N	Burn-in	Thinning
noSE	5.0×10^6	2.5×10^4	2500
noSE_noDD	5.0×10^6	2.5×10^4	2500
noSE_noDD+highM	3.0×10^6	1.5×10^4	1500
onlySEpre1947	5.0×10^6	2.5×10^4	2500
onlySEpre1947_noDD	5.0×10^6	2.5×10^4	2500
onlySEpre1947_noDD+highM	4.0×10^6	2.0×10^4	2000
noSEpre1947	5.0×10^6	2.5×10^4	2500
noSEpre1947_noDD	5.0×10^6	2.5×10^4	2500
noSEpre1947_noDD+highM	5.0×10^6	2.5×10^5	2500
SoG	5.0×10^6	2.5×10^4	2500
SoG_noDD	2.0×10^6	1.0×10^4	1000
SoG_noDD+highM	4.0×10^6	2.0×10^4	2000

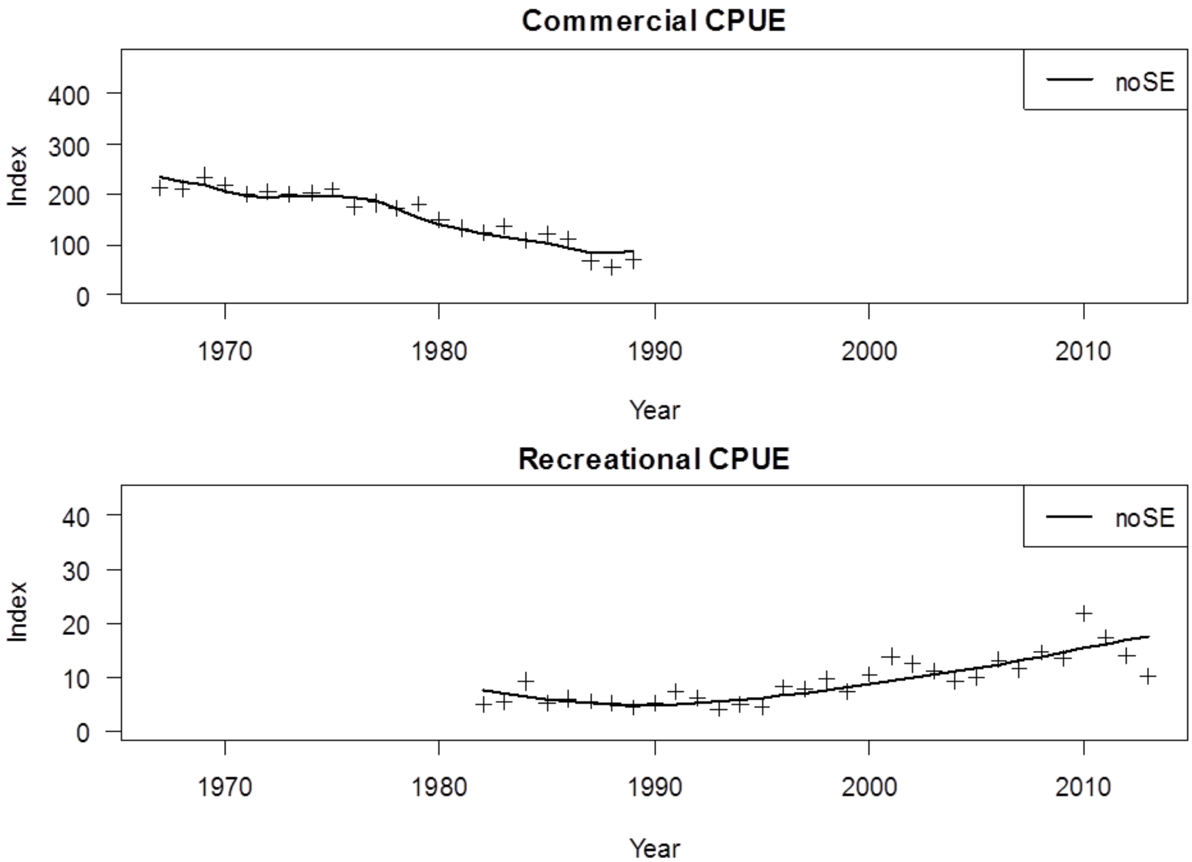


Figure E.1. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the noSE scenario.

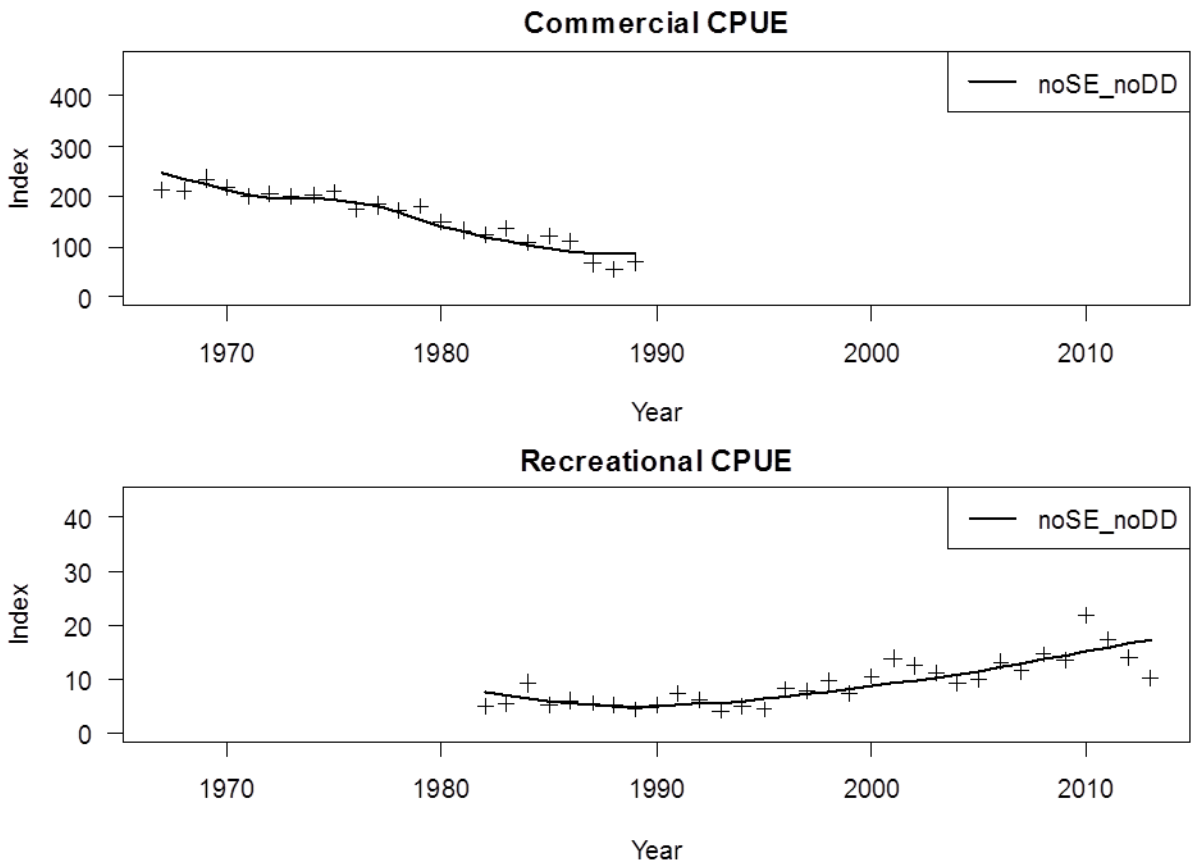


Figure E.2. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the noSE_noDD scenario.

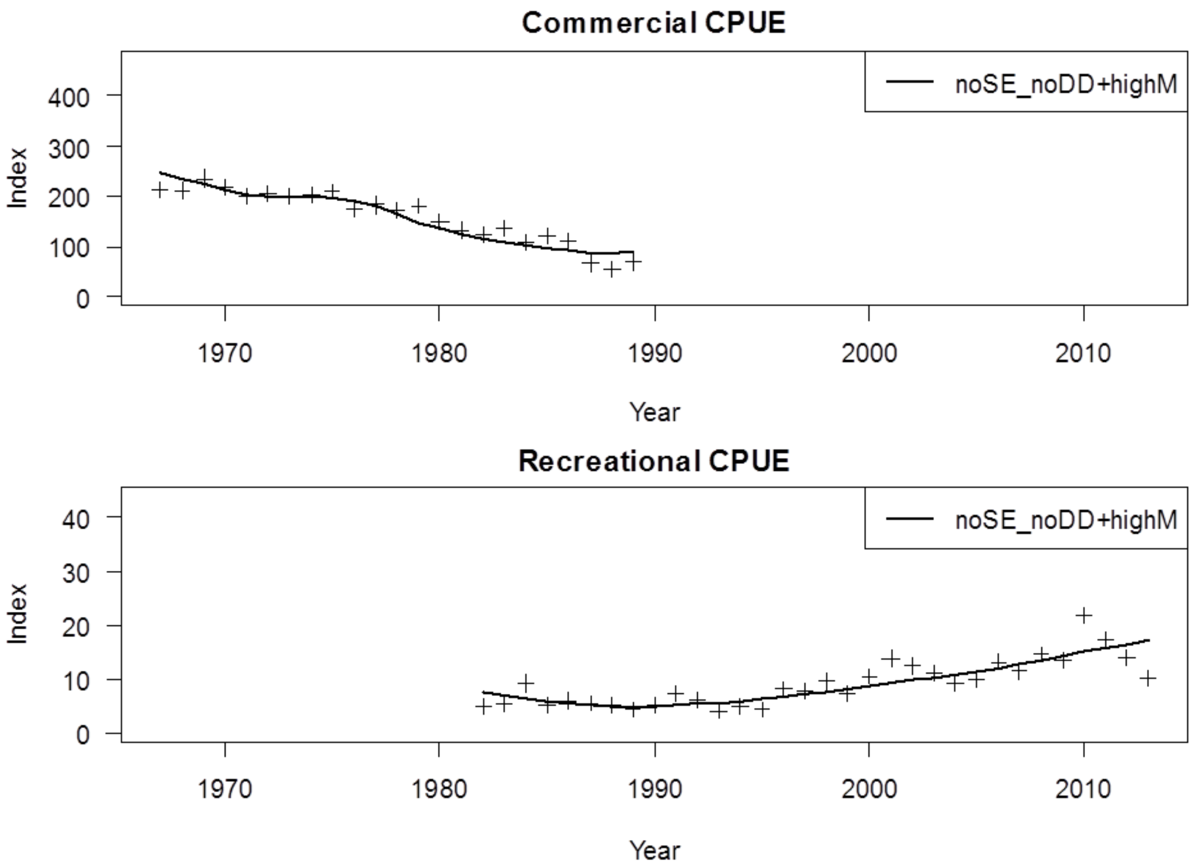


Figure E.3. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the noSE_noDD+highM scenario.

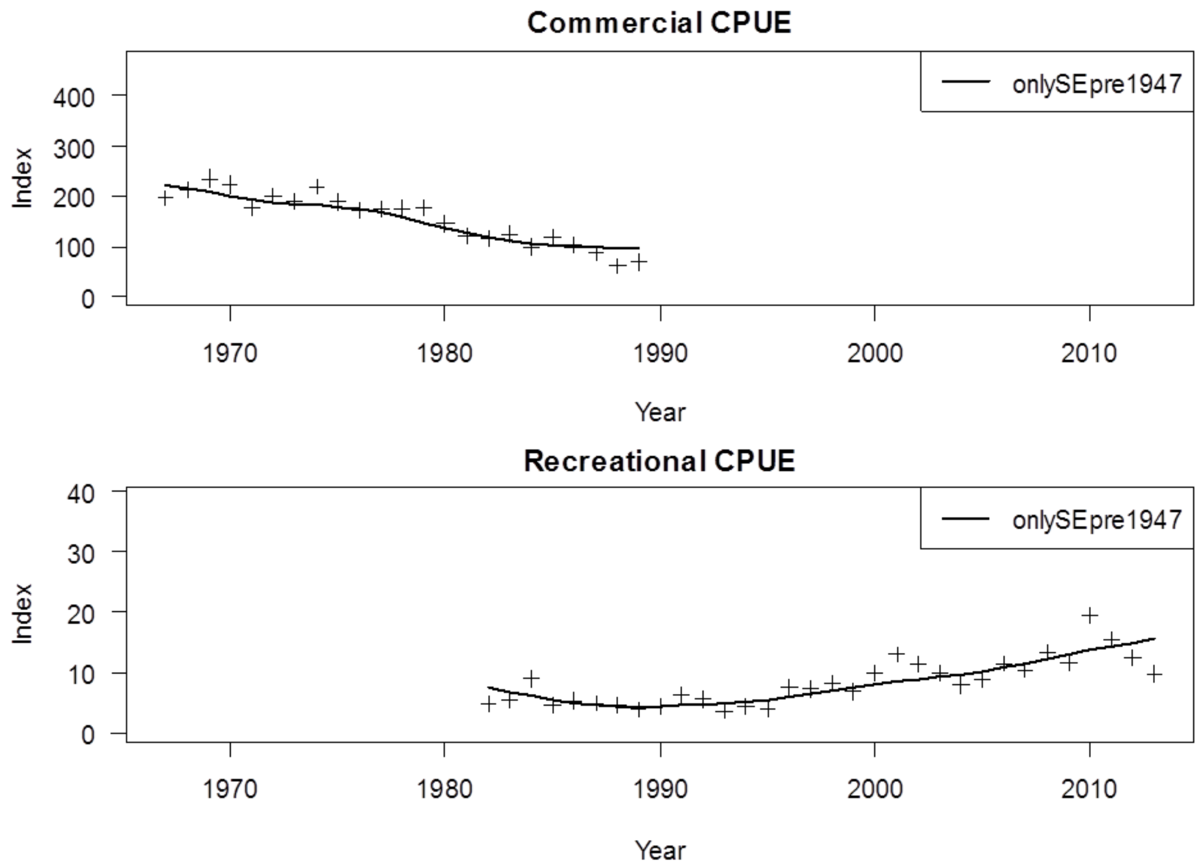


Figure E.4. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the onlySEpre1947 scenario.

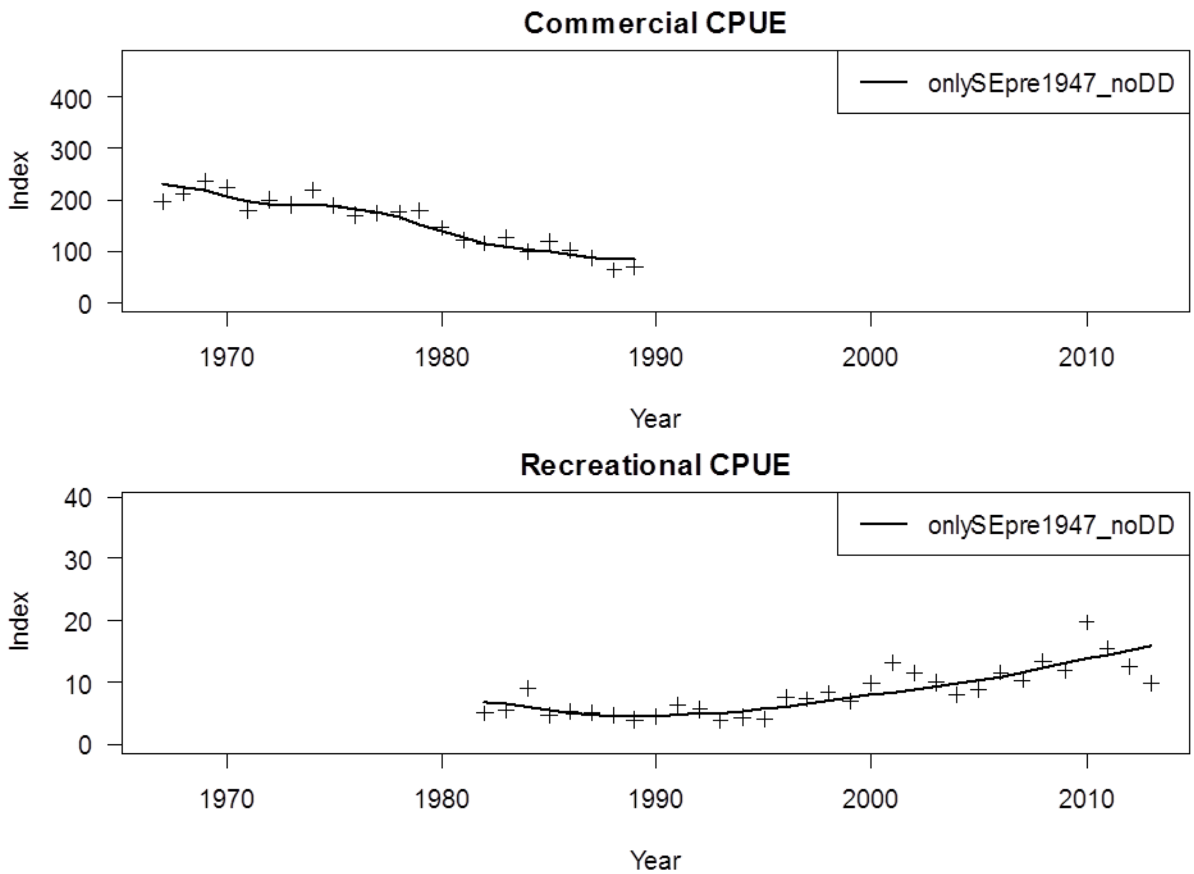


Figure E.5. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the onlySEpre1947_noDD scenario.

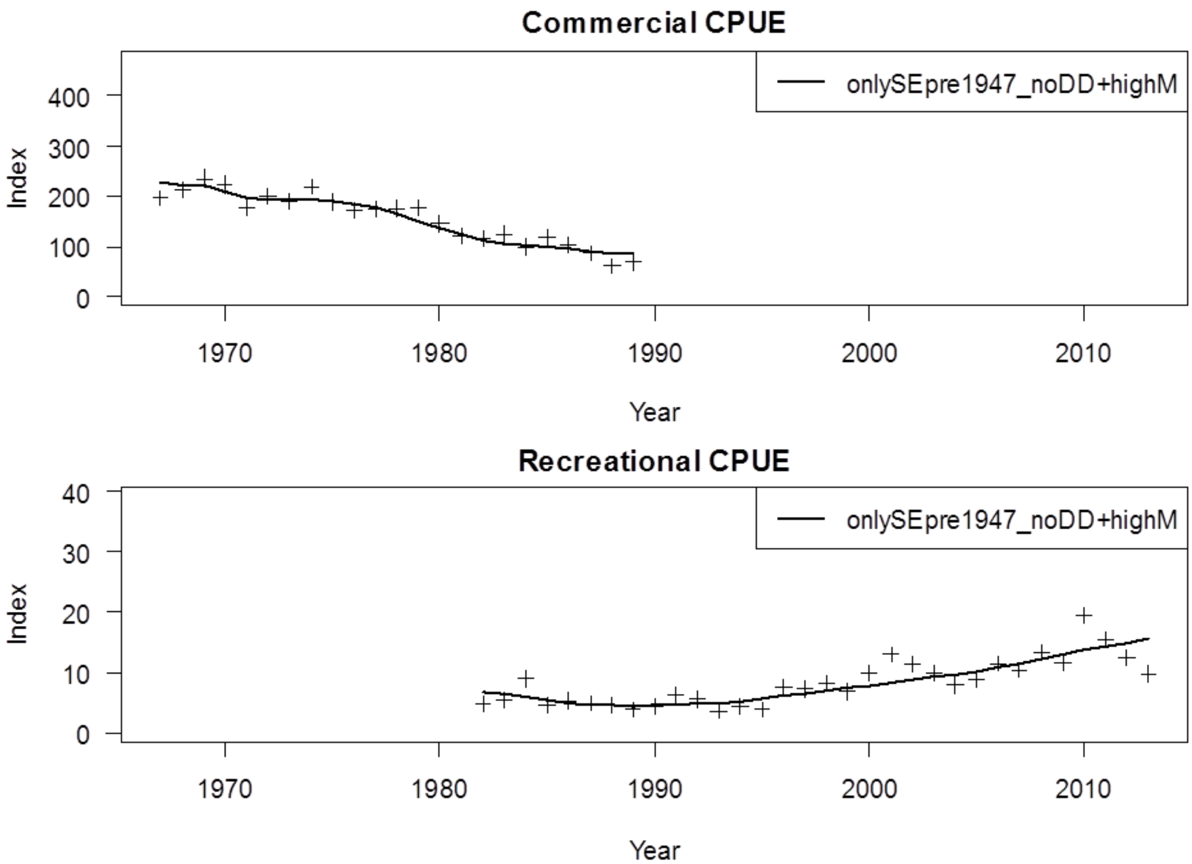
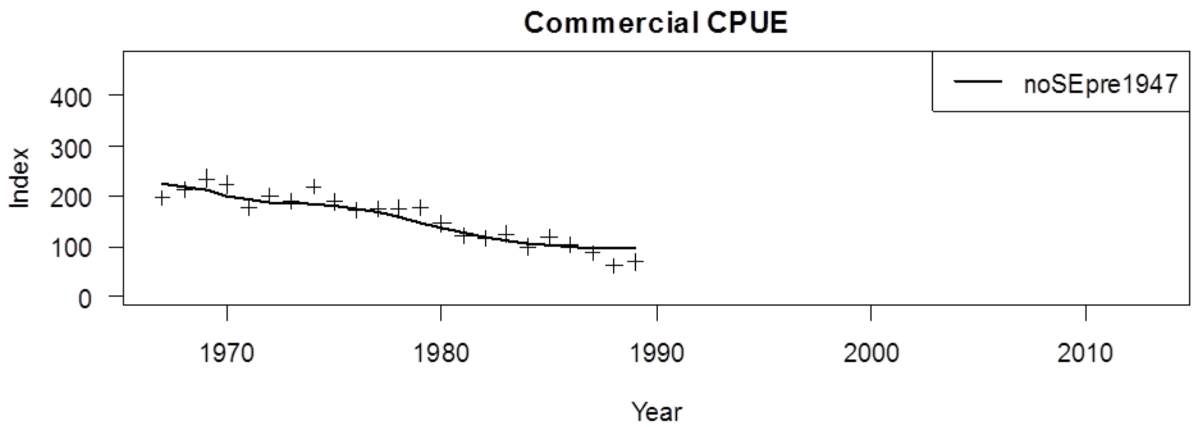


Figure E.6. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the onlySEpre1947_noDD+highM scenario.



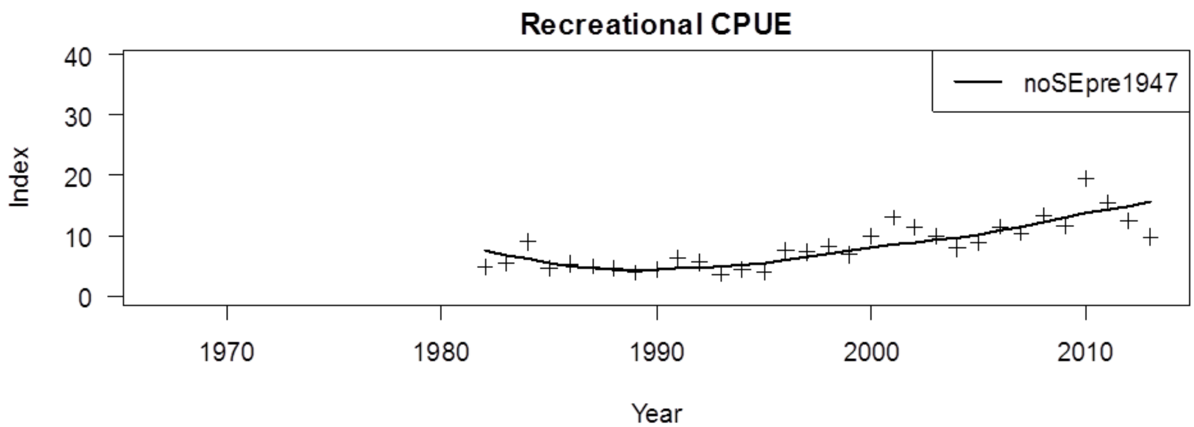


Figure E.7. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the noSEpre1947 scenario.

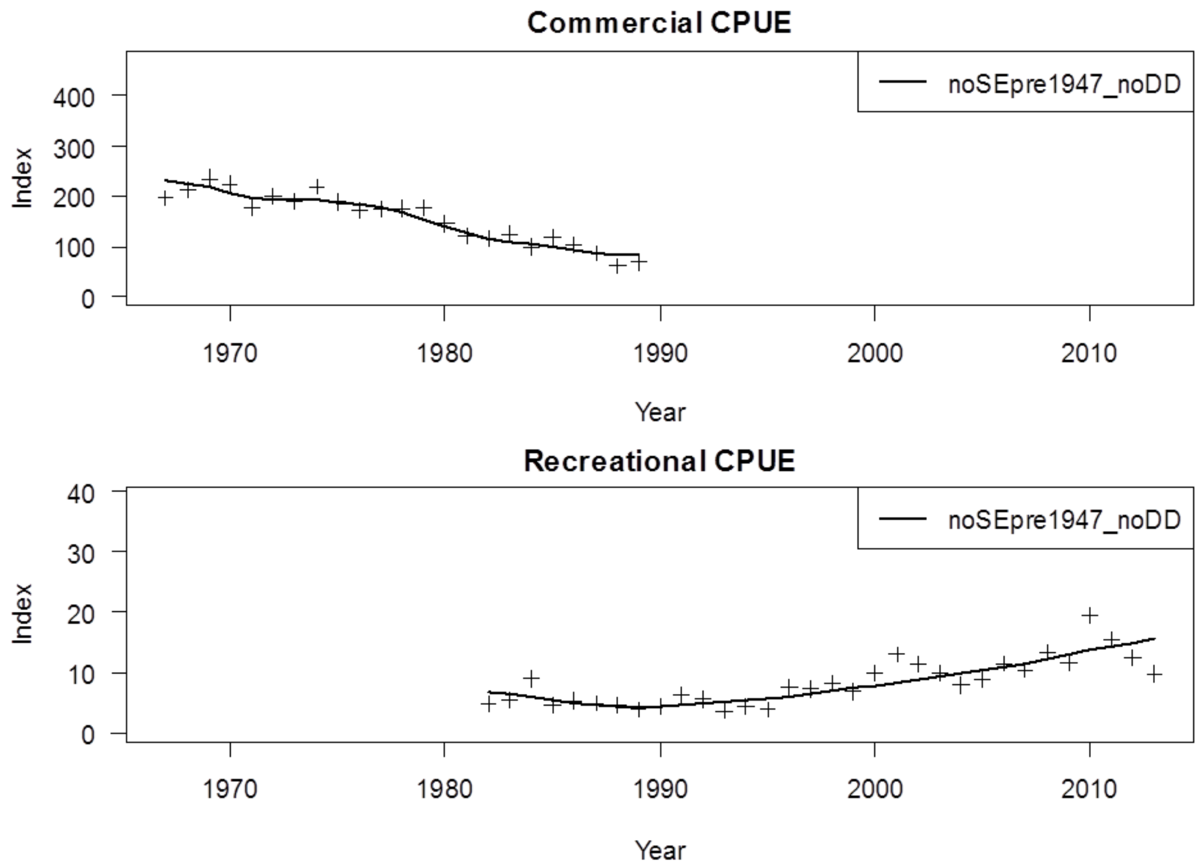


Figure E.8. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the noSEpre1947_noDD scenario.

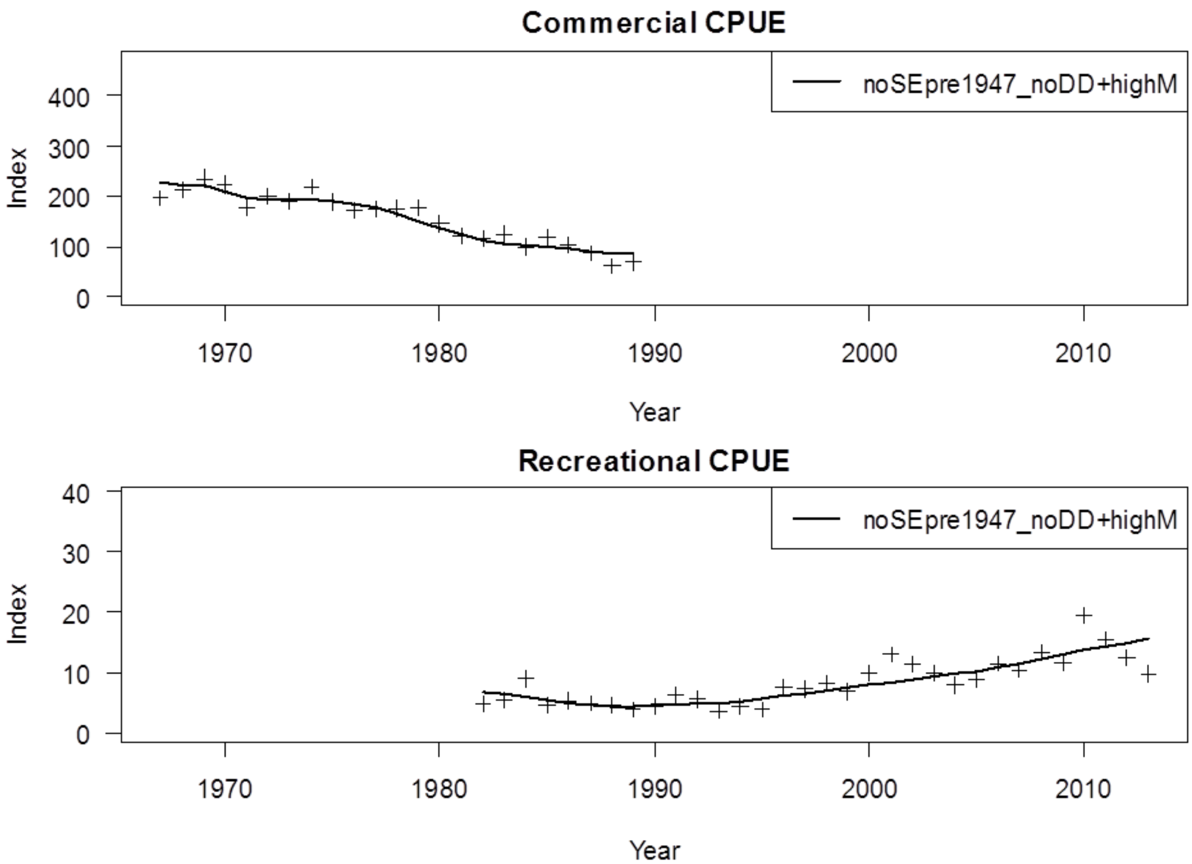


Figure E.9. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the noSEpre1947_noDD+highM scenario.

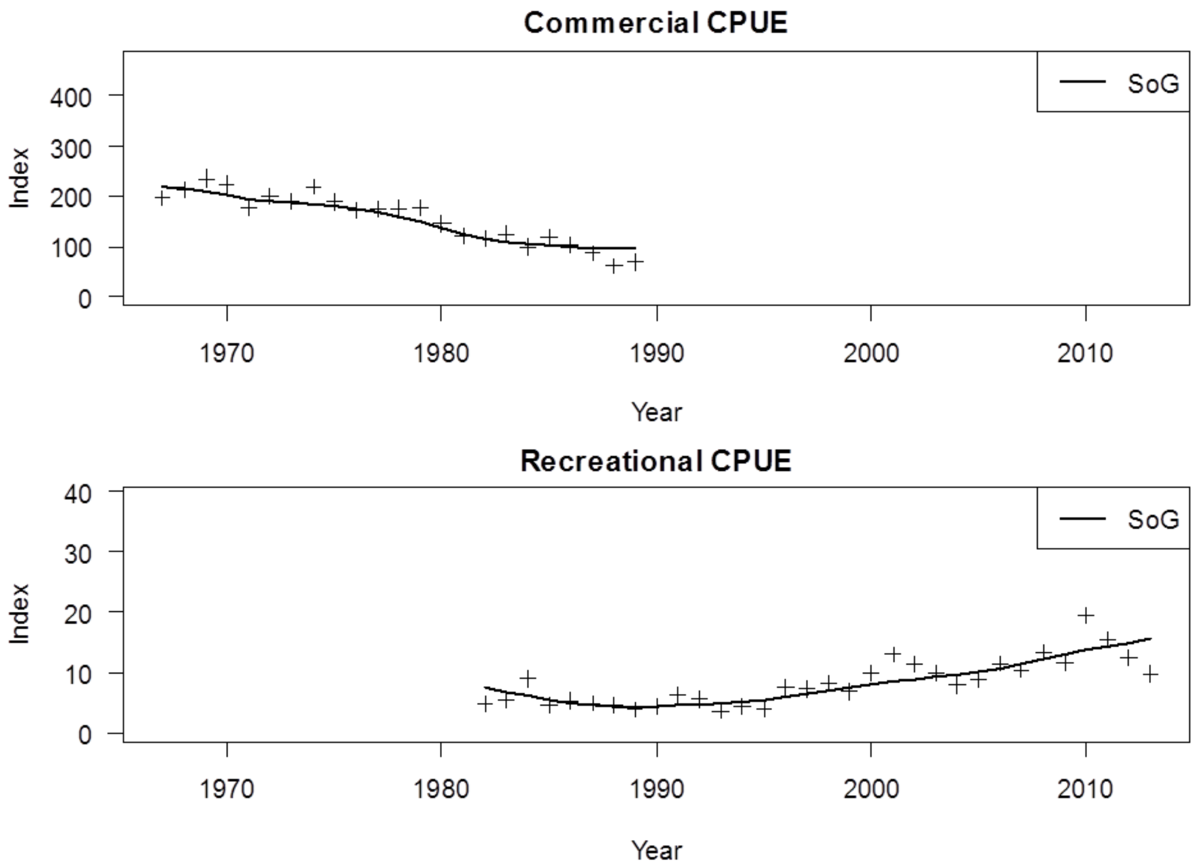


Figure E.10. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the SoG scenario.

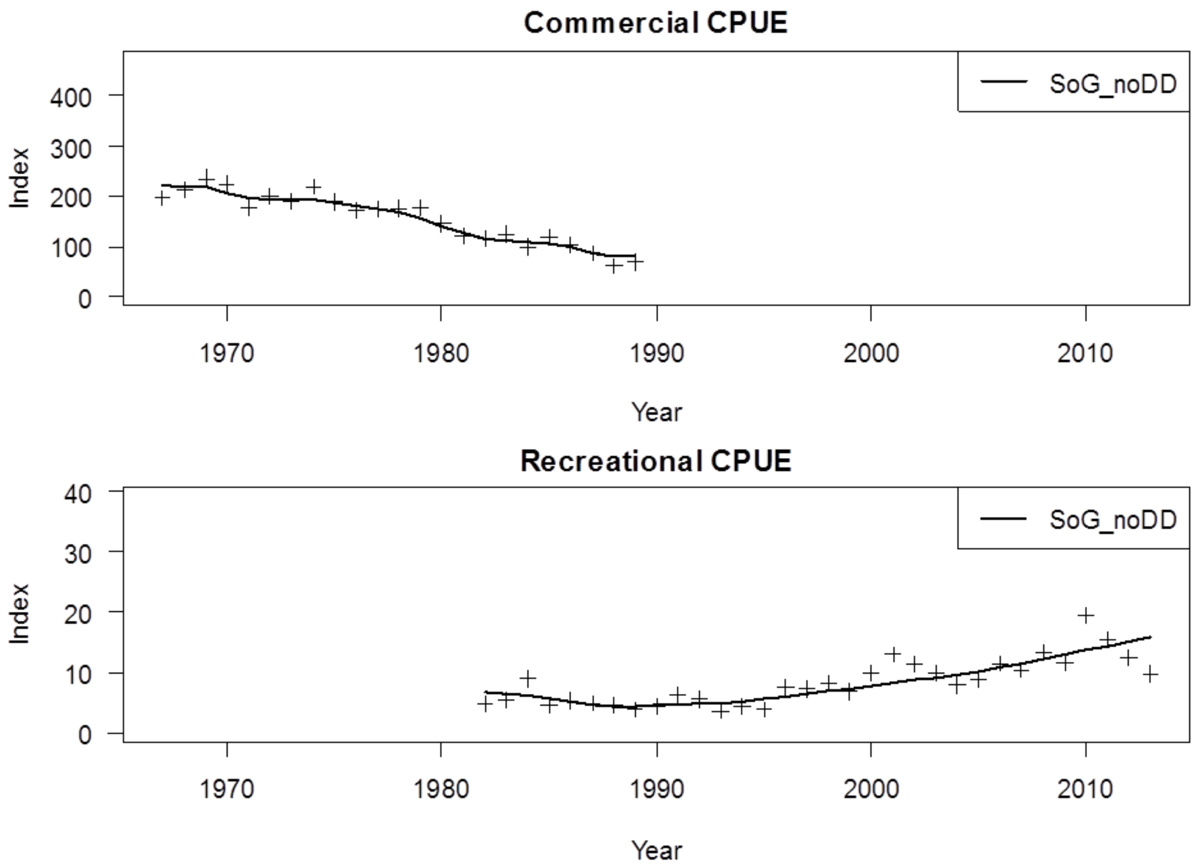


Figure E.11. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the SoG_noDD scenario.

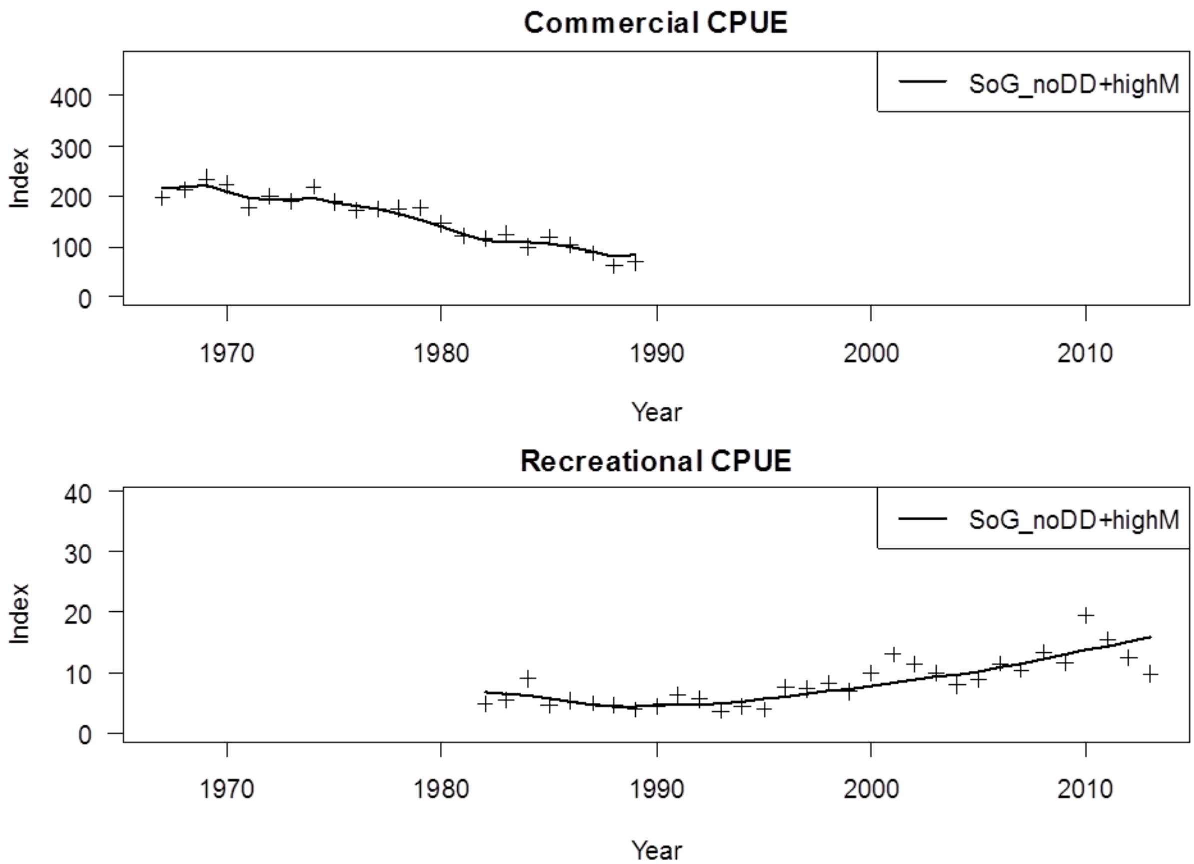


Figure E.12. Commercial and recreational fishery CPUE observations (+) with MPD model fits (solid line) for the SoG_noDD+highM scenario.

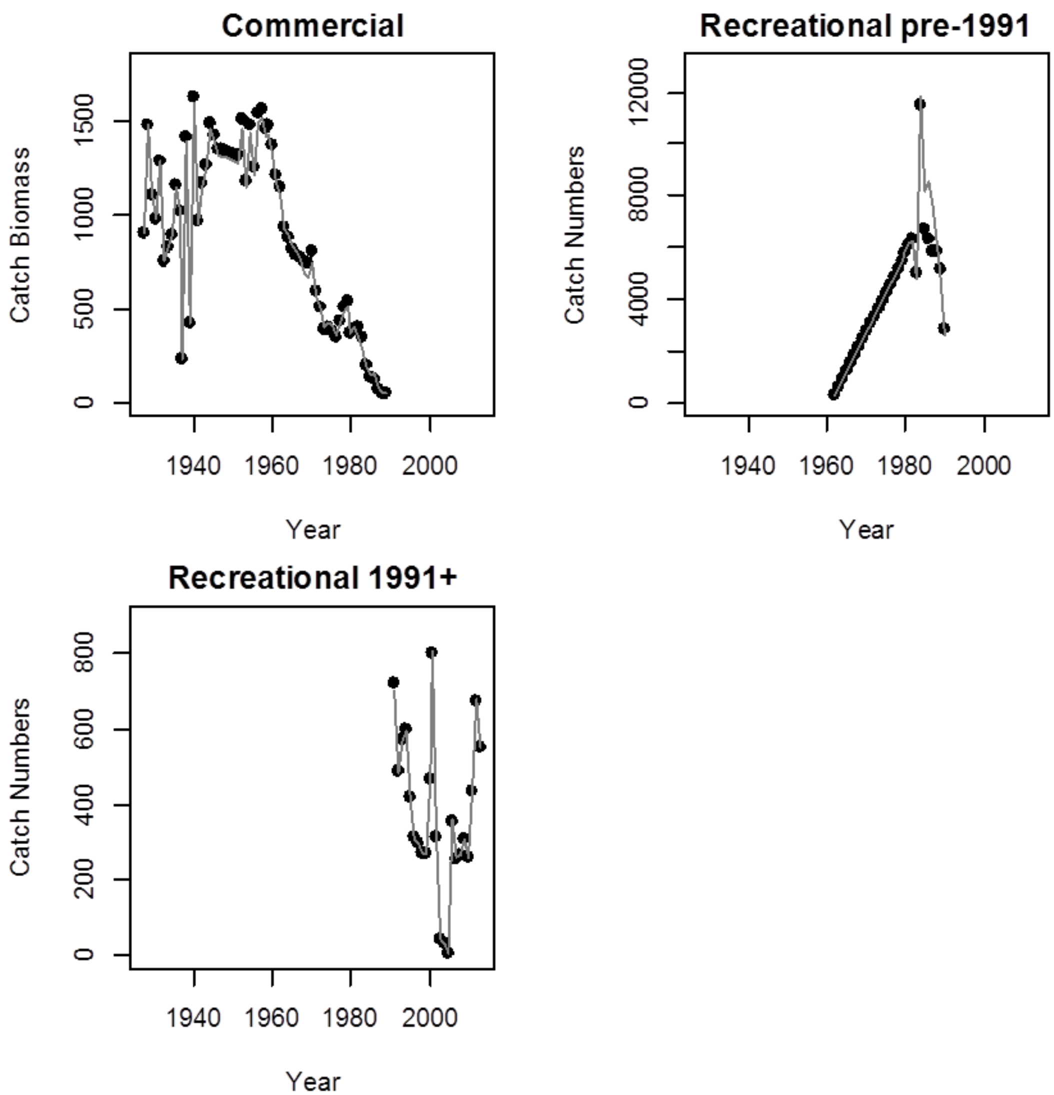


Figure E.13. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the noSE scenario.

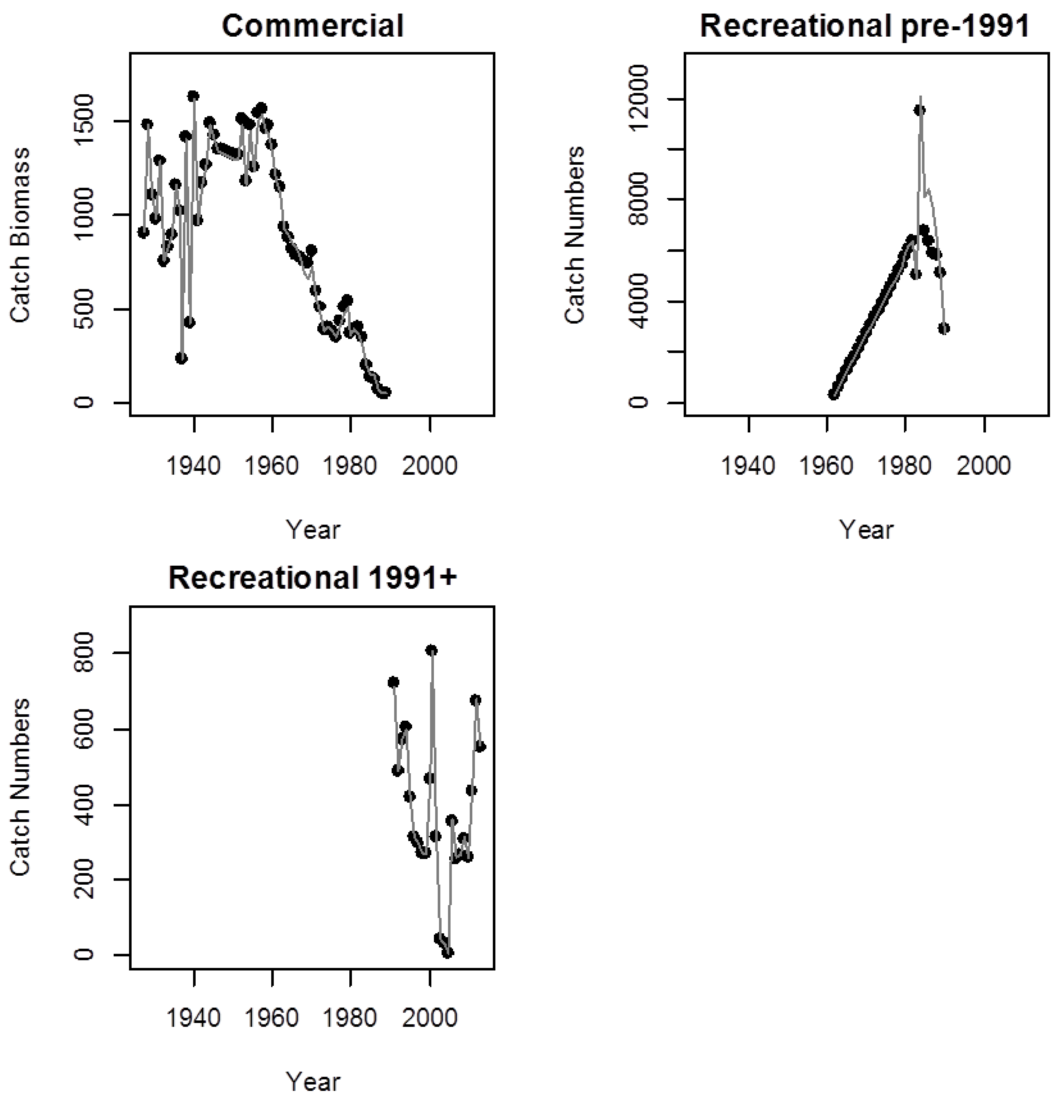


Figure E.14. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the noSE_noDD scenario.

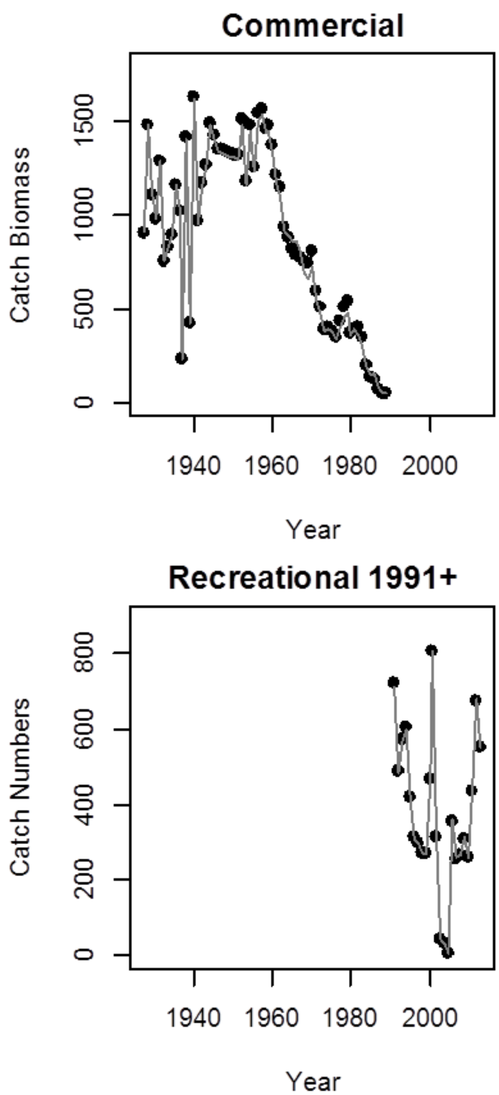


Figure E.15. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the noSE_noDD+highM scenario.

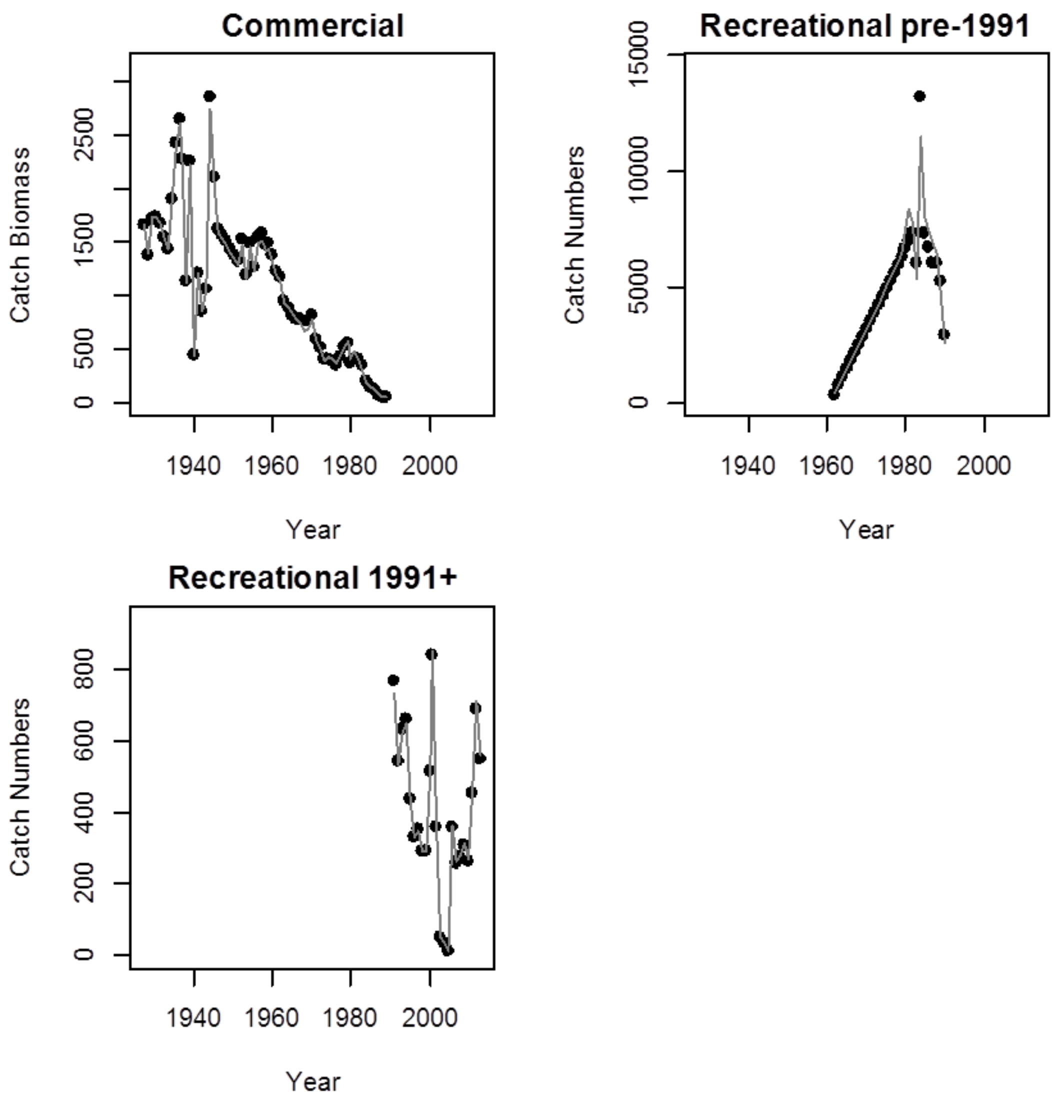


Figure E.16. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the onlySE1947 scenario.

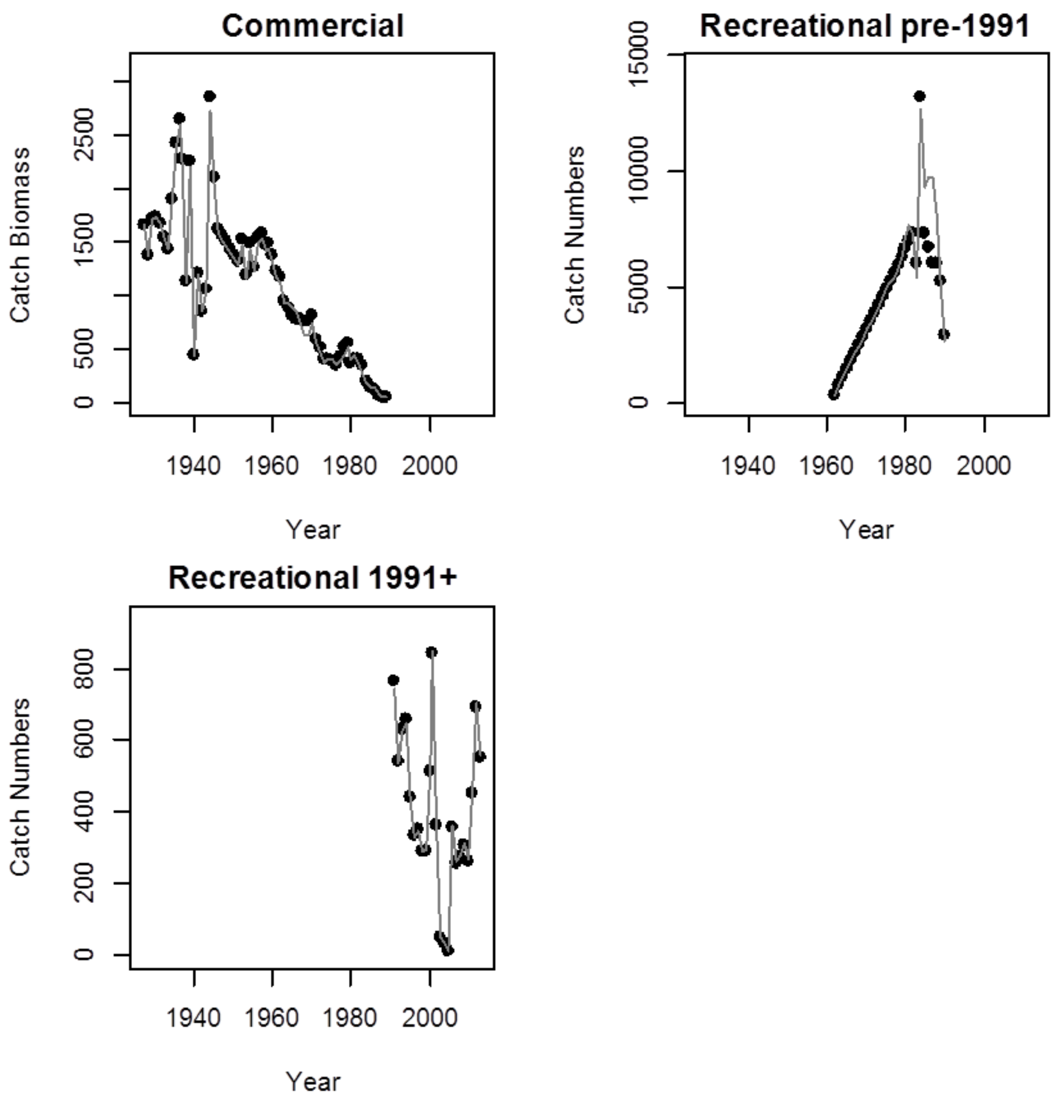


Figure E.17. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the onlySE1947_noDD scenario.

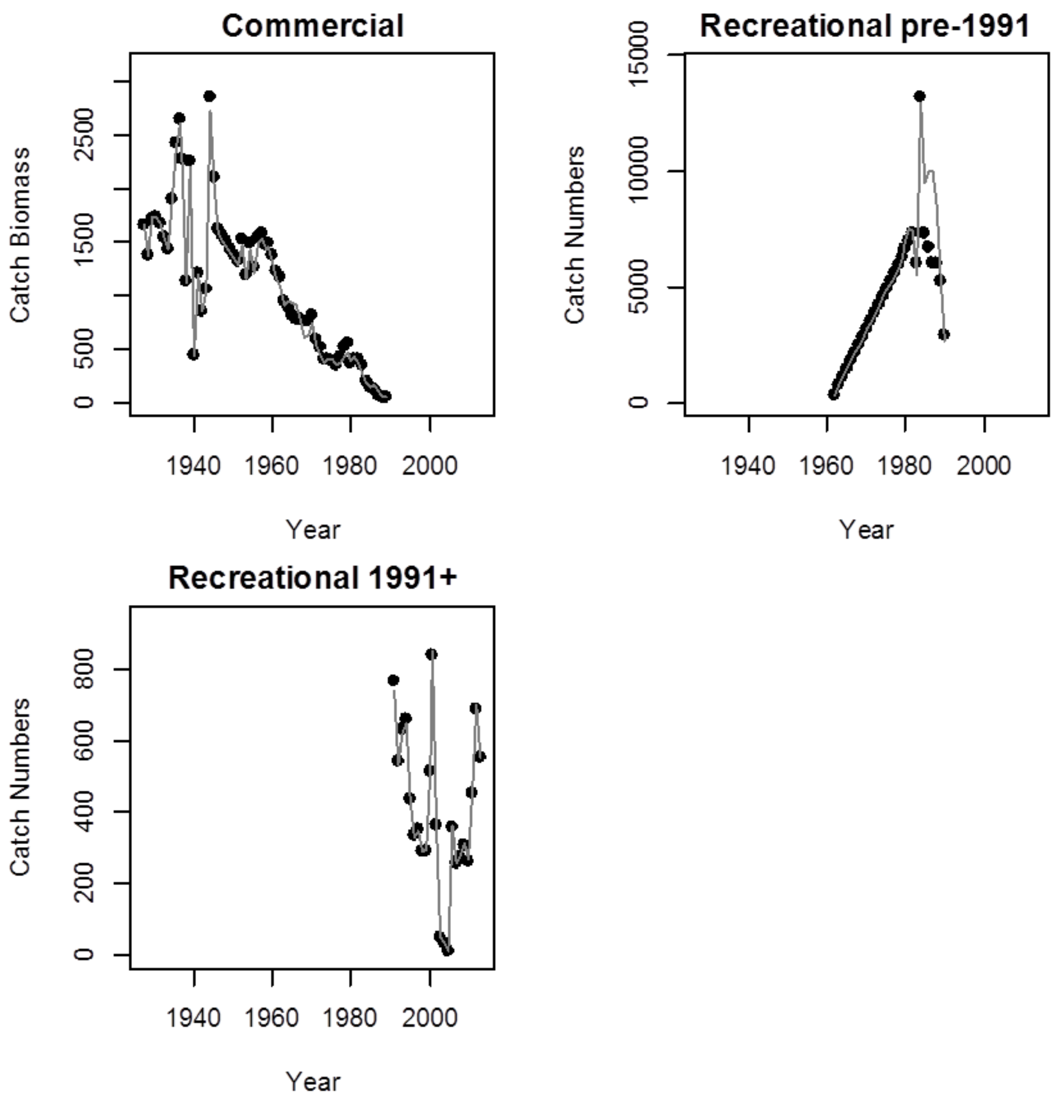


Figure E.18. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the onlySE1947_noDD+highM scenario.

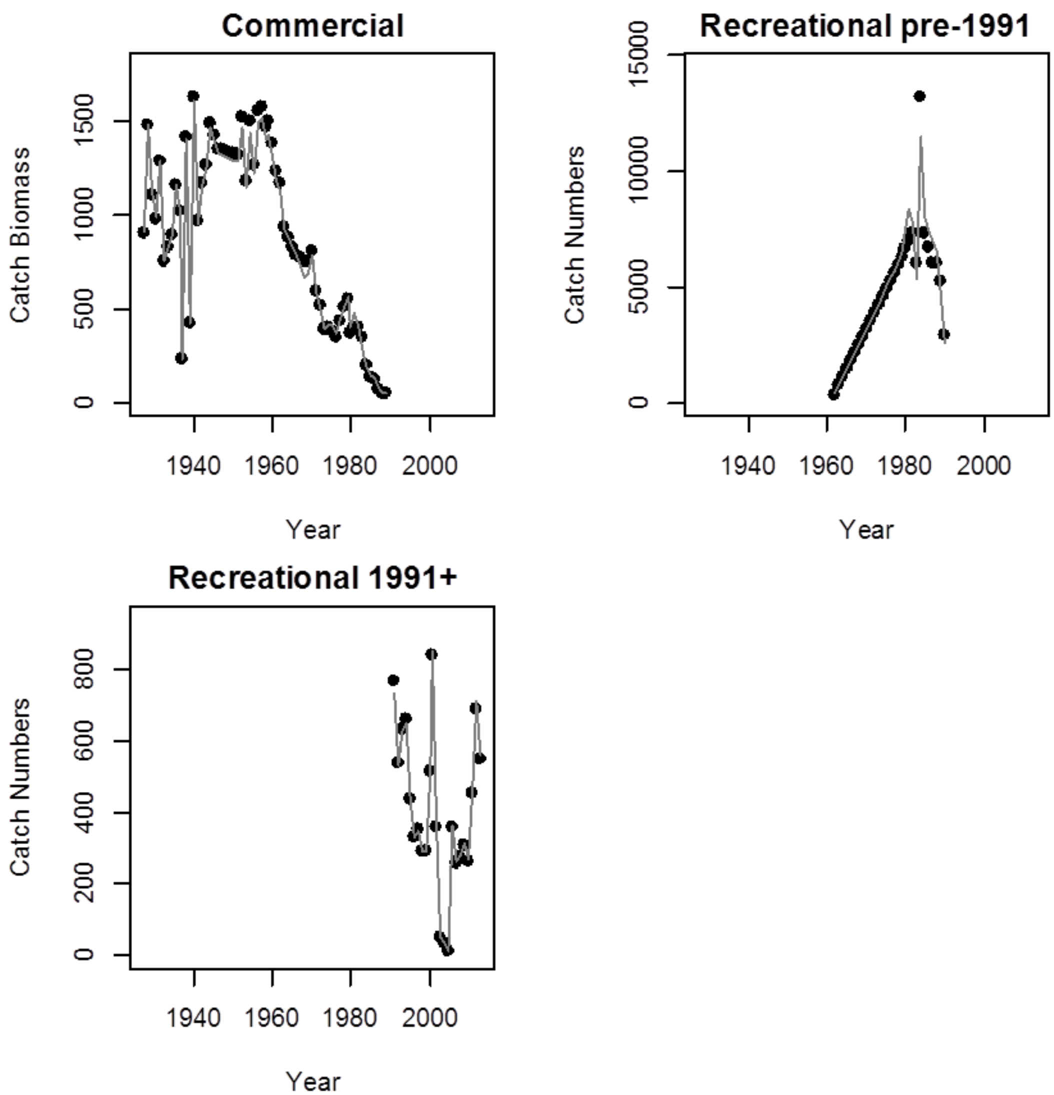


Figure E.19. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the noSE1947 scenario.

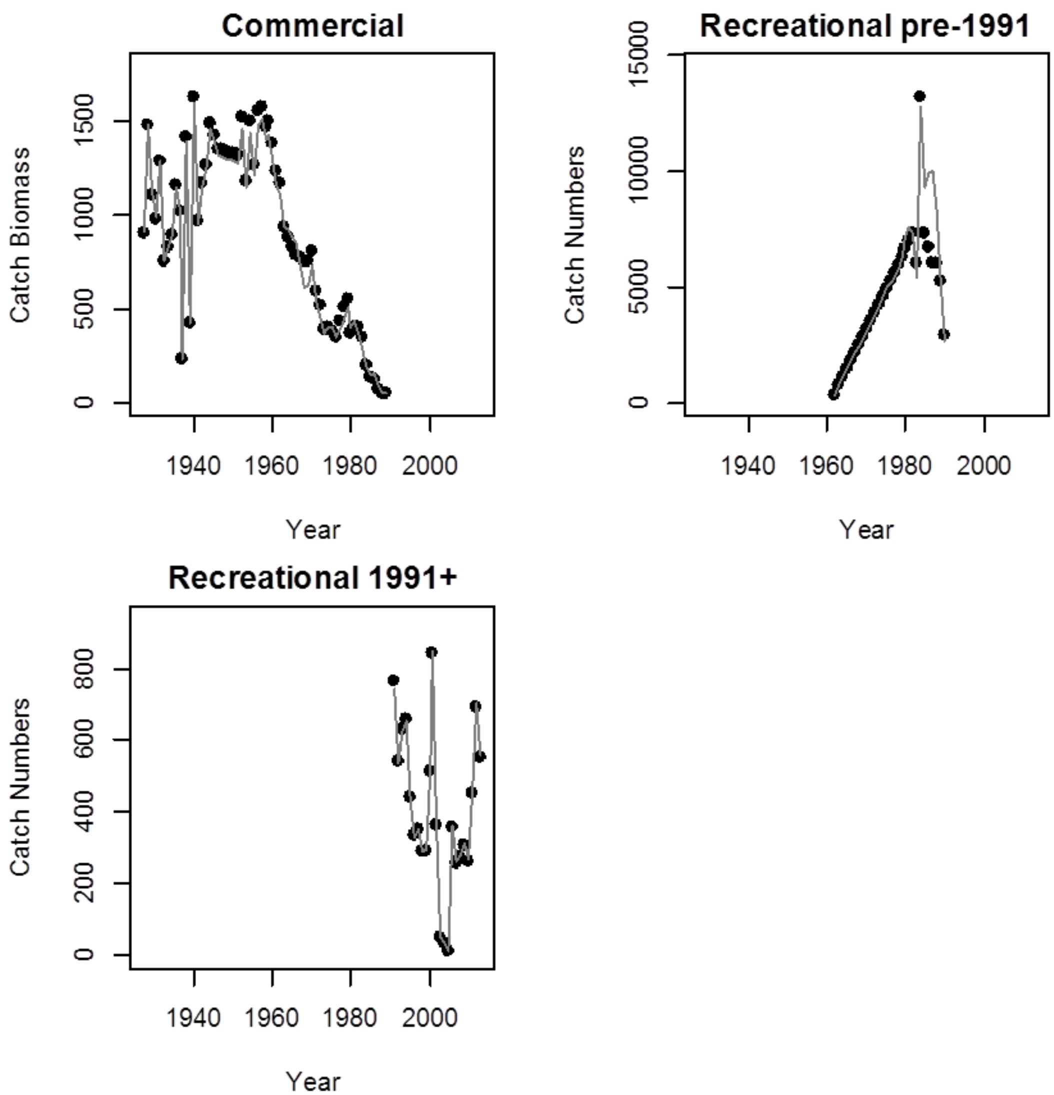


Figure E.20. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the noSE1947_noDD scenario.

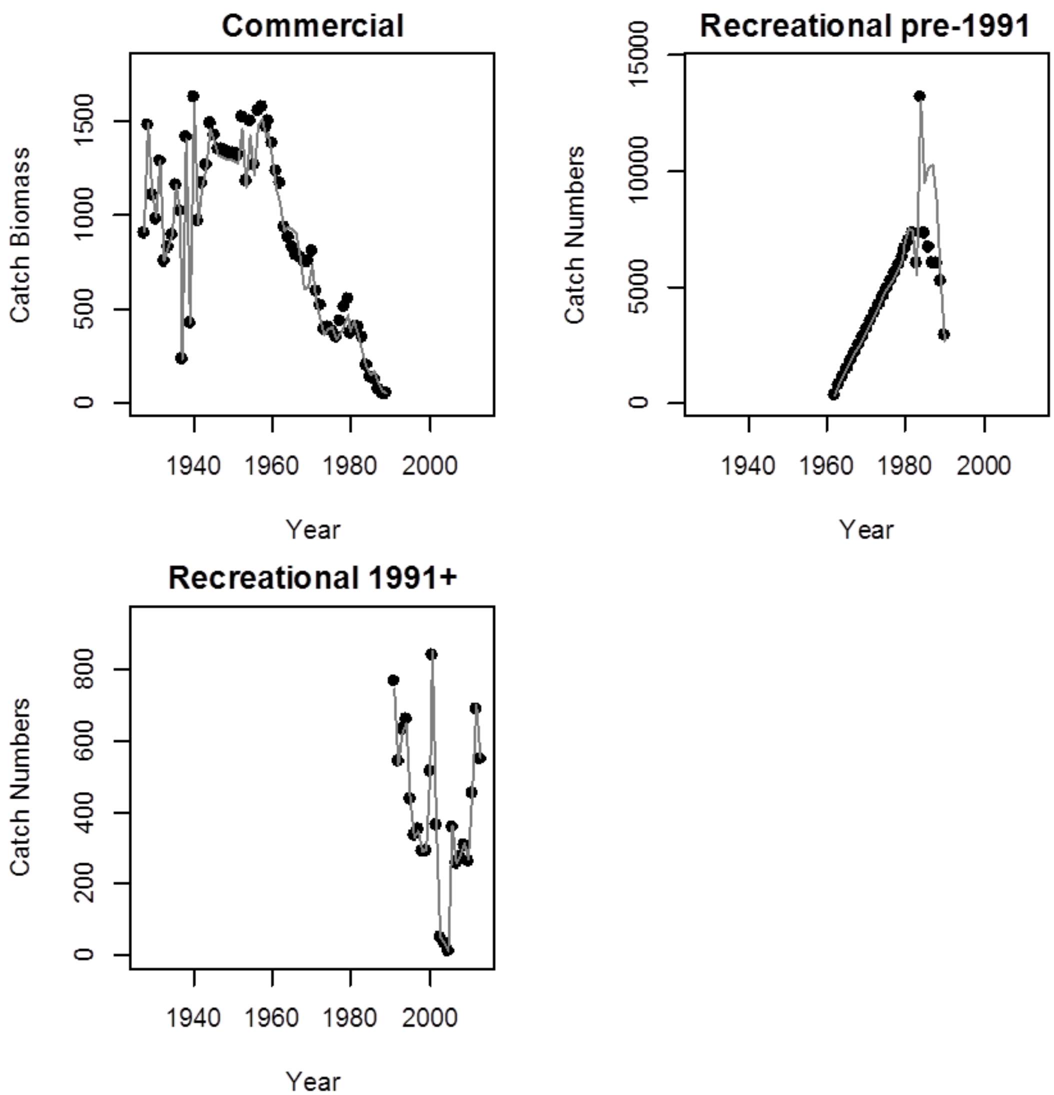


Figure E.21. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the noSE1947_noDD+highM scenario.

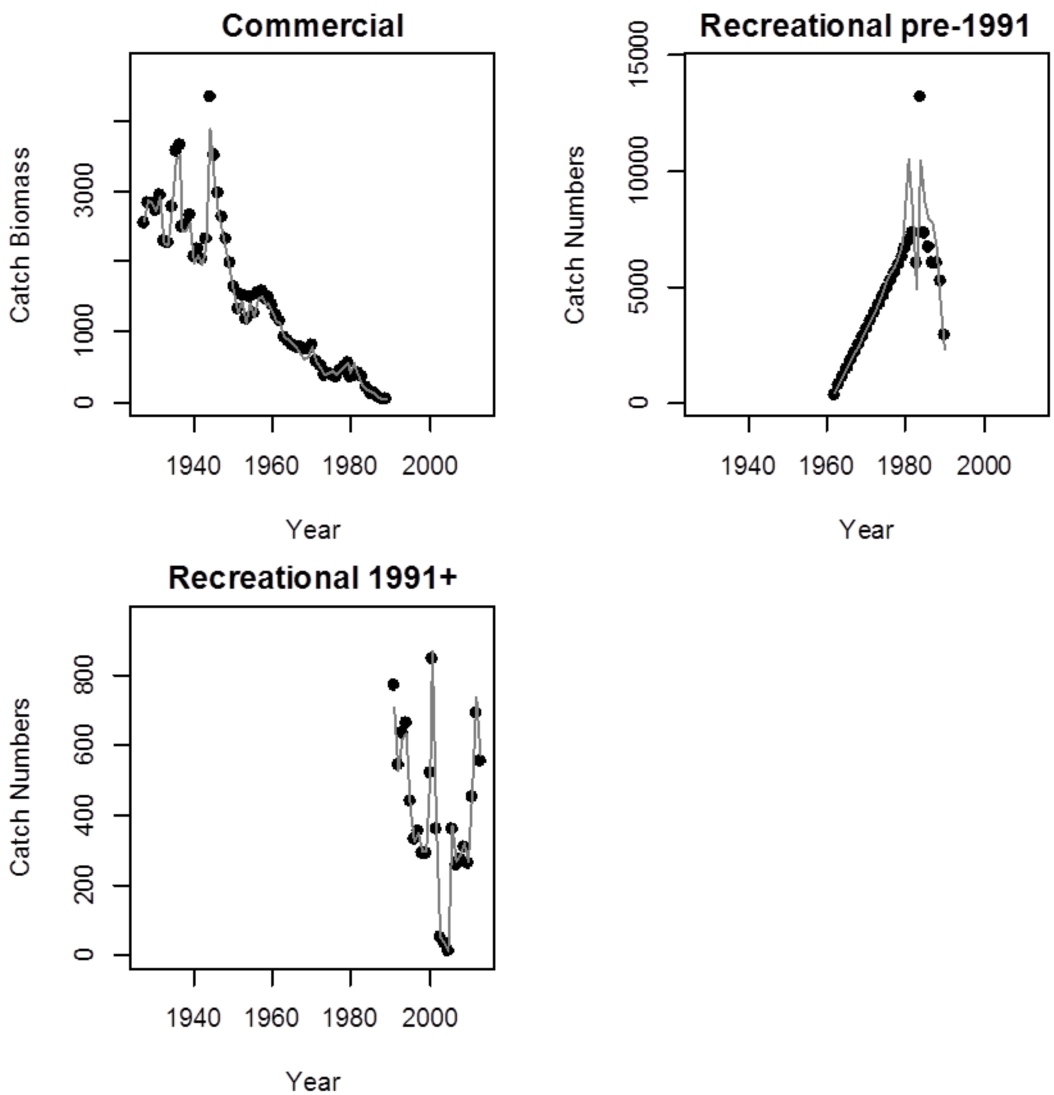


Figure E.22. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the SoG scenario.

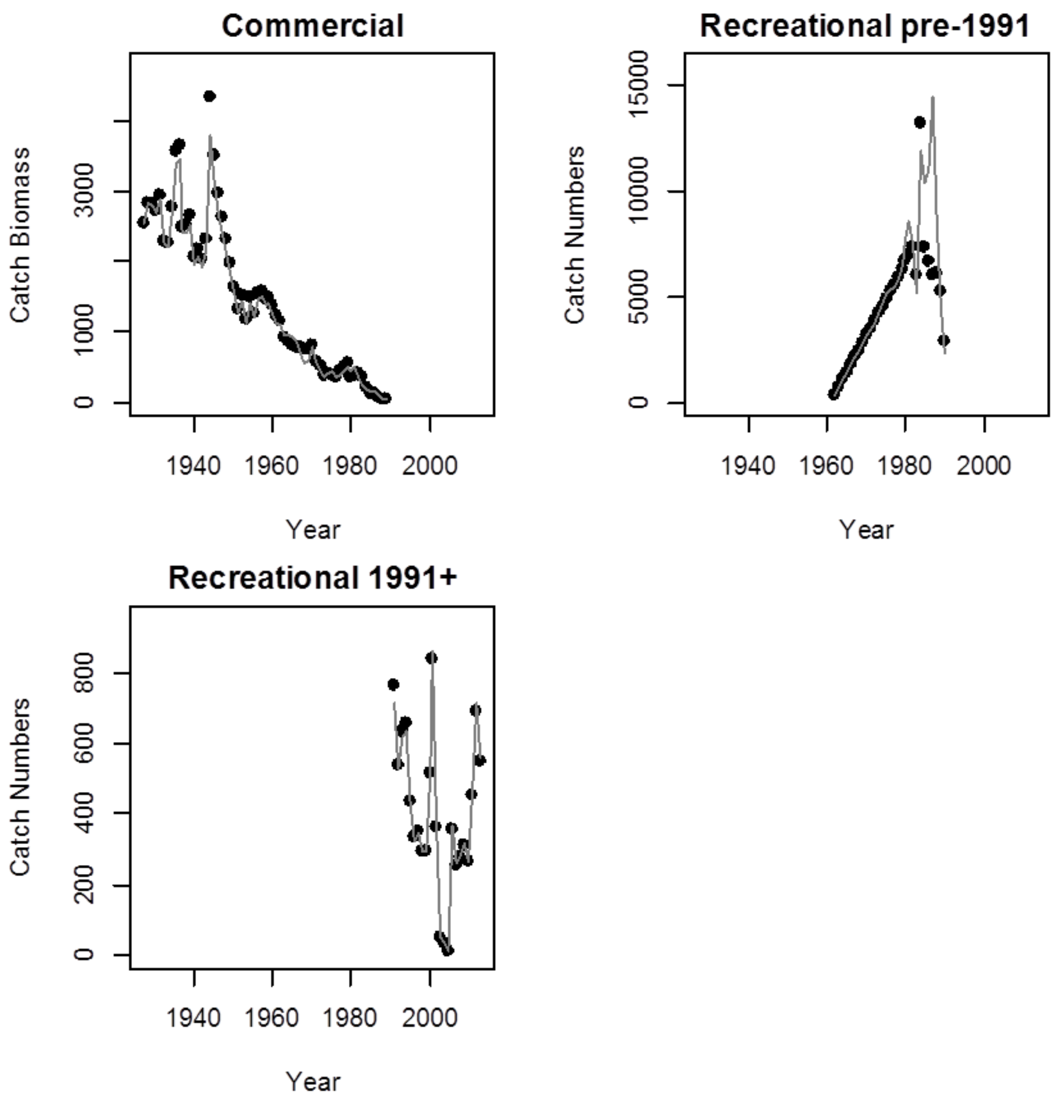


Figure E.23. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the SoG_noDD scenario.

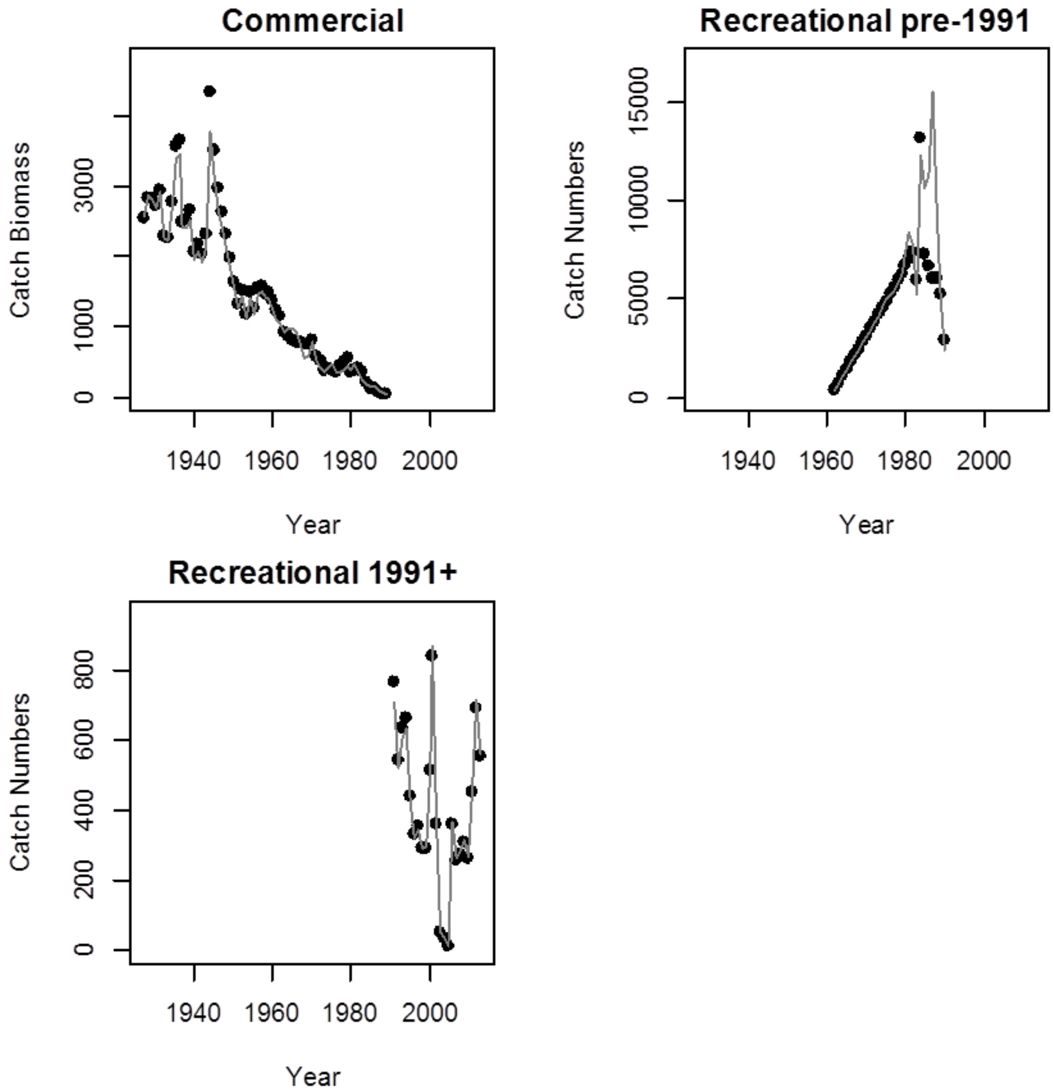


Figure E.24. Catch observations (points) with MPD model fits (solid line) for each of the three gear types in the SoG_noDD+highM scenario.

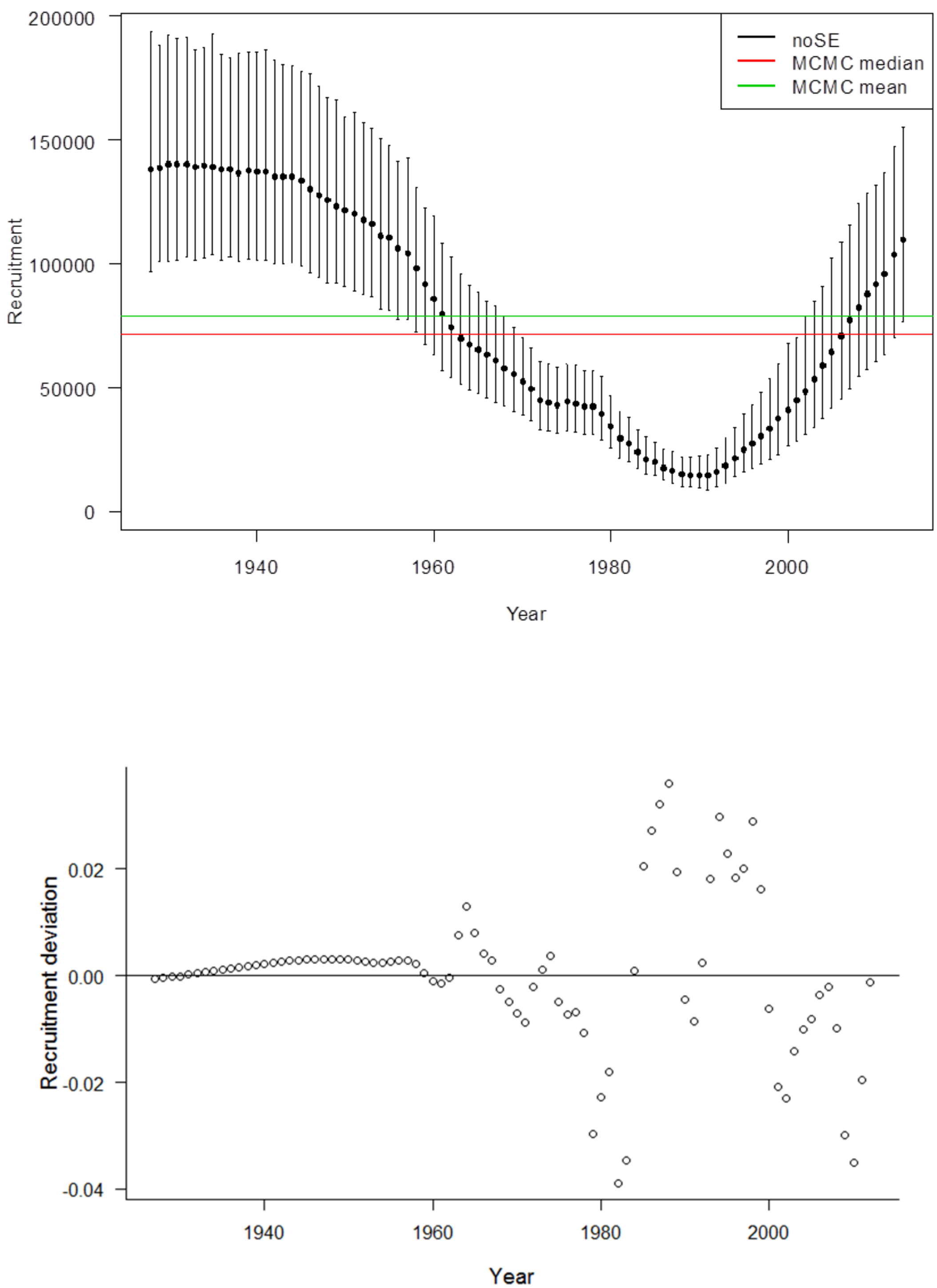
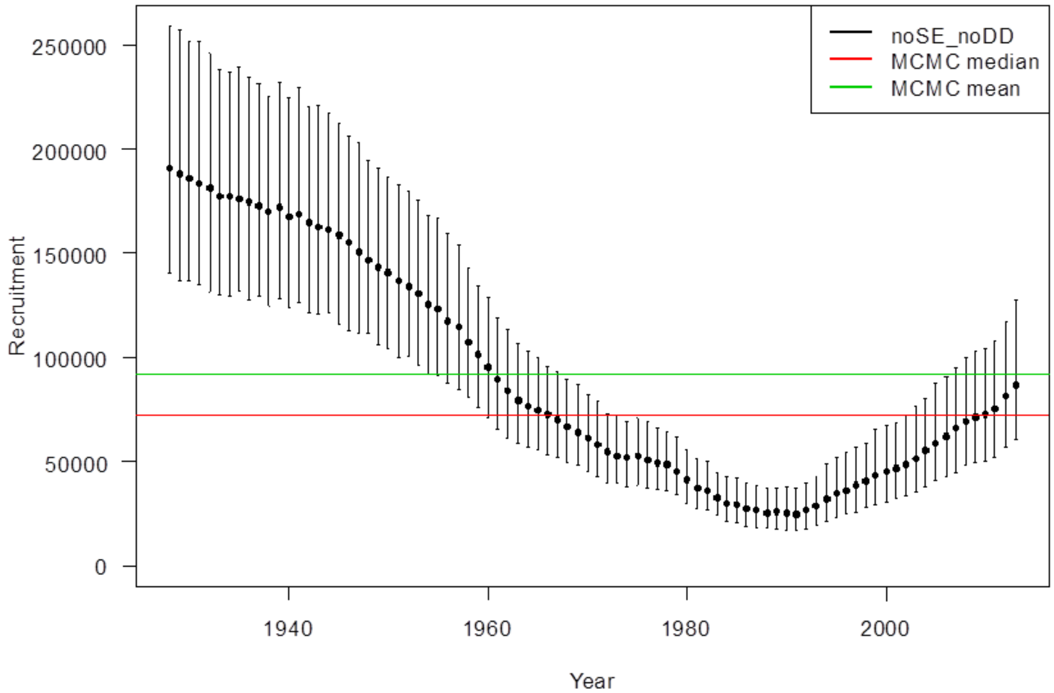


Figure E.25. Top: posterior distributions for recruitment (in numbers) over time in the noSE scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



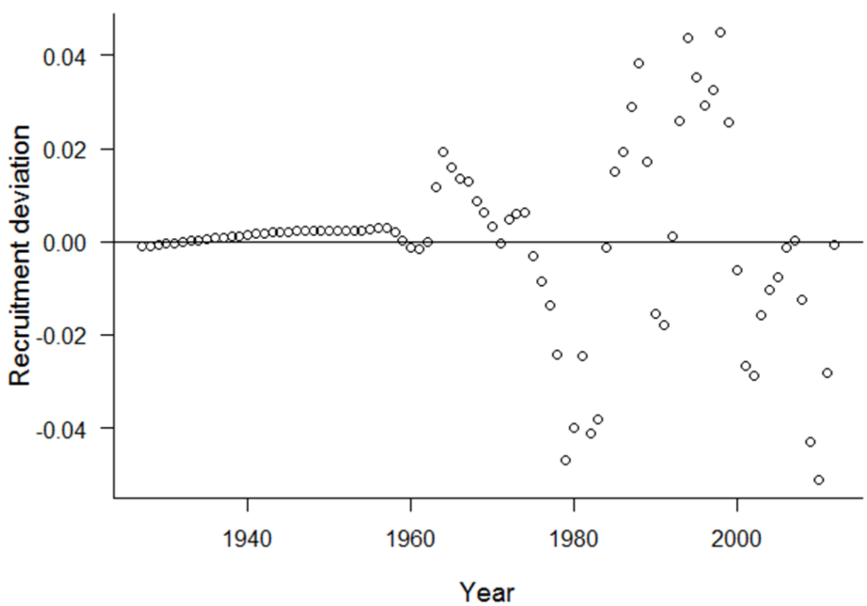
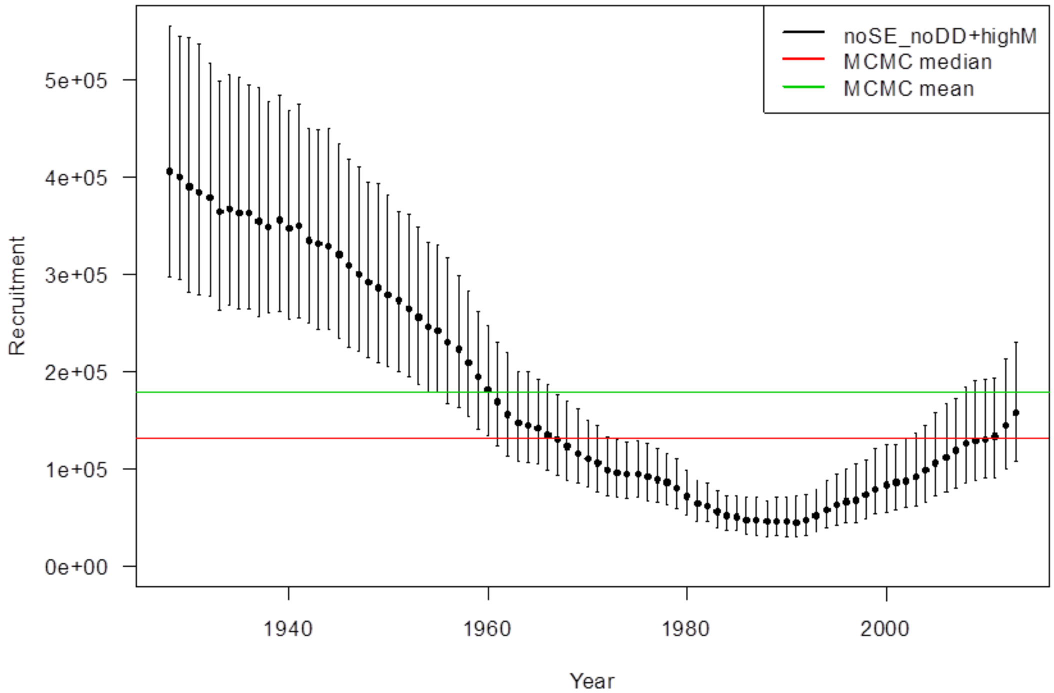


Figure E.26. Top: posterior distributions for recruitment (in numbers) over time in the noSE_noDD scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



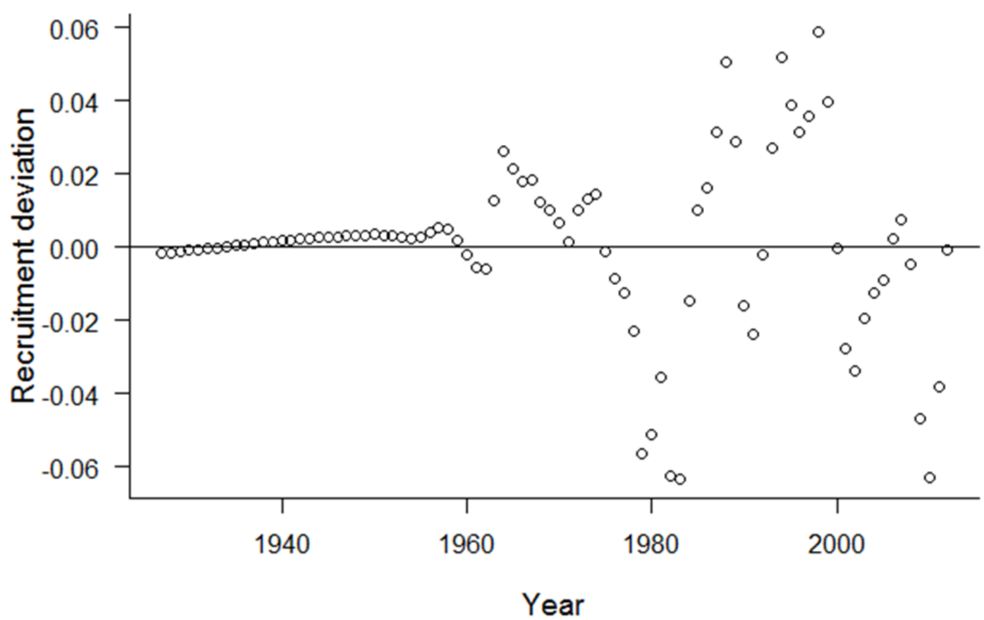


Figure E.27. Top: posterior distributions for recruitment (in numbers) over time in the noSE_noDD+highM scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.

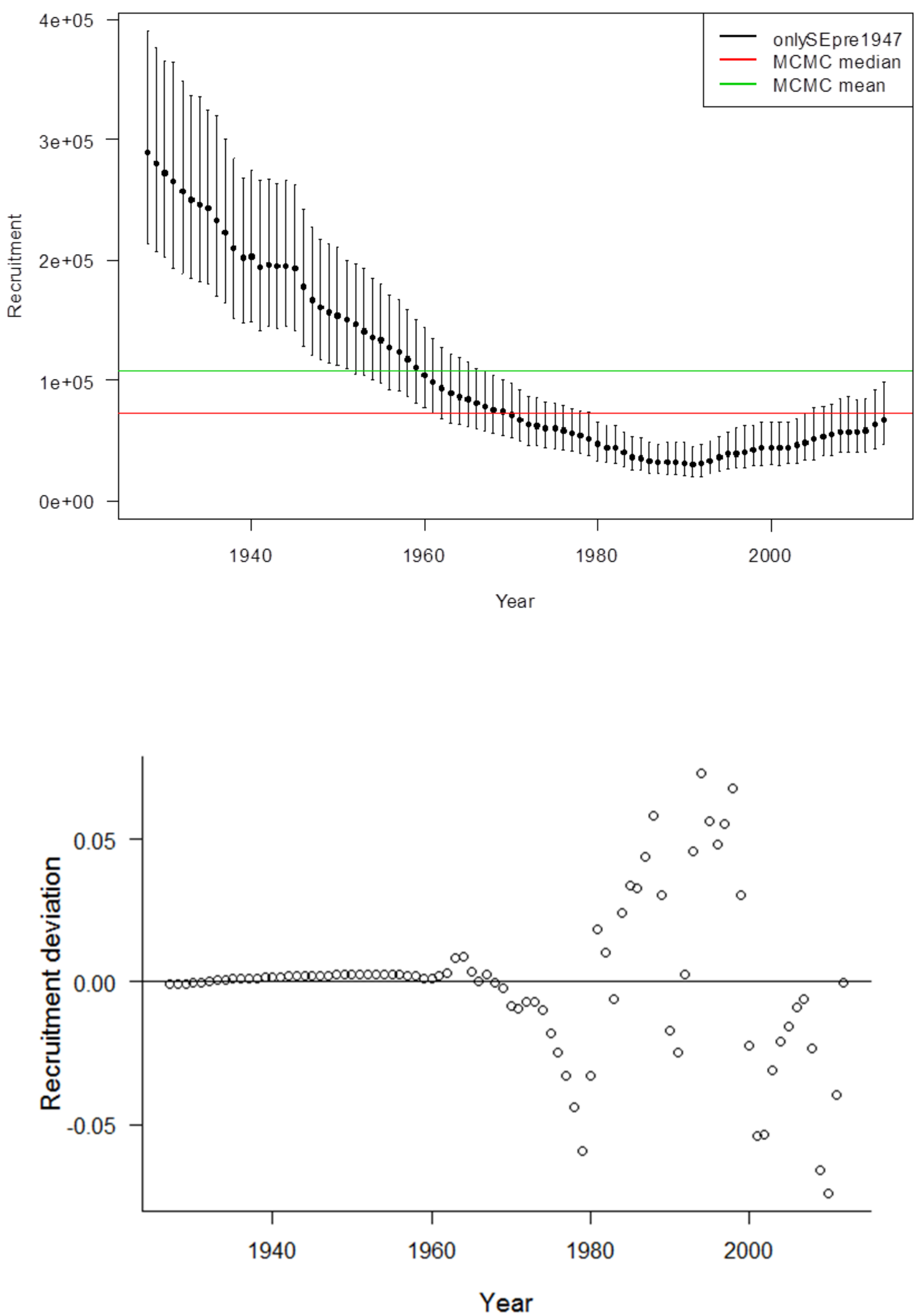
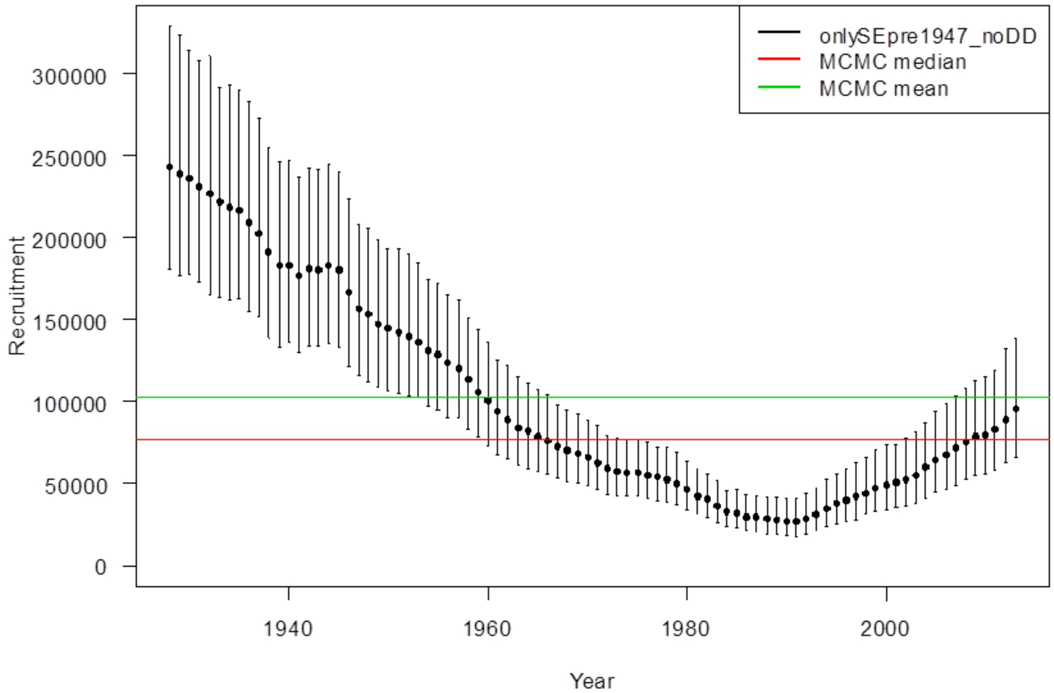


Figure E.28. Top: posterior distributions for recruitment (in numbers) over time in the onlySEpre1947 scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



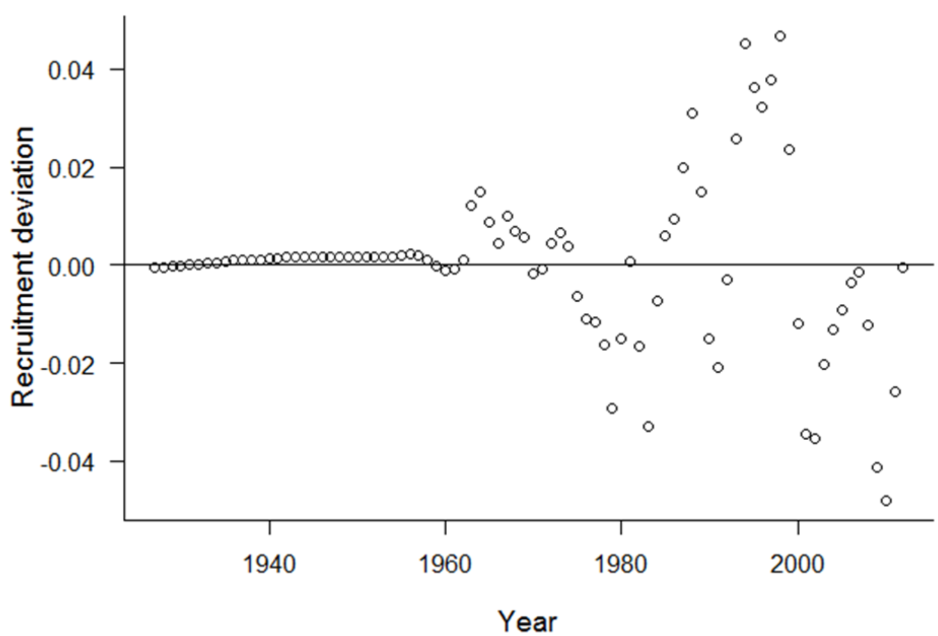
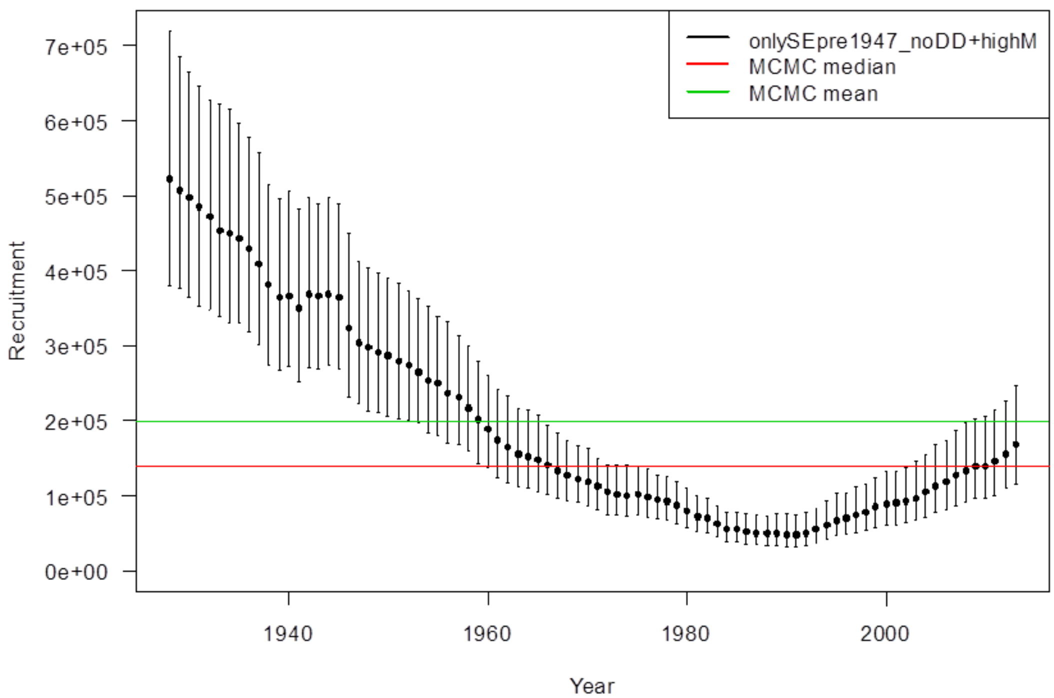


Figure E.29. Top: posterior distributions for recruitment (in numbers) over time in the onlySEpre1947_noDD scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



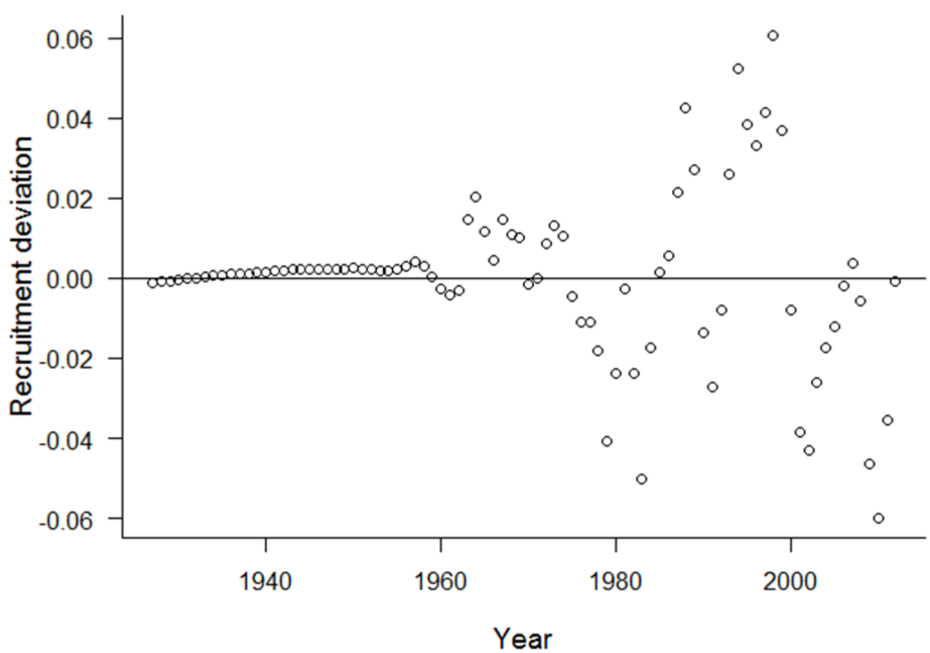
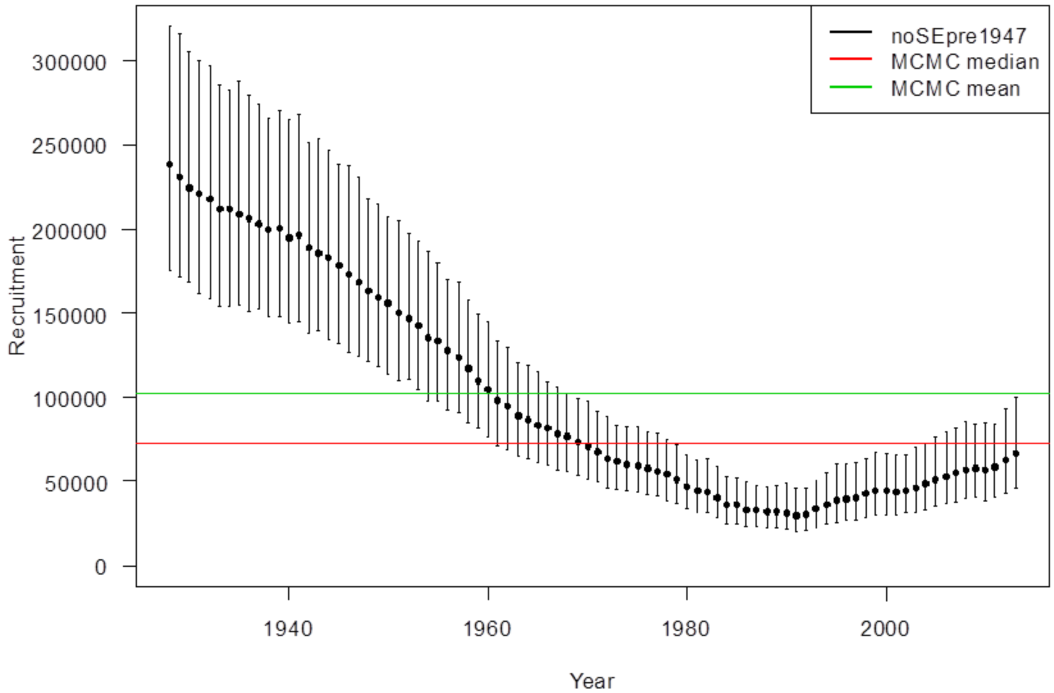


Figure E.30. Top: posterior distributions for recruitment (in numbers) over time in the onlySEpre1947_noDD+highM scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



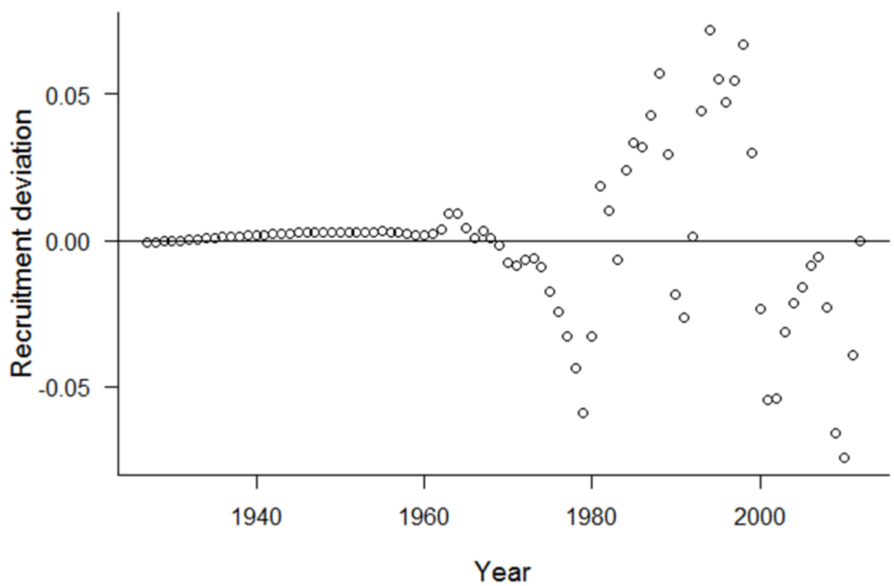
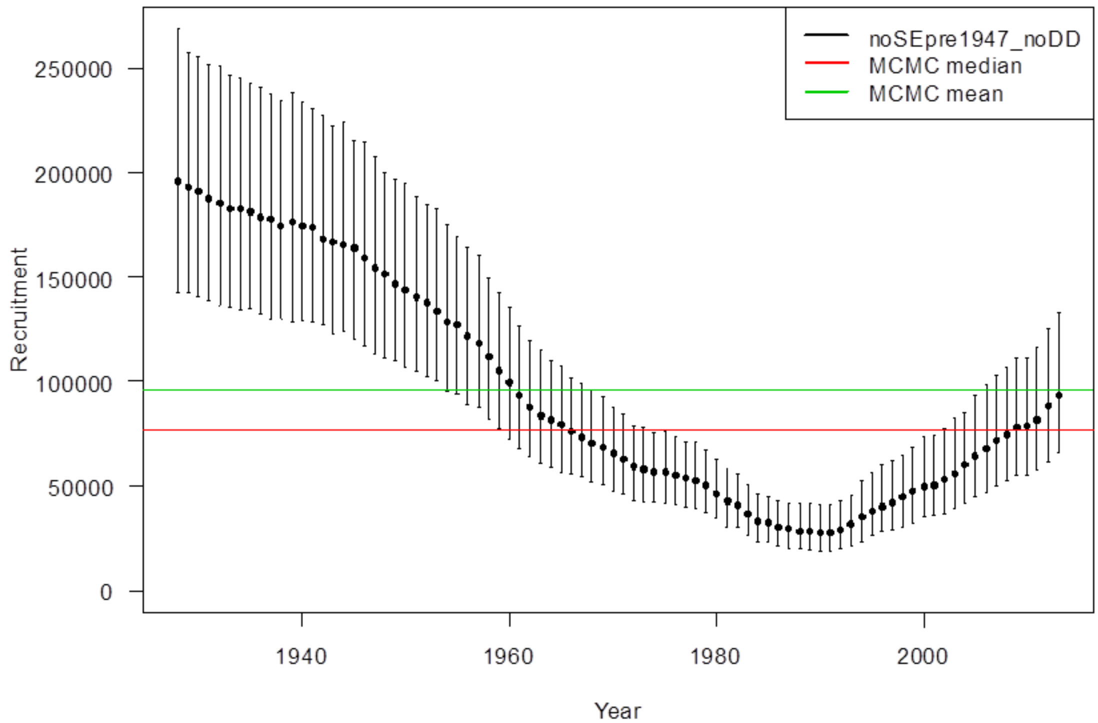


Figure E.31. Top: posterior distributions for recruitment (in numbers) over time in the noSEpre1947 scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



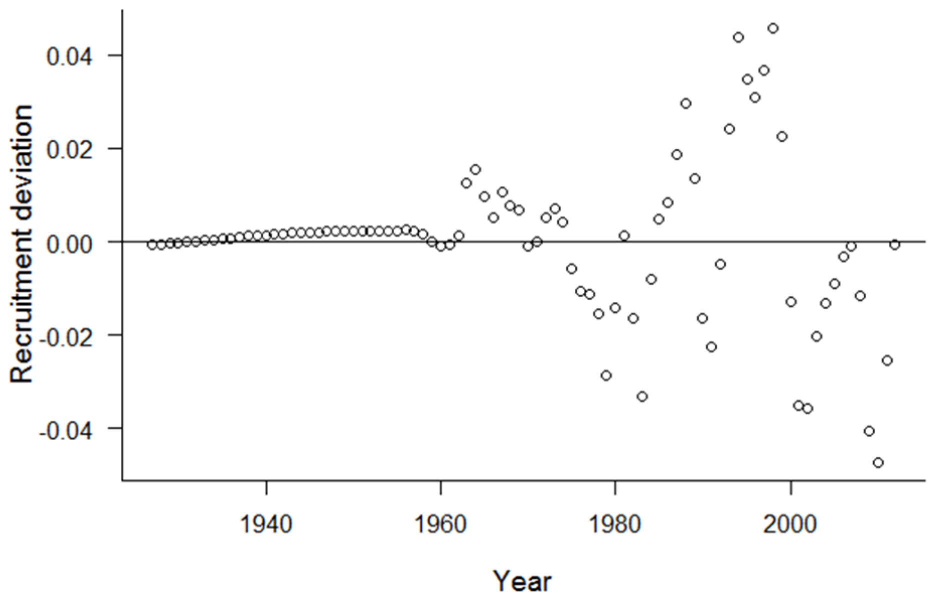


Figure E.32. Top: posterior distributions for recruitment (in numbers) over time in the noSEpre1947_noDD scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.

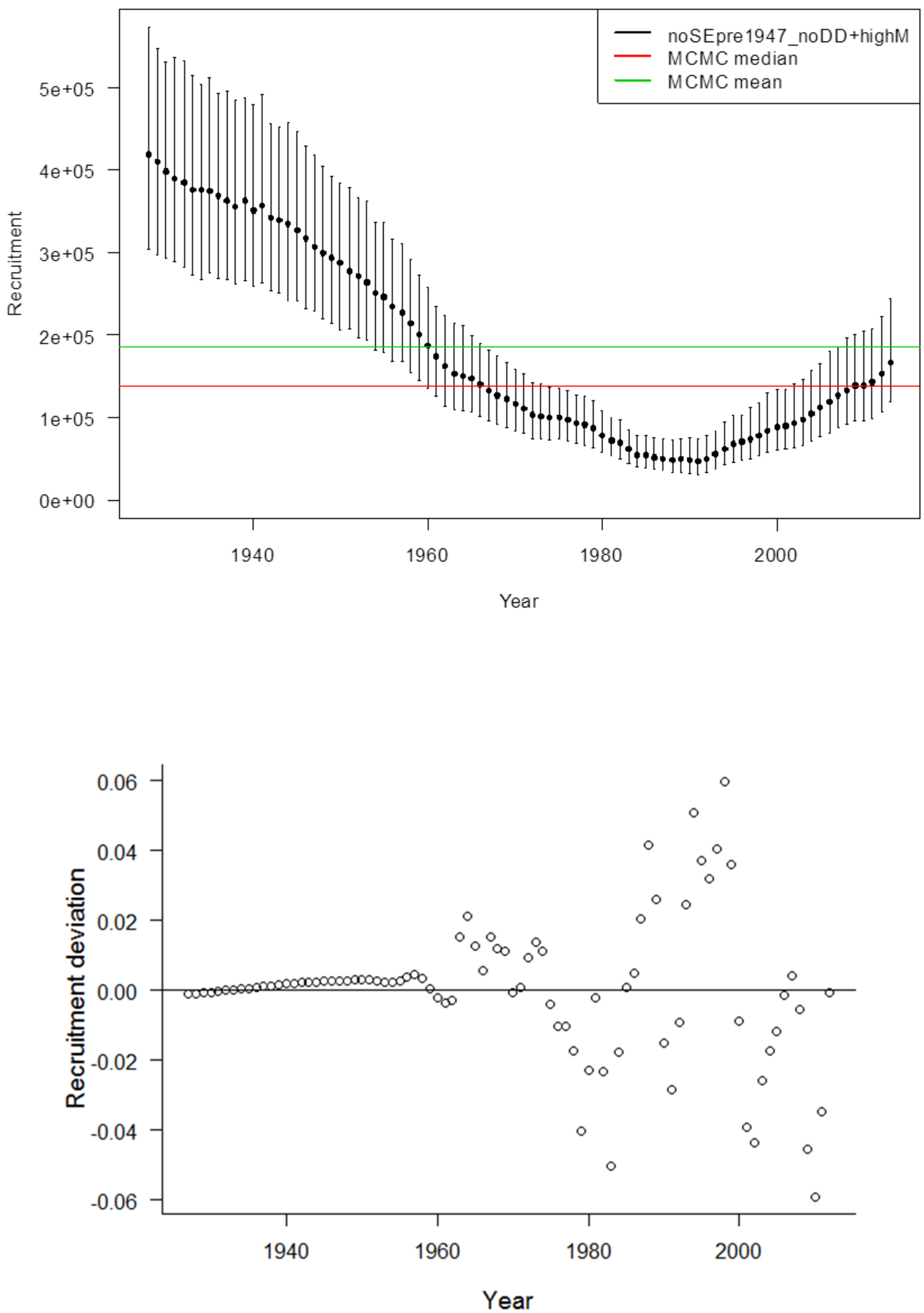
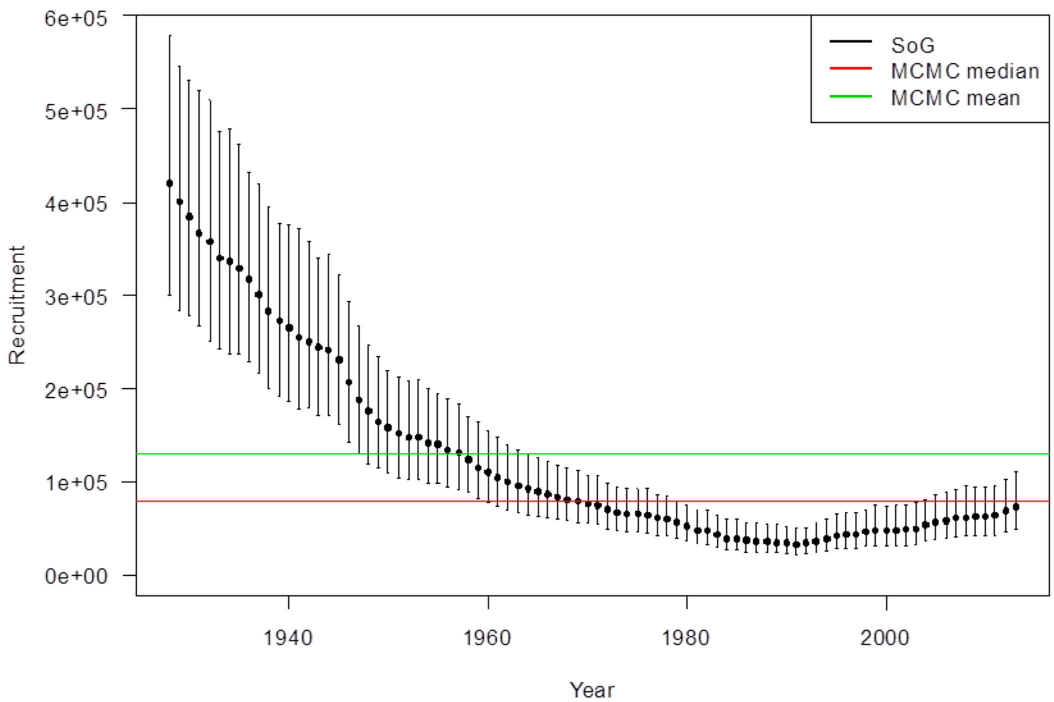


Figure E.33. Top: posterior distributions for recruitment (in numbers) over time in the noSEpre1947_noDD+highM scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



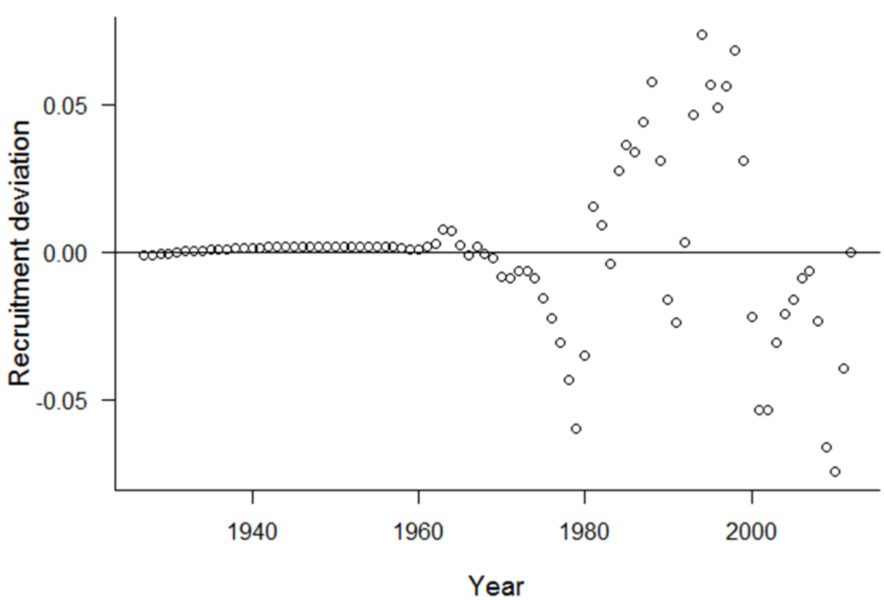
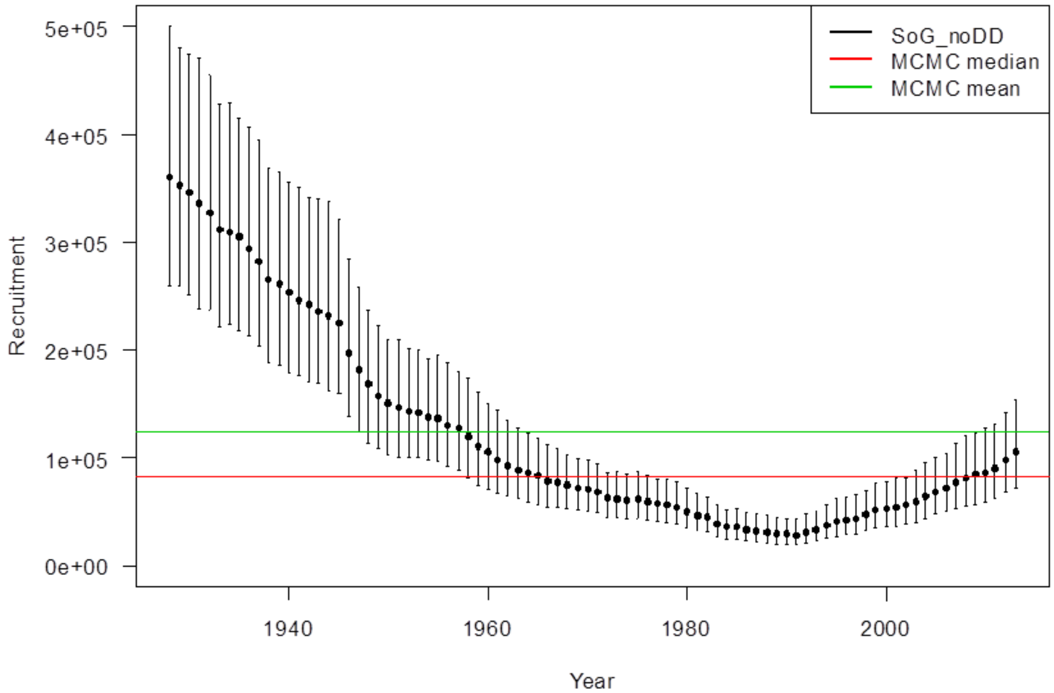


Figure E.34. Top: posterior distributions for recruitment (in numbers) over time in the SoG scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



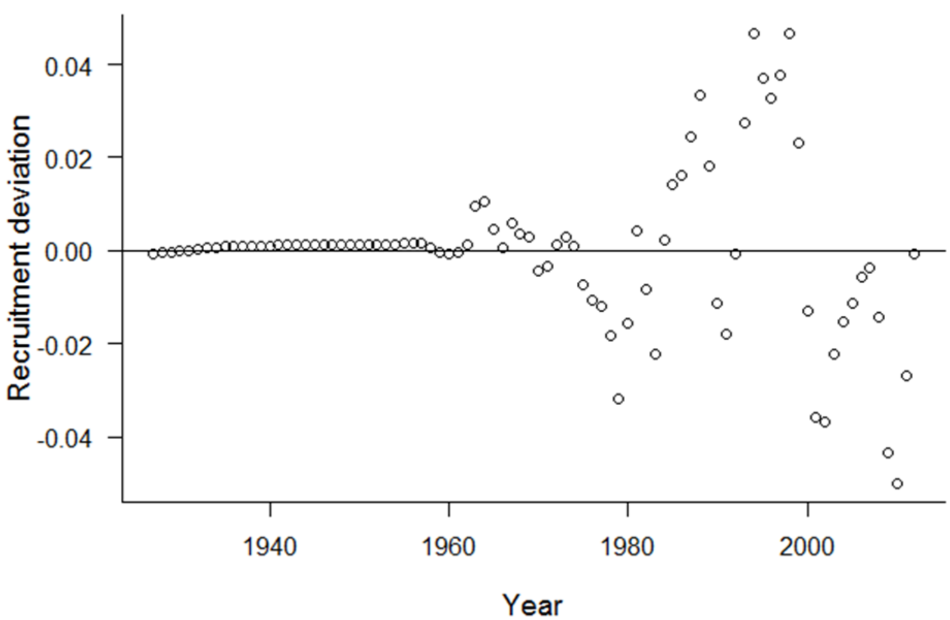
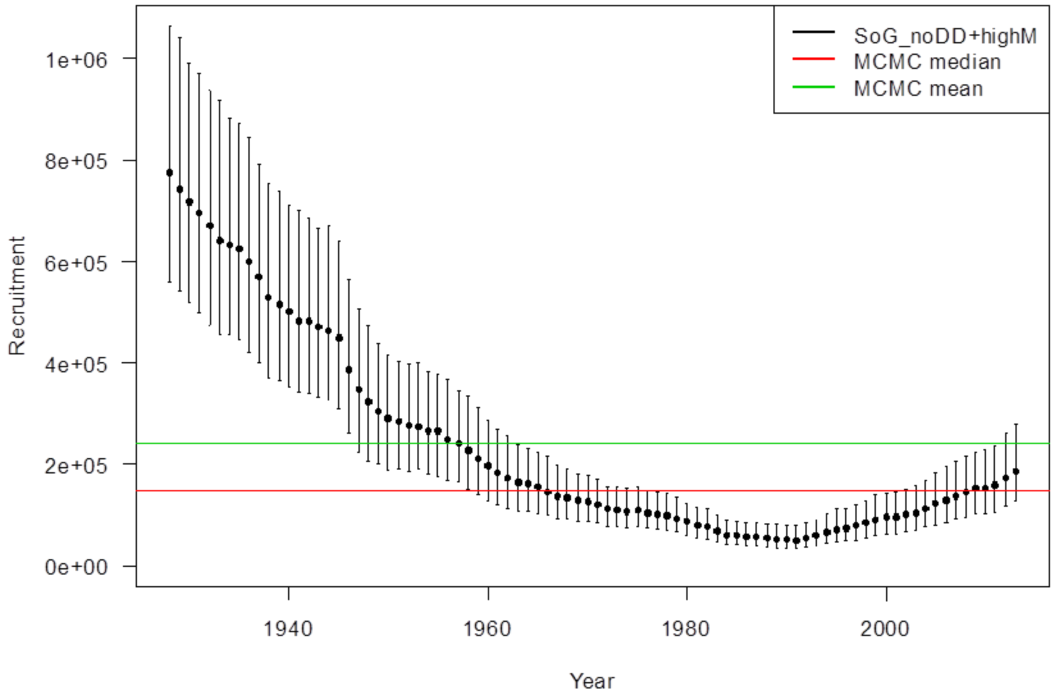


Figure E.35. Top: posterior distributions for recruitment (in numbers) over time in the SoG_noDD scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.



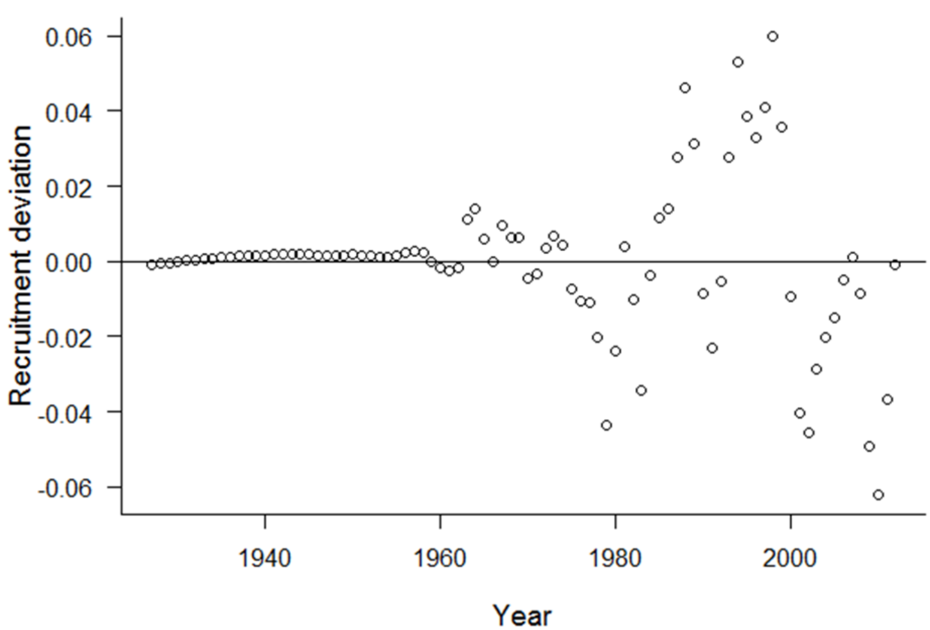


Figure E.36. Top: posterior distributions for recruitment (in numbers) over time in the SoG_noDD+highM scenario, represented as the median posterior estimate (points) and 95% credibility interval (error bars). Also shown are the long-term median recruitment and mean recruitment levels. Bottom: log of annual recruitment deviations, ω_t, from the MDP fit for the same scenario.

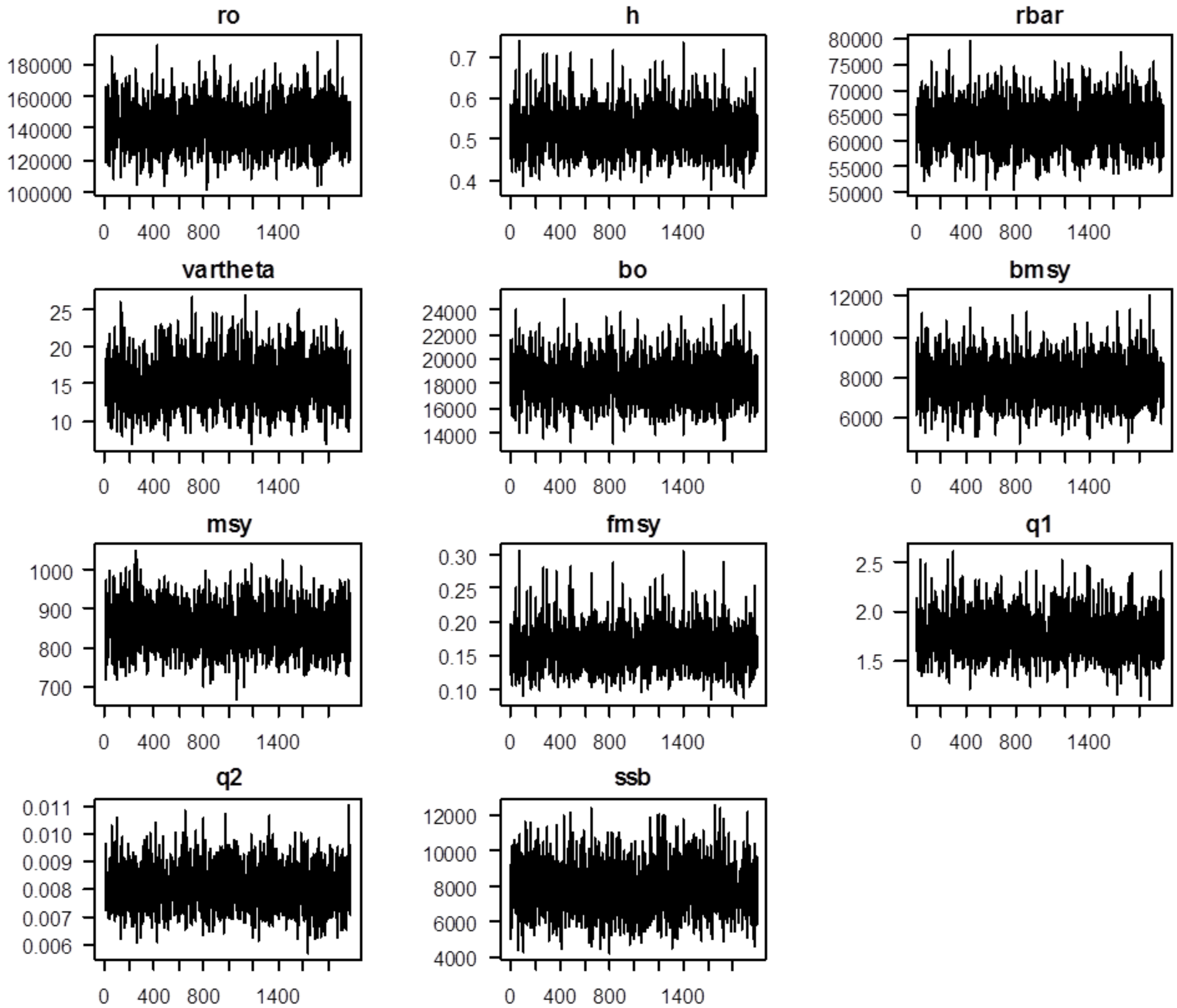


Figure E.37. MCMC traces for estimated parameters in the noSE scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

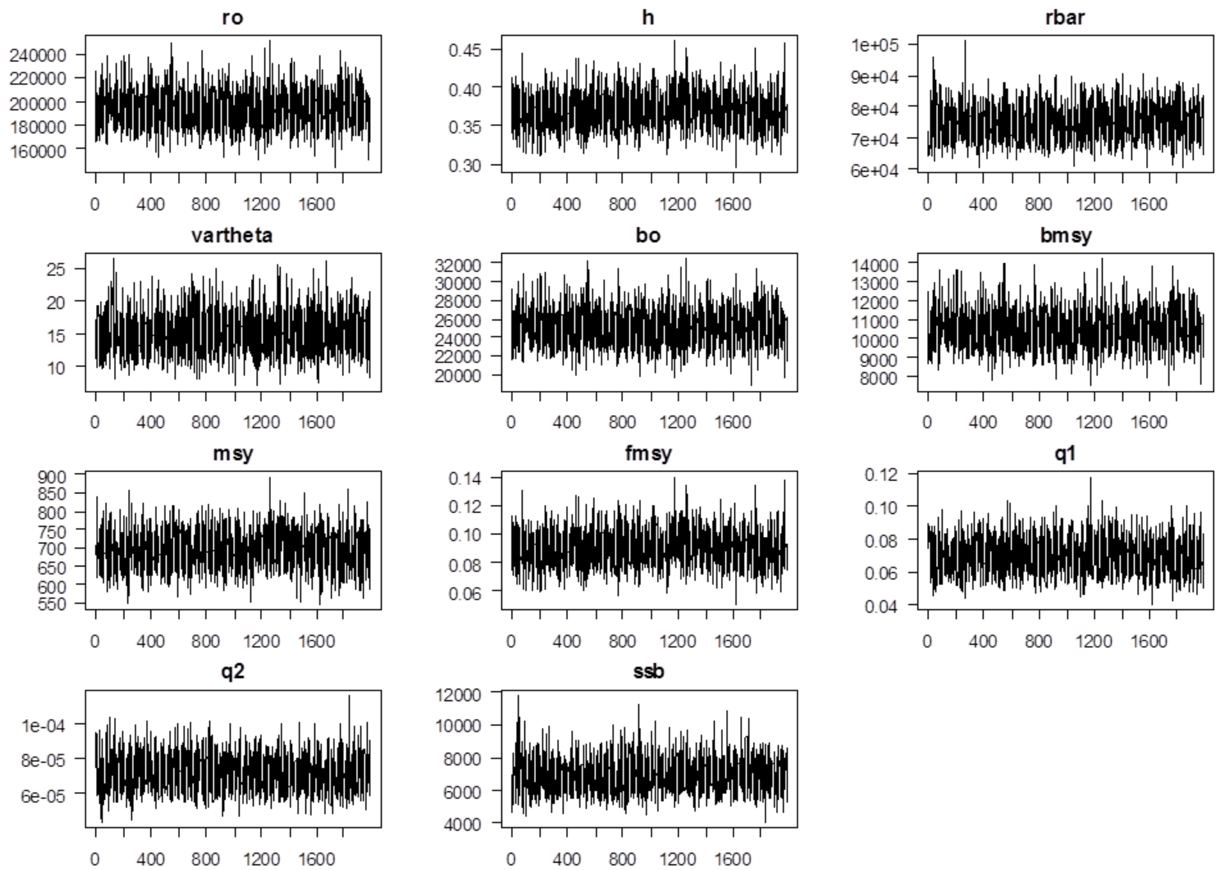


Figure E.38. MCMC traces for estimated parameters in the noSE_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

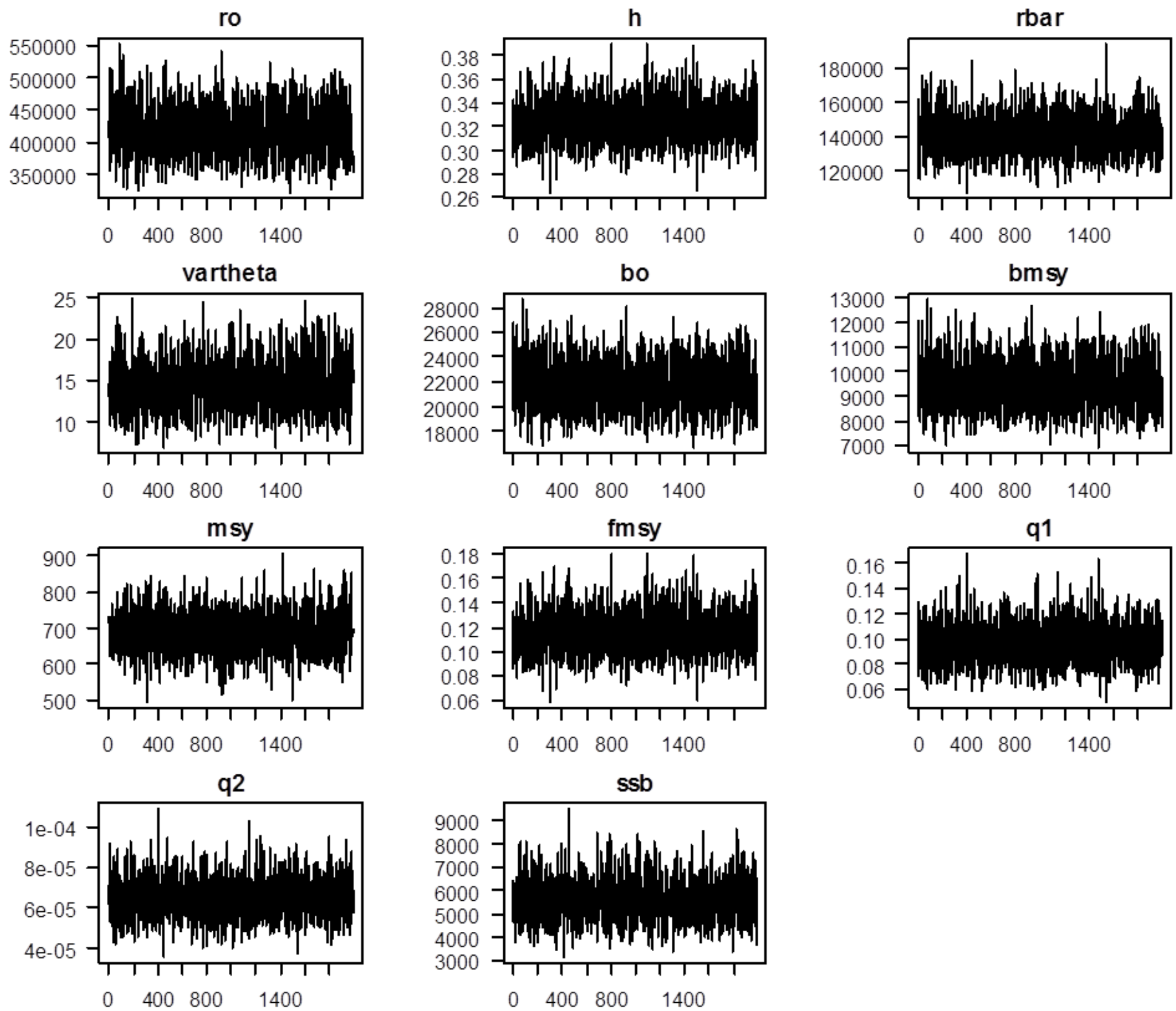


Figure E.39. MCMC traces for estimated parameters in the noSE_noDD+highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

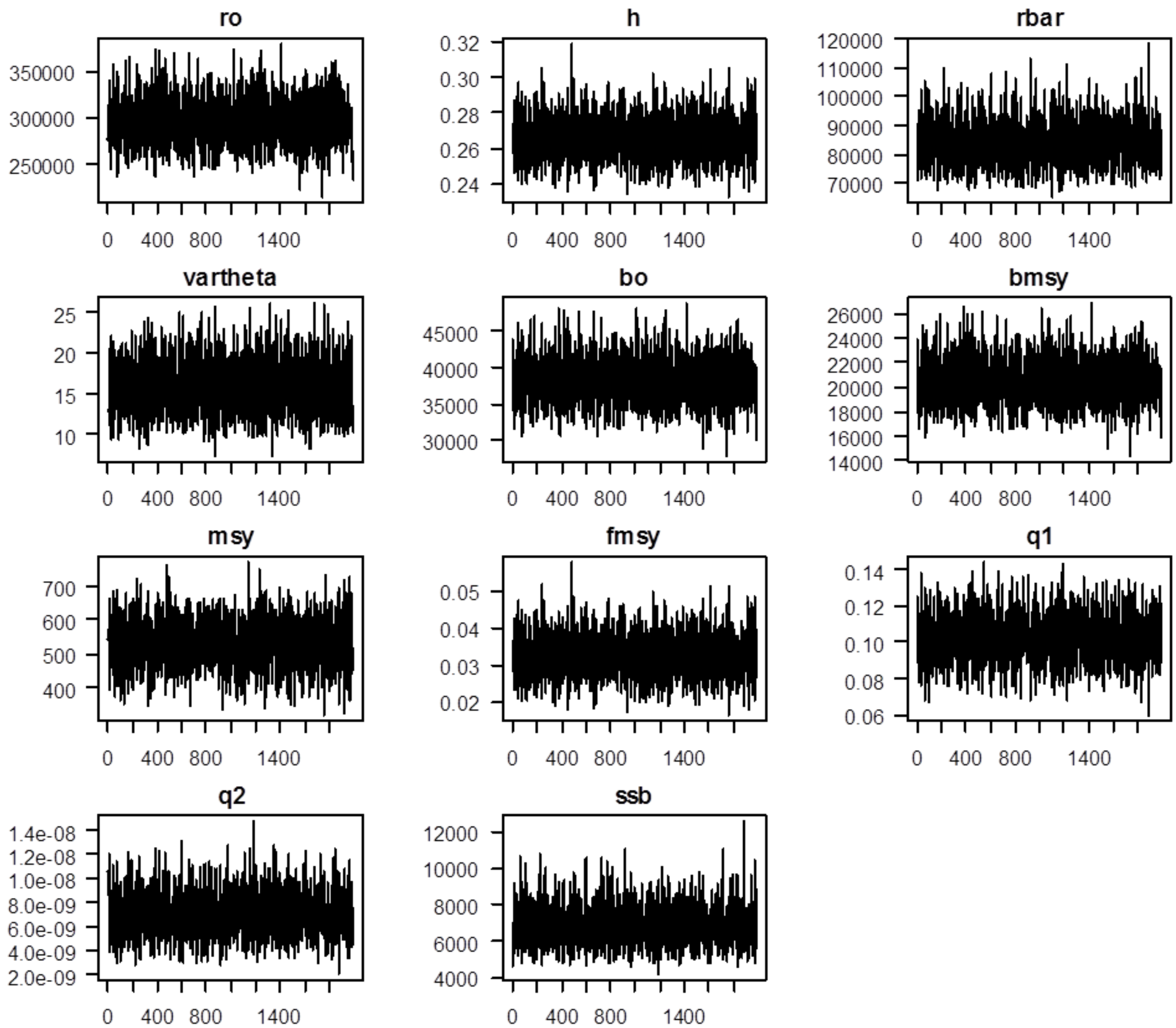


Figure E.40. MCMC traces for estimated parameters in the onlySEpre1947 scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

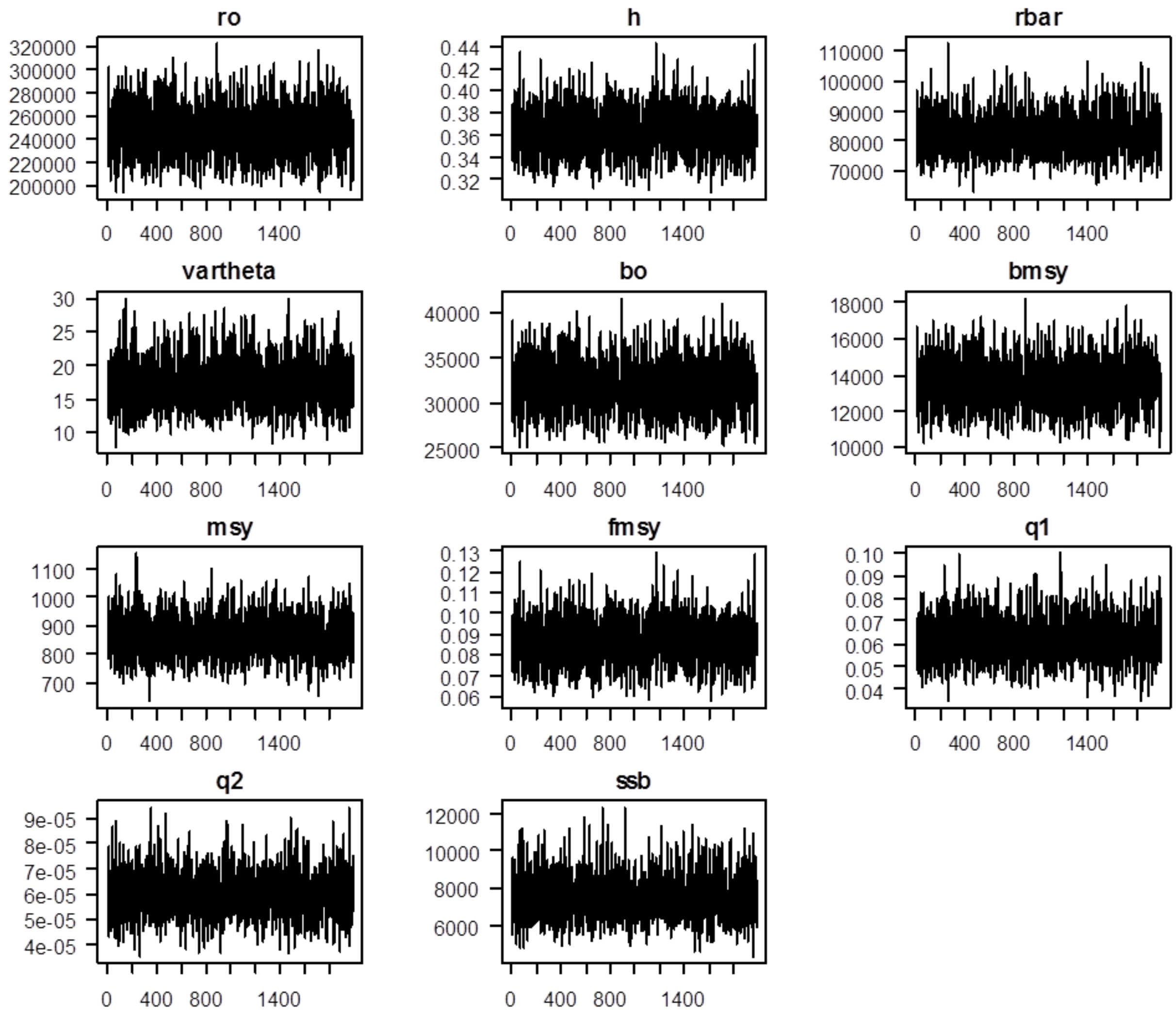


Figure E.41. MCMC traces for estimated parameters in the onlySEpre1947_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

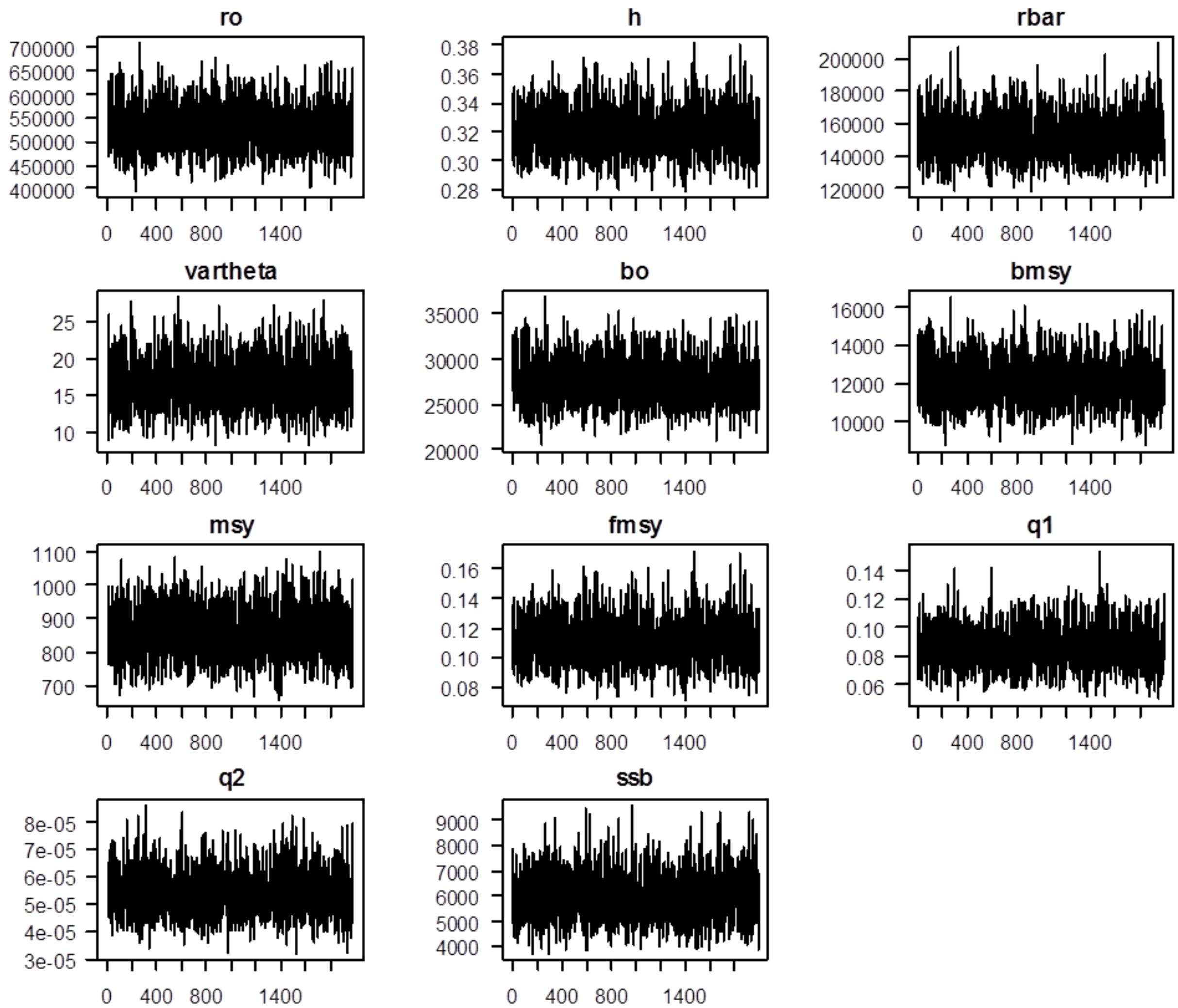


Figure E.42. MCMC traces for estimated parameters in the onlySEpre1947_noDD+highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

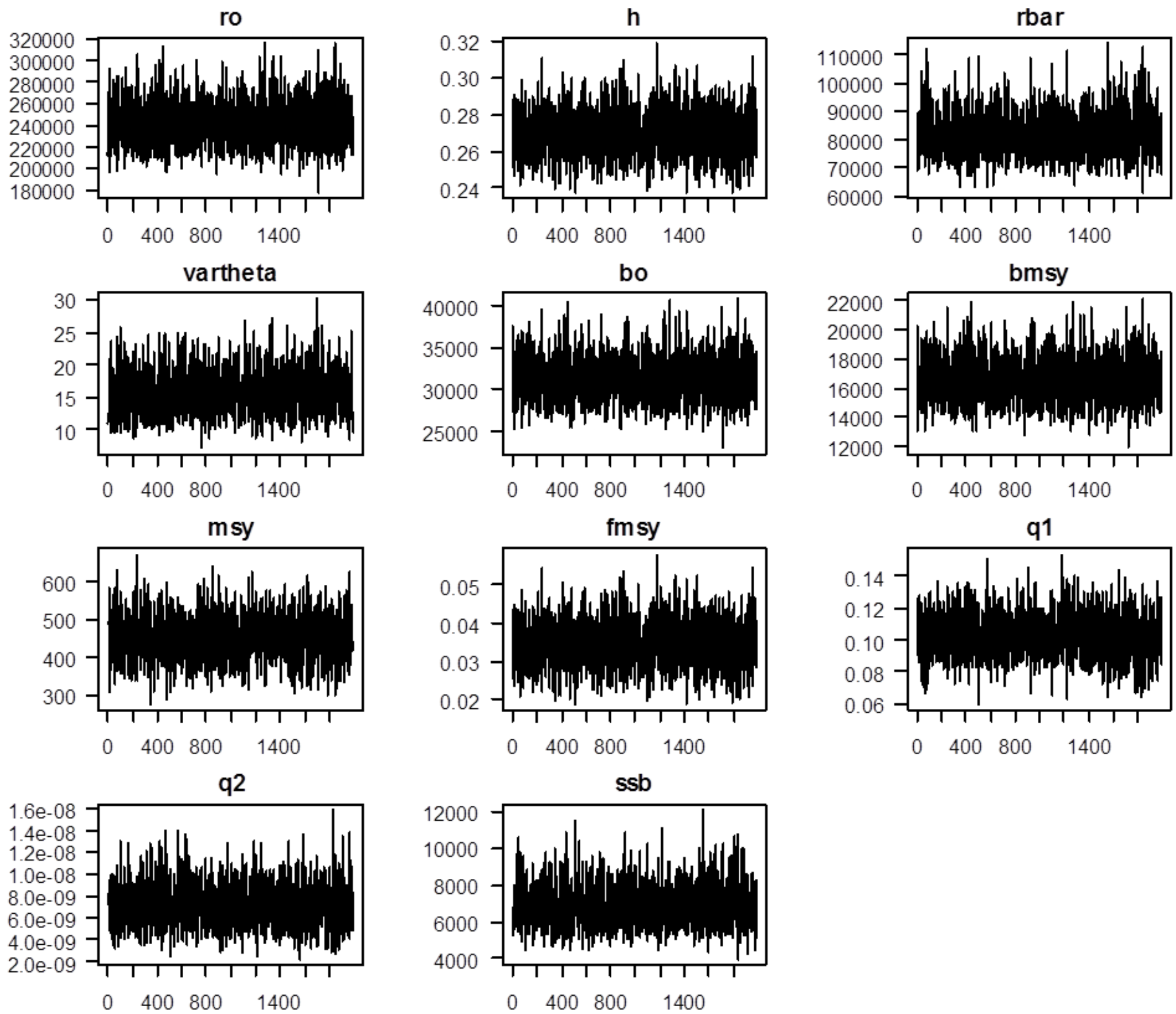


Figure E.43. MCMC traces for estimated parameters in the noSEpre1947 scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

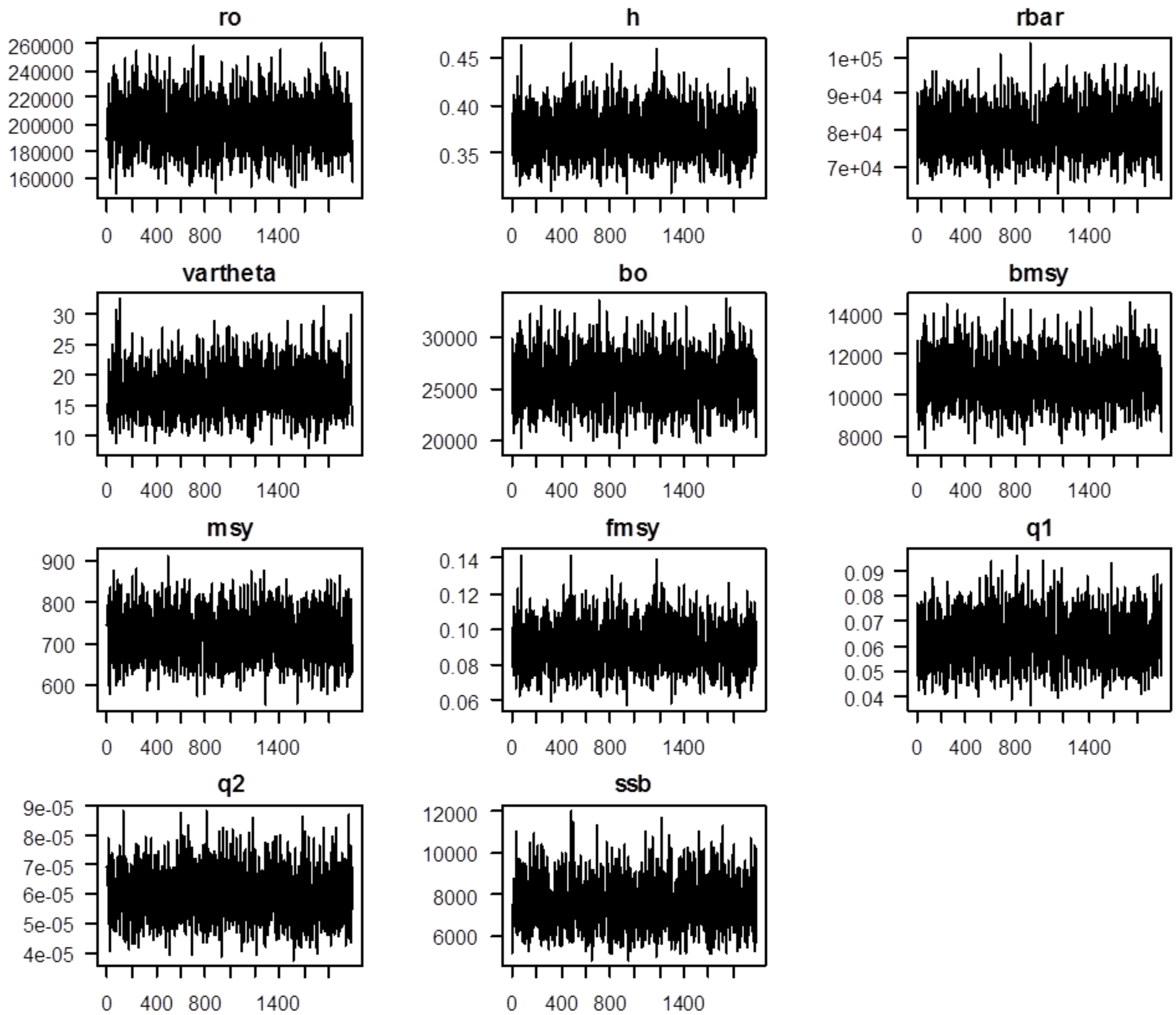


Figure E.44. MCMC traces for estimated parameters in the noSEpre1947_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

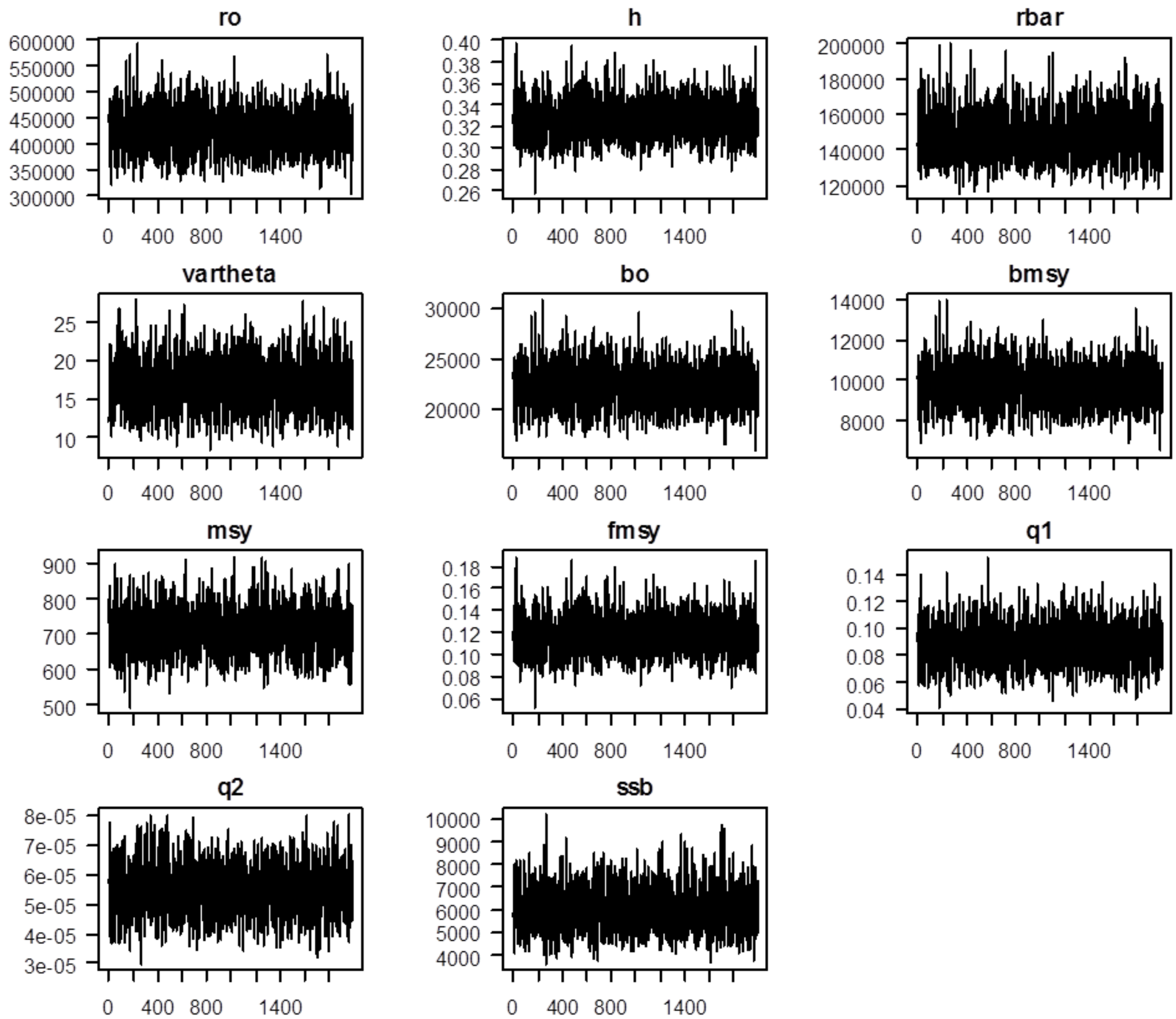


Figure E.45. MCMC traces for estimated parameters in the noSEpre1947_noDD_highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

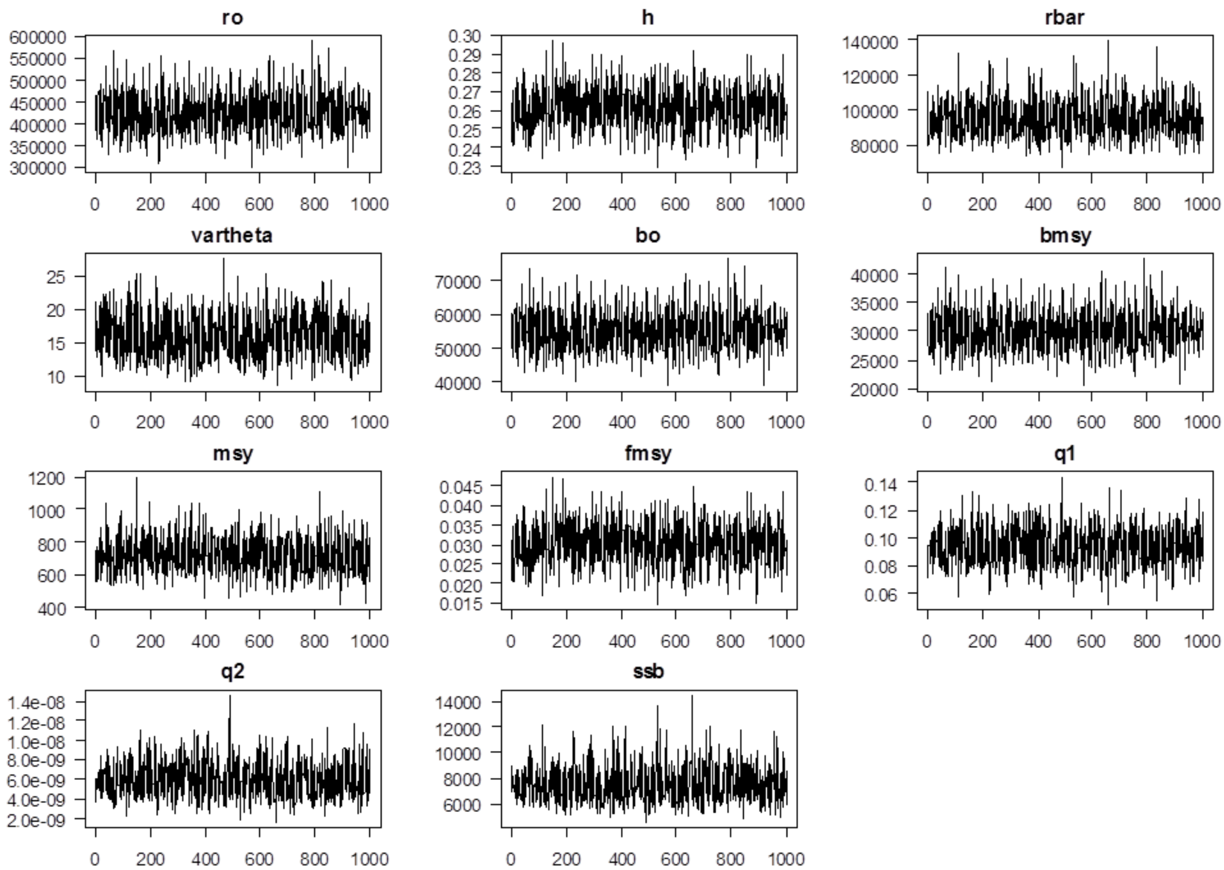


Figure E.46. MCMC traces for estimated parameters in the SoG scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

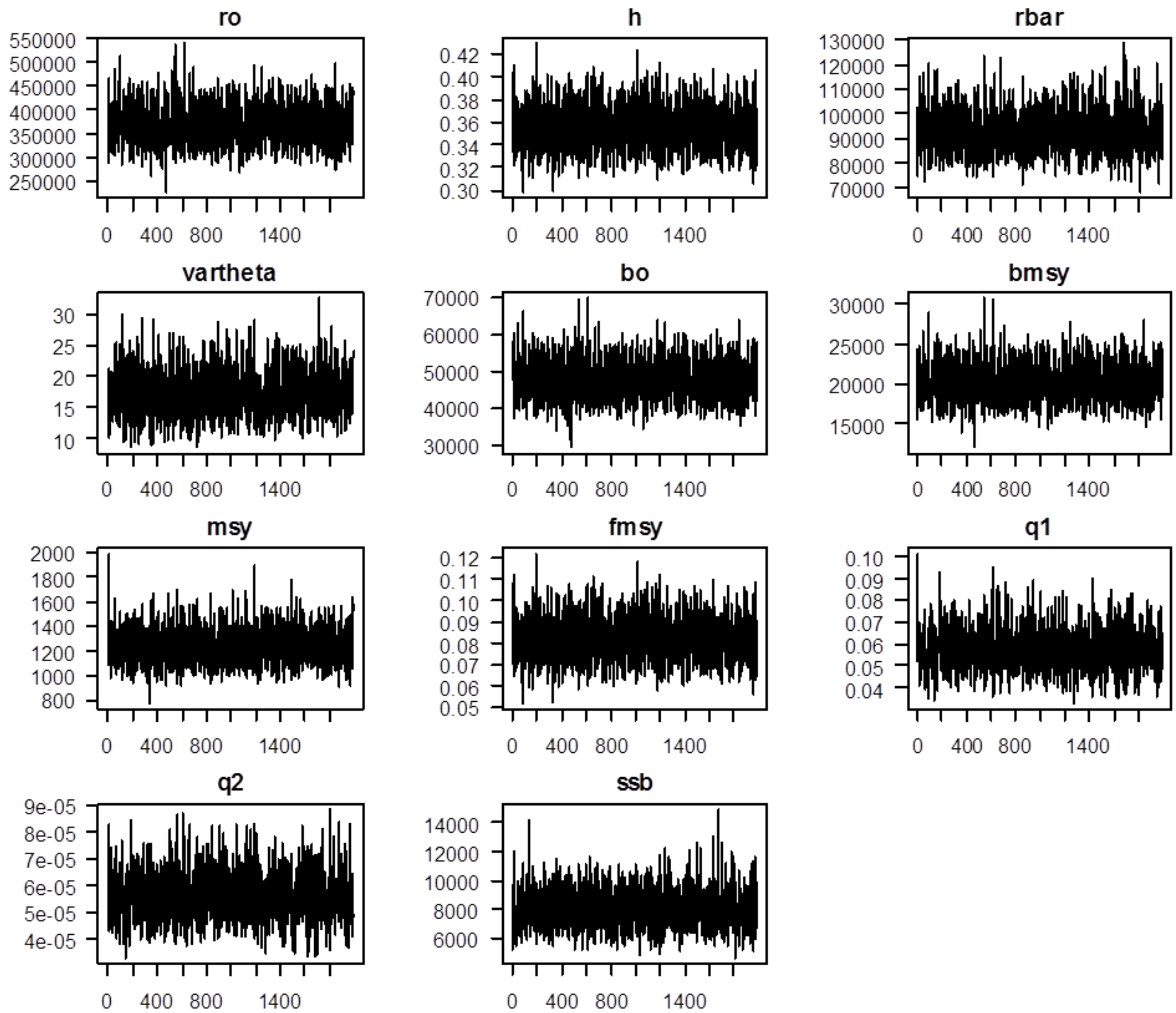


Figure E.47. MCMC traces for estimated parameters in the SoG_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

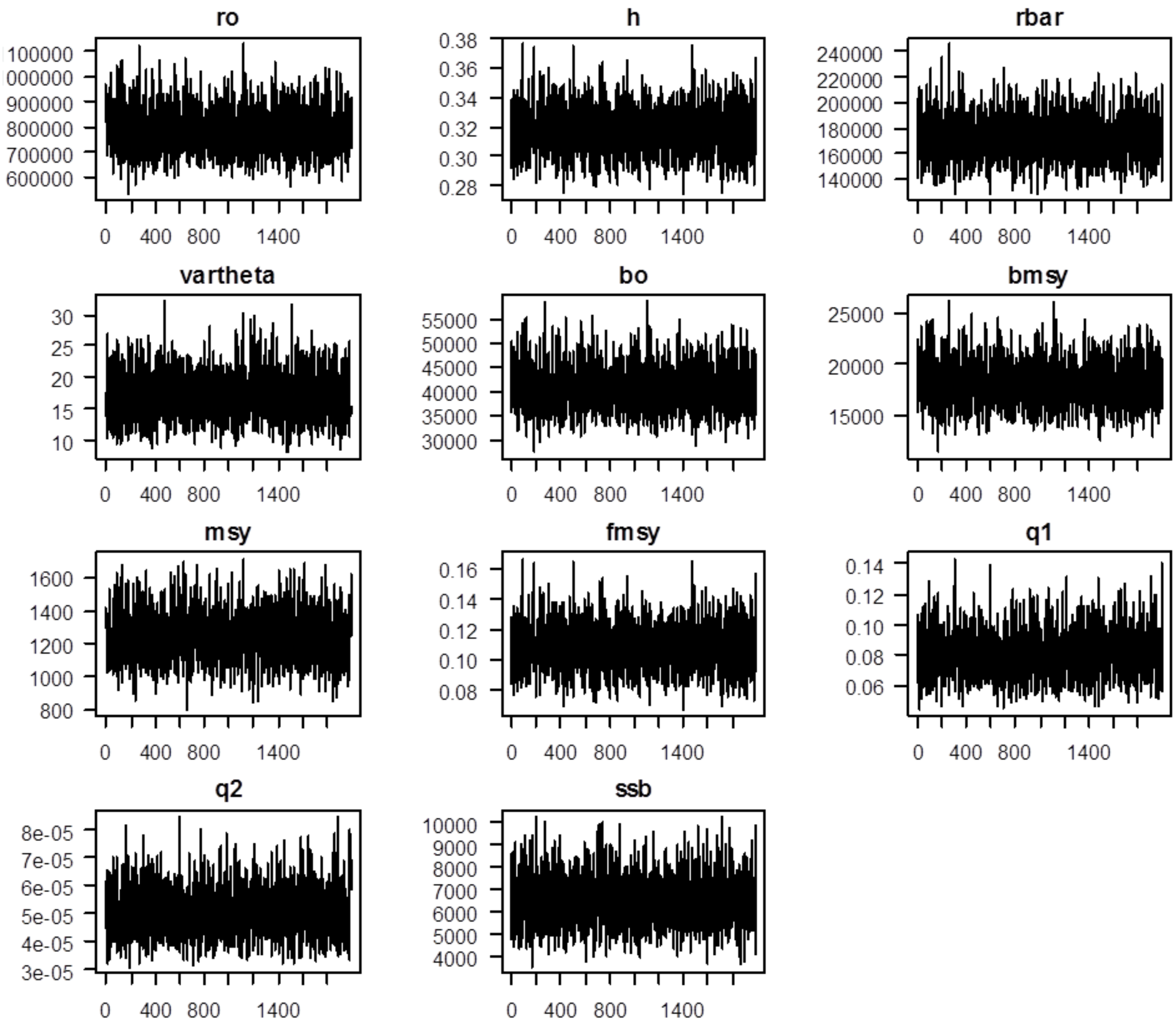


Figure E.48. MCMC traces for estimated parameters in the SoG_noDD+highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

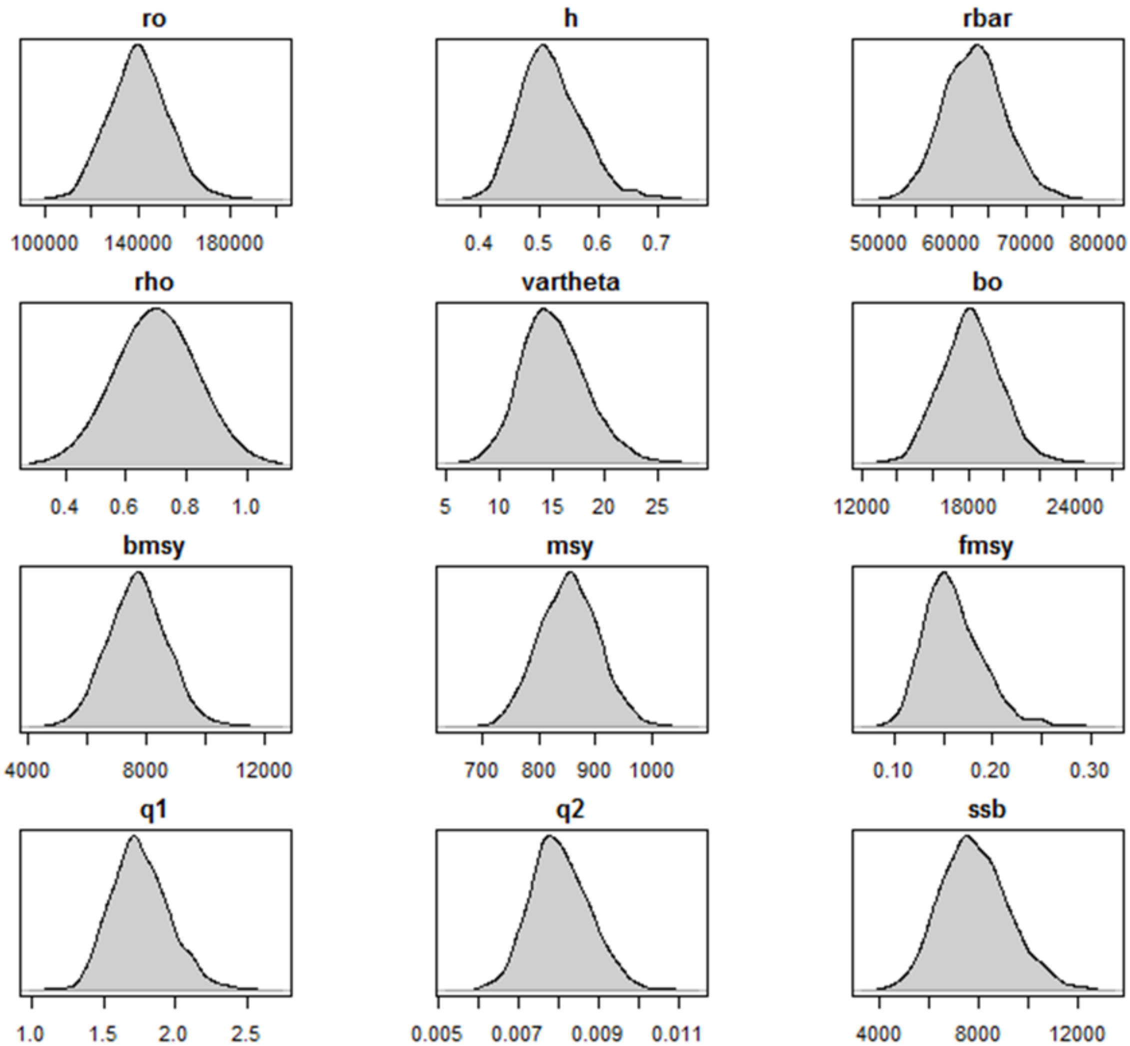


Figure E.49. Marginal posterior densities for estimated model parameters and MSY quantities from the noSE scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

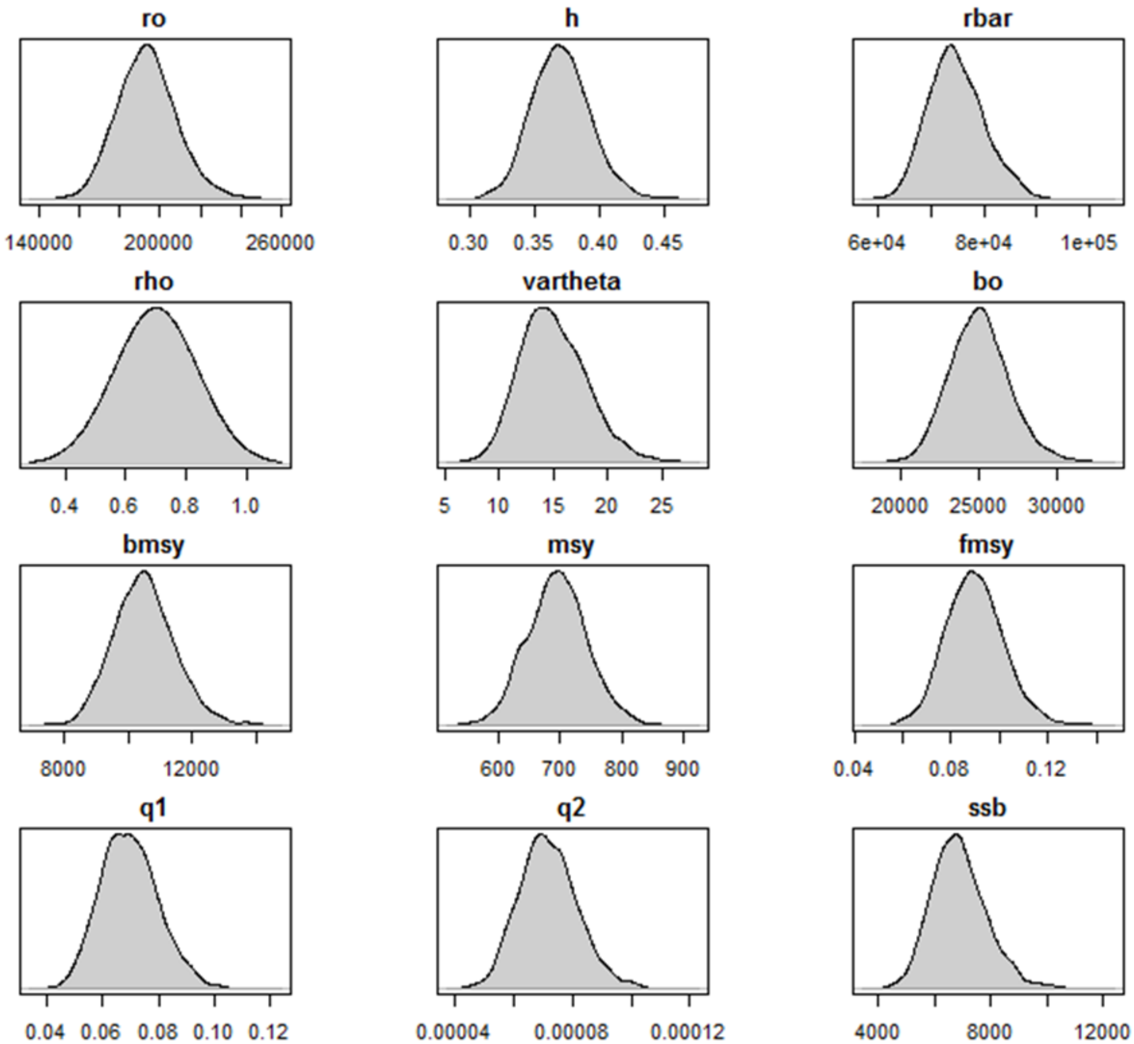


Figure E.50. Marginal posterior densities for estimated model parameters and MSY quantities from the noSE_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

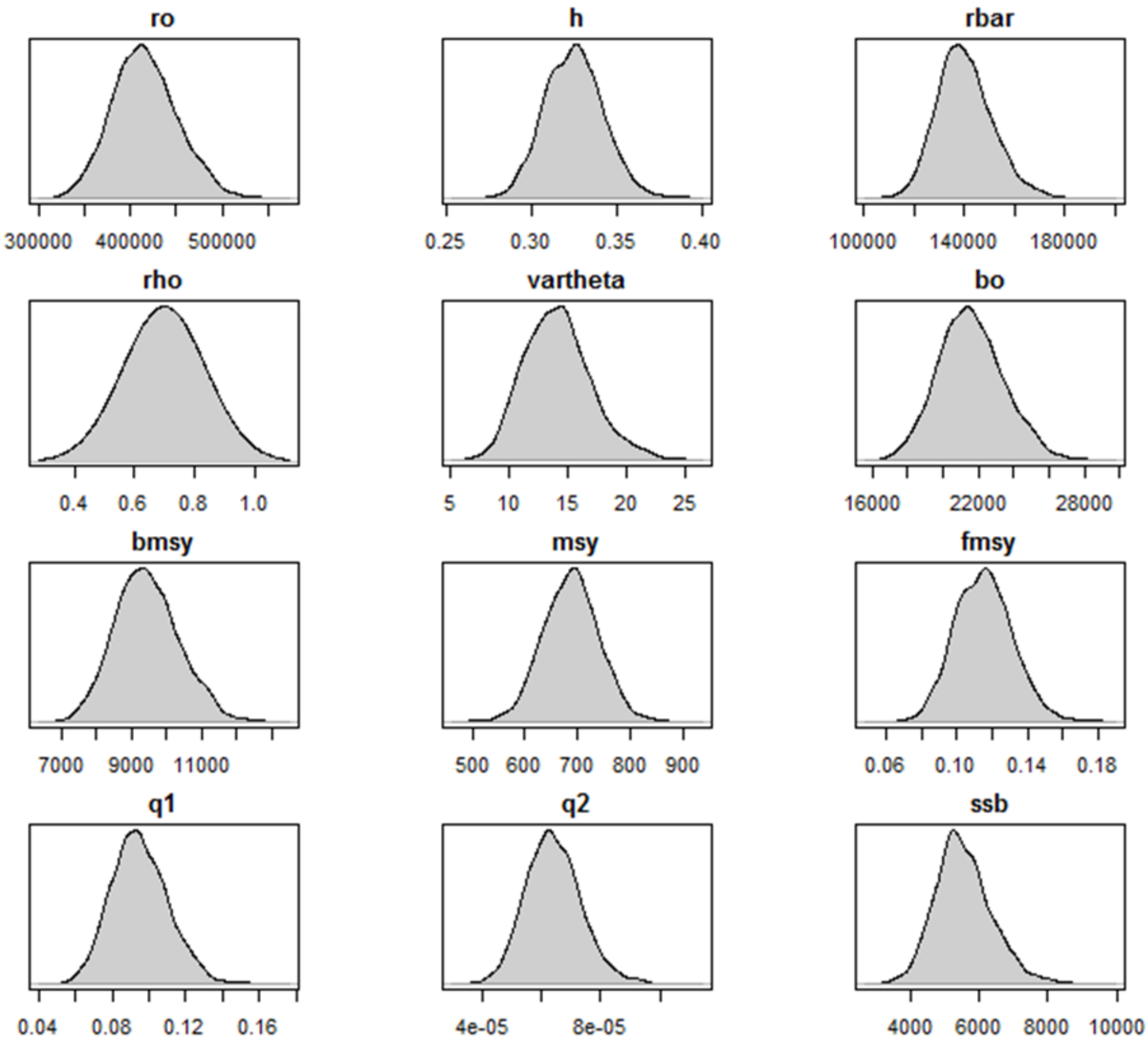


Figure E.51. Marginal posterior densities for estimated model parameters and MSY quantities from the noSE_noDD+highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

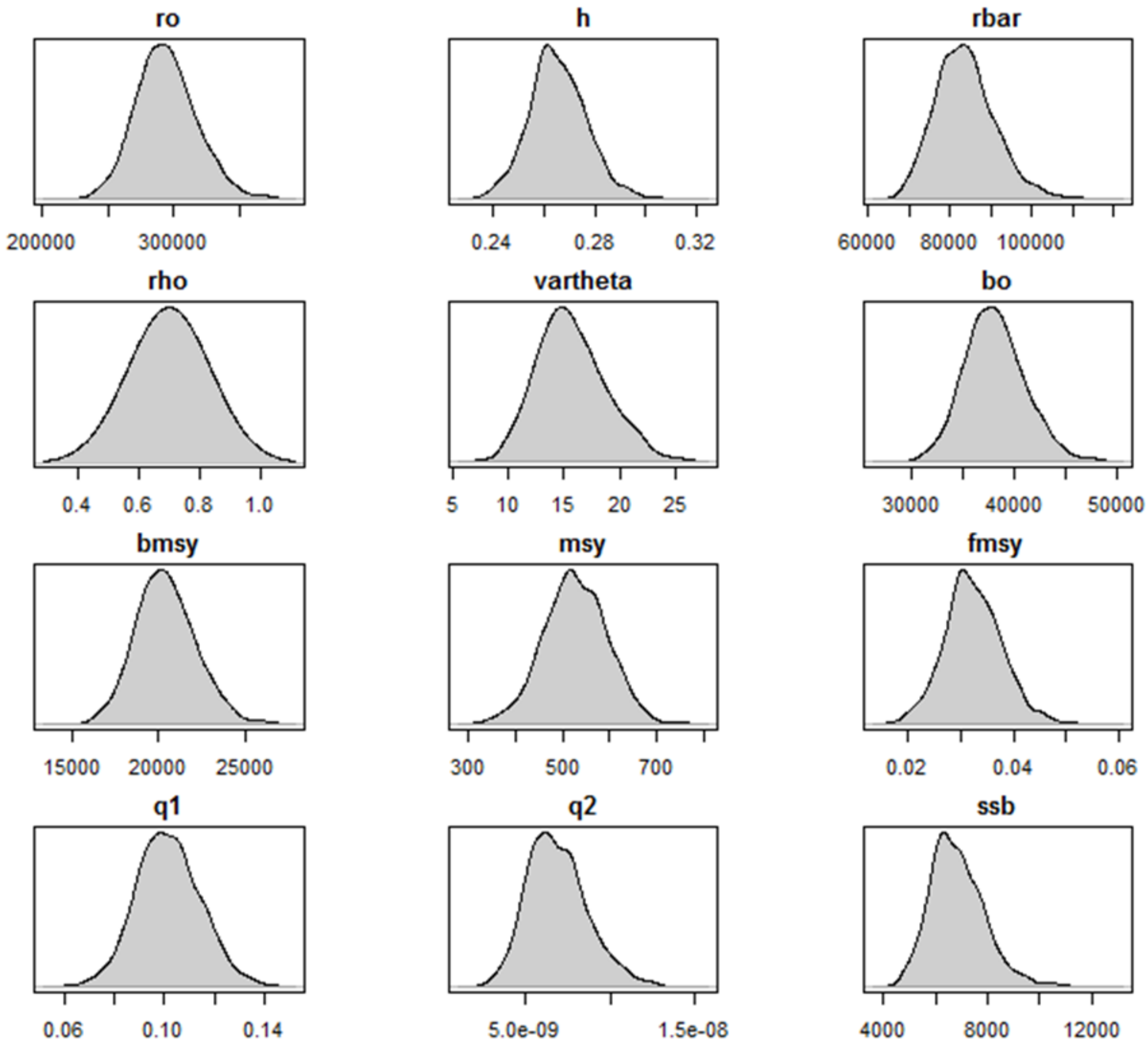


Figure E.52. Marginal posterior densities for estimated model parameters and MSY quantities from the onlySEpre1947 scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

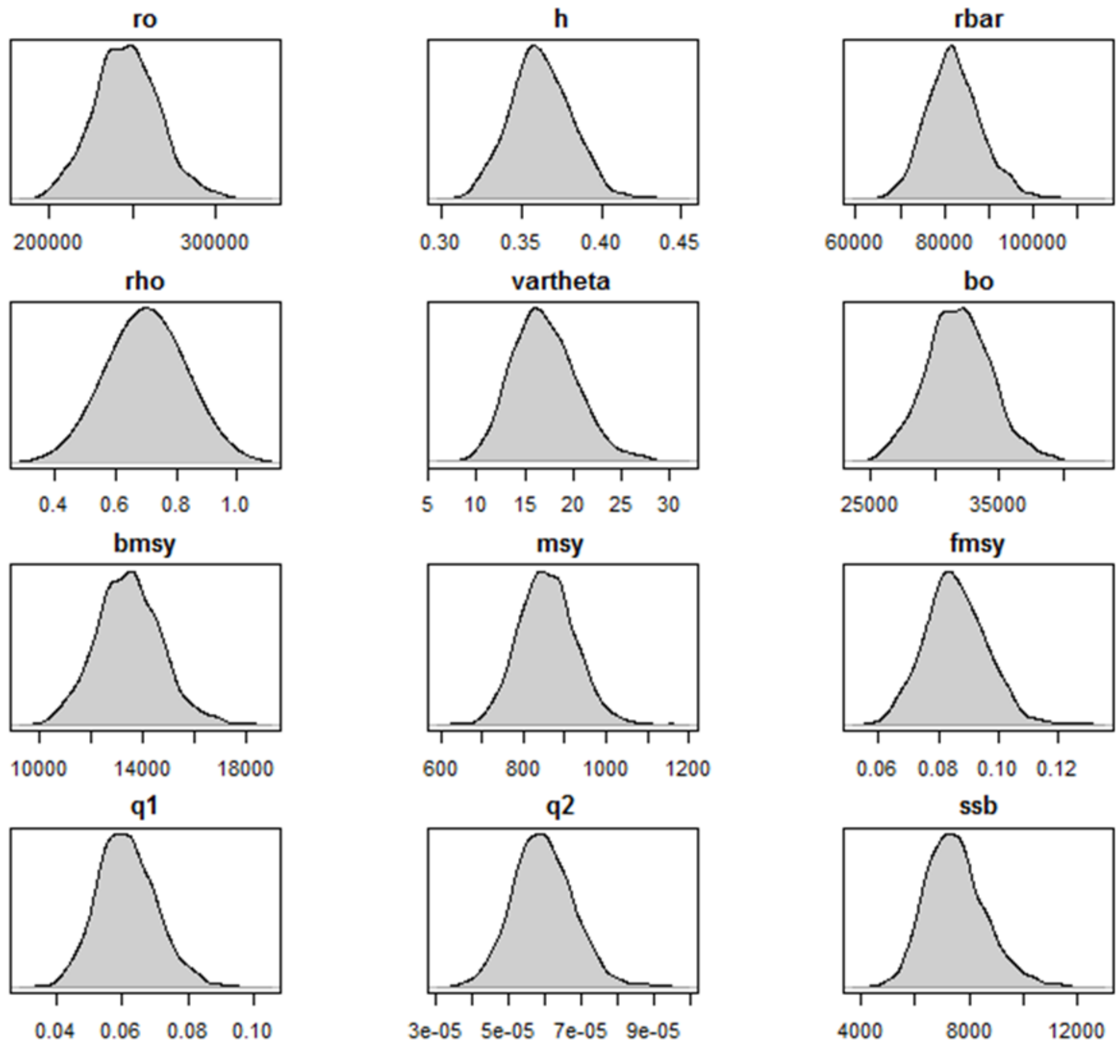


Figure E.53. Marginal posterior densities for estimated model parameters and MSY quantities from the onlySEpre1947_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

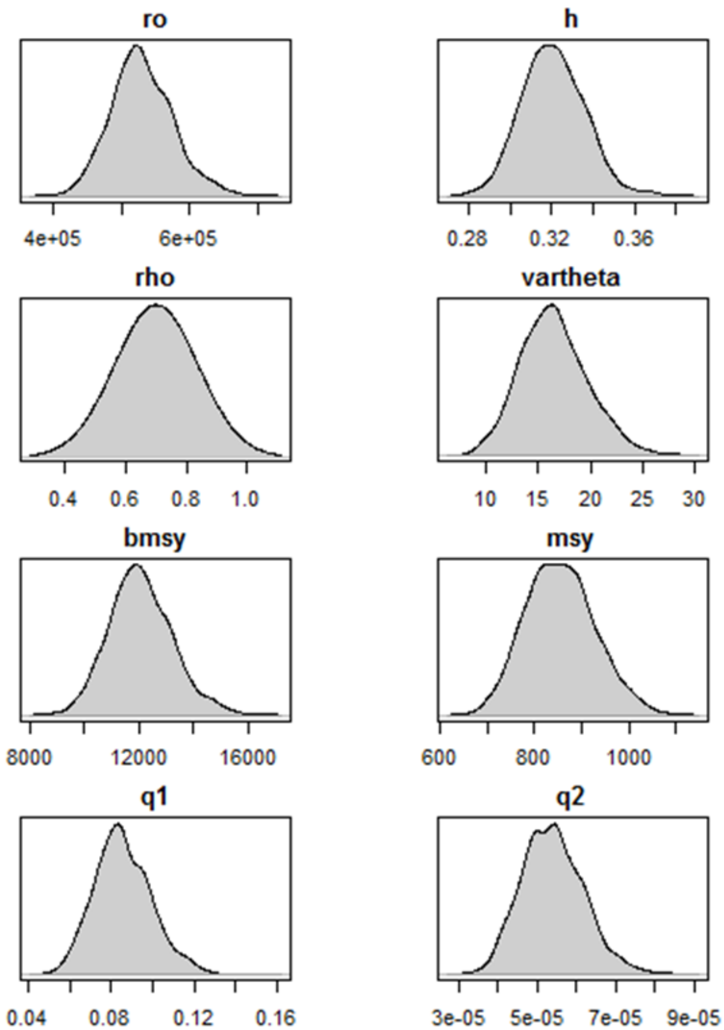


Figure E.54. Marginal posterior densities for estimated model parameters and MSY quantities from the onlySEpre1947_noDD+highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

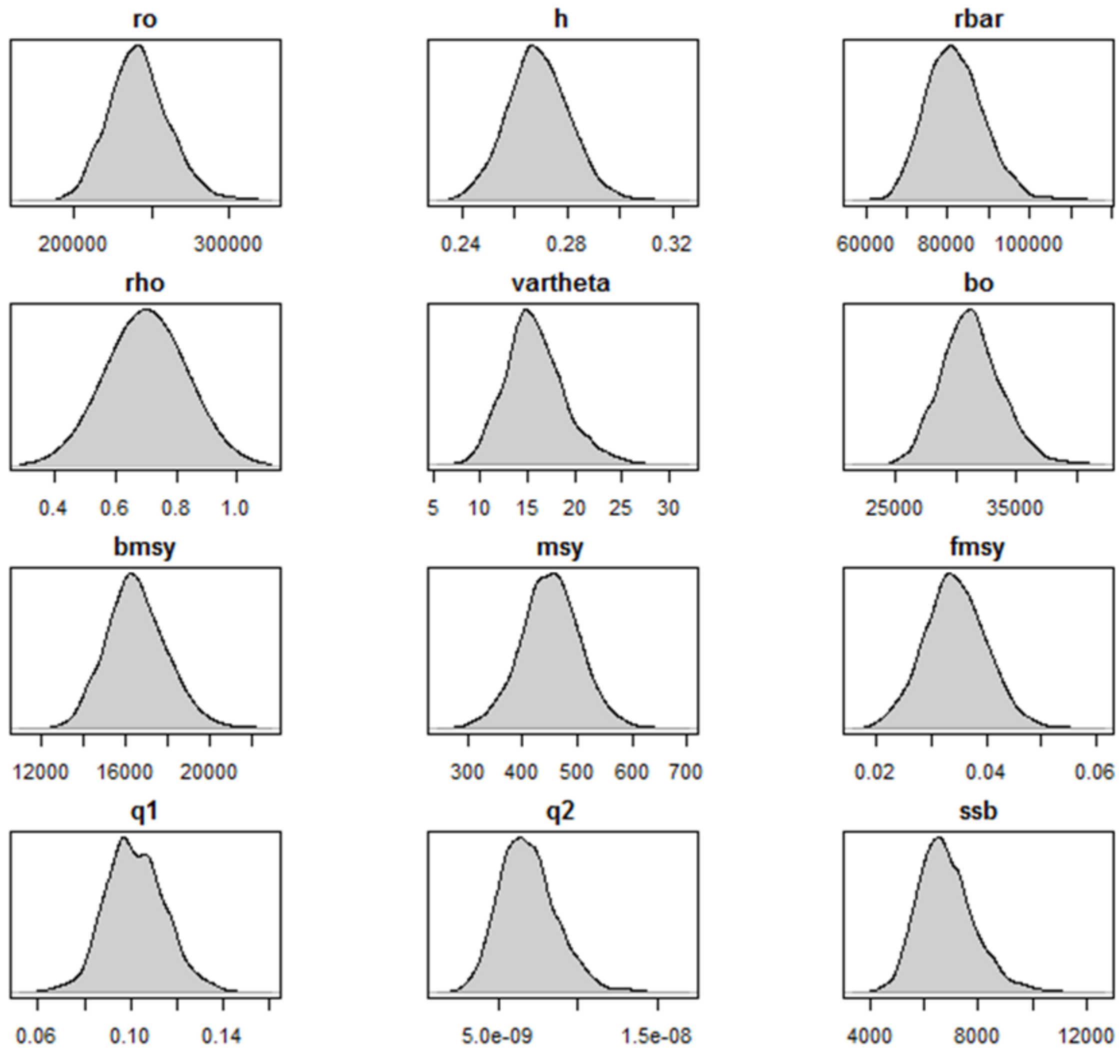


Figure E.55. Marginal posterior densities for estimated model parameters and MSY quantities from the noSEpre1947 scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

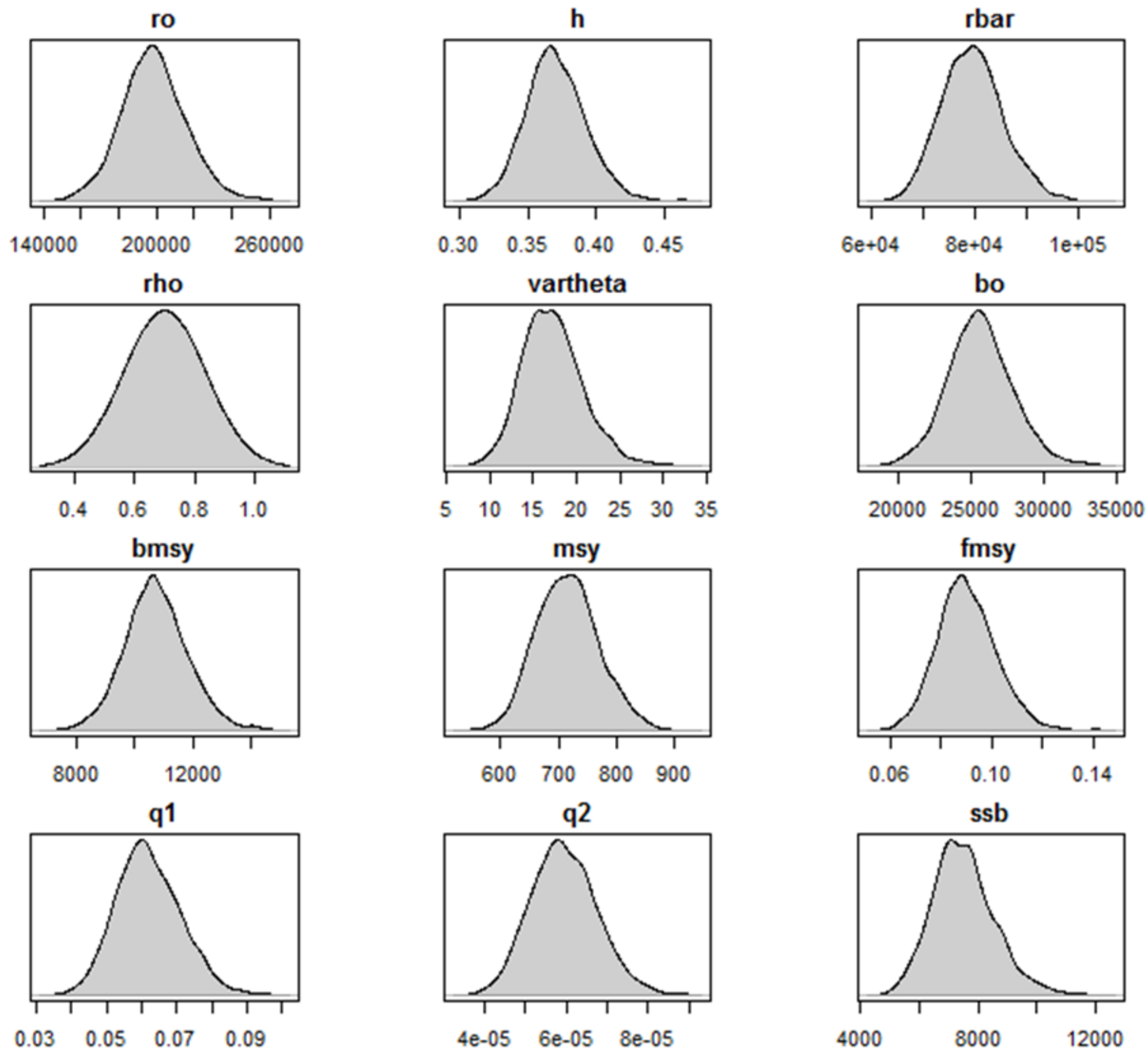


Figure E.56. Marginal posterior densities for estimated model parameters and MSY quantities from the noSEpre1947_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

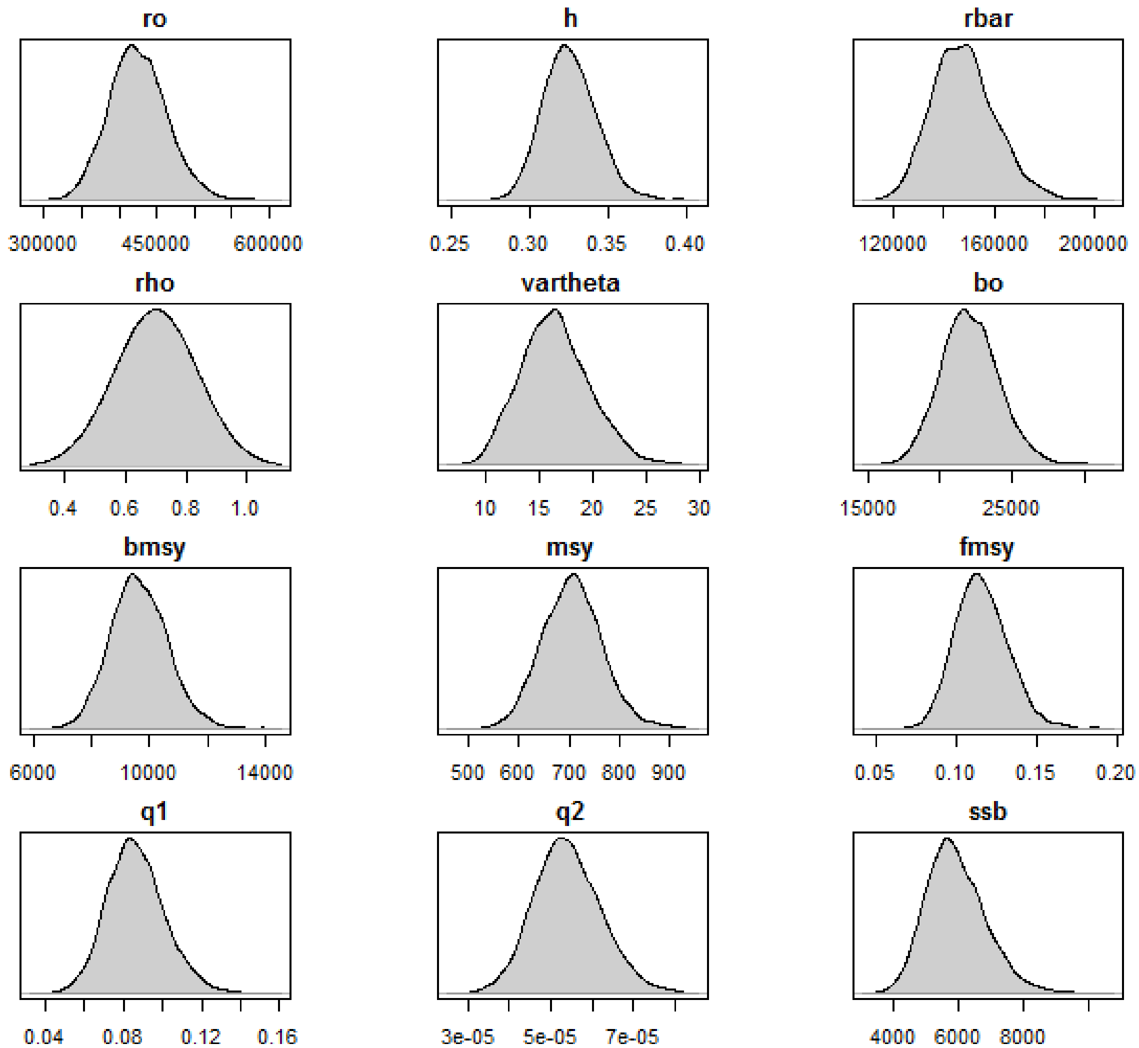


Figure E.57. Marginal posterior densities for estimated model parameters and MSY quantities from the noSEpre1947_noDD+highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

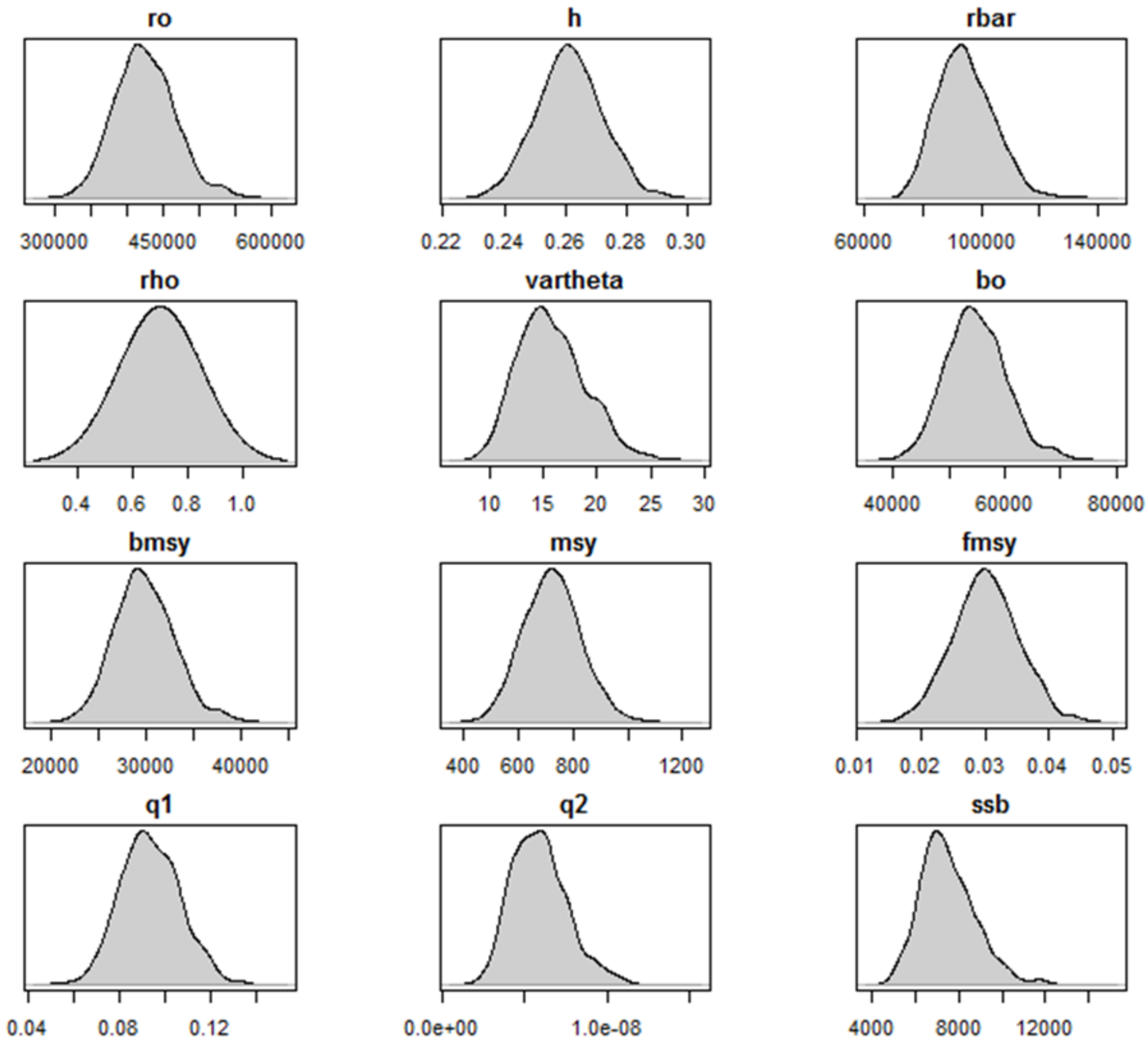


Figure E.58. Marginal posterior densities for estimated model parameters and MSY quantities from the SoG scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

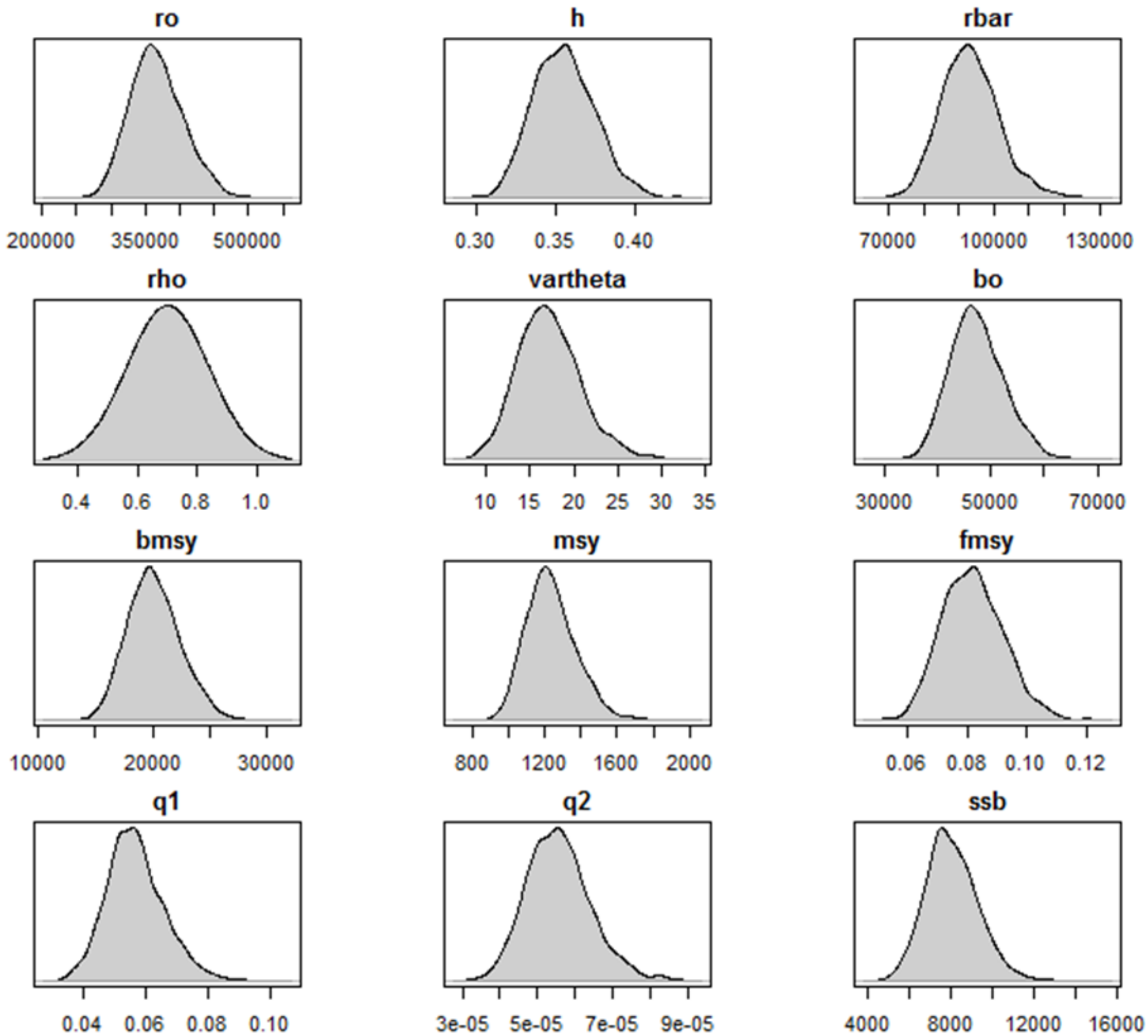


Figure E.59. Marginal posterior densities for estimated model parameters and MSY quantities from the SoG_noDD scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

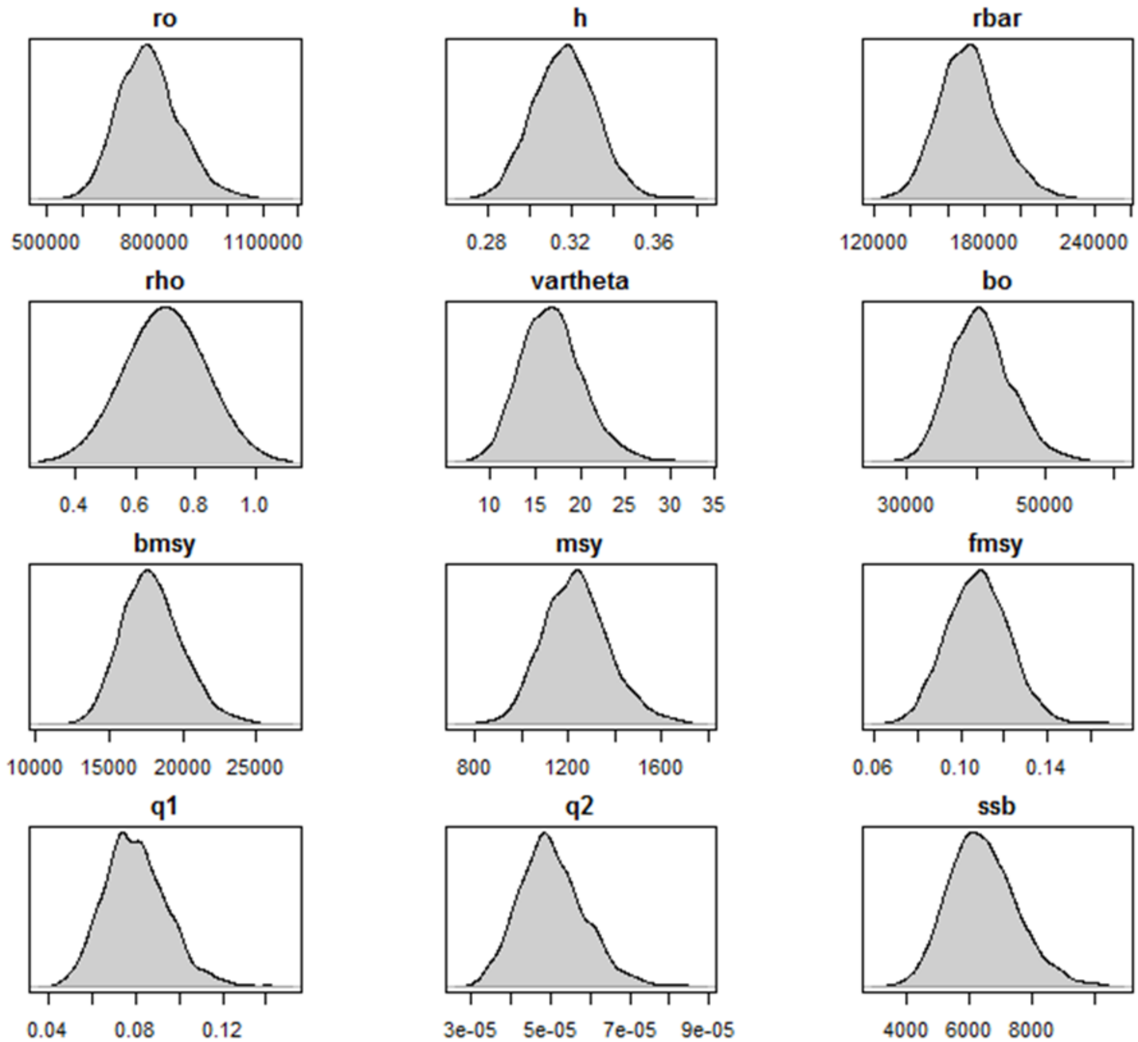


Figure E.60. Marginal posterior densities for estimated model parameters and MSY quantities from the SoG_noDD+highM scenario. Notation is as follows: ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

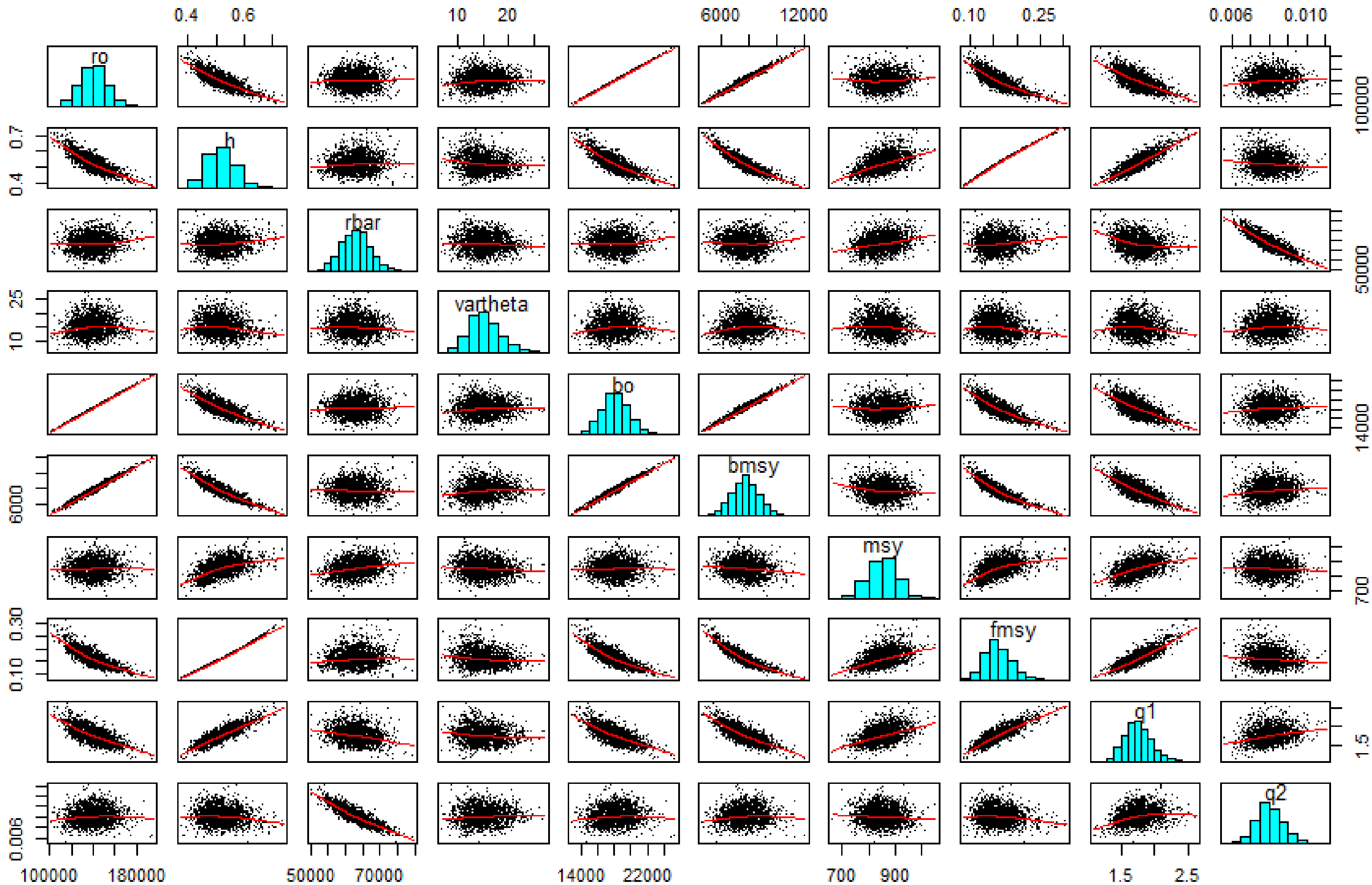


Figure E.61. Pairs plot for noSE scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

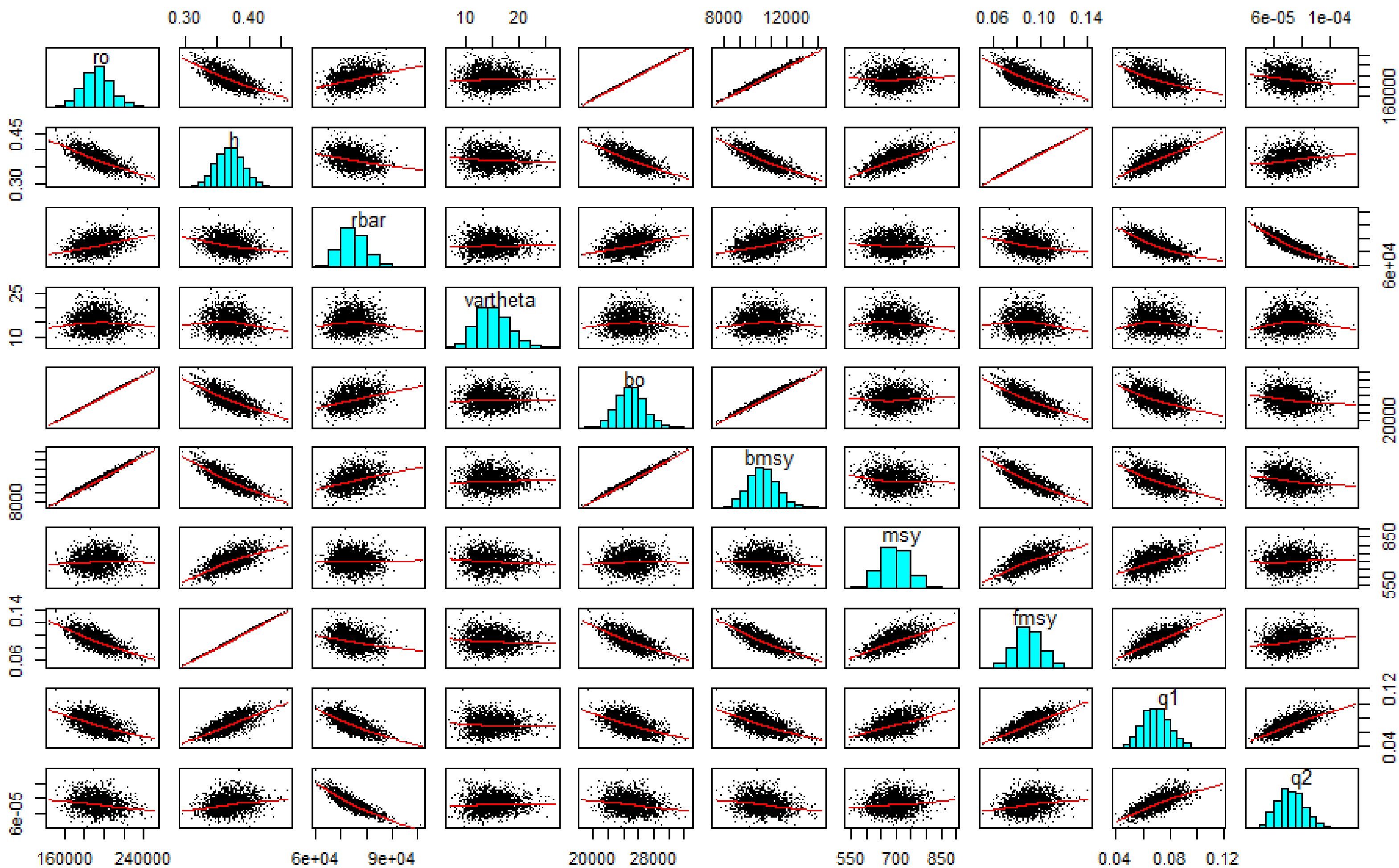


Figure E.62. Pairs plot for noSE_noDD scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

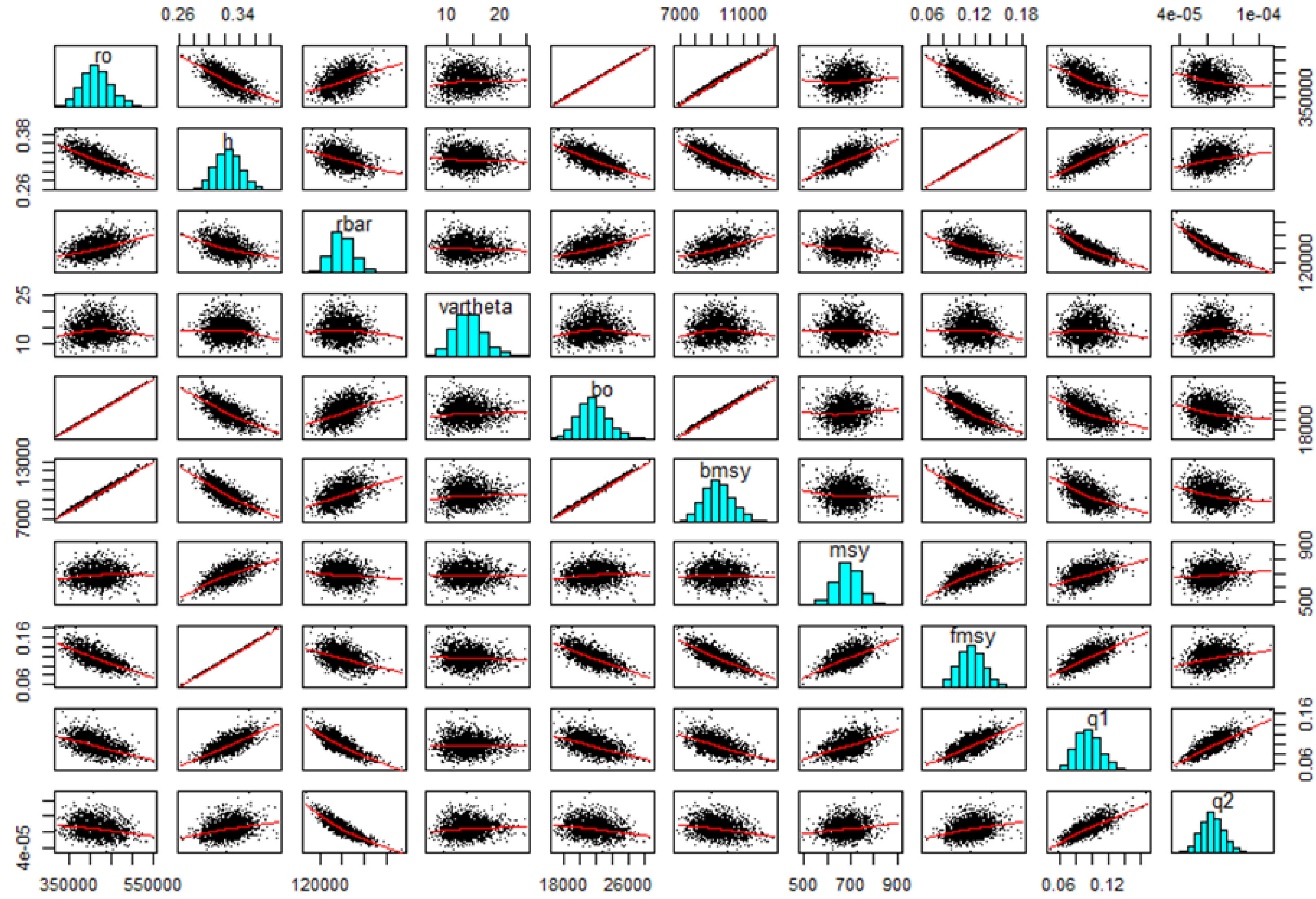


Figure E.63. Pairs plot for noSE_noDD+highM scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

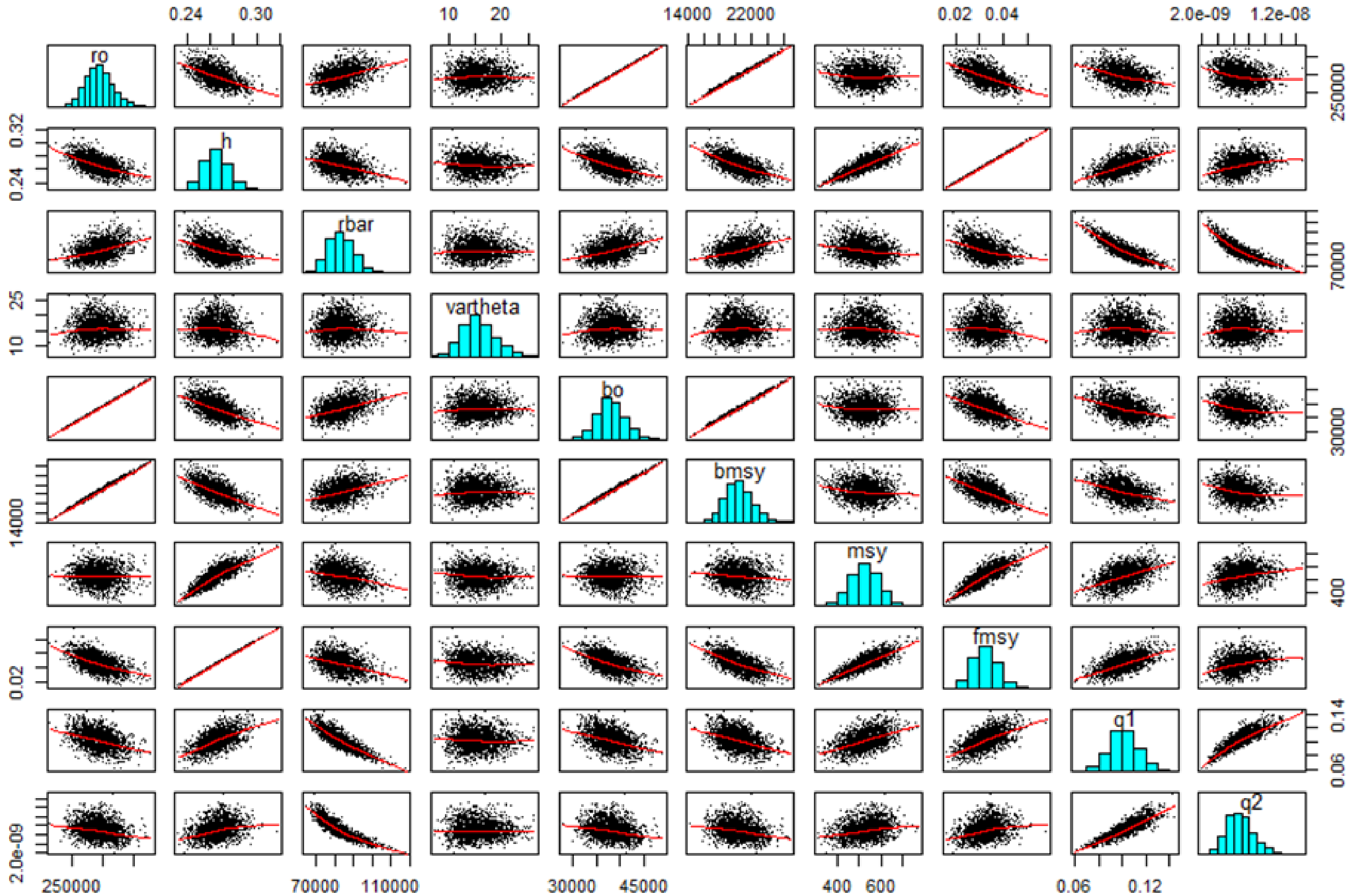


Figure E.64. Pairs plot for onlySEpre1947 scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

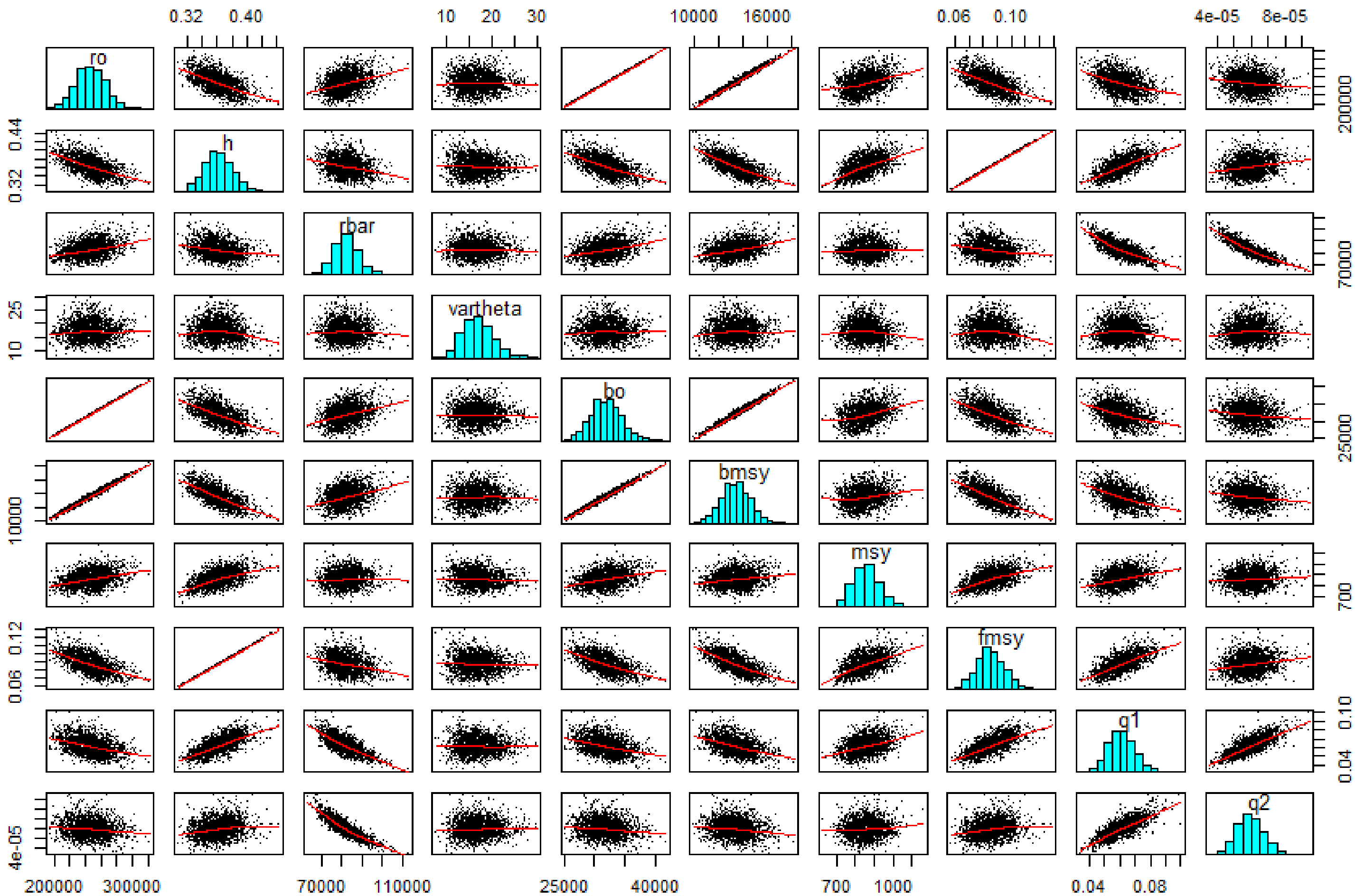


Figure E.65. Pairs plot for onlySEpre1947_noDD scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

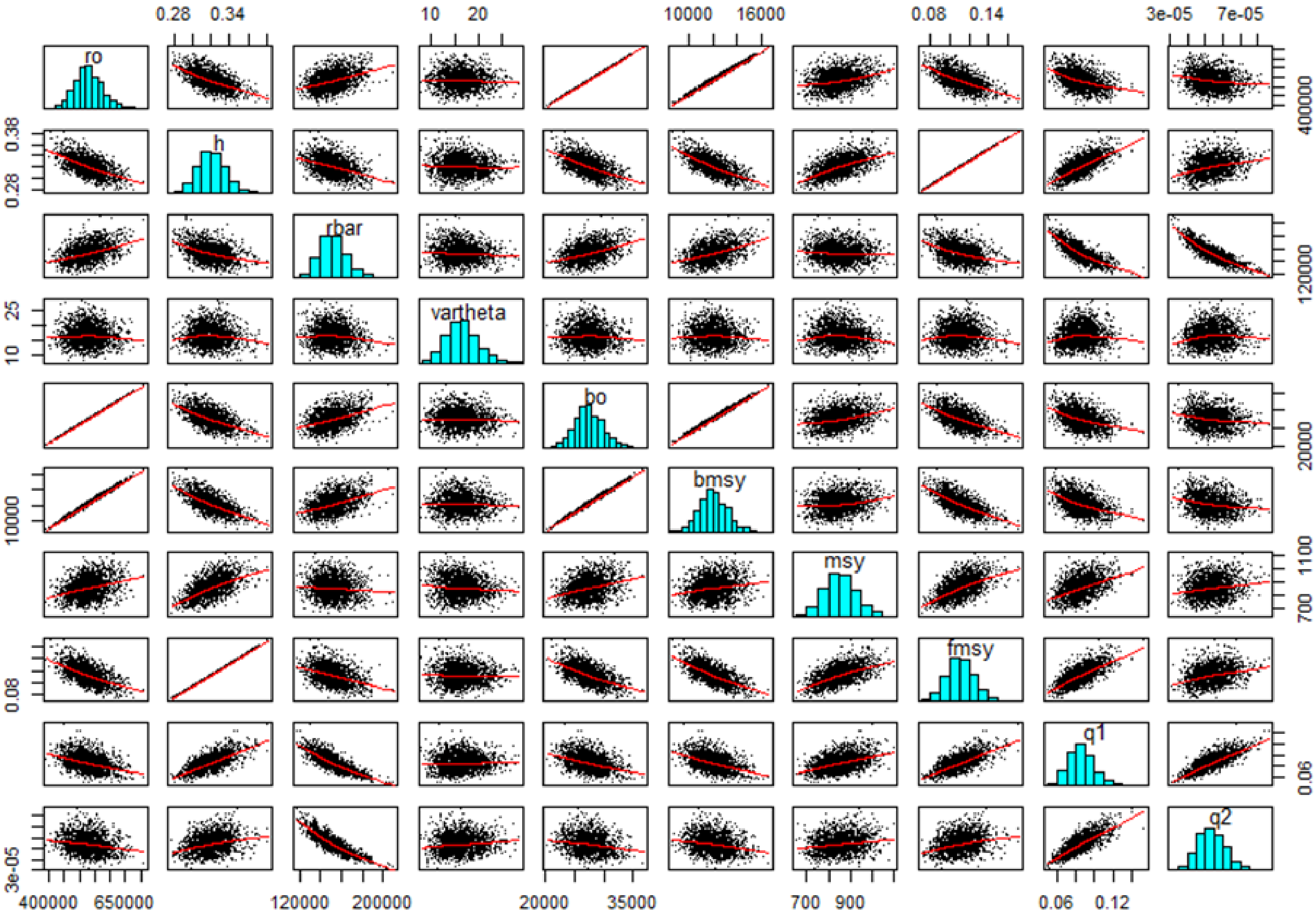


Figure E.66. Pairs plot for onlySEpre1947_noDD+highM scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

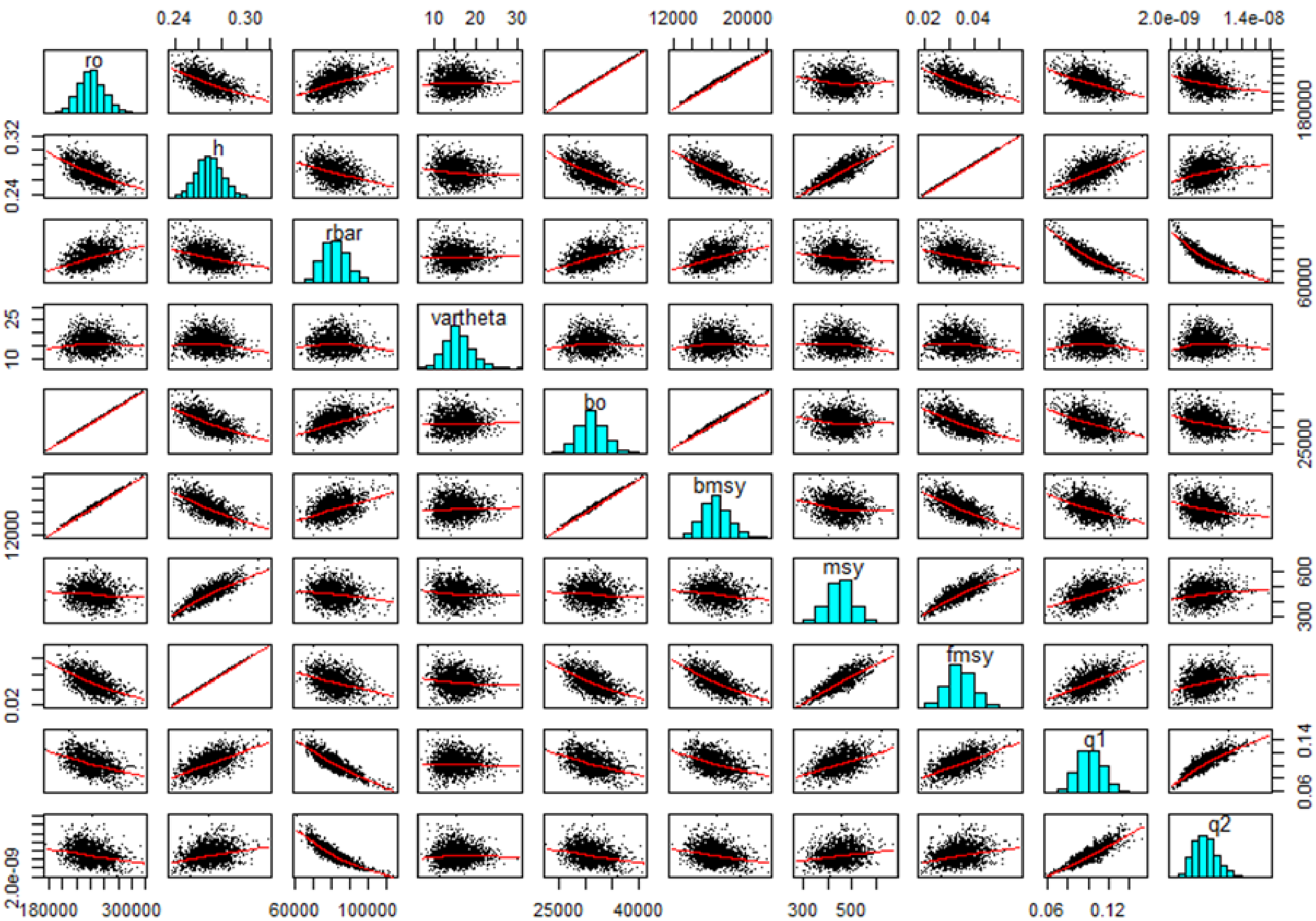


Figure E.67. Pairs plot for noSEpre1947 scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

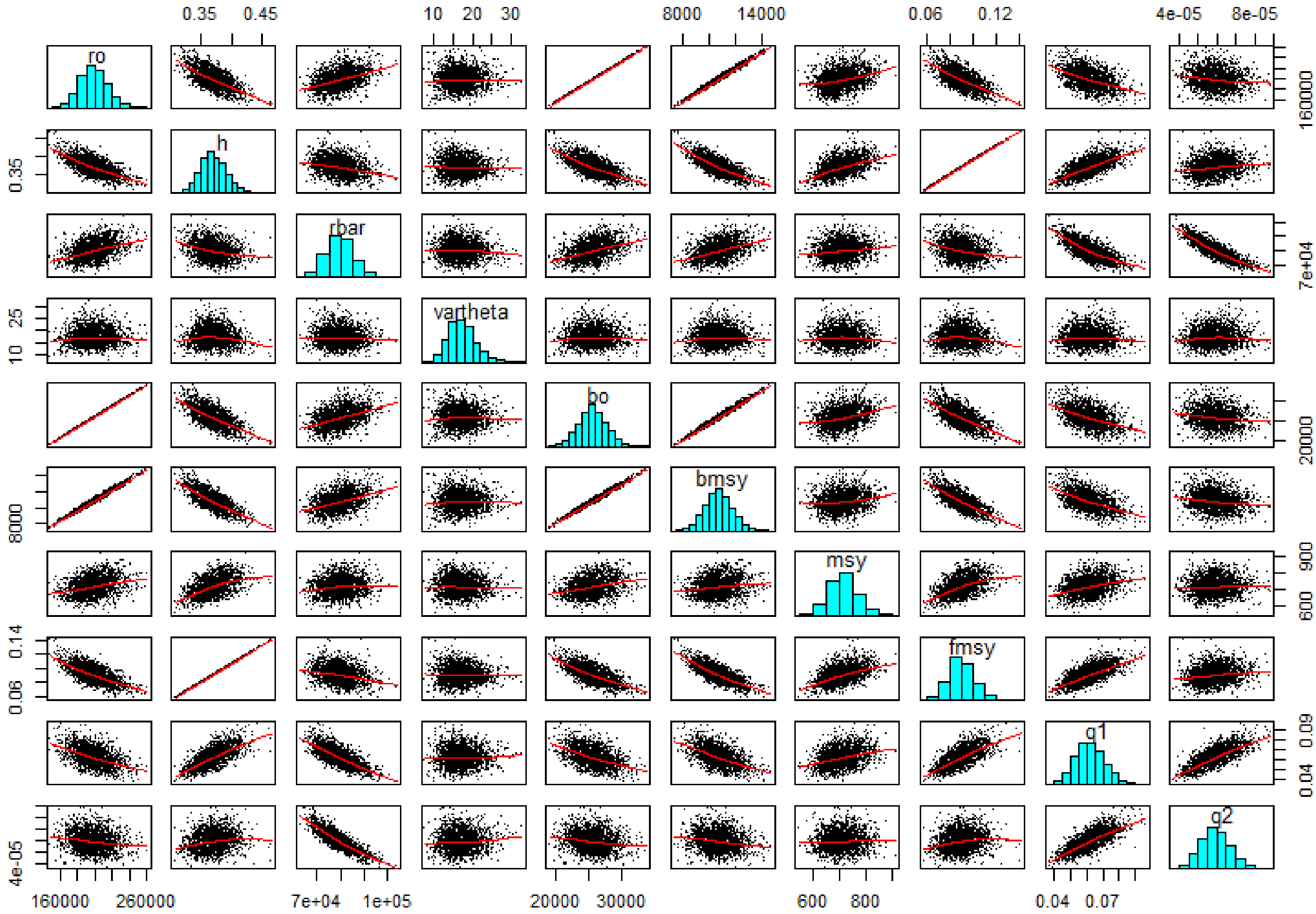


Figure E.68. Pairs plot for noSEpre1947_noDD scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

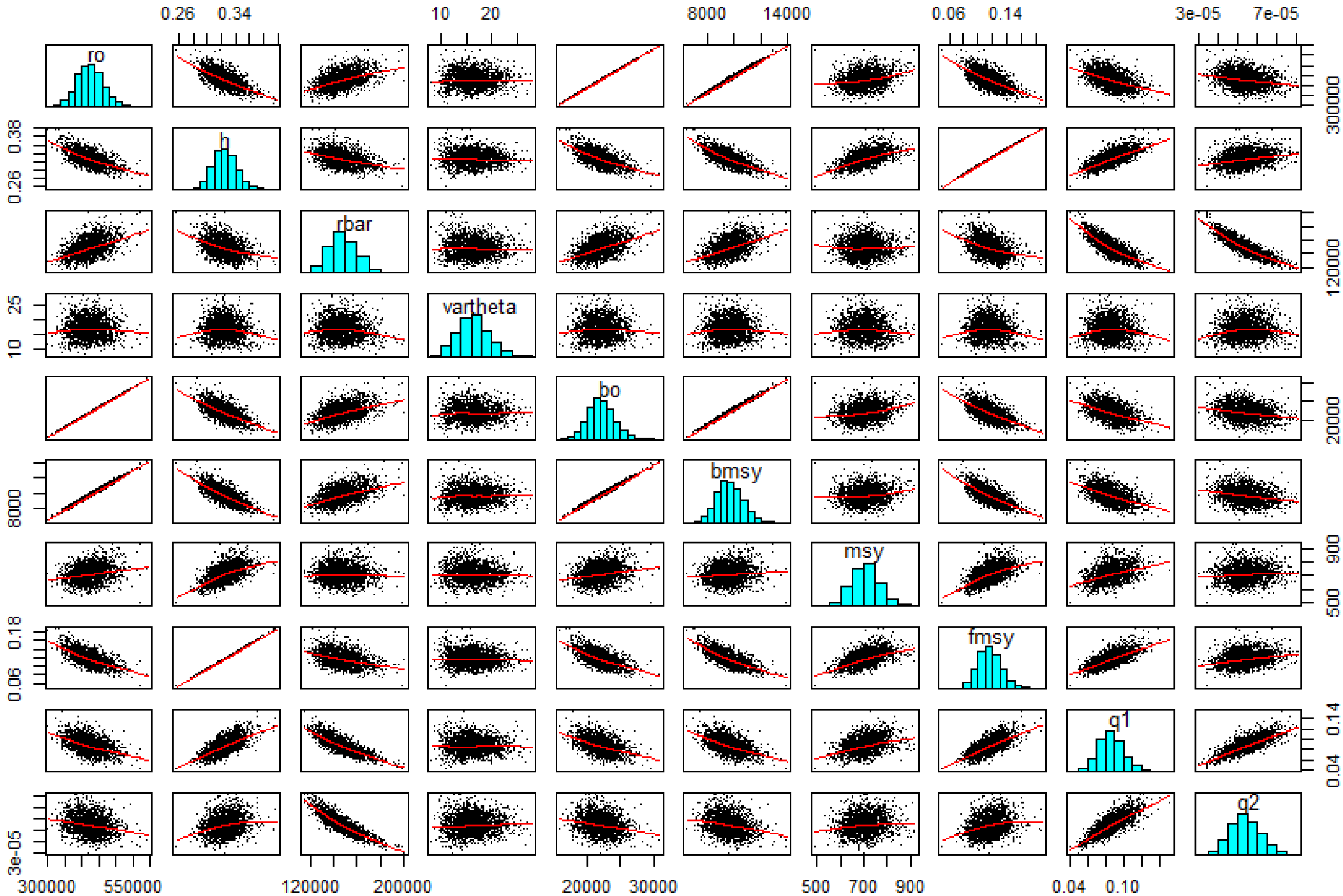


Figure E.69. Pairs plot for noSEpre1947_noDD+highM scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

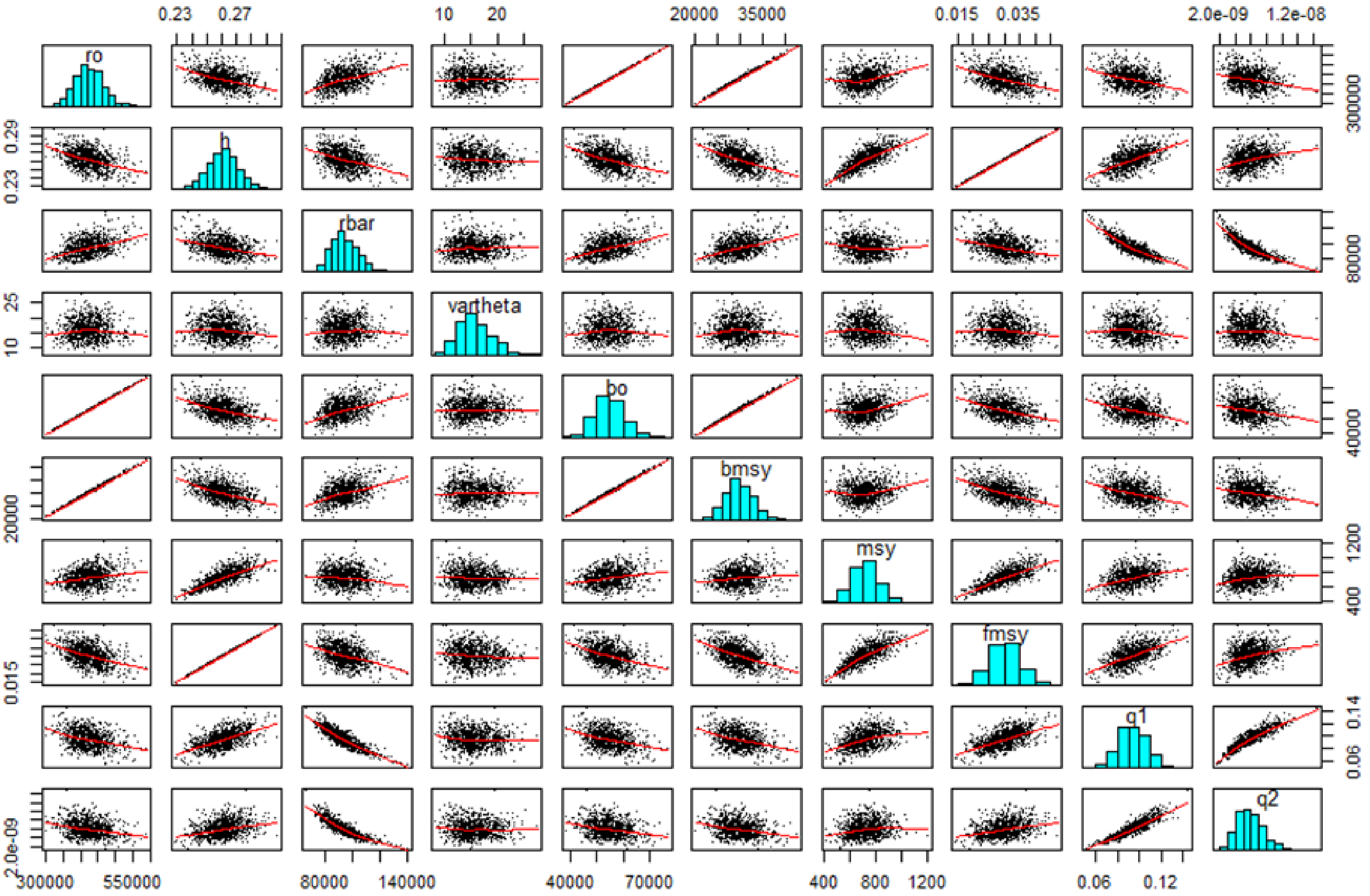


Figure E.70. Pairs plot for SoG scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

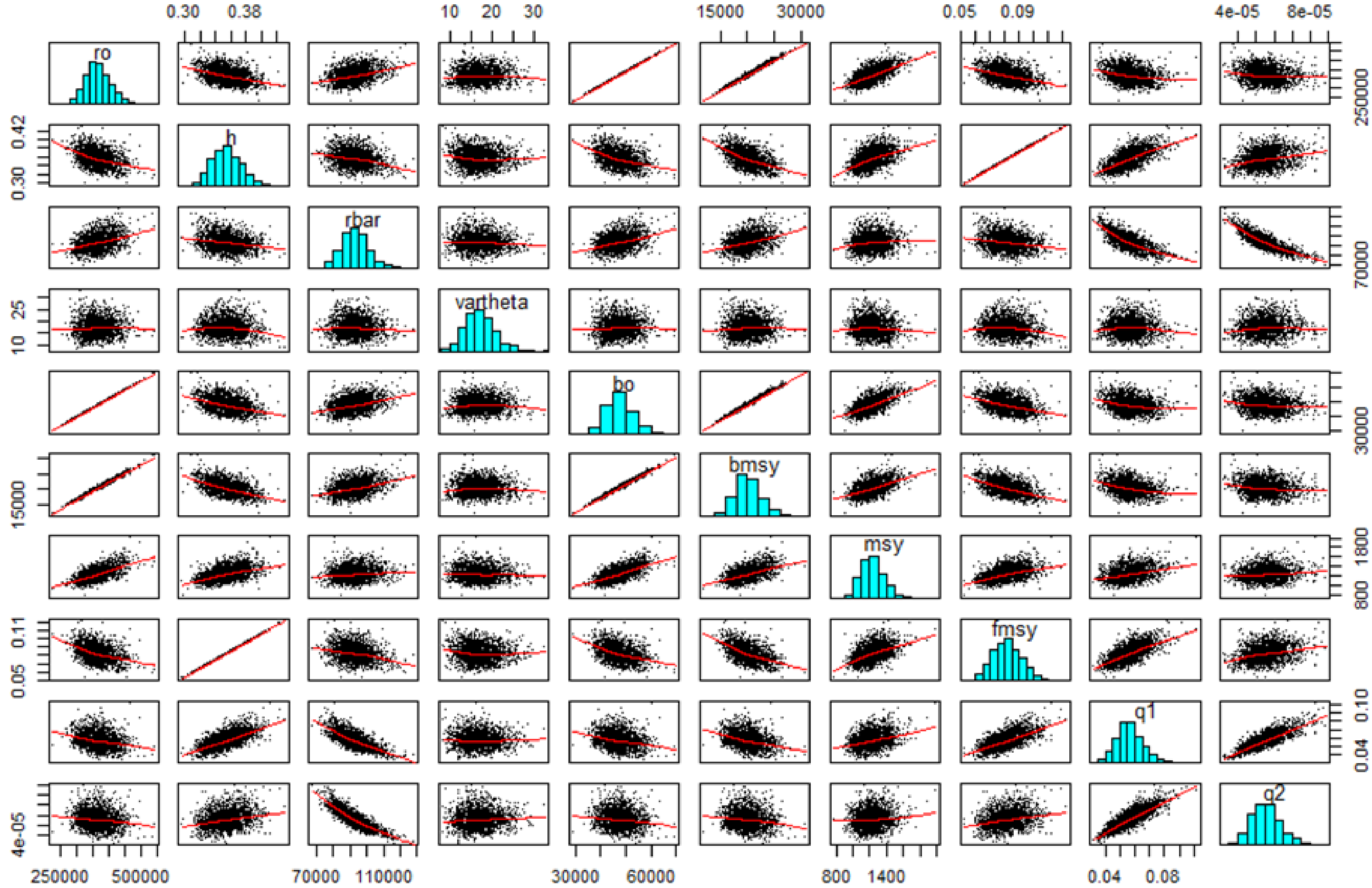


Figure E.71. Pairs plot for SoG_noDD scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.

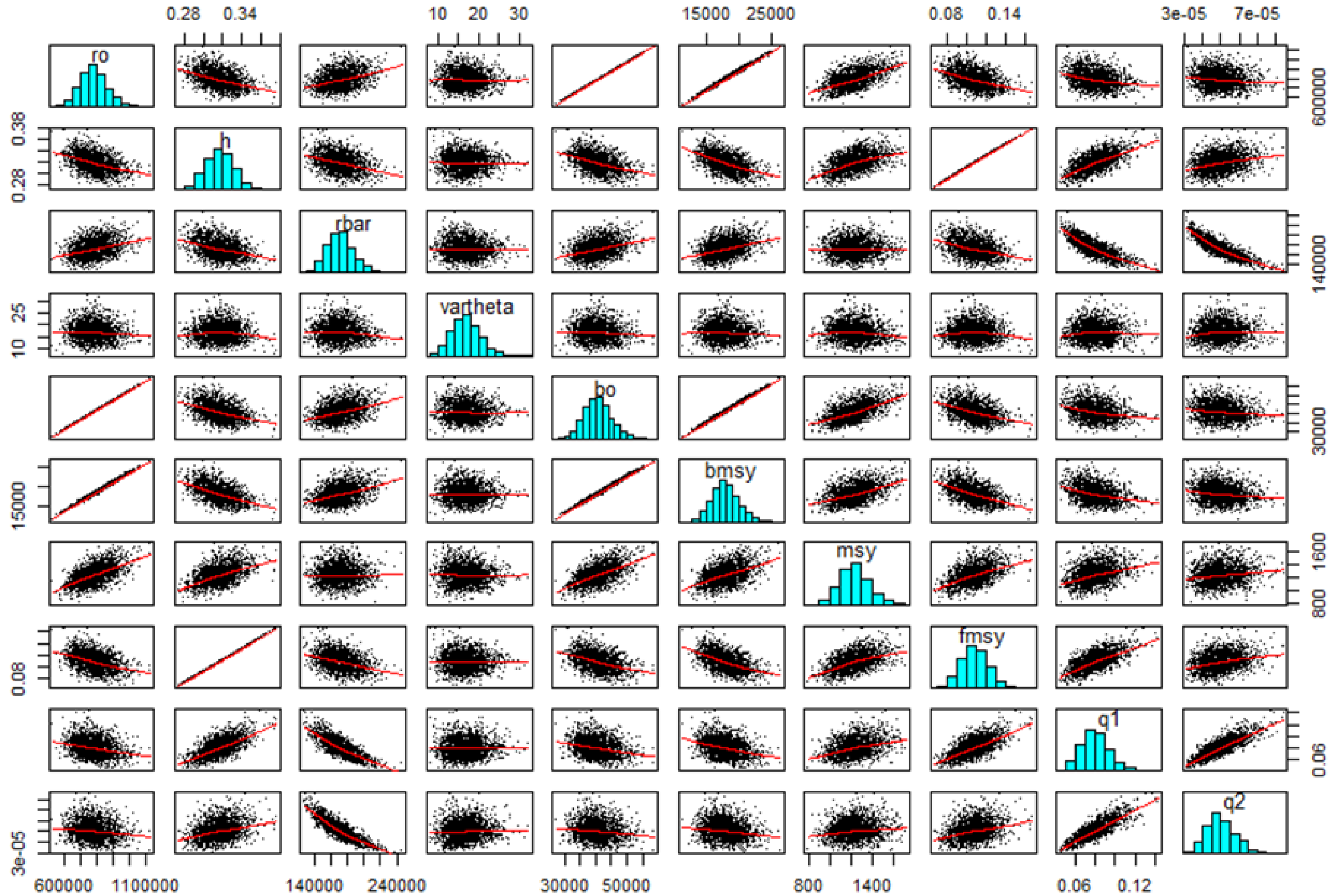


Figure E.72. Pairs plot for SoG_noDD+highM scenario. ro = Unfished equilibrium recruitment, h = steepness, rbar = average recruitment, vartheta = total variance, bmsy = spawning biomass associated with maximum sustainable yield, msy = maximum sustainable yield, fmsy = fishing mortality associated with maximum sustainable yield, q1 = catchability coefficient for commercial fishery CPUE index, q2 = catchability coefficient for recreational fishery CPUE index, ssb = spawning biomass in 2014.