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Estimating among-assessment variation in overfishing limits

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Abstract

Among-assessment variation in historical spawning biomass trajectories (σ) has formed the basis for setting the buffer for scientific uncertainty for US west coast groundfish and coastal pelagic species management since the analysis of Ralston et al. (2011) was conducted. This approach may underestimate the true extent of scientific uncertainty, which relates to the overfishing limit that is a function of both biomass and the proxy for the fishing mortality corresponding to F_{MSY} and pertains to the future and not the past. An approach is developed and applied to species in the US west coast groundfish fishery that bases the calculation of σ on projected biomass and overfishing limits, accounting for uncertainty in future recruitment as well as among-assessment variation. Including the assessments conducted since 2011 in the historical biomass method has a negligible impact of the perceived extent of scientific uncertainty (σ~0.389). Conducting projections rather than using historical estimates leads to a higher value for σ (0.422) and basing measures of uncertainty on projected overfishing limits rather than spawning biomass leads to a value for σ of 0.533. Allowing for stochasticity in recruitment does not change the values noticeably (the value of σ is 0.485 when it is based on overfishing limits and stochastic recruitment).

Keywords: Groundfish, Projection, Stock Synthesis, Uncertainty

Introduction

Answering the legislative call to improve US fisheries includes pursuing new ways to characterize and quantify the scientific uncertainty that informs fisheries management (Cadrin et al. 2015). In this context, scientific uncertainty is defined as the uncertainty inherent in data collection as translated through stock assessment methods (Federal Register 2009). Overall goals of the Magnuson-Stevens Fishery Conservation and Management Act (MSA) are to manage US fisheries to ensure that the amount of fish harvested each year will provide the greatest overall benefit, particularly in food production and recreational opportunities, to the nation, and thoroughly account for the conservation and sustainability of marine ecosystems (Federal Register 2009).

One outcome of the pursuit of this goal is the adoption of "precautionary harvest control rules that are designed to reduce 'risk-neutral' point estimates of catch based on the amount of uncertainty in the estimates" (Ralston et al. 2011). For example, groundfish species managed in the US northeast Pacific by the Pacific Fishery Management Council (PFMC) are classified into three categories based on the quantity and quality of data available for assessments: 1) a Category 1 species has catch-at-age, catch-at-length, or other data that inform a relatively data-rich, quantitative stock assessment; 2) a Category 2 species has some biological indicators, which may include a relatively data-limited quantitative stock assessment or non-quantitative assessment; and 3) a Category 3 species has few available data (*e.g.*, landed biomass) (PFMC 2014a). The harvest control rules that define the Allowable Biological Catch (ABC) for US west coast groundfish and coastal pelagic species rely on the estimation of an Overfishing Limit (OFL) and a buffer for scientific uncertainty (Figure 1). The catch limit for any species must be equal to, or lower than, the ABC.

The default magnitude of the buffer for a species managed by the PFMC is defined by Category and was first described by Ralston et al. (2011). In that work, it was assumed that scientific uncertainty can be characterized using a log-normal distribution with a mean of one and a standard error in log-space, σ, given the observation that time series for historical spawning biomass and OFL produced by assessments conducted in Stock Synthesis demonstrate variation among assessments. Ralston et al. (2011) used the variation in historical biomass as a proxy for model specification error (i.e., a type of scientific uncertainty). Sigma, σ, for Category 1 species (most data rich and robust stock assessments) was quantified by the estimated coefficient of variation (CV) of the among-assessment variation in annual estimates of historical spawning biomass (based on 81 Category 1 assessments from 17 groundfish and coastal pelagic species species). Due to the data-limited nature of Category 2 and 3 species, the uncertainty associated with estimates of an OFL is difficult to quantify, and the scientific uncertainty is presumed to be higher. The Scientific and Statistical Committee of the PFMC recommended, and the PFMC adopted, setting a minimum CV at 0.36 for Category 1 species, doubling the (assumed) uncertainty (CV=0.72) for Category 2 species, and quadrupling the assumed uncertainty (CV=1.44) for Category 3 species (Ralston et al. 2011).

It is possible to further understand the patterns in overestimating or underestimating quantities more directly related to setting of catch limits (*i.e.*, the OFL) derived from stock assessment and expand on the precedent set by Ralston et al. (2011). Using historical estimates of spawning stock biomass to calculate σ (hereby referenced as the *historical biomass method*) assumes the uncertainty in the OFL arises only from the uncertainty in terminal-year biomass and this assumption can lead to negatively biased estimates of scientific uncertainty (Ralston et al. 2011). Estimating σ by quantifying how projections of OFLs (hereby known as the *projection-based method*) vary among assessments of the same stocks is a direct measure of the management quantity of interest. Projections capture some of the uncertainty in the estimates of current stock abundance and age-structure and how the abundance and age-/size-structure change over time. As prescribed by Shertzer et al. (2008), quantifying the variation in OFL projections also captures some of the uncertainty in the estimation of the target fishing mortality rate (in the case of US fisheries, F_{MSY} or a proxy thereof).

Here we compare the historical biomass method for estimating σ to a projection-based method. Further comparisons include replicating the historical biomass method with the addition of new assessments completed after 2011 (*i.e.,* the year the original Ralston et al. analysis was completed) and projecting spawning biomass in addition to OFLs. The projections of OFLs and spawning biomass provide a unique opportunity to quantify how σ for each species (*i.e.,* species-specific σ) and pooled across all species (*i.e.,* pooled σ) varies into the future and among taxonomic groups.

Materials and Methods

Sources of uncertainty

Variation in estimates of OFLs and spawning biomass among multiple assessments of the same species can arise from multiple sources: 1) chosen model structure; 2) fixed parameter values and prior distribution selection for other parameters; 3) changes in data availability; 4) the composition of the group established to review the assessment; 5) the members of the stock assessment team conducting the assessment; and 6) the version of software that was used (Ralston et al. 2011). Accounting for this variation among historical assessments and projected values for OFL is integral for informing management advisory bodies as they review scientific advice for fisheries managers.

Scientific uncertainty is associated with each step of calculating an OFL: 1) estimating the current exploitable biomass; and 2) projecting biomass for a pre-specified number of years while applying an estimate of (or proxy for) F_{MSY} to the forecasts of future biomass (Ralston et al. 2011). The historical biomass- and projection-based methods differ in terms of how many of these sources of uncertainty are considered when calculating σ.

Data utilized

The stock assessments for groundfish and coastal pelagic species included in PFMC management plans were used to ensure comparability between the historical biomass- and projection-based methods (Table 1 of the supplementary materials). Assessments for these species exhibited variability in the estimates of historical biomass among multiple stock assessments for the same species (Figure 2 from Ralston et al. 2011). Assessments completed in Stock Synthesis (Methot and Wetzel, 2013) provided the necessary quantities required for projecting spawning biomass and OFLs (Table 2 of the supplementary materials). However, the groundfish and coastal pelagic species and accompanying assessments utilized for the comparison of the historical biomass- and projection-based methods were a subset of the total available because not all assessments were conducted in Stock Synthesis (*e.g.,* stock assessments published before 2007) or were conducted using a version of Stock Synthesis that does not report the quantities required to project OFLs or spawning biomass (Table 2 of the supplementary materials; *e.g.,* stock assessments completed in an older version of Stock Synthesis [pre-V2.00] or use an obsolete selectivity pattern). Specifically, projections of OFLs and spawning biomass were only conducted for species with assessments completed in Stock Synthesis V3.03a or later (Methot and Wetzel 2013).

Spawning biomass estimates were reported in terms of spawning output (eggs) based on the non-proportional egg-to-weight relationship described by Dick (2009) in recent assessments of bocaccio, chilipepper rockfish, darkblotched rockfish, and yelloweye rockfish. Comparing variation across multiple assessments for these species required the units of spawning output to be the same (*i.e.*, some assessments reported spawning output in metric tons and others reported it in eggs). Thus, spawning biomass in metric tons was calculated for assessments with spawning output reported in eggs:

$$SSB_y = \sum_{a}^{A} W_{a,f} N_{y,a} m_a \qquad \text{(Equation 1)}$$

where SB_y is spawning biomass in year y, a is age, A is the age plus group, $W_{a,f}$ is female weight-at-age, $N_{y,a}$ is female numbers-at-age, and m_a is the female maturity-at-age. Female weight-at-age was calculated as follows:

$$W_{a,f} = \sum_{l} W_l \, m_l \, \rho_{a,l} \qquad \text{(Equation 2)}$$

here W_l is female weight-at-length, m_l is the female proportion mature-at-length, and $\rho_{a,l}$ is the proportion of animals of age a than in length-class l.

Projecting overfishing limits and spawning biomass

One goal of the projection-based method was to evaluate the extent to which uncertainty changes into the future. Species-specific σ and pooled (across species) σ for both OFL and spawning biomass for each year into the future were calculated. Projections were based on the best estimates of biomass, age-structure, and selectivity from the stock assessment outputs, and these estimates change over time. Thus, to further characterize uncertainty, projections were started from multiple historical years (1998, 2003, and 2008) and stochastic projections based on a stock-recruitment relationship with log recruitment deviations with bias correction were conducted, along with deterministic projections.

OFLs were computed by applying a target harvest rate, F_{target} (U.S. west coast groundfish: $F_{50\%}$ for rockfish, $F_{45\%}$ for roundfish, and $F_{30\%}$ for flatfish) to estimates of current biomass. F_{target} is the target harvest rate that results in an expected decline in spawning biomass-per-recruit equal to 50% (for rockfish), 45% (for roundfish), or 30% (for flatfish) (PFMC 2014a).

The estimated natural mortality and projected fishing mortality for the time series covered in the assessment were used to calculate total mortality, Z for projections:

$$Z_{s,a} = M_{s,a} + \sum_{f} F_{target} S_{s,a,f} \psi_f \qquad \text{(Equation 3)}$$

where a is age, s is sex, and f is fleet. S is selectivity by age, sex, and fleet at the end of the year before the projections start (i.e., 1998, 2003, and 2008), and ψ_f is the fishing mortality rate by fleet, f. Z was then used to project the numbers-at-age by sex forward:

$$N_{y+1,s,a} = N_{y,s,a-1}e^{-Z_{s,a-1}} \qquad \text{if } 1 \leq a < A$$
$$N_{y+1,s,A} = N_{y,s,A-1}e^{-Z_{s,A-1}} + N_{y,s,A}e^{-Z_{s,A}} \qquad \text{if } a = A \qquad \text{(Equation 4)}$$

where N is the numbers-at-age by year and sex, and A is the plus group. The numbers-at-age for the first year of projection period were extracted from the Stock Synthesis report file.

The projected numbers-at-age were converted to spawning stock biomass using Equation 1.

The projected numbers of fish at age-0 were calculated using the Beverton Holt stock-recruitment relationship and log recruitment deviations with bias correction were added for stochastic projections (Equations 6 and 7 respectively):

$$N_{y,s,a=0} = \frac{4hR_0SSB/SSB_0}{(1-h)+(5h-1)SSB/SSB_0} \qquad \text{(Equation 6)}$$

$$N_{y,s,a=0} = \frac{4hR_0SSB/SSB_0}{(1-h)+(5h-1)SSB/SSB_0}e^{\varepsilon_y-\sigma_r{}^2/2} \qquad \text{(Equation 7)}$$

where R_0 is unfished recruitment, h is the steepness parameter, SSB_0 is the unfished spawning stock biomass, and $e^{\varepsilon_y-\sigma_r{}^2/2}$ are-log recruitment deviations with bias correction. The unfished spawning stock biomass was computed using numbers-at-age and fecundity at unfished equilibrium.

Equation 7 pertains to the future. However, several of the stocks are fairly long-lived, such that variation in recruitment will not impact spawning biomass / the OFL for several years into the future. To address this concern, Equation 7 was used to generate recruitment estimates for the start year and N_{age}-1 earlier years where N_{age} is the number of age-classes in the assessment, with the extent of variation defined by the asymptotic standard errors for the annual recruitment deviations. Thus, if a recruitment is uninformed by the stock assessment (e.g., a "LATE" recruitment deviation in Stock Synthesis), it will be treated the same way as a future recruitment whereas if it is precisely estimated, the recruitment value will be almost identical to the value in the assessment. The generated recruitment values are then projected to the start year given the values of Z-at-age estimated in the assessment.

OFLs by year were calculated as follows:

$$OFL_y = \sum_s \sum_f \sum_a W_{s,f,a}F_{target}S_{s,a,f}\psi_f\frac{N_{y,s,a}(1-e^{-Z_{s,a}})}{Z_{s,a}} \qquad \text{(Equation 8)}$$

where W is the selected-weighted retained weight by age, sex and fleet for the end of the year before the projections start.

Quantifying uncertainty in projections

The variation (*i.e.,* σ) in projected OFLs and spawning biomass calculated using the squared deviations from the appropriate mean estimate in log-space was used to compare the projection-based method with the historical biomass-method. This approach (method 2 of three tested by Ralston et al. [2011]) was selected as the preferred method for calculating uncertainty by the

Scientific and Statistical Committee of the PFMC during the review of the historical biomass approach. Unlike the historical biomass method, σ was calculated accounting for four dimensions: projection year, species (year and species were treated as a sampling unit by Ralston [2011]), projection start-year and the replicate trajectories of spawning biomass and OFL due to sampling of future (and past) recruitment deviations (stochastic projections only). Point estimates of σ were pooled over these dimensions to characterize the corresponding contribution to scientific uncertainty. Specific and pooled σ were calculated for projected OFLs and spawning biomass. However, for brevity, X is used in Table 1-3 to represent these quantities for simplicity of presentation.

Historical biomass method

Since the inception of σ in 2011, 16 of the 17 groundfish and coastal pelagic species used to inform σ have new assessments (Table 4). These assessments were included in this update to the species-specific σ and pooled σ produced using the historical-based-biomass method. New (i.e., since 2009) assessments for Pacific whiting were not included in the update because the management structure changed due to the implementation of international treaty (*i.e.*, 15 of the 17 original stocks were updated). For comparison to the projections-based method proposed in this paper, the Ralston et al. (2011) method is also applied to only the species and assessment years that could be used in the projections-based analysis. The updated species-specific estimate of σ was based on method 2 of Ralston et al. (2011), *i.e.*:

$$\overline{\ln[B_t]} = \frac{1}{n_t}\sum_i \ln[B_{i,t}]$$

$$\sigma = \sqrt{\frac{1}{\sum_t (n_t - 1)}\sum_t \sum_i \left(\ln\left[B_{i,t}\right] - \overline{\ln[B_t]}\right)^2} \qquad \text{(Equation 15)}$$

where B_t is spawning stock biomass by year, n_t is the number of available assessments for year t ($n_t > 2$) and i is the individual assessment.

Results

Updating σ based on the historical biomass method

Consistent with Ralston et al. (2011), the groundfish and coastal pelagic species stock assessments utilized in the update of σ were data-rich species that have been assessed more than once (15 groundfish and two coastal pelagic species) and "update" assessments, where data were simply refreshed and not extensively reviewed, were not included. With the additional assessments included, the number of assessments used for this meta-analysis ranged from three (chilipepper rockfish and cabezon) to 23 (Pacific whiting). Historical biomass trajectories for the 17 species are presented in Supplementary Figure 1.

Species-specific results

The distribution of residuals (Equation 15) for the 17 species is shown in Supplementary Figure 2. These distributions are bimodal for the species with few assessments available and biomass trajectories that do not intersect (*e.g.*, shortspine thornyhead and yelloweye rockfish). Chilipepper rockfish, which exhibited a bimodal residual distribution in Ralston et al. (2011), no longer appears to be bimodal with the addition of the results from the 2015 stock assessment. Most of the residual distributions still appear to be unimodal. Some distributions exhibit long tails (*e.g.*, yellowtail rockfish and petrale sole). Darkblotched rockfish and widow rockfish have a more uniform distribution following the addition of recent stock assessments. This may be related to the increased number of assessments, and many biomass trajectories that do not intersect. The number of deviations and the estimated log-scale standard deviation for each of the species are presented in Table 4. The log-scale standard deviations range from 0.154 (cabezon) to 0.974 (shortspine thornyhead), with an average of 0.367.

Pooled results

The unweighted, pooled distributions of residuals for four groupings of species are shown in Supplementary Figure 3. The distributions are close to normal for all groupings, whereas before roundfish, flatfish, and coastal pelagic species exhibited some non-normal features (Fig. 3 of Ralston et al., 2011). The pooled point estimates of σ from this update, the accompanying approximate 95% confidence intervals, and the original pooled point estimates of σ from Ralston et al. (2011) are reported in Table 5. Pooling the deviations across all species (Supplementary Figure 3) leads to a point estimate of σ=0.389. If the residuals are assumed to be independent, an approximate 95% confidence interval based on the chi-squared distribution is $0.374 \leq \sigma \leq 0.406$ (Table 5).

Sensitivities

The historical biomass method for updating σ was repeated with the subset of species that were used in the projection-based method (*i.e.*, bocaccio rockfish, canary rockfish, darkblotched rockfish, petrale sole, Pacific Ocean perch, widow rockfish, and lingcod). The species-specific among-assessment variation is shown in Table 6. This analysis yielded a pooled point estimate of σ=0.342, with an approximate 95% confidence interval of $0.309 \leq \sigma \leq 0.352$.

Estimates of σ based on projections

Example trajectories and results for one species

Figure 1 shows time-trajectories of spawning biomass for bocaccio rockfish based on three start years (1998, 2003, and 2008) and three stock assessments (conducted in 2009, 2011, and 2015). Results are shown for deterministic projections (no variation about the estimated stock-recruitment relationship), when allowance is made for future variation about the stock-recruitment relationship, and when past and future uncertainty in recruitment are included. As expected, there is variability in future spawning biomass due to differences among assessments in key assumptions (*e.g.*, values of parameters such as unfished biomass and steepness). Further, allowing for uncertainty in recruitment leads to a greater spread of results. Allowing for uncertainty in past assessments leads to greater variation in spawning biomass in the first years of the projection period. The results for projected overfishing limits are qualitatively identical to those for spawning biomass (Fig. 2 for bocaccio rockfish; Supplementary figures 4-6 for the remaining species).

The projection year-pooled among-assessment variation in spawning biomass is quite low for bocaccio rockfish when future recruitment variation is ignored (0.0408 – 0.183 among start years;

0.123 pooled over start years; Table 7a) but is substantially higher when past and future recruitment uncertainty are included (0.305 – 0.385 among start years, 0.343 pooled over start years; Table 7a). The uncertainty in OFL projections is larger than in spawning biomass projections (start-year pooled values of 0.123 vs 0.385 for spawning biomass; start-year pooled values of 0.343 vs 0.506 for OFL).

Figures 3 and 4 show annual trajectories for σ for bocaccio rockfish (spawning biomass and OFL respectively) by start-year and pooled over start-year. The values of σ decline over 5-6 years and increase before declining (deterministic results) or stabilizing (stochastic results).

The within-assessment variation (due to stochastic recruitment) by start year and projection year for bocaccio rockfish are shown in Figures 5 (spawning biomass) and 6 (OFL). There is little within-assessment variation across the start-years. The variation across assessments differs the most during the first five projections years and stabilizes by the end of the 25 year projection period.

Estimating σ using all species

The values of σ by start-year and species (and pooled over start-year) are reported in Table 7a (spawning biomass) and 7b (OFL). The observation that allowing for uncertainty in recruitment leads to higher values for σ is true for bocaccio and lingcod. The values for σ are lower for the remaining species because the among-assessment variation is often greater than that due to stochastic recruitment (Supplementary Figures 6-8). Table 8 list the values of σ due solely to recruitment variation. These range from 0.0829 (canary rockfish; one of the longest-lived species) to 0.384 (bocaccio rockfish).

The observation for bocaccio that the variation in OFL is greater than in spawning biomass is not robust across among species, with σ based on spawning biomass larger than that based on OFL for lingcod, petrale sole and Pacific Ocean perch (Table 7).

The species-pooled values for $\bar{\sigma}$ are 0.422[1] and 0.372 when the projections are based on spawning biomass, and 0.533 and 0.485 when the projections are based on the OFL.

Figures 7 and 8 show the time-trajectories of species-pooled σ by start-year and aggregated over start years. The variation increases with time for spawning biomass (Fig. 7), but this is not the case for the OFL, which declines over time (Fig. 8).

Discussion

The hypothesis by Ralston et al. (2011) that accounting only for uncertainty in terminal year biomass leads to an under-estimate of the measure of scientific uncertainty is supported by the analyses of this paper. Specifically, the value of σ would be 0.389 based on the updated analyses of this paper compared to 0.358 by Ralston et al. (2011), which is substantially lower than the species- and start-year-pooled estimates of σ based on projected OFL (0.533 / 0.485 depending on whether recruitment stochasticity is accounted for or ignored). The projection-based method could be only applied to a sub-set of species (Tables 4 and 6), but the estimate of σ, using the historical biomass method, for the subset of species used for the projection-based method is slightly lower than for the entire set of available species (0.342 compared to 0.389), suggesting that the higher value for σ for the projection-based method is not a consequence of the choice of species.

The projection-based method captures more sources of uncertainty than the biomass-based method. In particular, it accounts for forecast error, which compounds over time, as well as the

[1] Confidence intervals are not provided for these estimates are they are not independent.

difference in error between projecting spawning biomass and projecting OFLs, with the latter being found to be consequential. Accounting for uncertainty in recruitment, both in the past and in the future, makes the calculations more complete, but does not qualitatively change the results; in fact, in several cases the value for σ was lower when account was taken of stochastic recruitment. The uncertainty estimates of projected biomass are nevertheless still likely underestimates owing, for example, to the assumption that quantities such as growth, natural mortality and the stock-recruitment relationship remain constant into the future. There is evidence for several species that these parameters are not stationary.

While it is more complete, the projection-based has limitations, including that it can only be easily applied when all the necessary information is available. Unfortunately, the detailed information needed to conduct projections for several of the assessments for which historical biomass trajectories is no longer available. In addition, assessments that were based on a different model structure could not be easily compared. This is not a major concern for the US west coast groundfish fishery as most assessments are conducted using Stock Synthesis and regions such as New Zealand where almost all assessments are conducted using CASAL (Bull et al., 2005; Doonan et al., 2016). However, this concern could be consequential for regions such as Australia where assessments are often based on bespoke models (Dichmont et al., 2016).

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Tables

Table 1. Equations for the projection-based method, where *s* is species, *y* is the projection start year (1998, 2003, 2008), *p* is the projection year (measured since the start year), and *i* is the individual assessment. $X_{s,p,i}$ are the estimates of OFL and spawning biomass for year *p*+*y*+1 based on assessment *i* starting in year *y*, and $n_{s,p}$ is the total number of projection estimates across all assessments for species *s* in projection year *p*.

	Deterministic stock-recruitment relationship	Stochastic stock-recruitment relationship	Equation
Species-, projection year- and start year-specific mean	$\overline{ln[X_{s,p}]_y} = \frac{1}{n_{s,p}}\sum_i ln[X_{s,p,i}]_y$	$\overline{ln[X_{s,p}]_y} = \frac{1}{100n_{s,p}}\sum_j\sum_i ln[X_{s,p,i,j}]$	1.1
Projection year-pooled, species-pooled, start-year-specific	$\sigma_y = \sqrt{\frac{1}{\sum_s\sum_p(n_{s,p}-1)}\sum_s\sum_p\sum_i(ln[X_{s,p,i}]_y - \overline{ln[X_{s,p}]_y})^2}$	$\sigma_y = \sqrt{\frac{1}{\sum_s\sum_p(100n_{s,p}-1)}\sum_s\sum_j\sum_i(ln[X_{s,p,i,j}]_y - \overline{ln[X_{s,p}]_y})^2}$	1.2a
Projection year-pooled, species-specific, start year-specific	$\sigma_{y,s} = \sqrt{\frac{1}{\sum_p(n_{s,p}-1)}\sum_p\sum_i(ln[X_{s,p,i}]_y - \overline{ln[X_{s,p}]_y})^2}$	$\sigma_{y,s} = \sqrt{\frac{1}{\sum_p(100n_{s,p}-1)}\sum_s\sum_j\sum_i(ln[X_{s,p,i,j}]_y - \overline{ln[X_{s,p}]_y})^2}$	1.2b
Projection year-specific, species-pooled, start year-specific	$\sigma_{y,p} = \sqrt{\frac{1}{\sum_s(n_{s,p}-1)}\sum_s\sum_i(ln[X_{s,p,i}]_y - \overline{ln[X_{s,p}]_y})^2}$	$\sigma_{y,p} = \sqrt{\frac{1}{\sum_s(100n_{s,p}-1)}\sum_s\sum_j\sum_i(ln[X_{s,p,i,j}]_y - \overline{ln[X_{s,p}]_y})^2}$	1.2c
Projection year-specific, species-specific, start year-specific	$\sigma_{y,s,p} = \sqrt{\frac{1}{n_{s,p}-1}\sum_i(ln[X_{s,p,i}]_y - \overline{ln[X_{s,p}]_y})^2}$	$\sigma_{y,s,p} = \sqrt{\frac{1}{100n_{s,p}-1}\sum_j\sum_i(ln[X_{s,p,i,j}]_y - \overline{ln[X_{s,p}]_y})^2}$	1.2d

Table 2. Equations for summarizing the estimates of σ over projection start years

Start year-pooled among assessment estimate		Equations
Projection year-pooled, species-pooled mean	$\overline{\sigma} = \sqrt{\frac{1}{3}\sum_{y} \sigma_{y}^{2}}$	2.1a
Projection year-pooled, species-specific mean	$\overline{\sigma_{s}} = \sqrt{\frac{1}{3}\sum_{y} \sigma_{y,s}^{2}}$	2.1b
Projection year-specific, species-pooled mean	$\overline{\sigma_{p}} = \sqrt{\frac{1}{3}\sum_{y} \sigma_{y,p}^{2}}$	2.1c
Projection year-specific, species-specific mean	$\overline{\sigma_{s,p}} = \sqrt{\frac{1}{3}\sum_{y} \sigma_{y,s,p}^{2}}$	2.1d

Table 3. Equations for calculating within-assessment variability, where *j* indicates a stochastic projection, and $[X_{s,p,i,j}]_y$ are the stochastic projection estimates of OFL and spawning biomass by species, projection-year, assessment, stochastic replicate and start-year.

Within assessment estimate	Stochastic stock-recruitment relationship	Equation
Species-, projection year- and start year-specific mean	$\overline{ln[X_{s,p,i}]_y} = \frac{1}{100}\sum_j ln[X_{s,p,i,j}]_y$	3.1
Projection year-pooled, start-year, species-, and assessment-specific	$\sigma_{y,s,i} = \sqrt{\frac{1}{\sum_p(100-1)}\sum_j\sum_p(ln[X_{s,p,i,j}]_y - \overline{ln[X_{s,p,i}]_y})^2}$	3.2a
Projection and start year-, species-, and assessment-specific	$\sigma_{y,s,p,i} = \sqrt{\frac{1}{100-1}\sum_j(ln[X_{s,p,i,j}]_y - \overline{ln[X_{s,p,i}]_y})^2}$	3.2b

Table 4. Summary of stock-specific analyses using the historical biomass method. * indicates species with no new assessments since 2009.

Species group	Common name	Scientific name	2017 Update No. of assessments	2017 Update Deviations (n)	2017 Update Log-scale standard deviation	Ralston et al. 2011 No. of assessments	Ralston et al. 2011 Deviations (n)	Ralston et al. 2011 Log-scale standard deviation
Rockfish	bocaccio	*Sebastes paucisipinis*	8	85	0.242	5	61	0.367
	canary rockfish*	*Sebastes pinniger*	7	85	0.375	8	85	0.375
	chilipepper	*Sebastes goodei*	3	27	0.289	2	22	0.354
	darkblotched rockfish	*Sebastes crameri*	6	83	0.281	3	45	0.103
	Pacific Ocean perch	*Sebastes alutus*	5	45	0.502	3	20	0.352
	widow rockfish	*Sebastes entomelas*	7	68	0.417	5	61	0.241
	yelloweye rockfish	*Sebastes ruberrimus*	5	46	0.590	4	58	0.492
	yellowtail rockfish*	*Sebastes flavidus*	6	66	0.269	6	66	0.269
	shortspine thornyhead	*Sebastolobus alascanus*	4	32	0.974	3	39	0.923
Roundfish	cabezon*	*Scorpaenichthys marmoratus*	3	46	0.154	3	46	0.154
	lingcod	*Ophiodon elongatus*	5	45	0.278	4	56	0.263
	Pacific whiting	*Merluccius productus*	23	151	0.286	15	151	0.286
	sablefish	*Anoplopoma fimbria*	8	72	0.314	7	82	0.340
Flatfish	Dover sole	*Microstomus pacificus*	4	42	0.658	3	41	0.360
	petrale sole	*Eopsetta jordani*	5	69	0.199	3	41	0.227
Coastal pelagic	Pacific mackerel	*Scomber japonicus*	6	76	0.484	4	66	0.415
	Pacific sardine	*Sardinops sagax*	6	72	0.347	3	51	0.206

Table 5. Summary of pooled and species group-specific estimates of σ from assessments of groundfish and coastal pelagic species using the historical biomass method.

Group	Number of species	σ 2017 estimate	 95% CI	 Ralston 2011
rockfish	9	0.490	(0.403, 0.455)	0.418
roundfish	4	0.275	(0.256, 0.0.299)	0.281
flatfish	2	0.486	(0.0.380, 0.497)	0.299
coastal pelagic	2	0.422	(0.378, 0.476)	0.339
All species	17	0.389	(0.374, 0.406)	0.358

Table 6. Summary of stock-specific values for σ based on the historical biomass method for the subset of species with assessments included in the analyses based on the projection-based method.

		Sensitivity		
Common name	Scientific name	No. of stock assessments	Squared deviations (n)	Log-scale standard deviation
Bocaccio rockfish	*Sebastes paucisipinis*	3	85	0.241
Canary rockfish	*Sebastes pinniger*	3	85	0.374
Darkblotched rockfish	*Sebastes crameri*	3	83	0.281
Pacific Ocean perch	*Sebastes alutus*	2	45	0.502
Widow rockfish	*Sebastes entomelas*	3	68	0.417
Lingcod	*Ophiodon elongatus*	2	45	0.278
Petrale sole	*Eopsetta jordani*	2	69	0.199

Table 7. Estimates of σ by species and start-year as well as start-year and species-pooled values with 95% confidence intervals. Results are shown for analyses based on spawning biomass (a) and the OFL (b).

(a) Spawning biomass

	Deterministic Stock-Recruitment							Stochastic Stock-Recruitment						
Species	1998		2003		2008			1998		2003		2008		
	σ_y	CI	σ_y	CI	σ_y	CI	$\bar{\sigma}$	σ_y	CI	σ_y	CI	σ_y	CI	$\bar{\sigma}$
Pooled	0.450	0.415,0.491	0.405	0.374,0.442	0.408	0.377,0.446	0.422	0.399	0.396,0.401	0.358	0.356,0.360	0.361	0.358,0.363	0.372
	$\sigma_{y,s}$	CI	$\sigma_{y,s}$	CI	$\sigma_{y,s}$	CI	$\bar{\sigma}_s$	$\sigma_{y,s}$	CI	$\sigma_{y,s}$	CI	$\sigma_{y,s}$	CI	$\bar{\sigma}_s$
Bocaccio rockfish	0.183	0.153,0.228	0.0964	0.0806,0.120	0.0488	0.0408,0.0608	0.123	0.391	0.385,0.397	0.327	0.322,0.333	0.305	0.300,0.310	0.343
Canary rockfish	0.544	0.454,0.678	0.370	0.309,0.461	0.381	0.319,0.475	0.439	0.415	0.408,0.422	0.288	0.284,0.293	0.288	0.298,0.308	0.340
Darkblotched rockfish	0.180	0.149,0.223	0.222	0.185,0.276	0.223	0.186,0.278	0.209	0.163	0.160,0.165	0.175	0.173,0.178	0.186	0.183,0.189	0.175
Lingcod	0.194	0.151,0.269	0.0788	0.0615,0.110	0.0842	0.0658,0.117	0.130	0.196	0.192,0.200	0.146	0.143,0.149	0.139	0.136,0.142	0.162
Petrale sole	0.893	0.697,1.24	0.879	0.686,1.22	0.785	0.613,1.09	0.854	0.652	0.640,0.665	0.634	0.622,0.647	0.586	0.575,0.598	0.625
Pacific Ocean perch	0.575	0.480,0.717	0.553	0.462,0.689	0.596	0.498,0.743	0.575	0.525	0.517,0.534	0.503	0.495,0.512	0.534	0.525,0.543	0.521
Widow rockfish	0.0872	0.0681,0.121	0.159	0.124,0.222	0.323	0.253,0.451	0.214	0.156	0.153,0.159	0.143	0.140,0.146	0.229	0.225,0.234	0.180

(b) OFL

	Deterministic Stock-Recruitment							Stochastic Stock-Recruitment						
Species	1998		2003		2008		$\bar{\sigma}_s$	1998		2003		2008		$\bar{\sigma}_s$
	σ_y	CI	σ_y	CI	σ_y	CI	$\bar{\sigma}$	σ_y		σ_y		σ_y		$\bar{\sigma}$
Pooled	0.543	0.501,0.592	0.490	0.453,0.535	0.564	0.520,0.615	0.533	0.493	0.490,0.496	0.460	0.457,0.463	0.500	0.497,0.503	0.485
	$\sigma_{y,s}$	CI	$\sigma_{y,s}$	CI	$\sigma_{y,s}$	CI	$\bar{\sigma}_s$	$\sigma_{y,s}$		$\sigma_{y,s}$		$\sigma_{y,s}$		$\bar{\sigma}_s$
Bocaccio rockfish	0.164	0.137,0.204	0.414	0.345,0.515	0.504	0.421,0.628	0.38	0.401	0.395,0.408	0.530	0.521,0.538	0.570	0.561,0.580	0.506
Canary rockfish	0.945	0.789,1.17	0.766	0.640,0.954	0.411	0.343,0.512	0.741	0.815	0.802,0.828	0.660	0.650,0.671	0.362	0.356,0.368	0.640
Darkblotched rockfish	0.574	0.480,0.715	0.606	0.506,0.755	0.644	0.538,0.802	0.609	0.545	0.537,0.555	0.597	0.588,0.607	0.601	0.591,0.610	0.582
Lingcod	0.154	0.120,0.124	0.0599	0.0467,0.0833	0.0710	0.0554,0.0988	0.104	0.178	0.174,0.181	0.144	0.141,0.147	0.145	0.142,0.148	0.156
Petrale sole	0.148	0.116,0.206	0.220	0.172,0.306	0.607	0.474,0.842	0.382	0.208	0.204,0.212	0.244	0.239,0.248	0.471	0.462,0.481	0.329
Pacific Ocean perch	0.281	0.235,0.350	0.389	0.325,0.485	0.488	0.408,0.609	0.395	0.271	0.266,0.275	0.342	0.337,0.348	0.417	0.410,0.424	0.348
Widow rockfish	0.735	0.573,1.02	0.202	0.158,0.281	0.986	0.770,1.37	0.720	0.567	0.555,0.577	0.202	0.198,0.206	0.722	0.708,0.726	0.542

Table 8. Within-assessment variation by species (projection year-pooled) where A are the assessments based on the stochastic projections.

(a) Spawning biomass:

1998						
Species	A=1	CI	A=2	CI	A=3	CI
Bocaccio rockfish	0.286	(0.278,0.294)	0.274	(0.266,0.282)	0.335	(0.326,0.345)
Canary rockfish	0.0815	(0.0793,0.0839)	0.0782	(0.0761,0.0805)	0.122	(0.119,0.126)
Darkblotched rockfish	0.111	(0.108,0.114)	0.117	(0.114,0.120)	0.167	(0.163,0.172)
Lingcod	0.145	(0.142,0.150)	0.124	(0.121,0.128)		
Petrale sole	0.160	(0.156,0.165)	0.138	(0.135,0.143)		
Pacific Ocean perch	0.112	(0.109,0.116)	0.184	(0.189,0.189)	0.180	(0.175,0.185)
Widow rockfish	0.0845	(0.0822,0.0869)	0.142	(0.138,0.146)		

2003						
Species	A=1	CI	A=2	CI	A=3	CI
Bocaccio rockfish	0.281	(0.273,0.289)	0.256	(0.249,0.264)	0.320	(0.311,0.329)
Canary rockfish	0.0840	(0.0817,0.0864)	0.0748	(0.0728,0.0770)	0.112	(0.109,0.116)
Darkblotched rockfish	0.0954	(0.0928,0.0981)	0.0940	(0.0915,0.0967)	0.219	(0.213,0.225)
Lingcod	0.129	(0.126,0.133)	0.132	(0.129,0.136)		
Petrale sole	0.173	(0.168,0.178)	0.154	(0.150,0.159)		
Pacific Ocean perch	0.123	(0.119,0.126)	0.166	(0.162,0.171)	0.178	(0.173,0.183)
Widow rockfish	0.0643	(0.0626,0.0662)	0.149	(0.145,0.154)		

2008						
Species	A=1	CI	A=2	CI	A=3	CI
Bocaccio rockfish	0.264	(0.267,0.271)	0.259	(0.252,0.267)	0.332	(0.323,0.341)
Canary rockfish	0.0806	(0.0785,0.0830)	0.0841	(0.0818,0.0865)	0.104	(0.101,0.107)
Darkblotched rockfish	0.120	(0.117,0.124)	0.106	(0.103,0.109)	0.193	(0.188,0.199)
Lingcod	0.131	(0.128,0.135)	0.118	(0.115,0.122)		
Petrale sole	0.150	(0.146,0.154)	0.212	(0.206,0.218)		
Pacific Ocean perch	0.147	(0.143,0.151)	0.182	(0.177,0.188)	0.178	(0.174,0.184)
Widow rockfish	0.070	(0.0680,0.0718)	0.151	(0.147,0.156)		

(b) OFL

			1998			
Species	A=1	CI	A=2	CI	A=3	CI
Bocaccio rockfish	0.321	(0.312,0.330)	0.337	(0.328,0.347)	0.384	(0.373,0.395)
Canary rockfish	0.0829	(0.0807,0.0853)	0.0930	(0.0905,0.957)	0.141	(0.137,0.145)
Darkblotched rockfish	0.139	(0.133,0.141)	0.149	(0.145,0.154)	0.221	(0.215,0.228)
Lingcod	0.154	(0.150,0.158)	0.135	(0.131,0.138)		
Petrale sole	0.180	(0.175,0.185)	0.158	(0.154,0.163)		
Pacific Ocean perch	0.154	(0.150,0.159)	0.206	(0.201,0.213)	0.192	(0.187,0.198)
Widow rockfish	0.107	(0.104,0.110)	0.229	(0.223,0.236)		

			2003			
Species	A=1	CI	A=2	CI	A=3	CI
Bocaccio rockfish	0.339	(0.330,0.349)	0.344	(0.334,0.354)	0.414	(0.403,0.426)
Canary rockfish	0.0970	(0.0943,0.0997)	0.102	(0.0996,0.105)	0.140	(0.136,0.144)
Darkblotched rockfish	0.125	(0.121,0.128)	0.129	(0.125,0.133)	0.256	(0.249,0.263)
Lingcod	0.138	(0.135,0.142)	0.142	(0.138,0.146)		
Petrale sole	0.192	(0.166,0.175)	0.170	(0.166,0.175)		
Pacific Ocean perch	0.178	(0.173,0.183)	0.183	(0.178,0.187)	0.193	(0.187,0.198)
Widow rockfish	0.0892	(0.0868,0.0918)	0.217	(0.212,0.224)		

			2008			
Species	A=1	CI	A=2	CI	A=3	CI
Bocaccio rockfish	0.318	(0.309,0.327)	0.361	(0.351,0.371)	0.457	(0.445,0.471)
Canary rockfish	0.0884	(0.0860,0.0909)	0.118	(0.115,0.121)	0.117	(0.114,0.120)
Darkblotched rockfish	0.155	(0.151,0.159)	0.138	(0.135,0.142)	0.214	(0.208,0.220)
Lingcod	0.141	(0.137,0.144)	0.130	(0.126,0.133)		
Petrale sole	0.170	(0.165,0.174)	0.246	(0.239,0.253)		
Pacific Ocean perch	0.206	(0.201,0.212)	0.198	(0.193,0.204)	0.200	(0.190,0.201)
Widow rockfish	0.129	(0.125,0.132)	0.206	(0.201,0.212)		

Figures

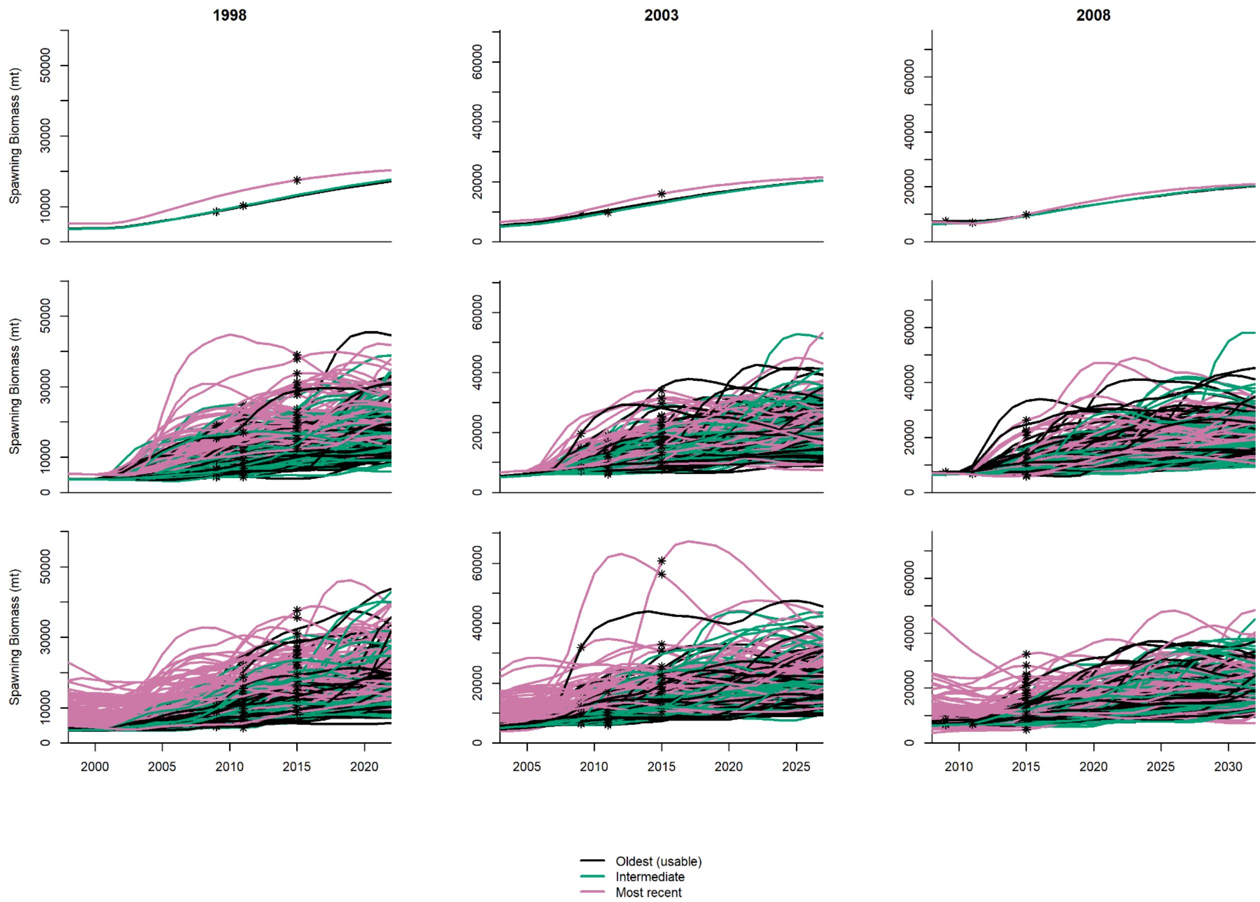


Figure 1. Time-trajectories of spawning biomass for bocaccio rockfish based on three start years (1998, 2003, and 2008; columns) and three stock assessments (2009, 2011, and 2015; solid dots). Results are shown in the upper panels for the deterministic projections, in the center panels for stochastic projections that only consider uncertainty in future recruitment, and in the lower panels for stochastic projections that account for uncertainty in past and future recruitment.

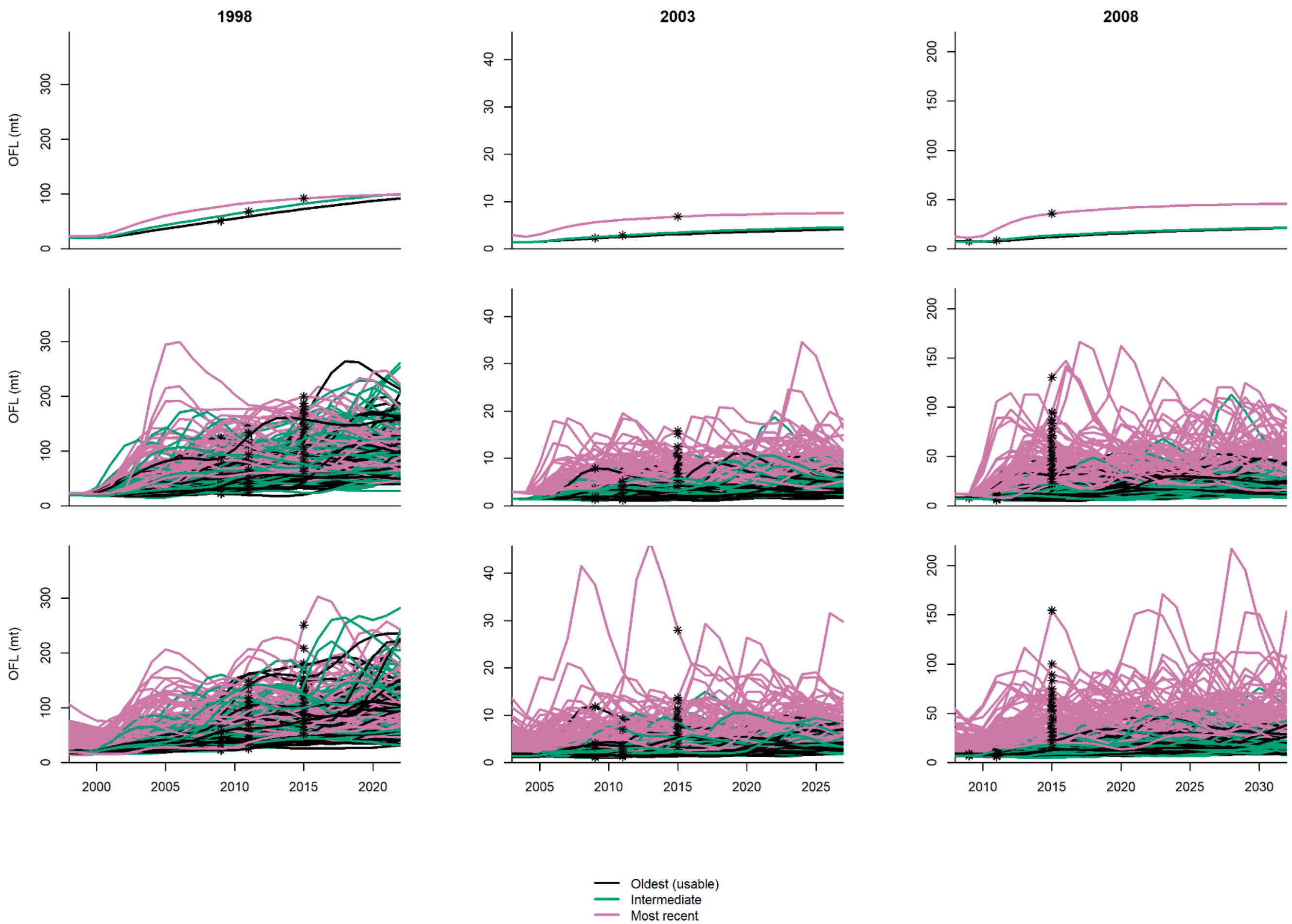
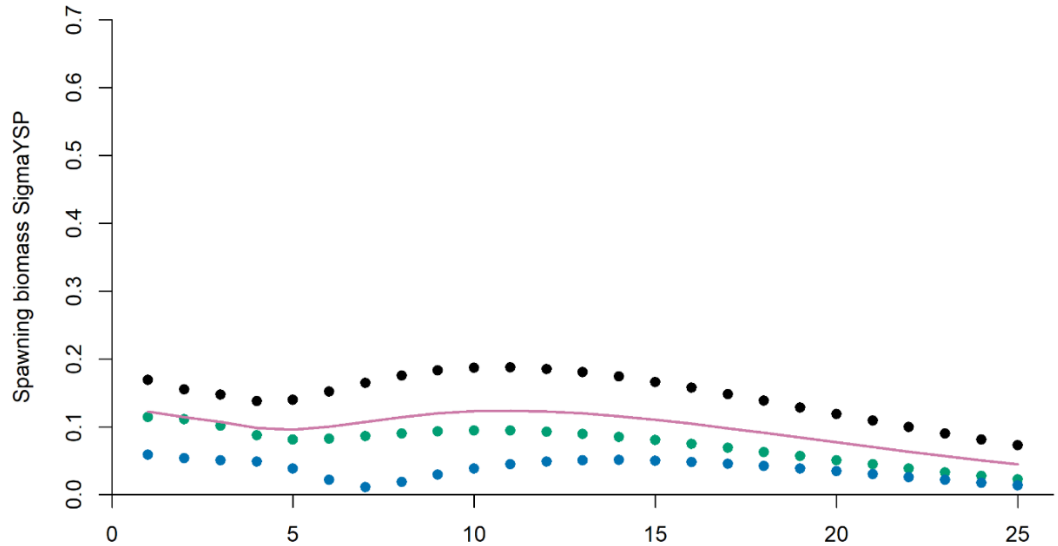


Figure 2. As for Figure 1, except the results pertain to the OFL.



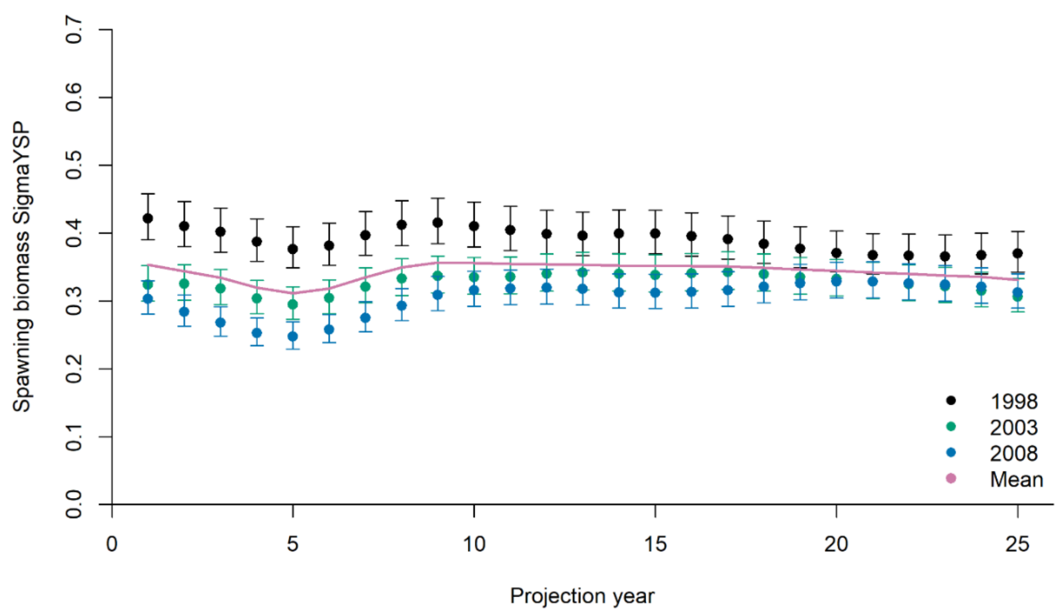


Figure 3. Values of σ for bocaccio rockfish based on spawning biomass. Results are shown for deterministic (upper panel) and stochastic (lower panel) analyses by start year and pooled over start-years. The whiskers in the lower panel indicate 95% confidence intervals (no 95% confidence intervals are shown in the upper panel owning to small sample size).

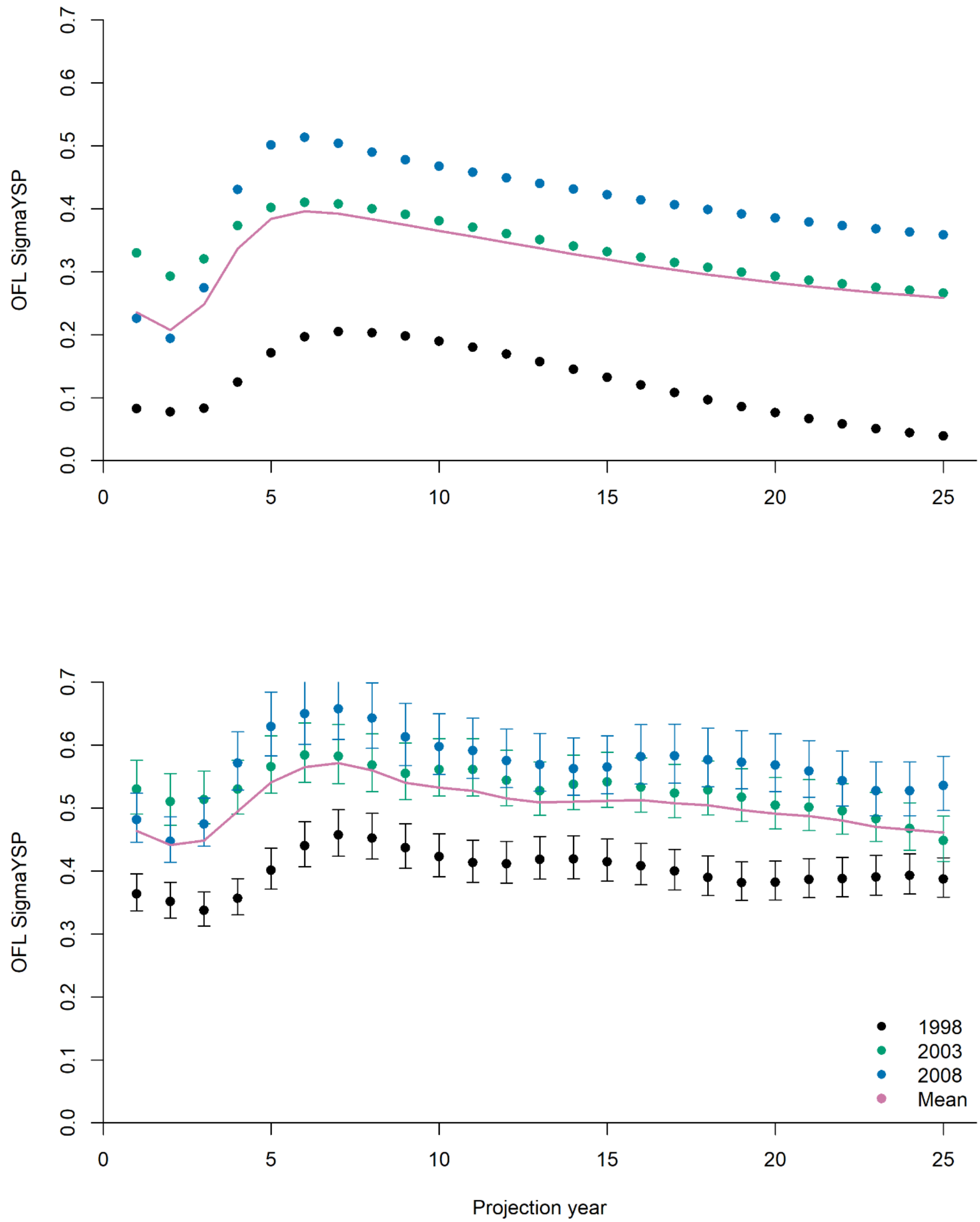


Figure 4. As for Figure 3, except the results relate to the OFL.

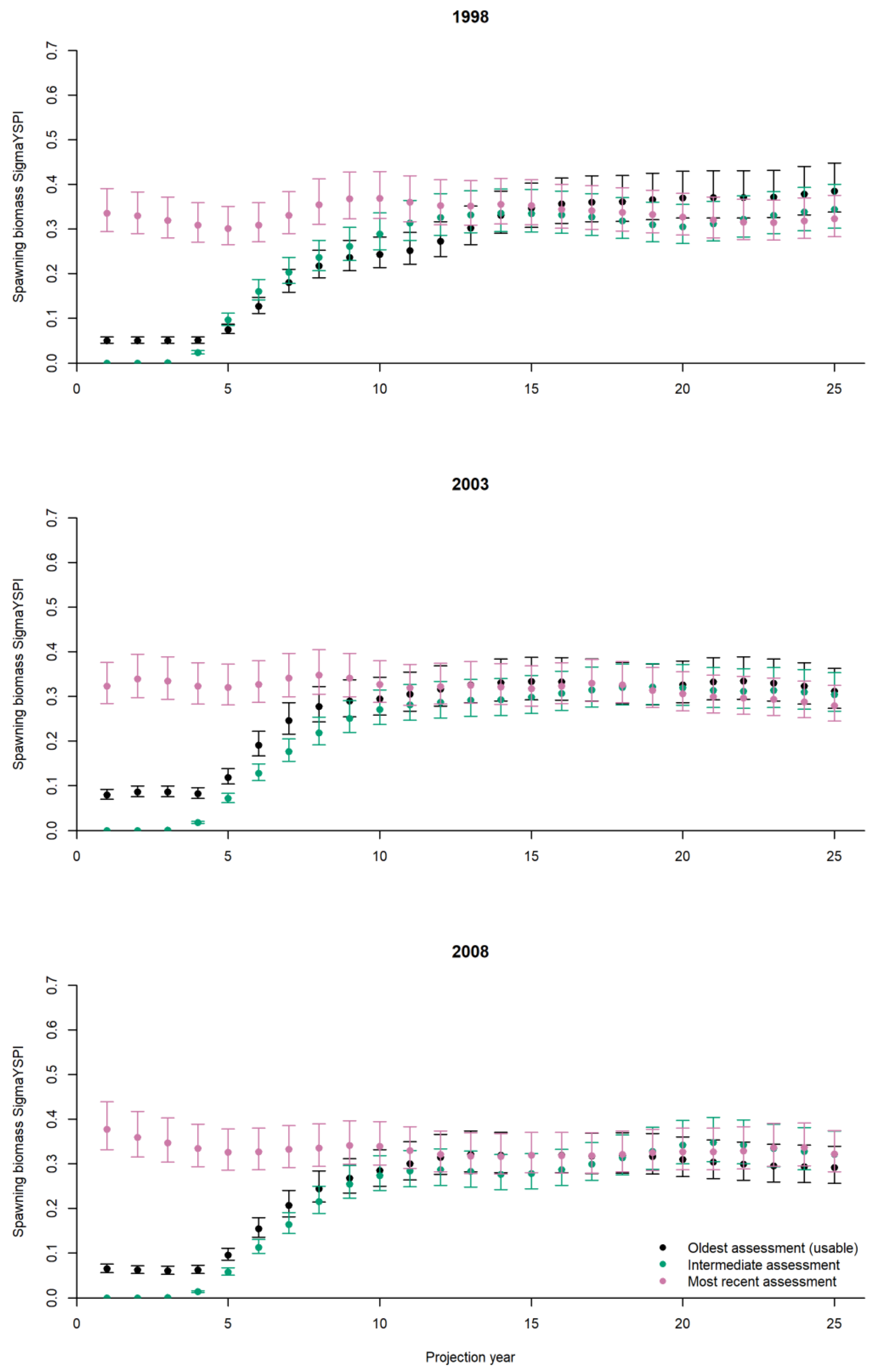


Figure 5. Values of within-assessment σ for bocaccio rockfish based on spawning biomass. Results are shown for stochastic analyses by start year and by assessment (2009, 2011, and 2015). The whiskers indicate 95% confidence intervals.

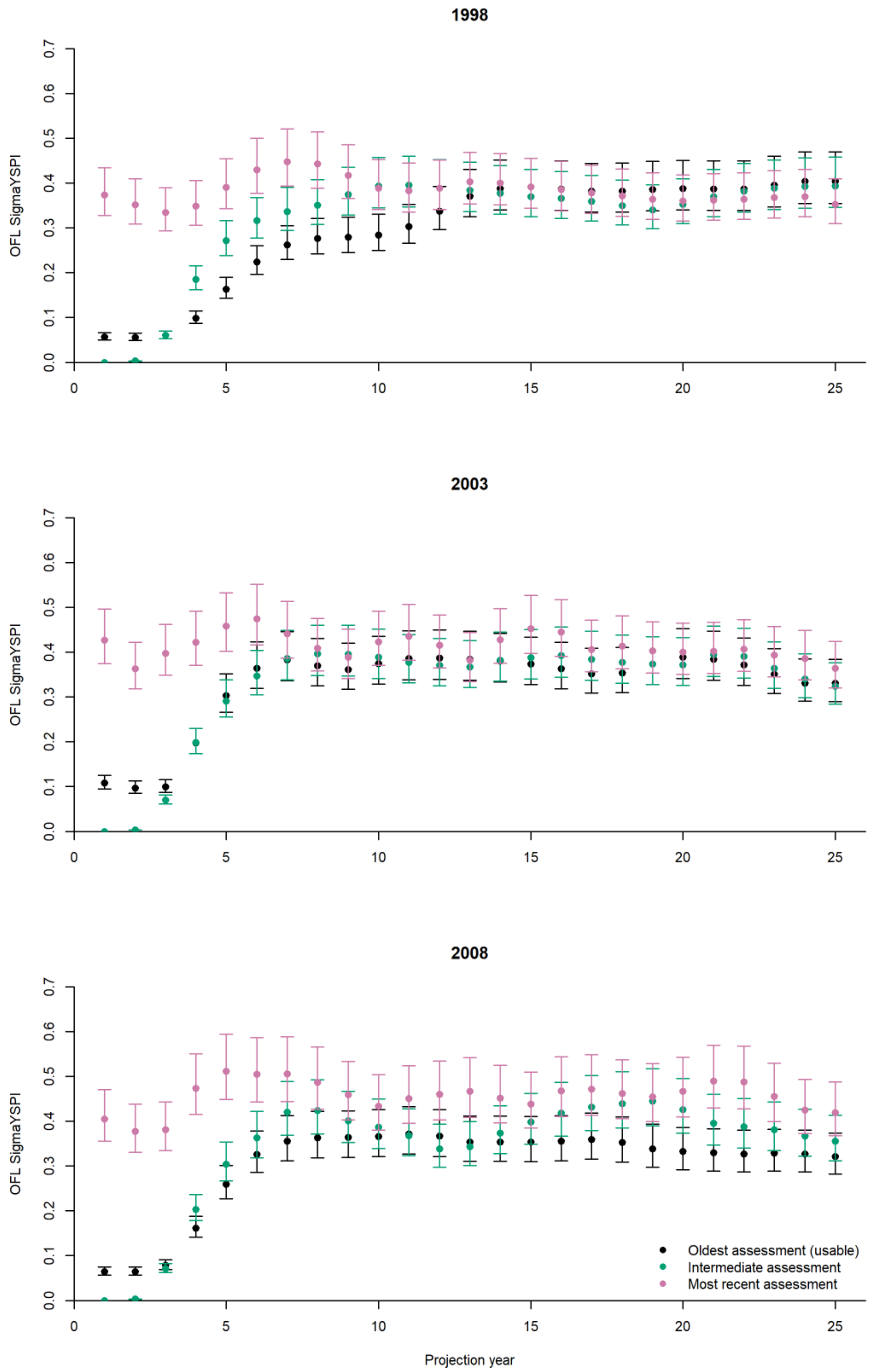


Figure 6. As for Figure 5, except the results relate to the OFL.

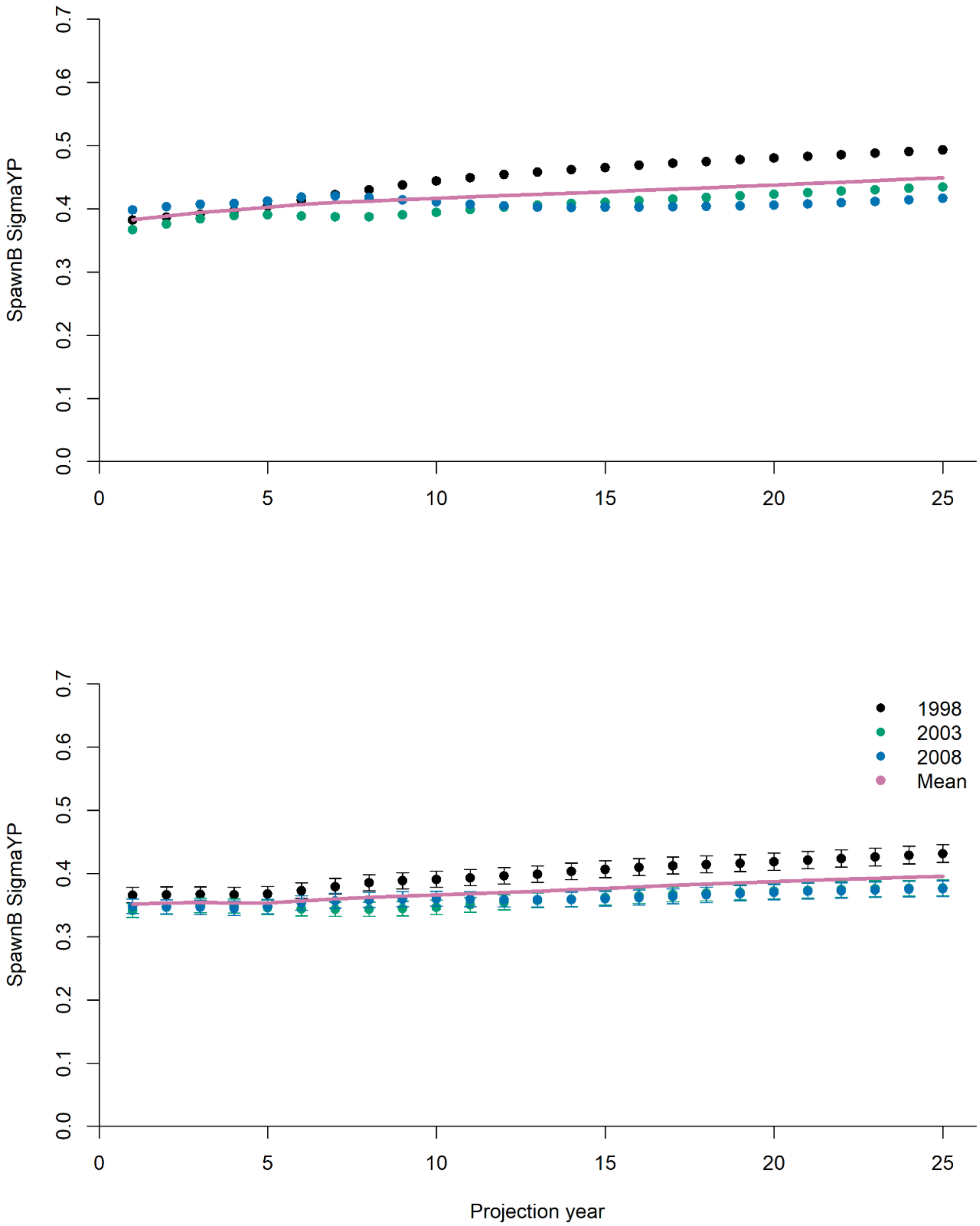


Figure 7. Values of σ aggregated over species based on spawning biomass. Results are shown for deterministic (upper panel) and stochastic (lower panel) analyses by start year and pooled over start-years. The whiskers in the lower panel indicate 95% confidence intervals (no 95% confidence intervals are shown in the upper panel owning to small sample size).

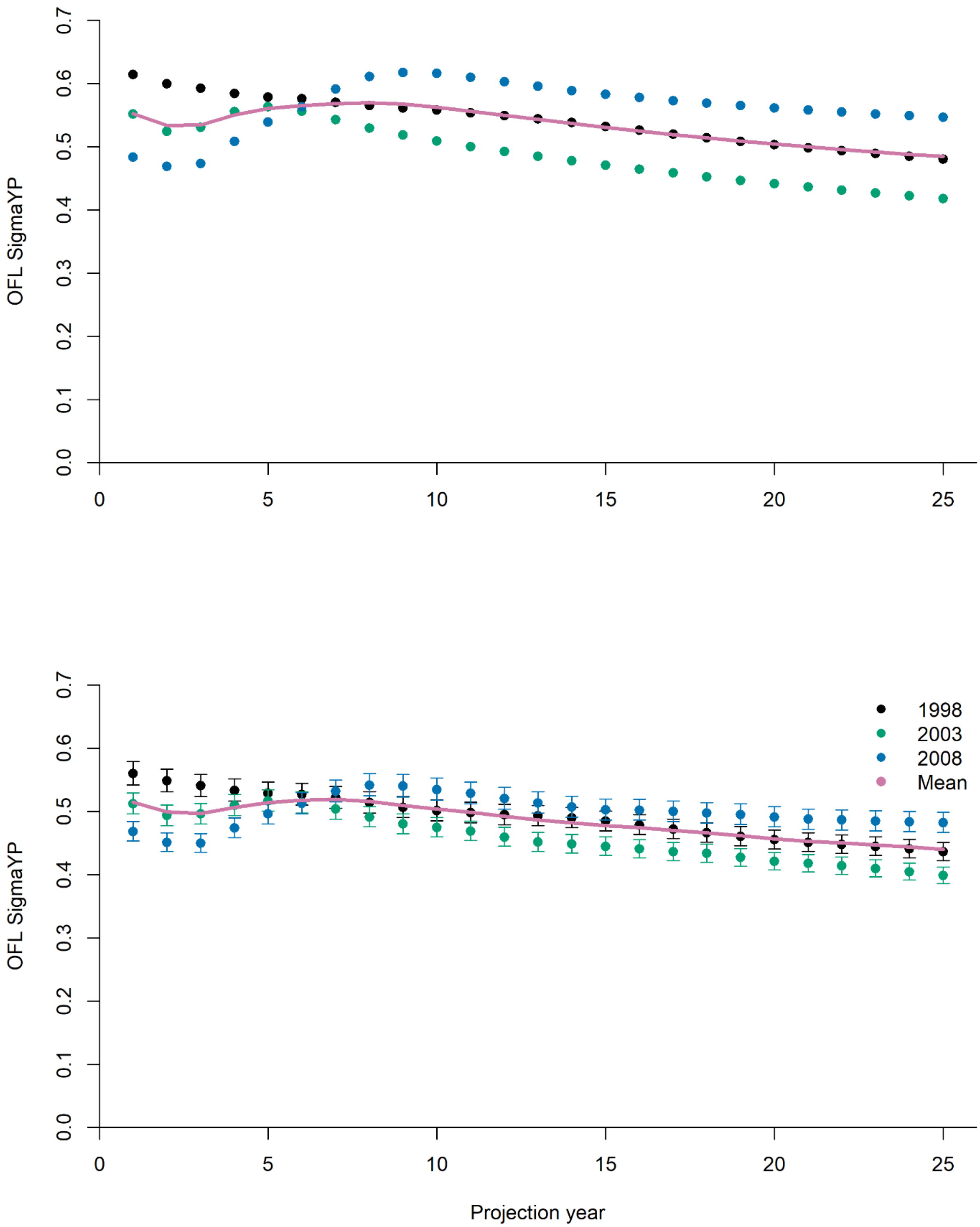


Figure 8. As for Figure 7, except the results relate to the OFL.

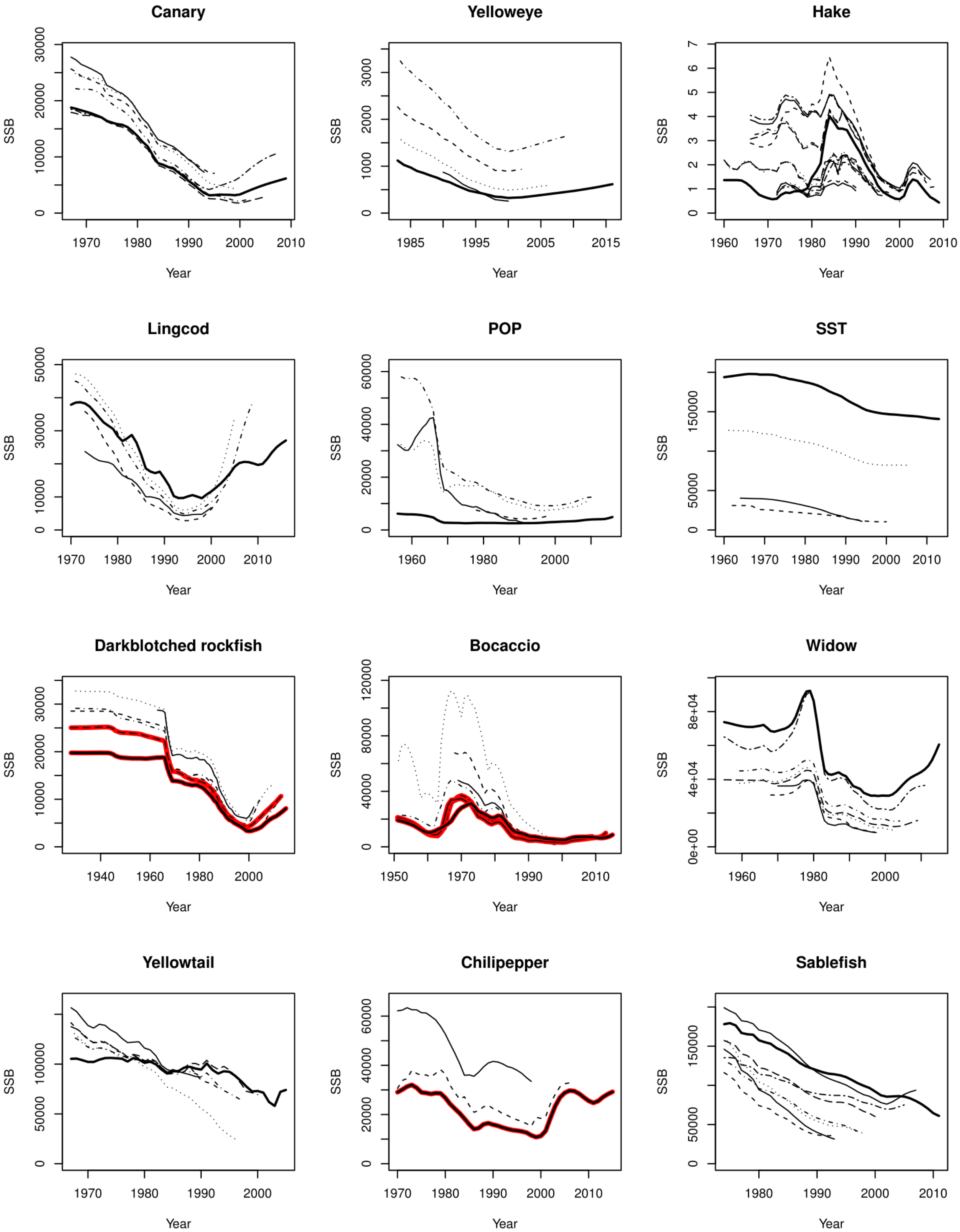
Supplementary Materials

Supplementary Table 1. The US west coast groundfish benchmark stock assessments used for conducting projections.

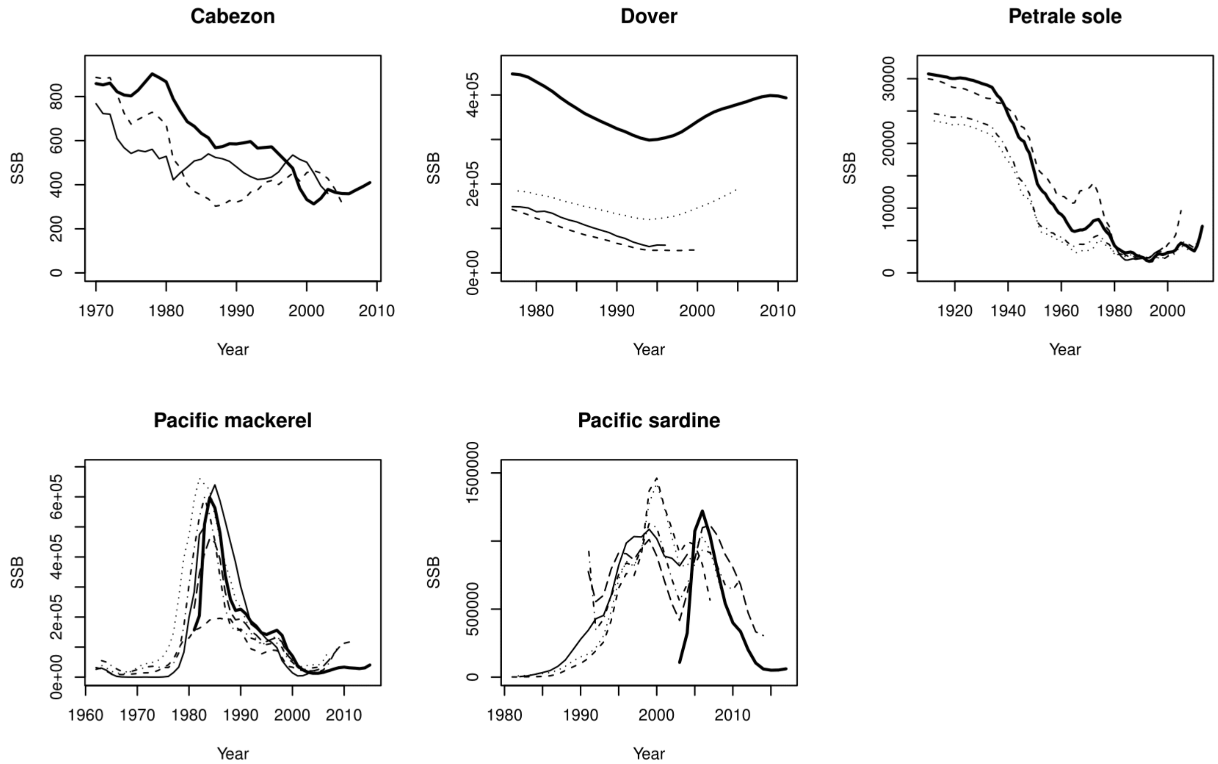
Species	Year	Authors
Bocaccio rockfish	2009	Field, Dick, Pearson, and MacCall
Sebastes paucispinis	2011	Field
	2015	He, Field, Pearson, Lefebvre, and Lindley
Canary rockfish	2009	Stewart
	2011	Wallace and Cope
	2015	Thorson and Wetzel
Darkblotched rockfish	2009	He, Punt, MacCall, and Ralston
Sebastes crameri	2011	He, Pearson, Dick, Field, Ralston, and MacCall
	2013	Ghosts
	2015	Hicks and Wetzel
Lingcod	2009	Hamel, Sethi, and Wadsworth
Ophiodon elongatus	2017	Haltuch, Wallace, Akselrud, Nowlis, Barnett, Valero, Tsou, and Lam
Petrale sole	2011	Haltuch, Hicks, and See
Eopsetta jordani	2013	Haltuch, Ono, and Valero
Pacific ocean perch	2011	Hamel and Ono
Sebastes alutus	2017	Wetzel, Cronin-Fine, and Johnson
Widow rockfish	2011	He, Pearson, Dick, Field, Ralston, and MacCall
Sebastes entomelas	2015	Hicks and Wetzel

Supplementary Table 2. The quantities extracted from Stock Synthesis report files to conduct OFL and spawning biomass projections. Reference year of interest refers to the last year of the assessment, as defined by the first year for which spawning biomass and OFL are projected.

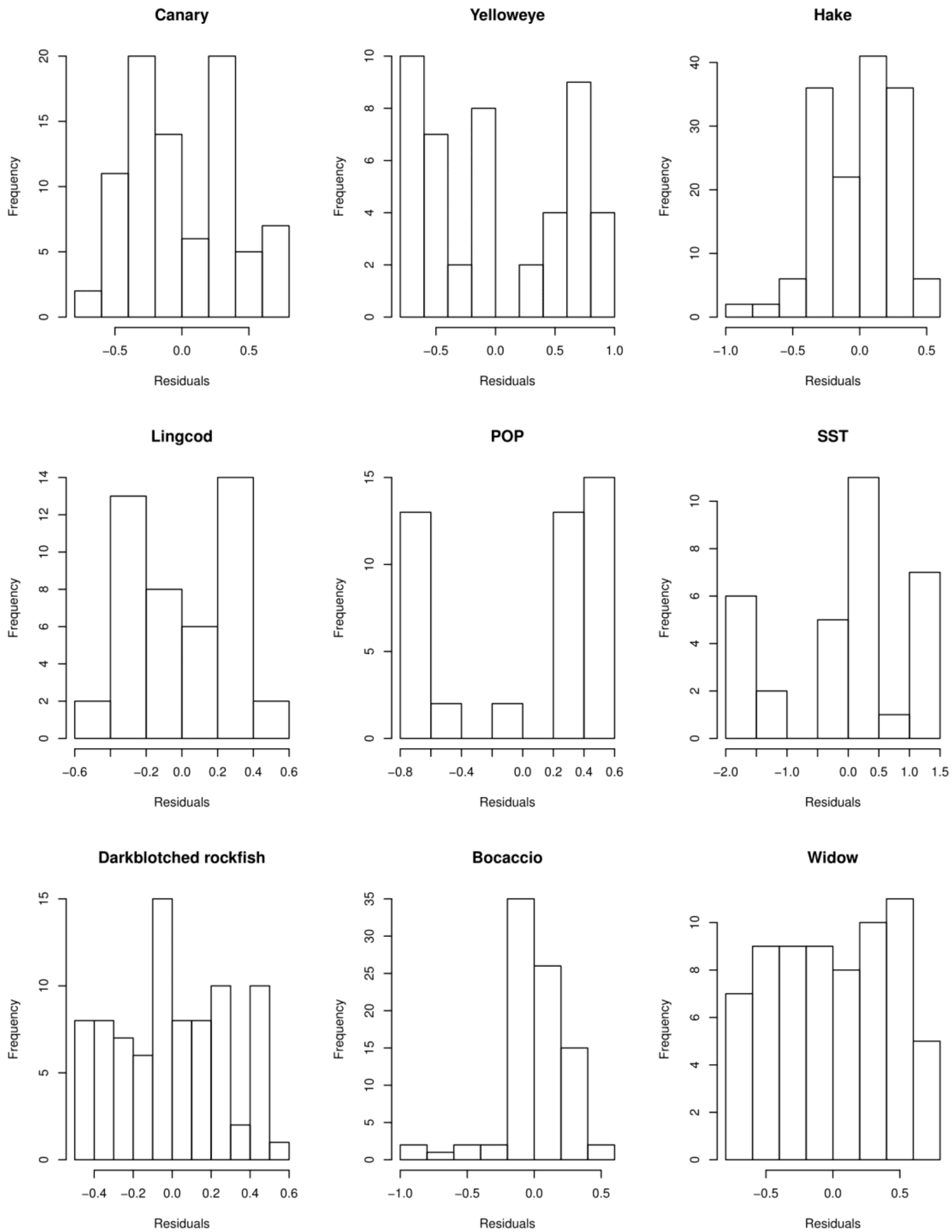
Stock Assessment Output
Numbers-at-age for reference year of interest, *N*
Fecundity (unfished and fished) for reference year of interest, ω
Selectivity at age by fleet, *S*
Selected-weighted retained weight by age and fleet, *W*
Natural mortality, *M*
Relative exploitation rate by fleet, *F*
Stock-recruit parameters
Unfished recruitment, R_0
Steepness, *h*



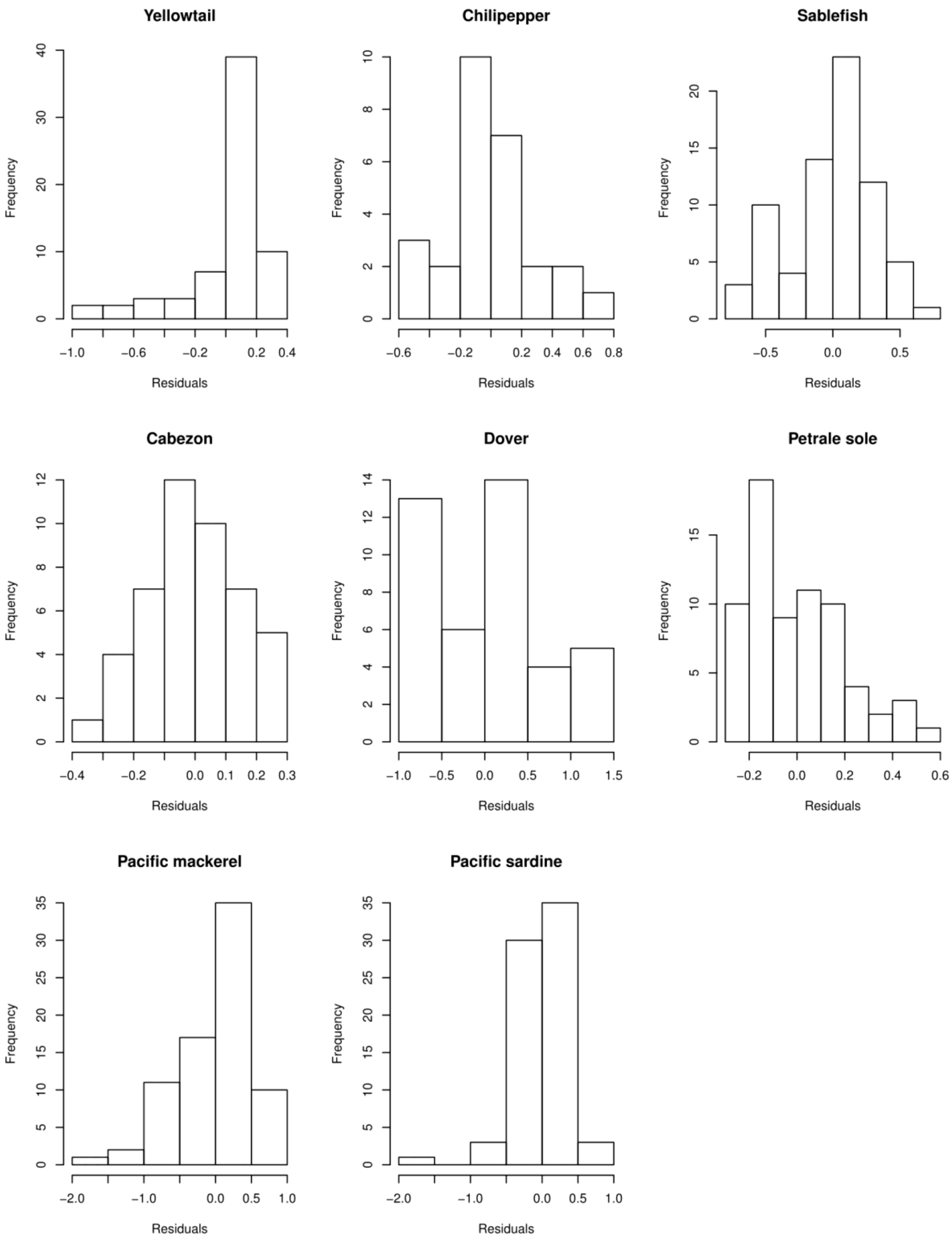
Supplementary Figure 1. Biomass time series for the 17 groundfish and coastal pelagic species from stock assessments conducted for the Pacific Fishery Management Council on the west coast of the United States. The thick, solid black line denotes the most recent assessment. The lines highlighted in red are the biomass trajectories that were recalculated to be in metric tons based on outputs from Stock Synthesis in eggs.



Supplementary Figure 1 continued.

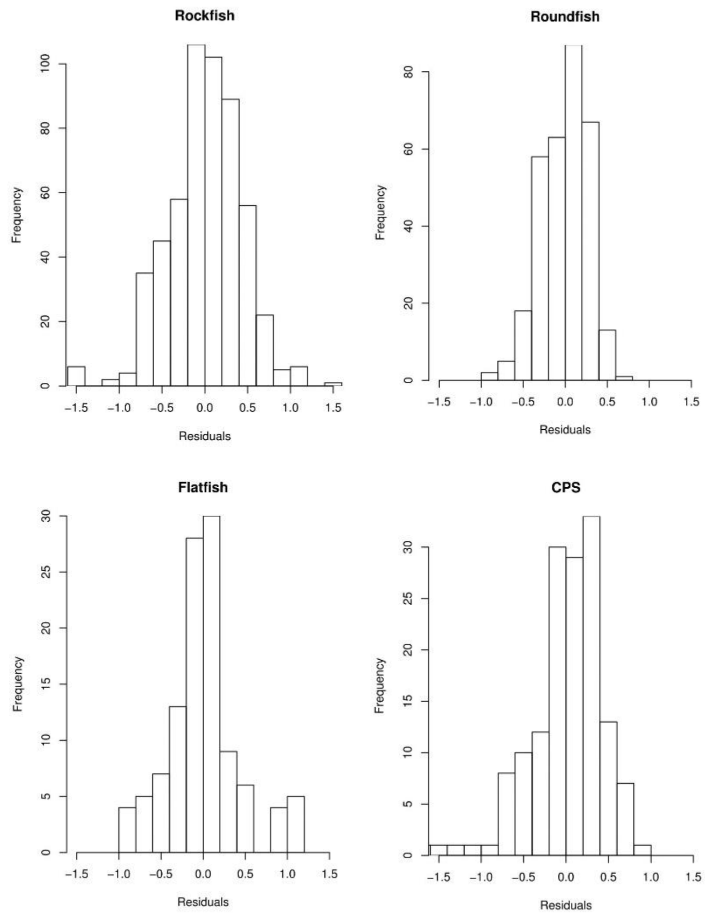


Supplementary Figure 2. Frequency distributions of log-scale biomass deviations for the 17 groundfish and coastal pelagic species in stock assessments conducted for the Pacific Fishery Management Council. Deviations were calculated from annual means taken from the biomass time series presented in Supplementary Figure 1.

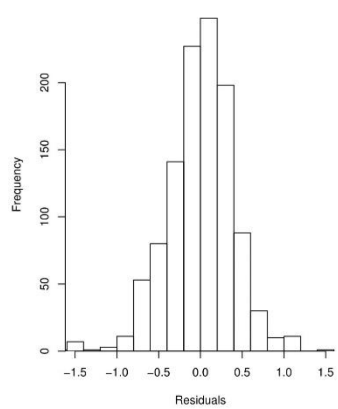


Supplementary Figure 2 continued.

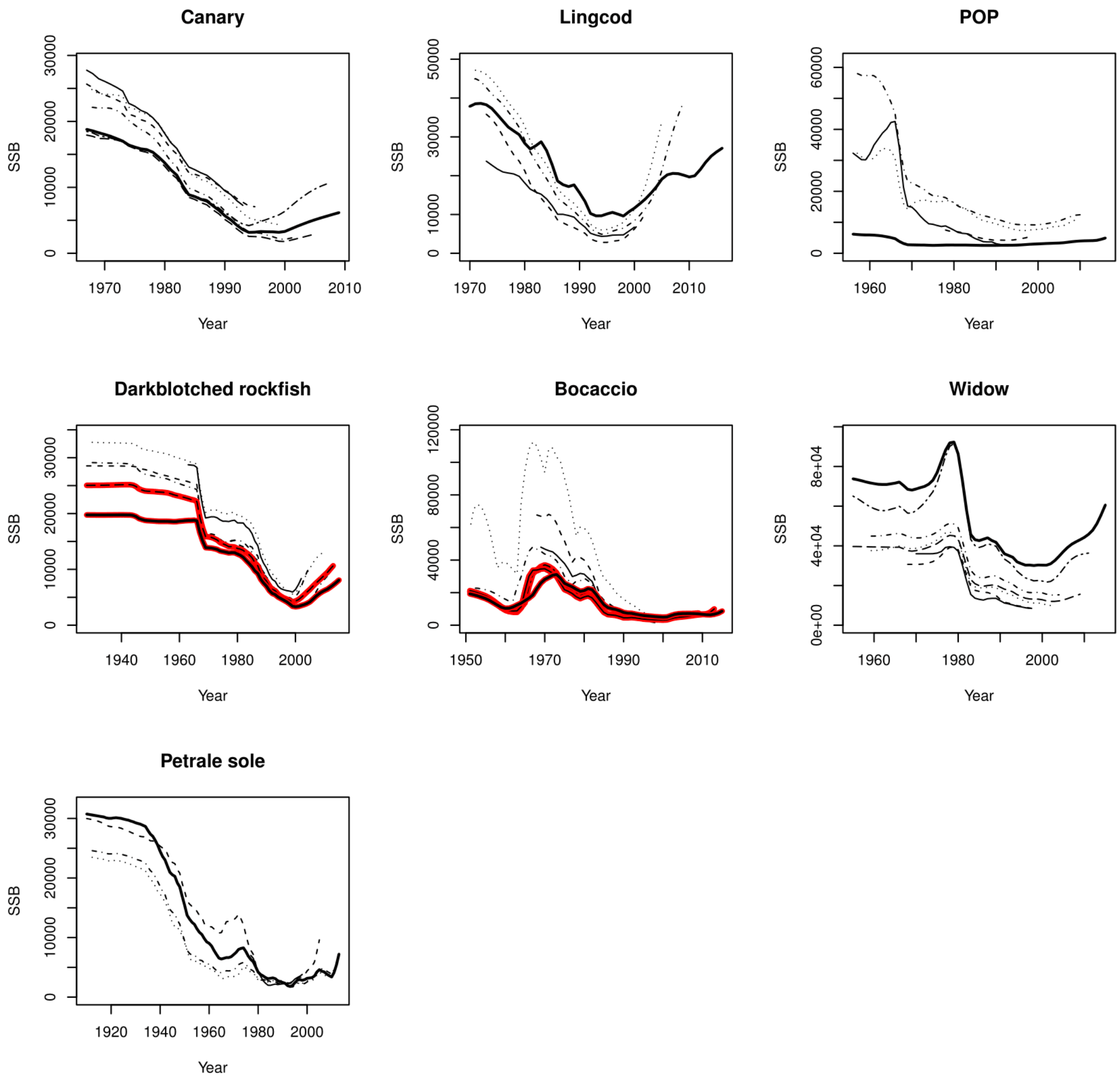
A



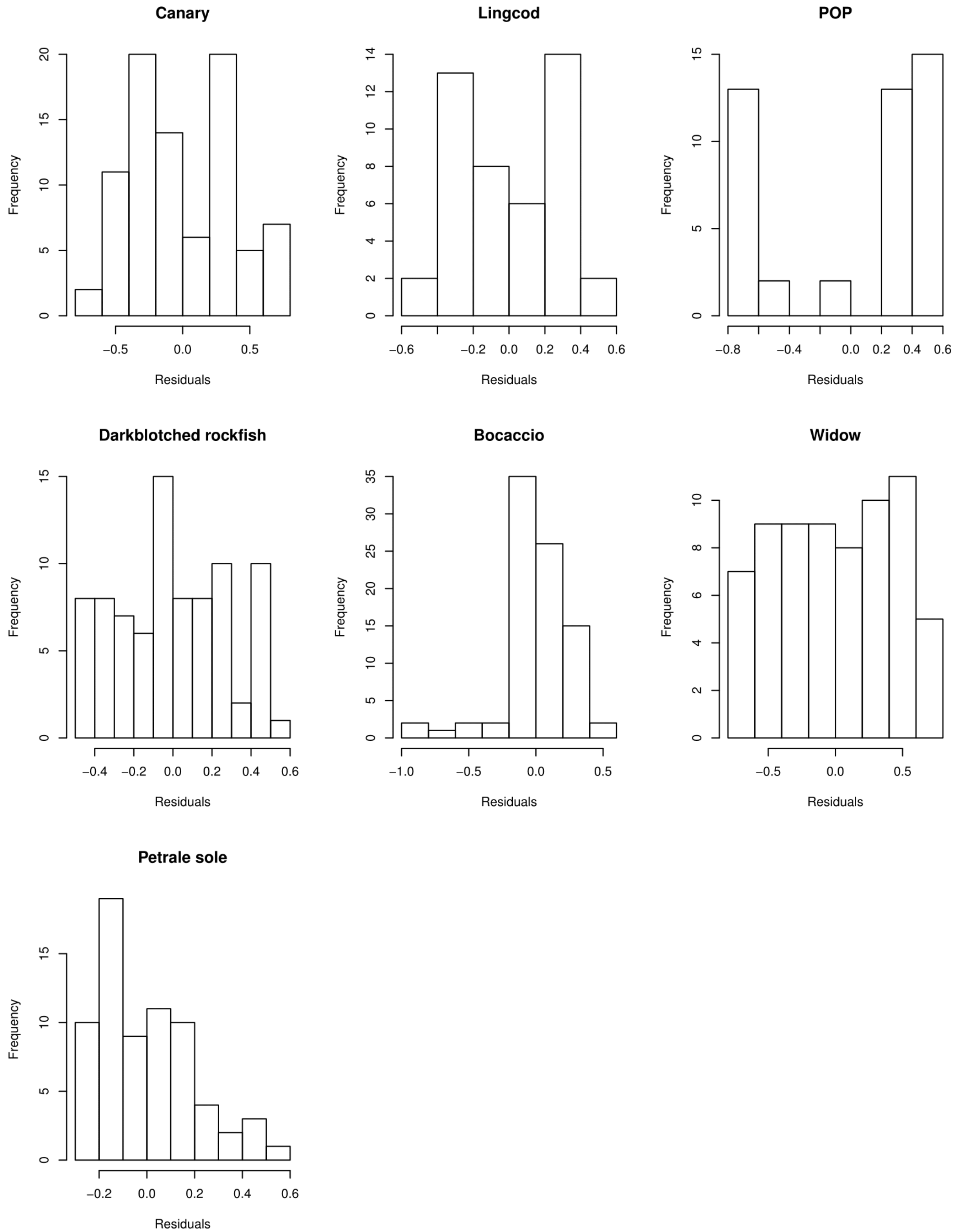
B



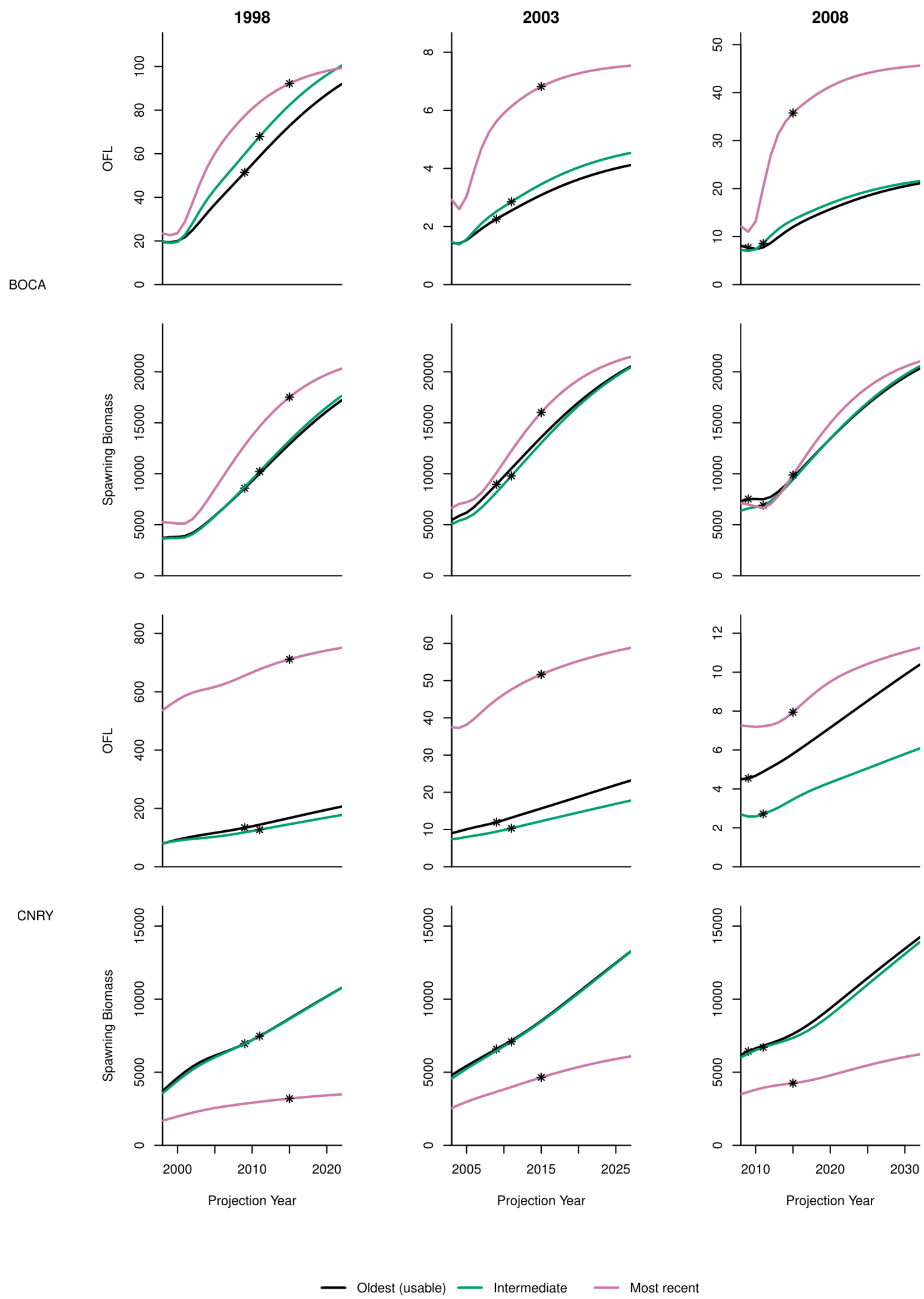
Supplementary Figure 3. Panel A) Composite distributions of log-deviations from the mean, pooled for four meta-analytic groupings (rockfish, roundfish, flatfish, and coastal pelagic species). Panel B) Aggregate distribution of log-deviations pooled over all 17 species.



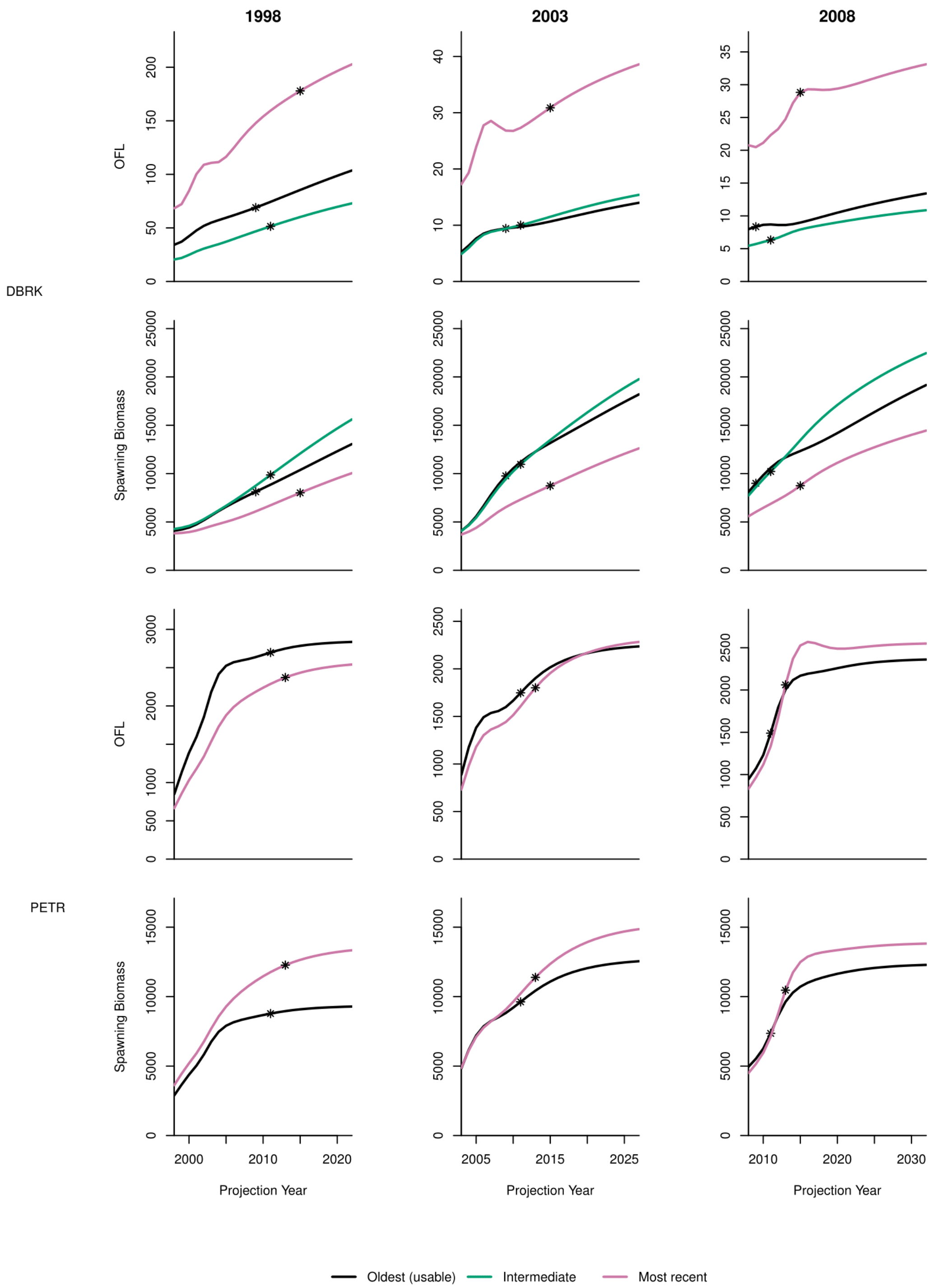
Supplementary Figure 4. Biomass time series for the subset of 7 groundfish species from stock assessments conducted for the Pacific Fishery Management Council on the west coast of the United States. The thick, solid black line denotes the most recent assessment.



Supplementary Figure 5. As for Supplementary Figure 2 for the subset of groundfish.



Supplementary Figure 6. Deterministic projections by species, with the upper panels for each species showing OFL projections and the lower panels spawning biomass projections.



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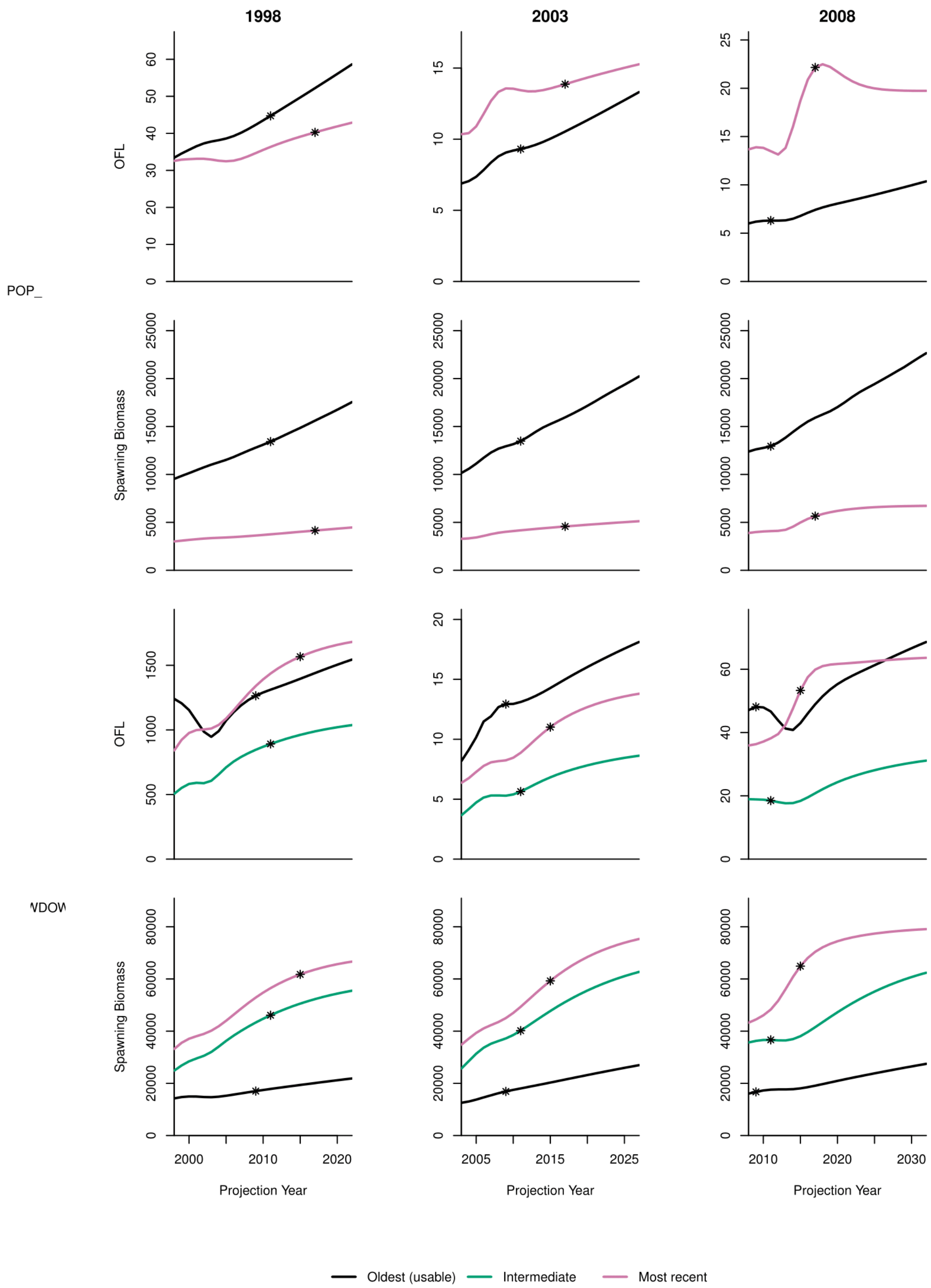
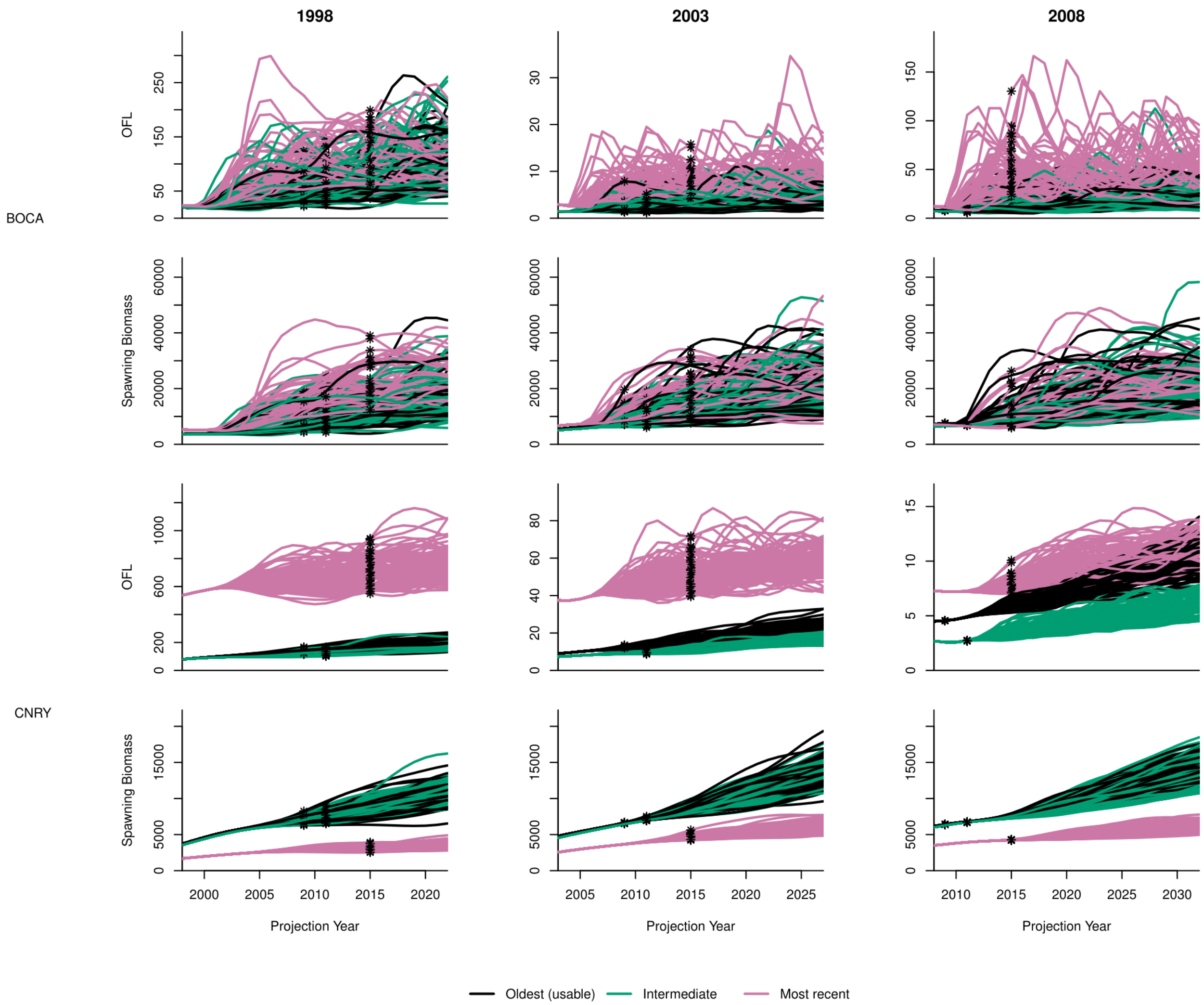
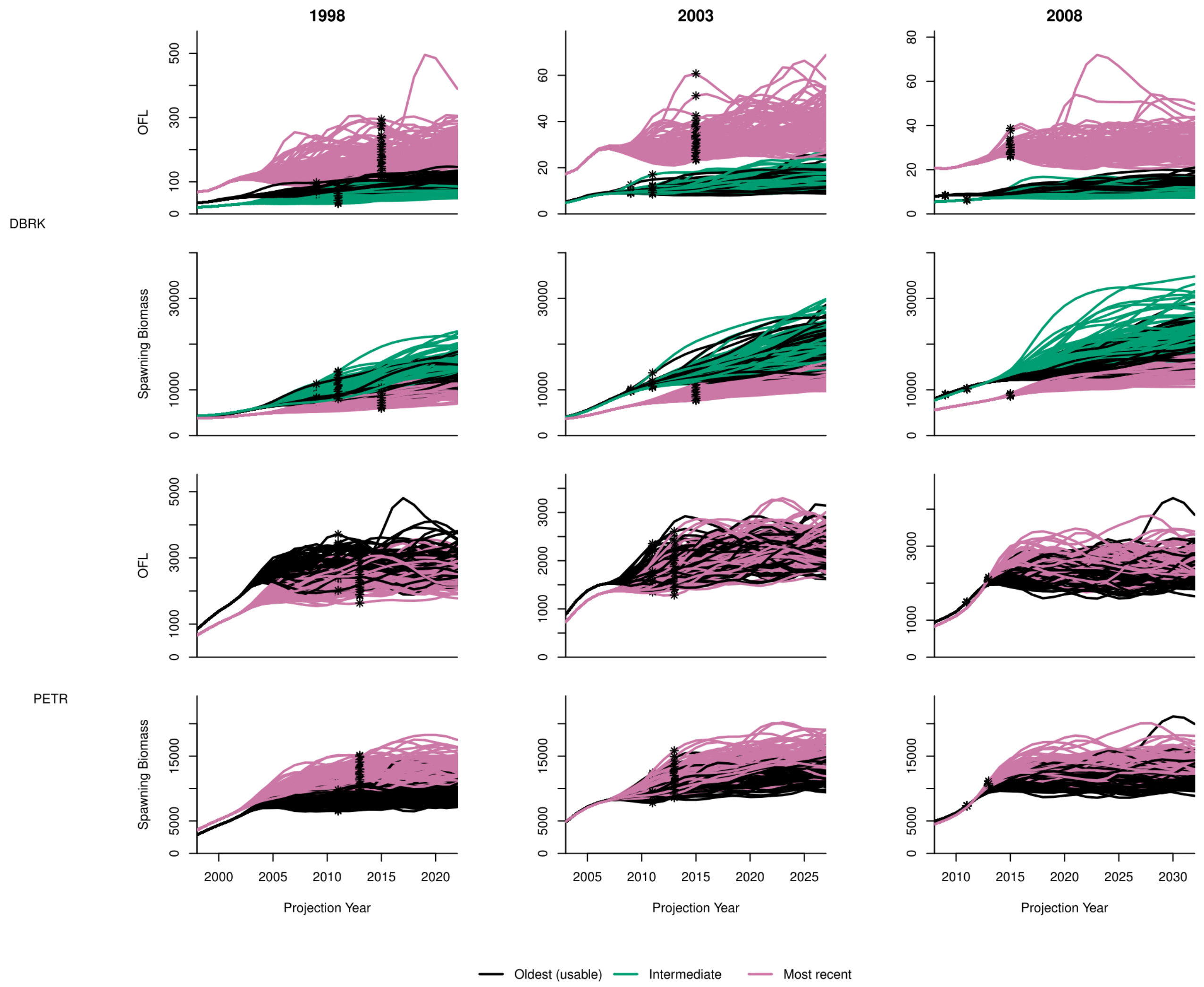


Supplementary Figure 6 continued



Supplementary Figure 7. Time-trajectories of spawning biomass for all species based on three start years (1998, 2003, and 2008; columns) and two to three stock assessments (solid dots). Results are shown for stochastic projections that only consider uncertainty in future recruitment.



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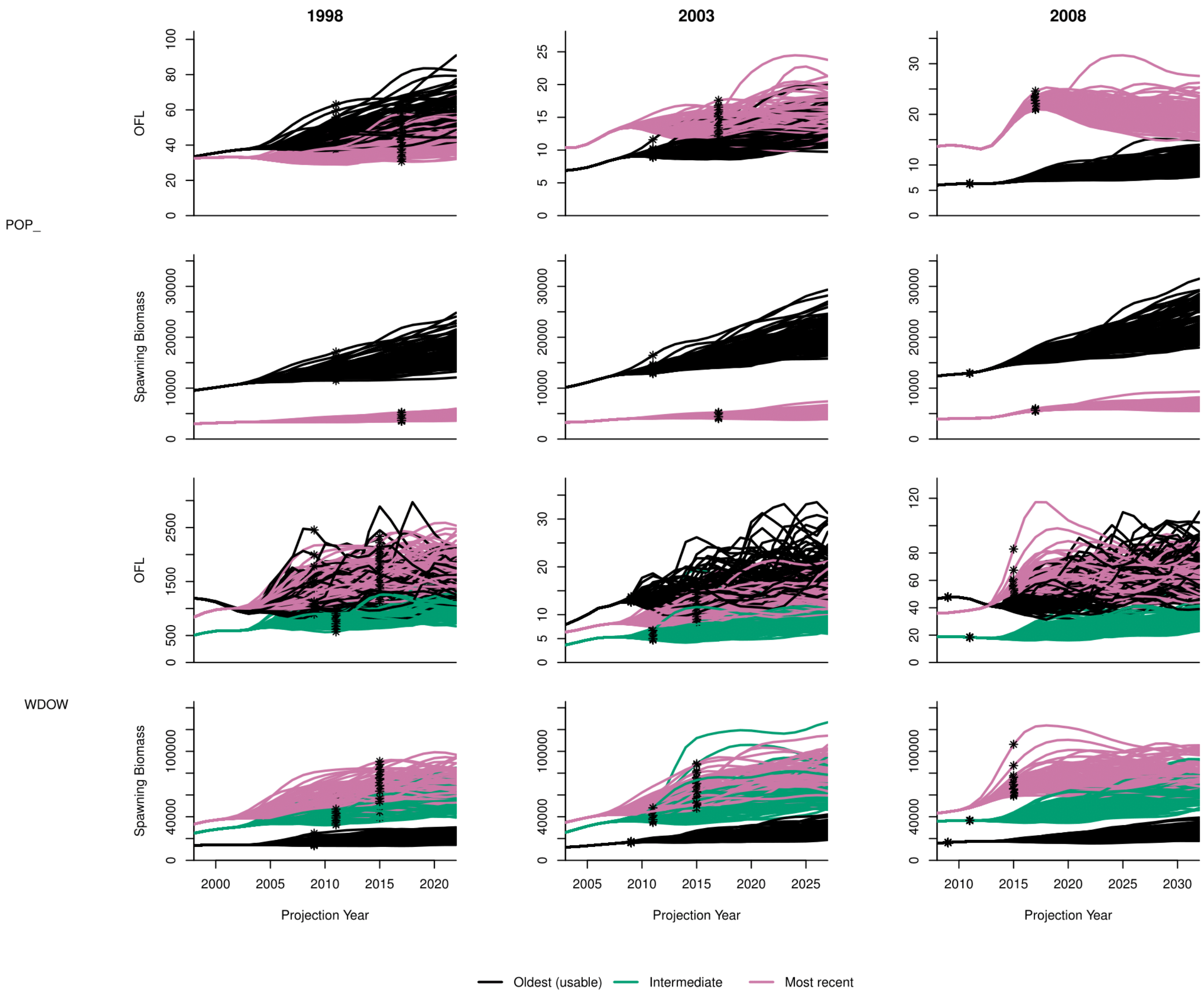

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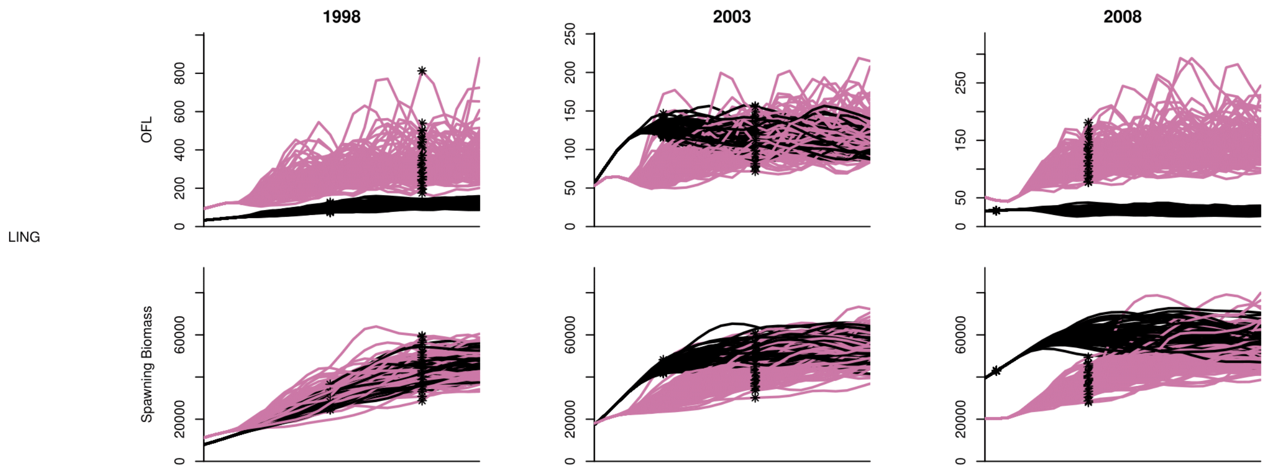

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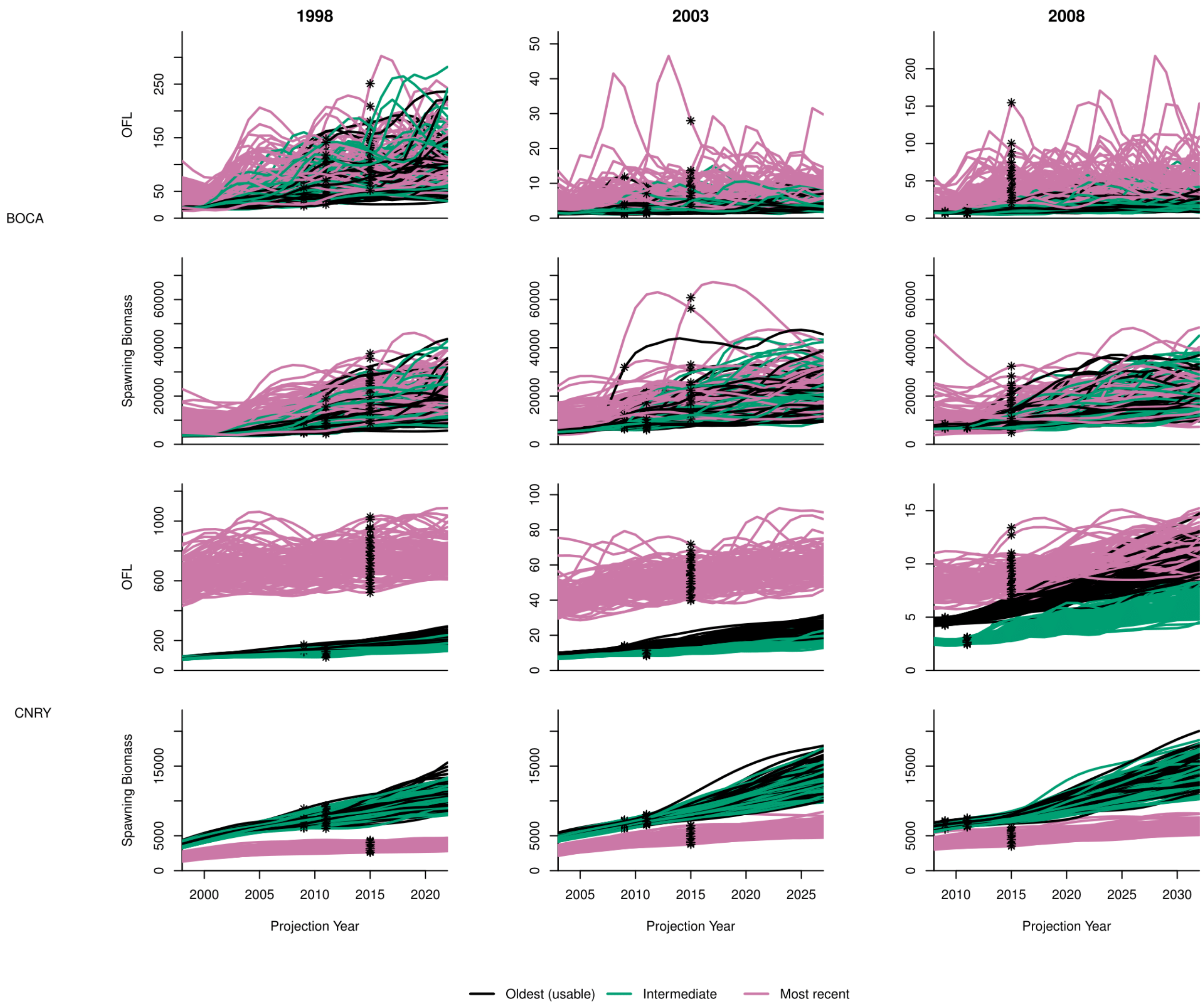
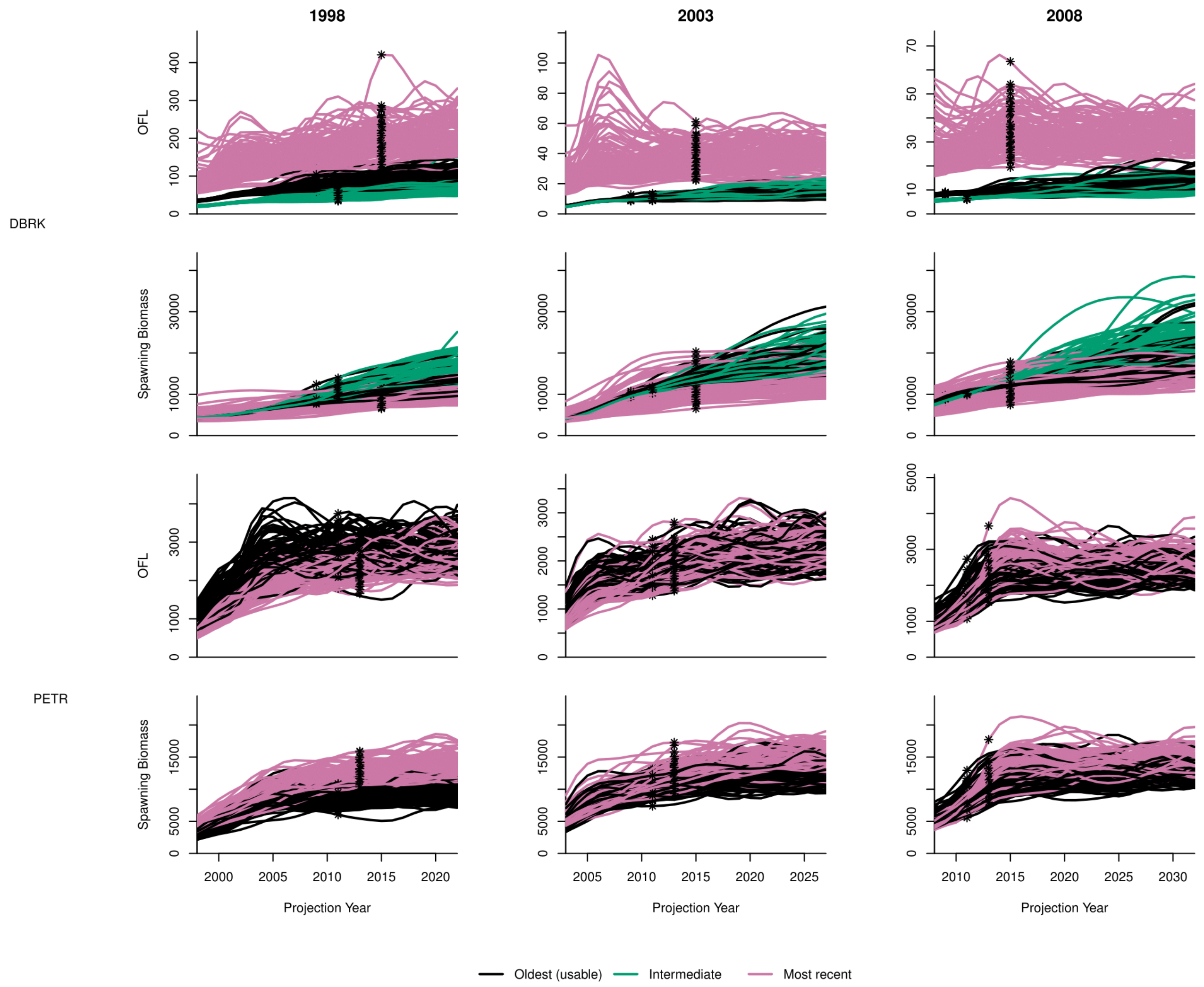


Supplementary Figure 8. Time-trajectories of spawning biomass for all species based on three start years (1998, 2003, and 2008; columns) and two to three stock assessments (solid dots). Results are shown for stochastic projections that account for uncertainty in past and future recruitment.



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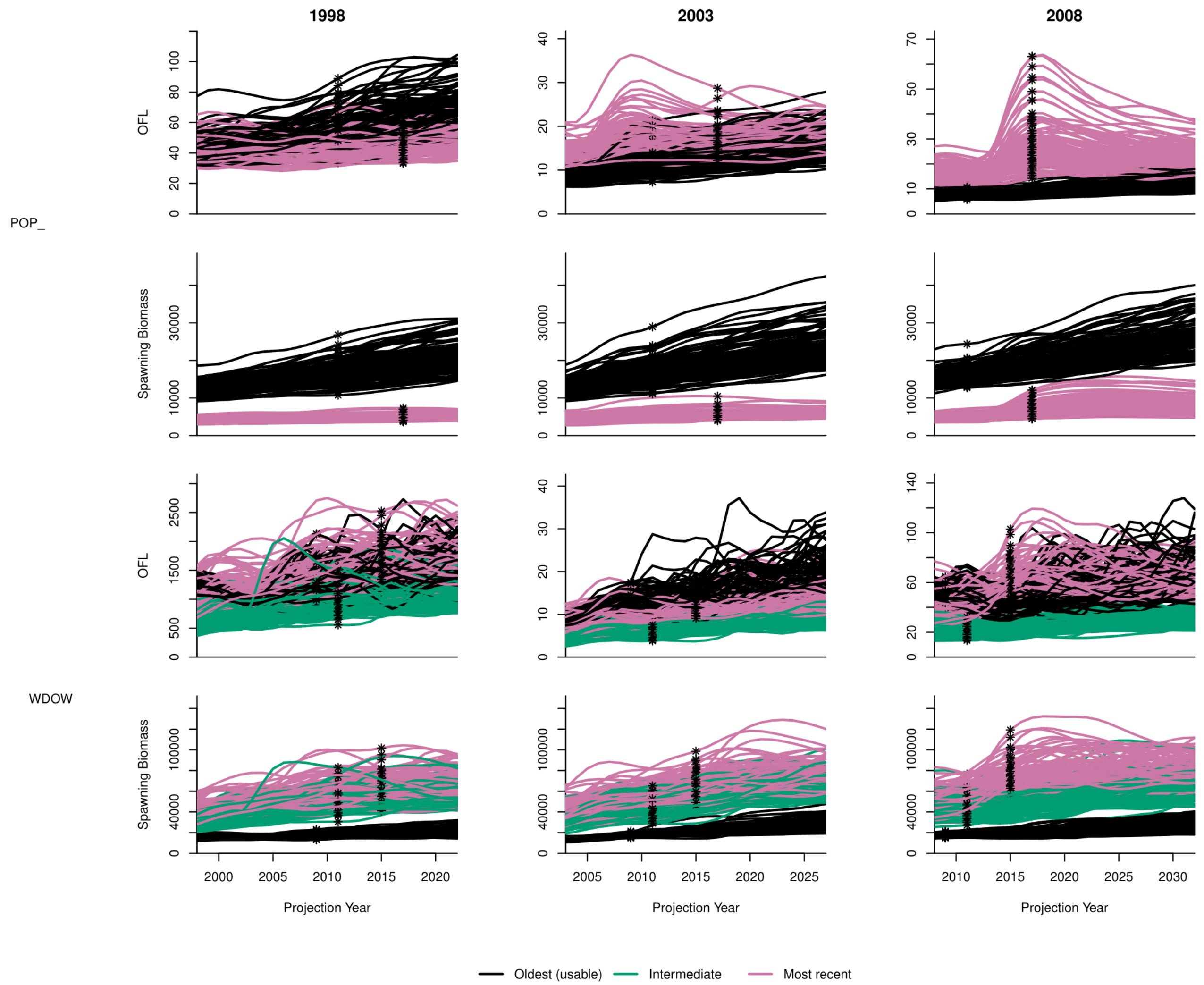

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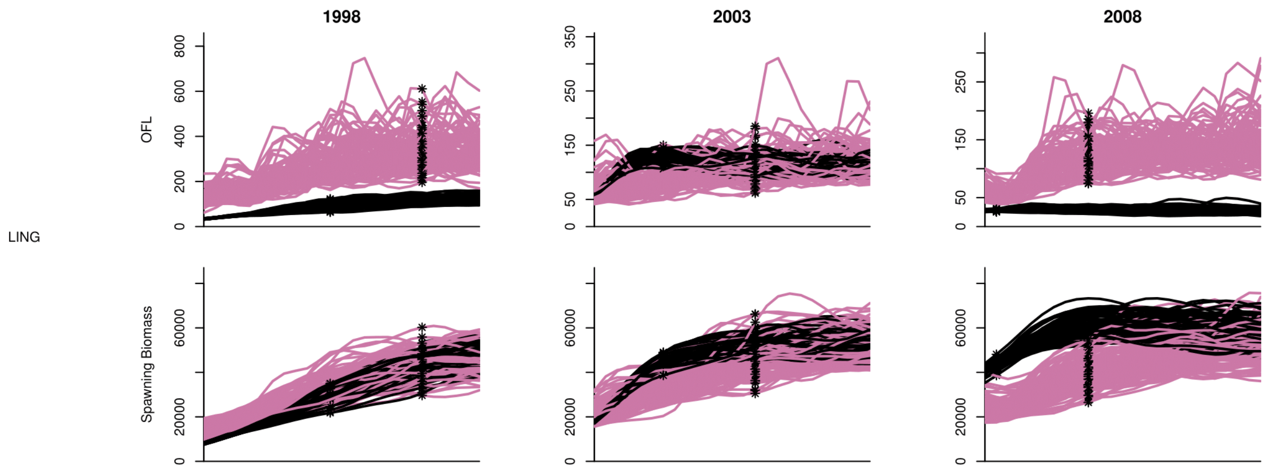

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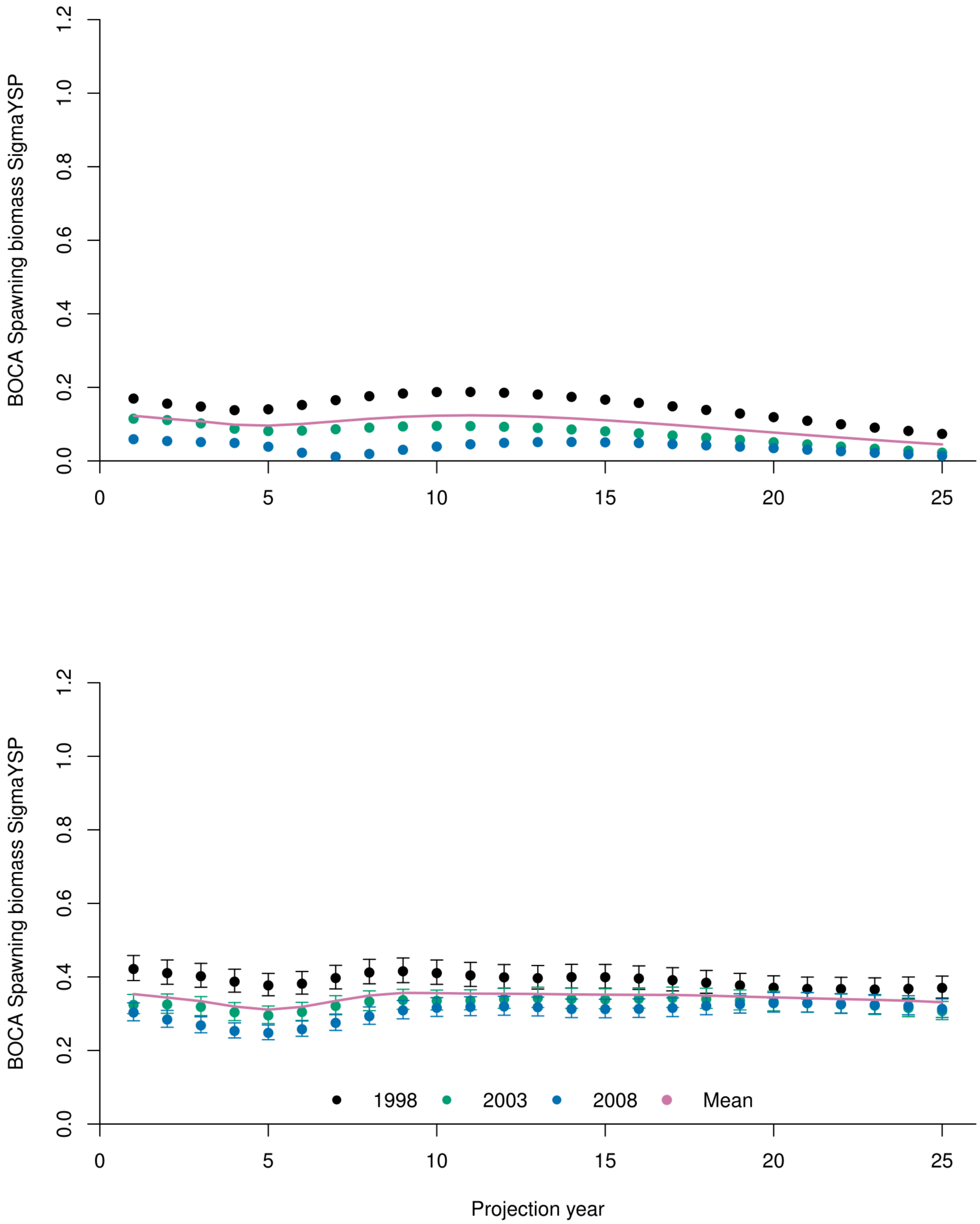
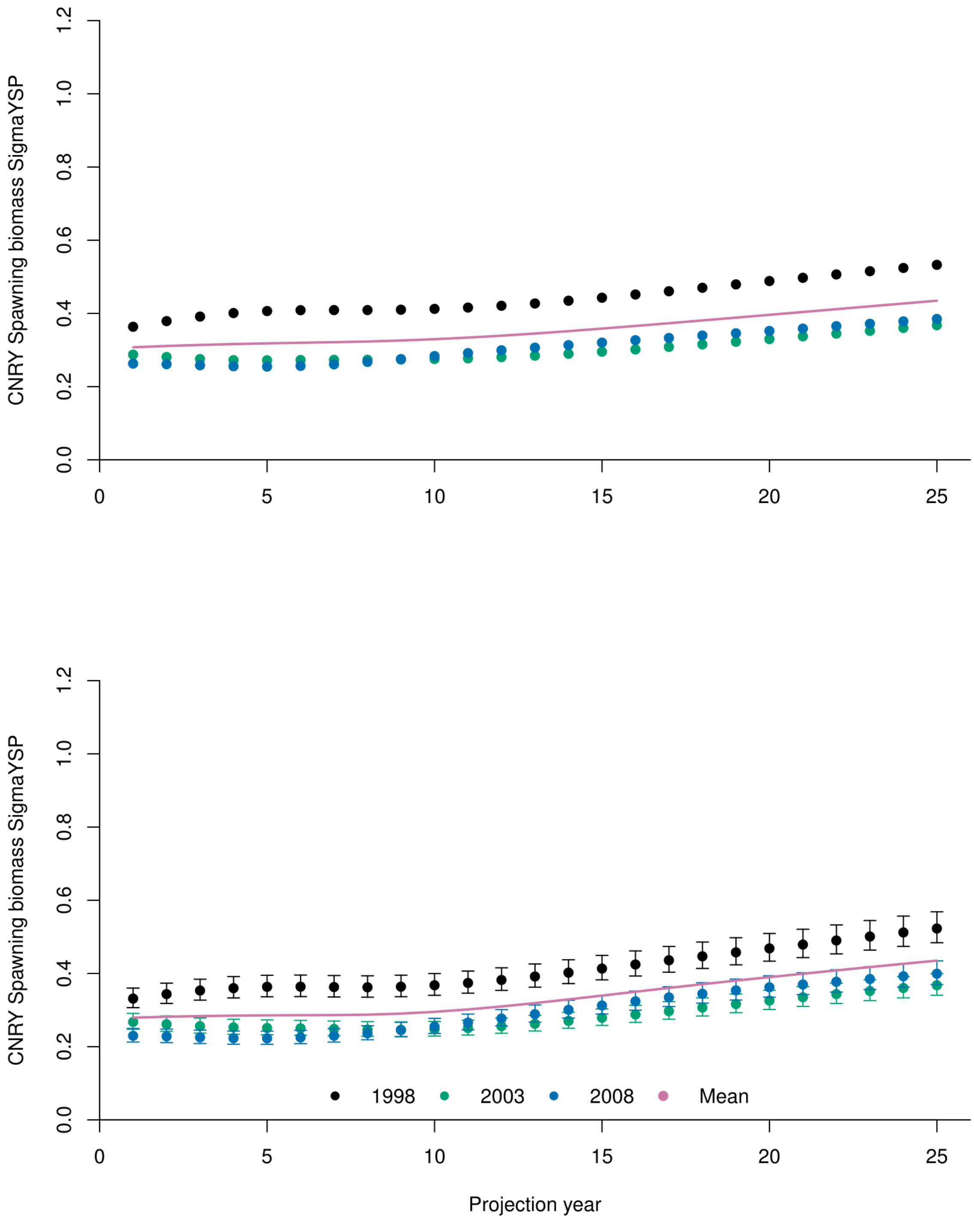


Supplementary Figure 9. Values of species-specific σ based on spawning biomass. Results are shown for deterministic (upper panel) and stochastic (lower panel) analyses by start year and pooled over start-years. The whiskers in the lower panel indicate 95% confidence intervals (no 95% confidence intervals are shown in the upper panel owning to small sample size).



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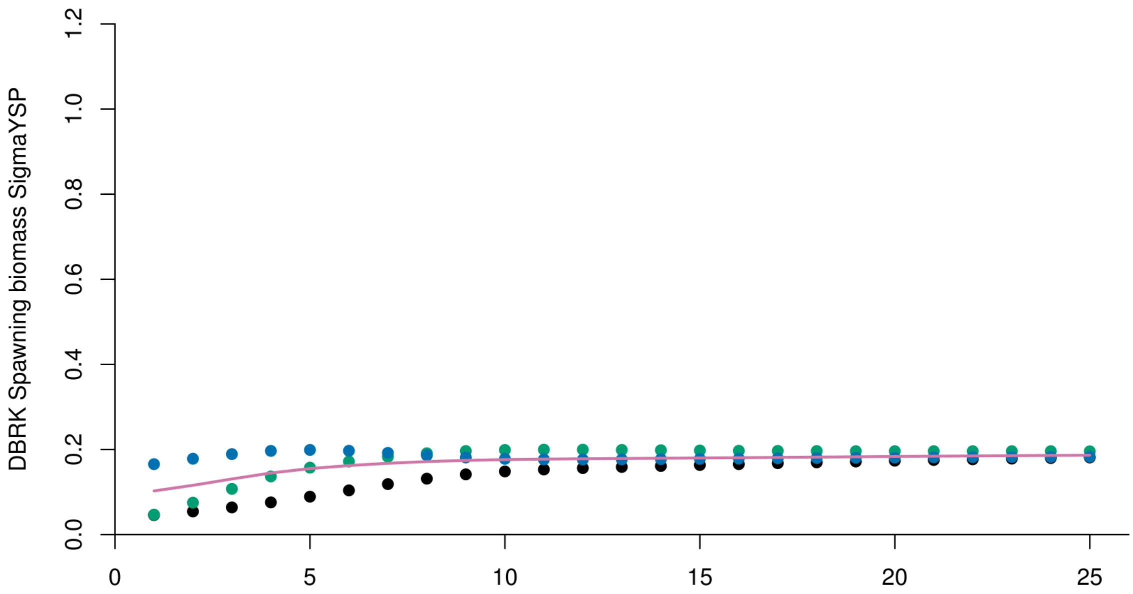

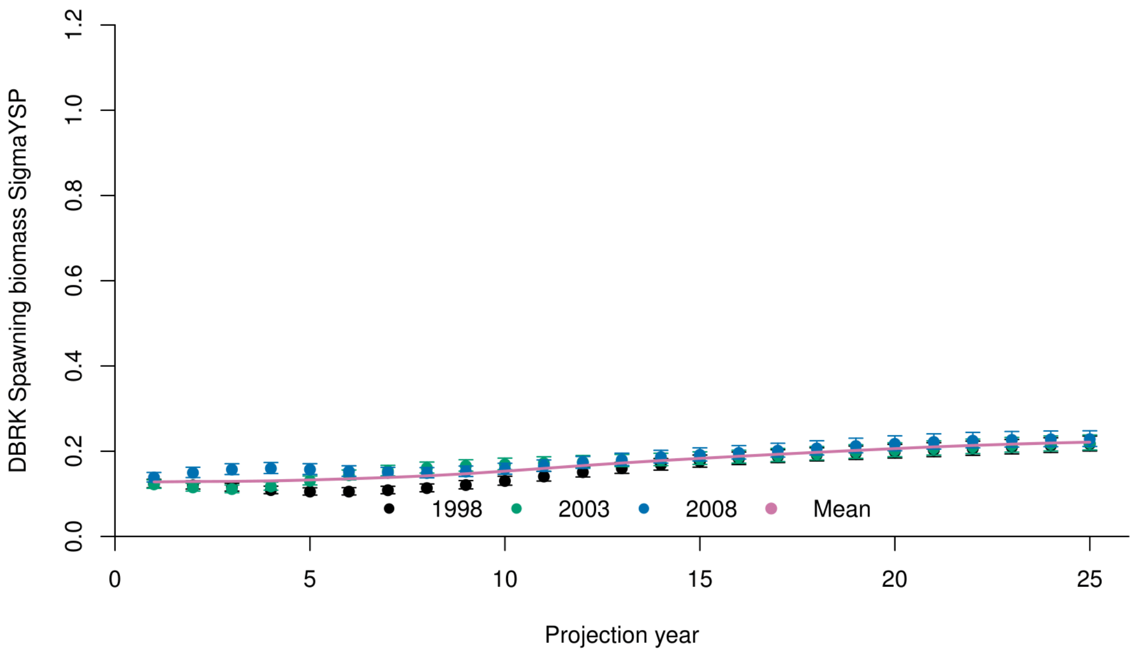

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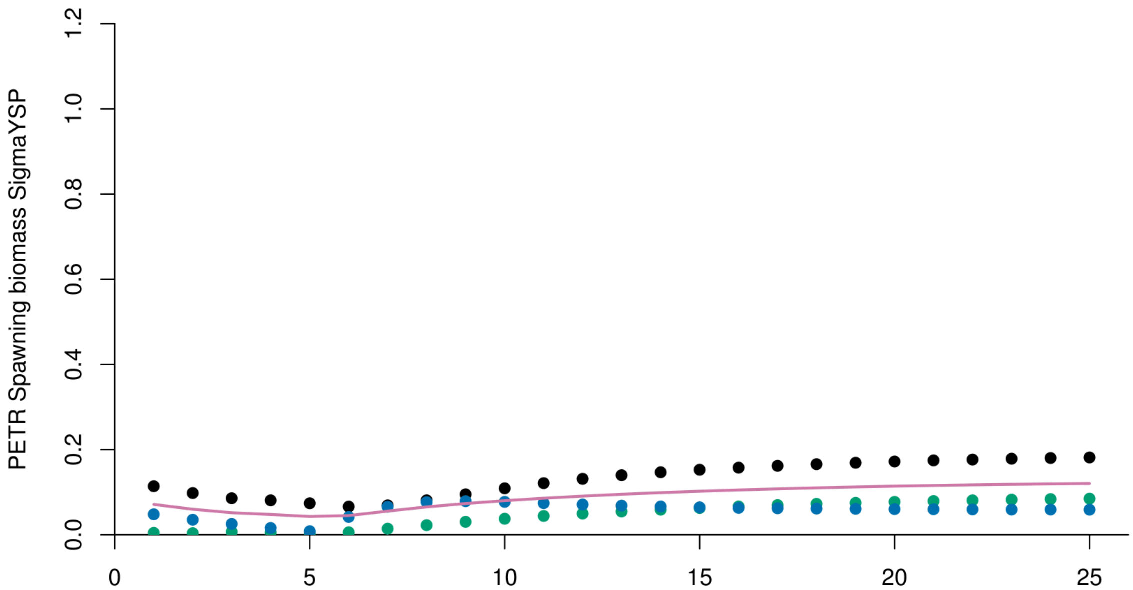

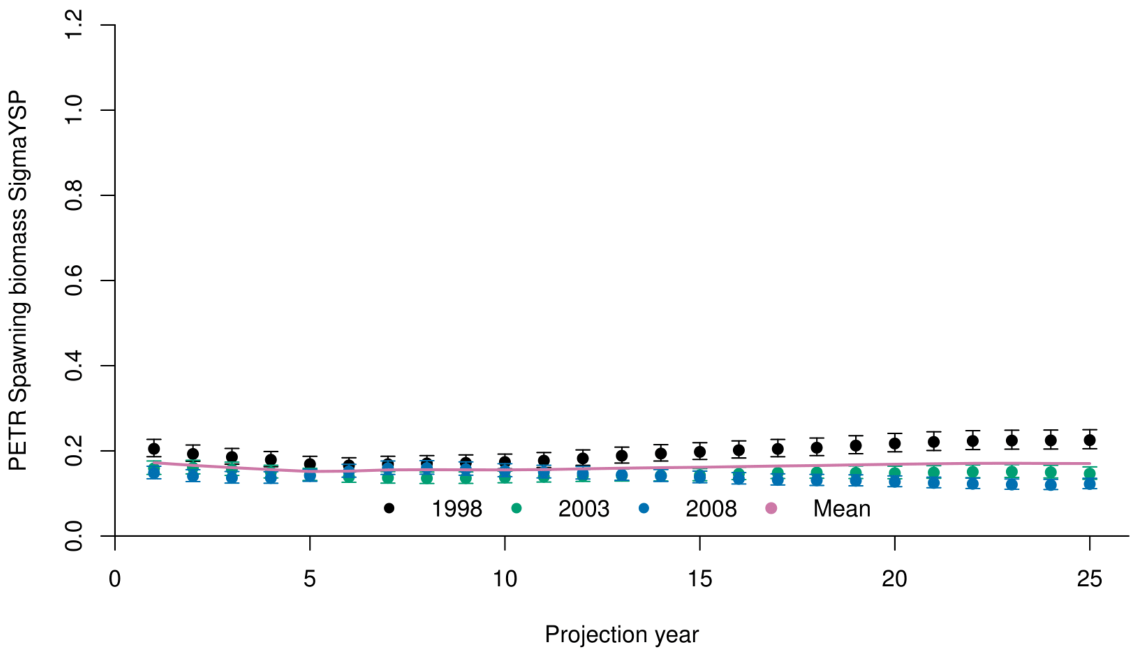

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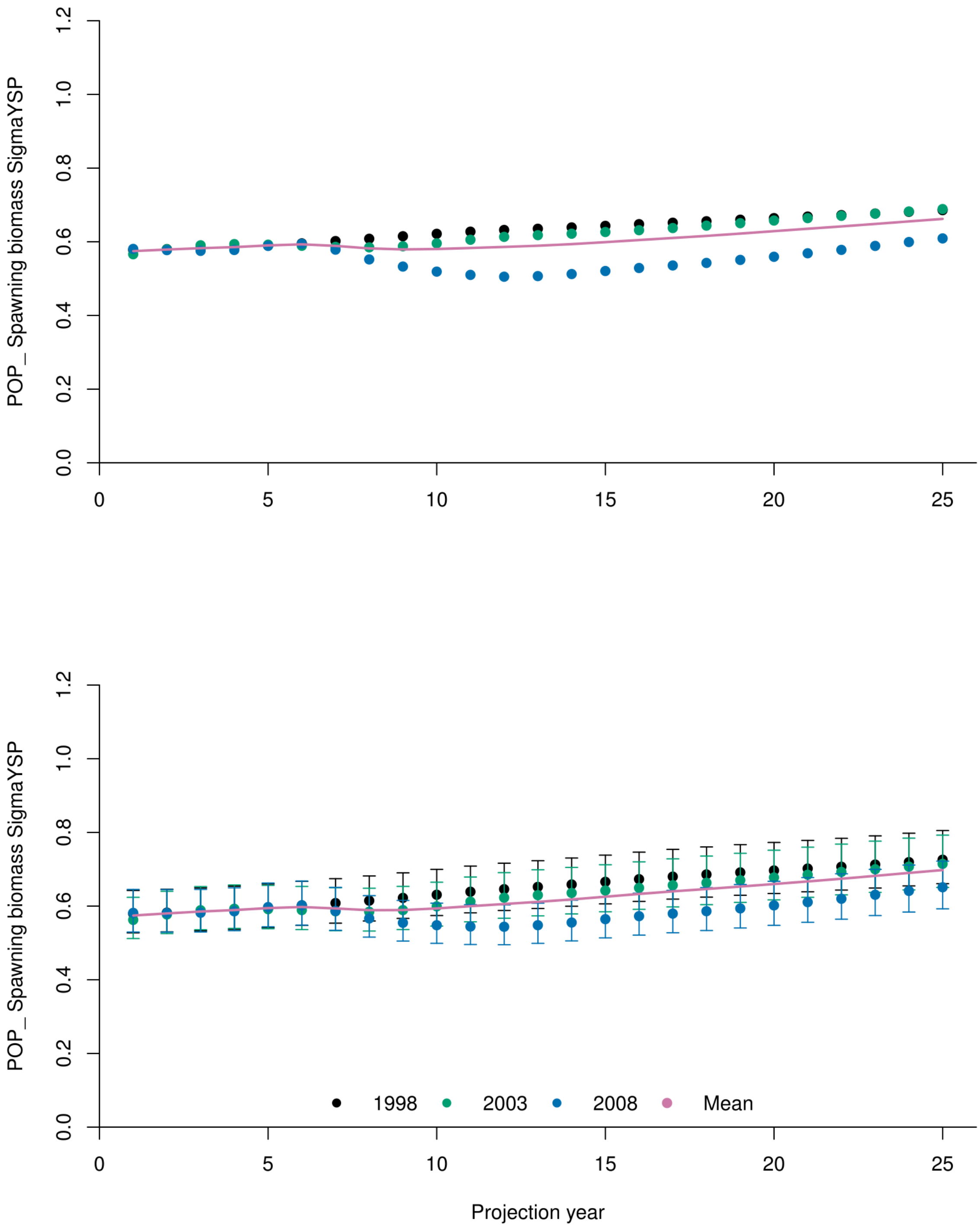

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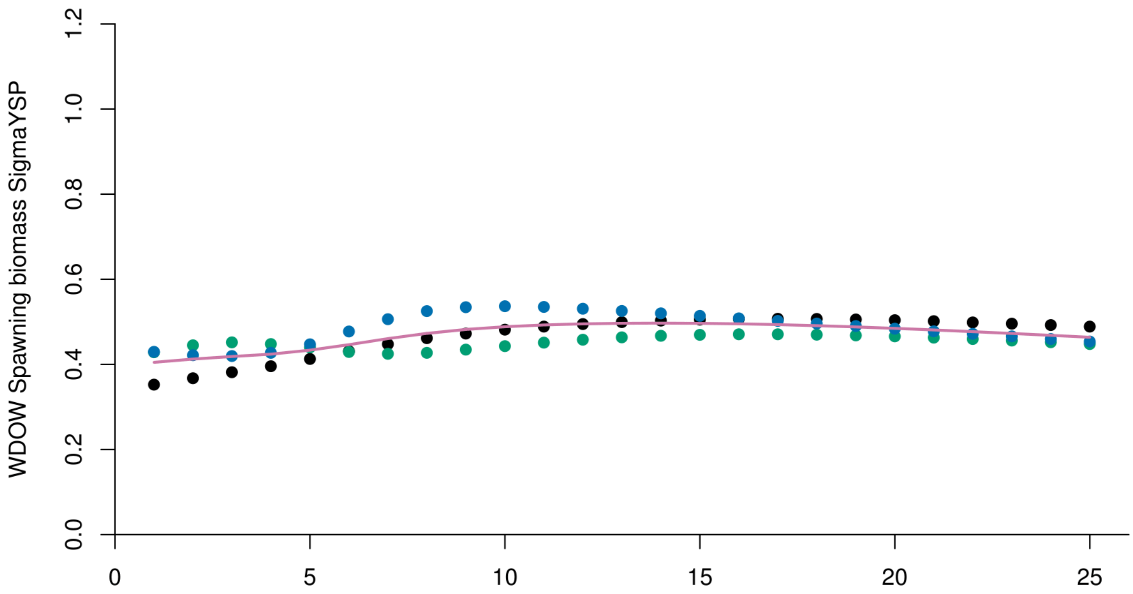

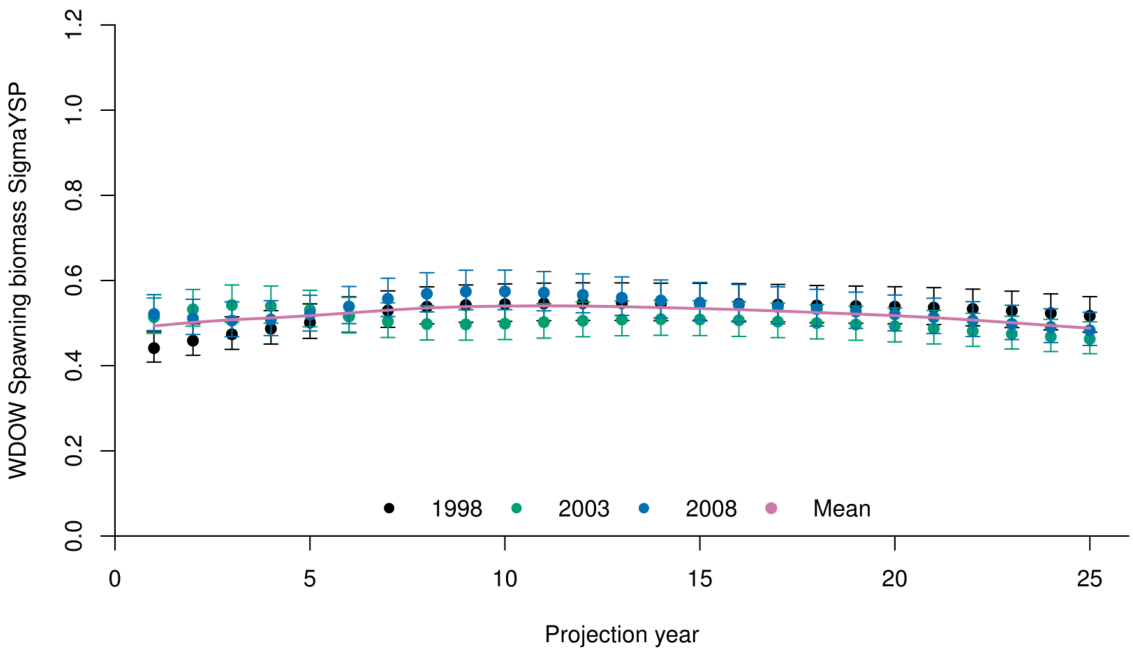

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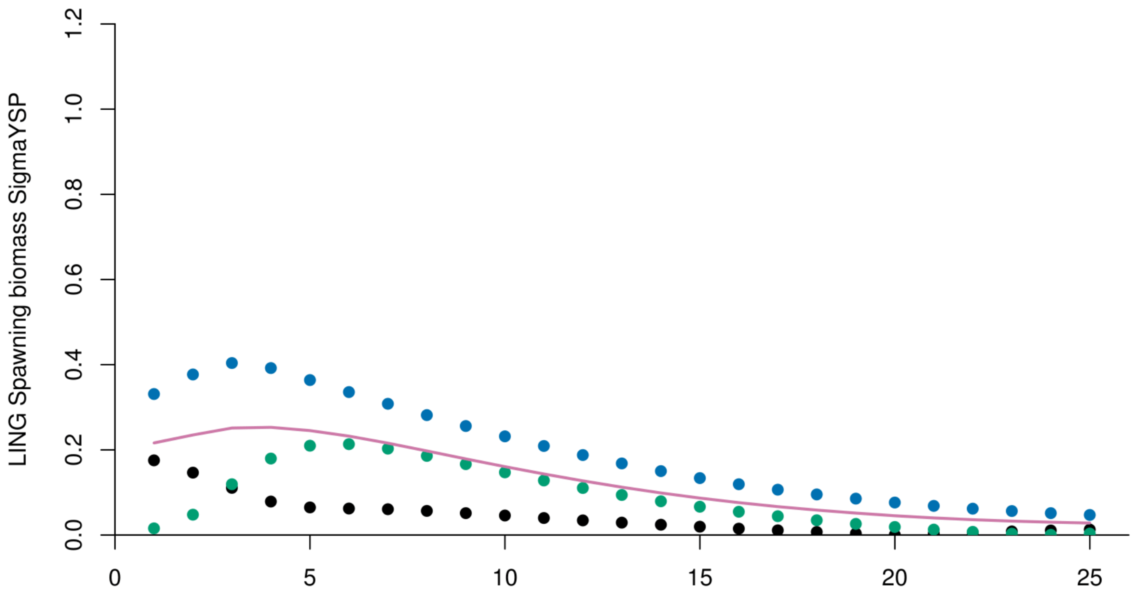

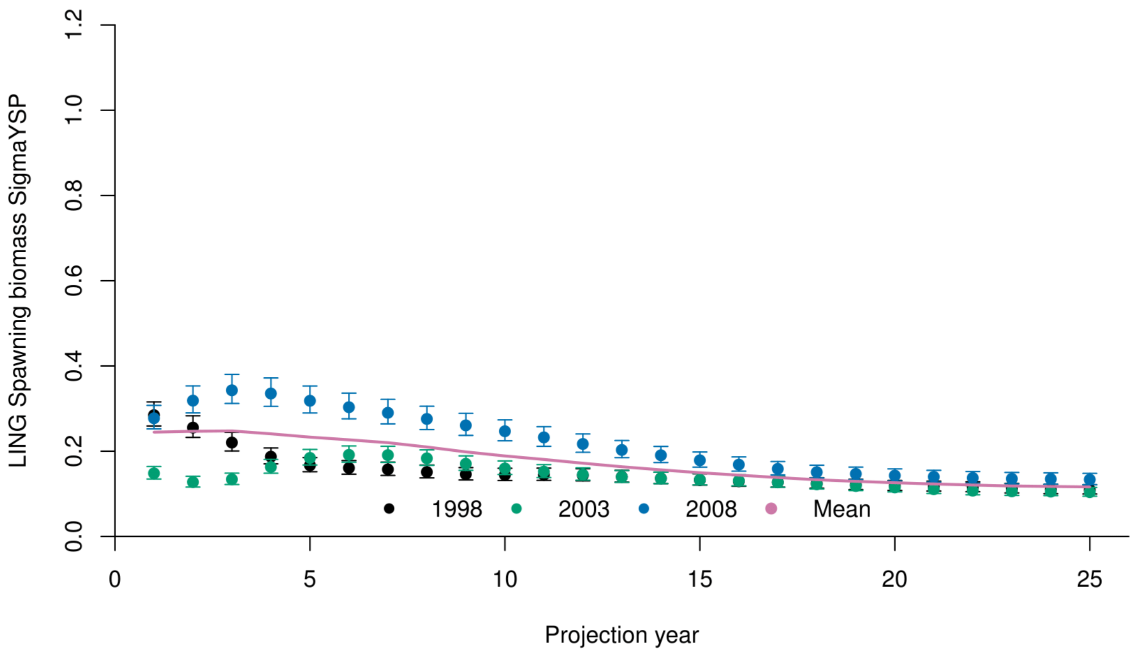

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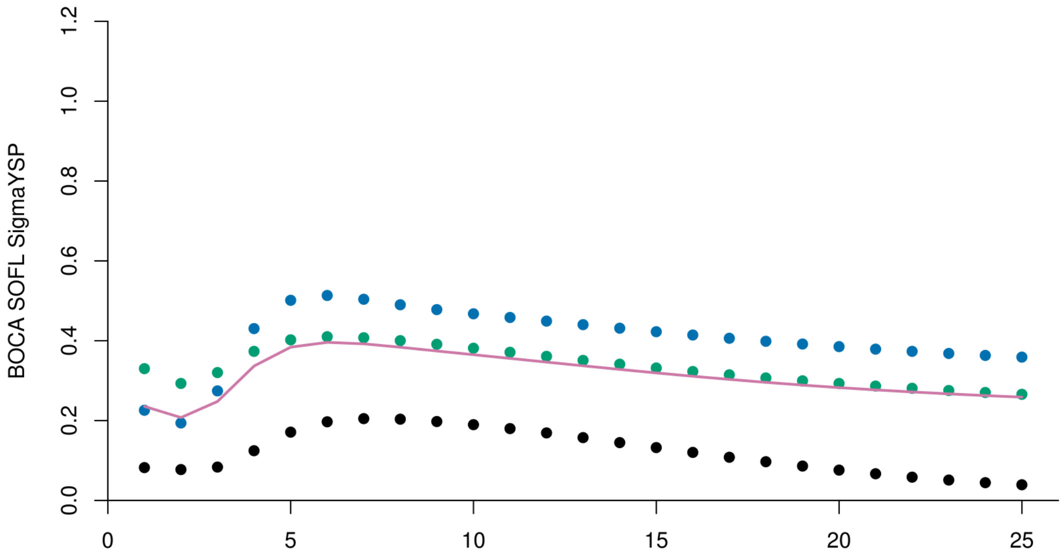
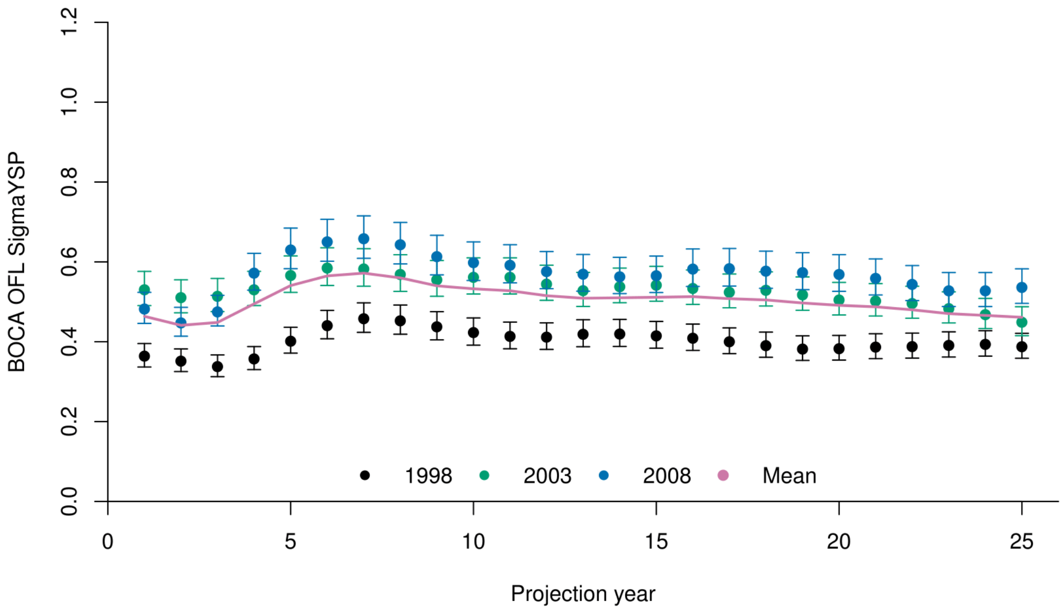
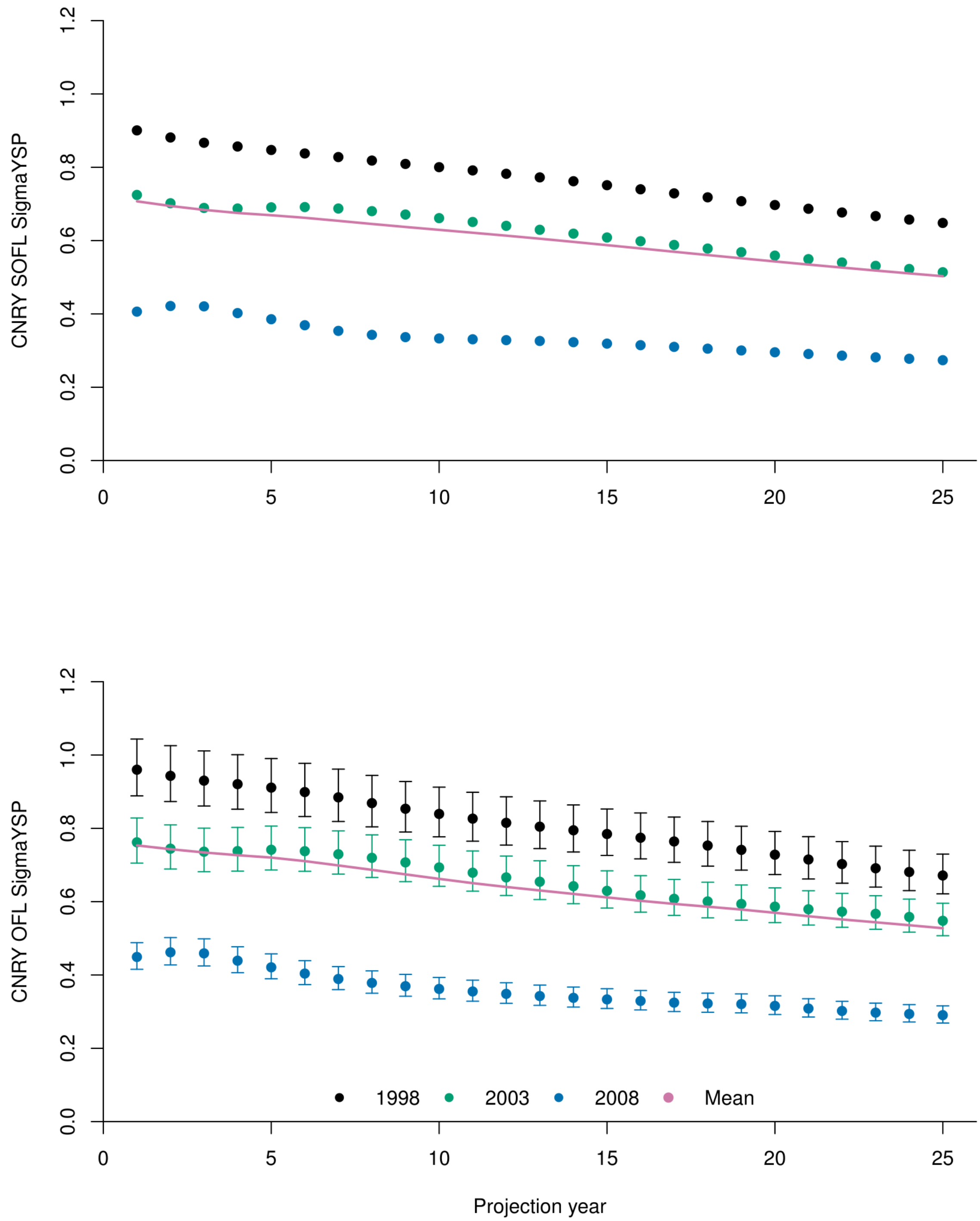




Supplementary Figure 10. Values of species-specific σ based on OFL. Results are shown for deterministic (upper panel) and stochastic (lower panel) analyses by start year and pooled over start-years. The whiskers in the lower panel indicate 95% confidence intervals (no 95% confidence intervals are shown in the upper panel owning to small sample size).



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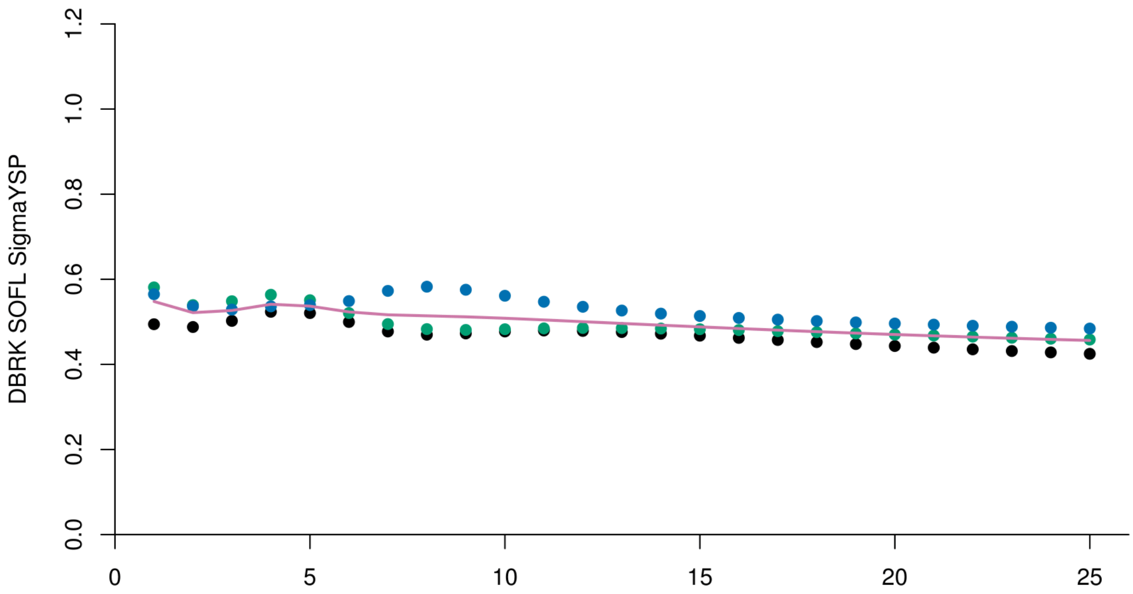

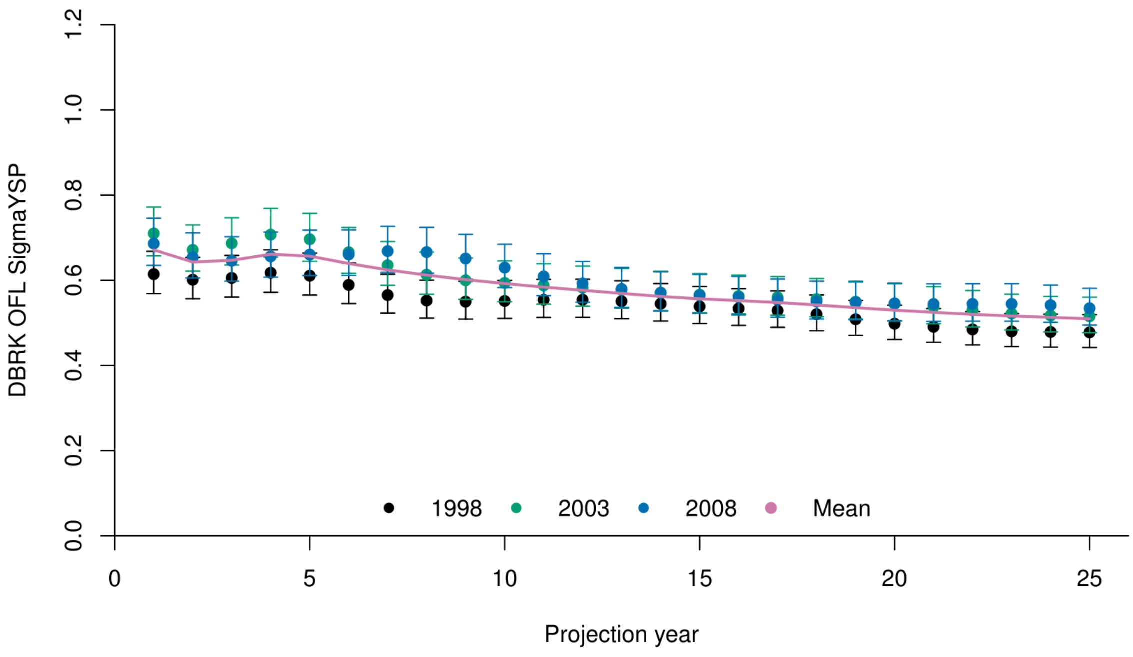

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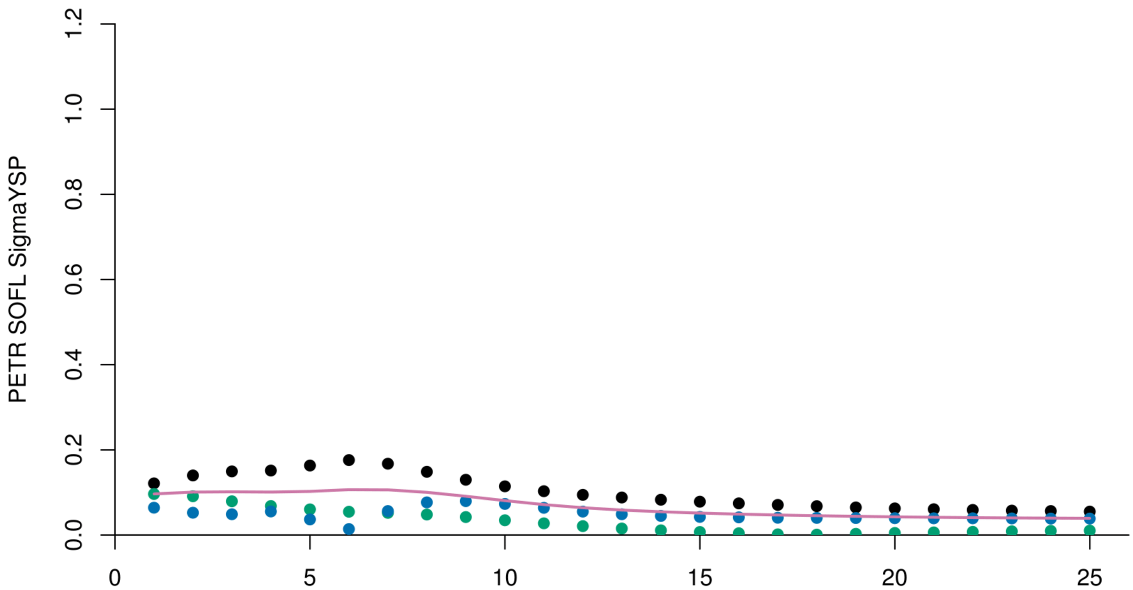

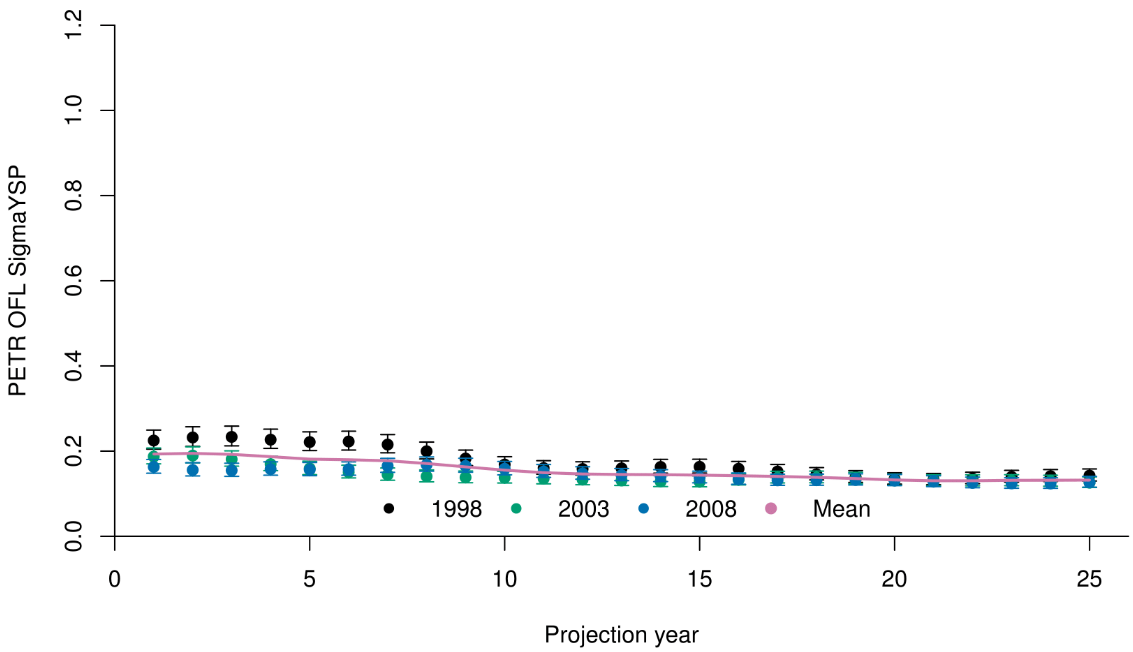

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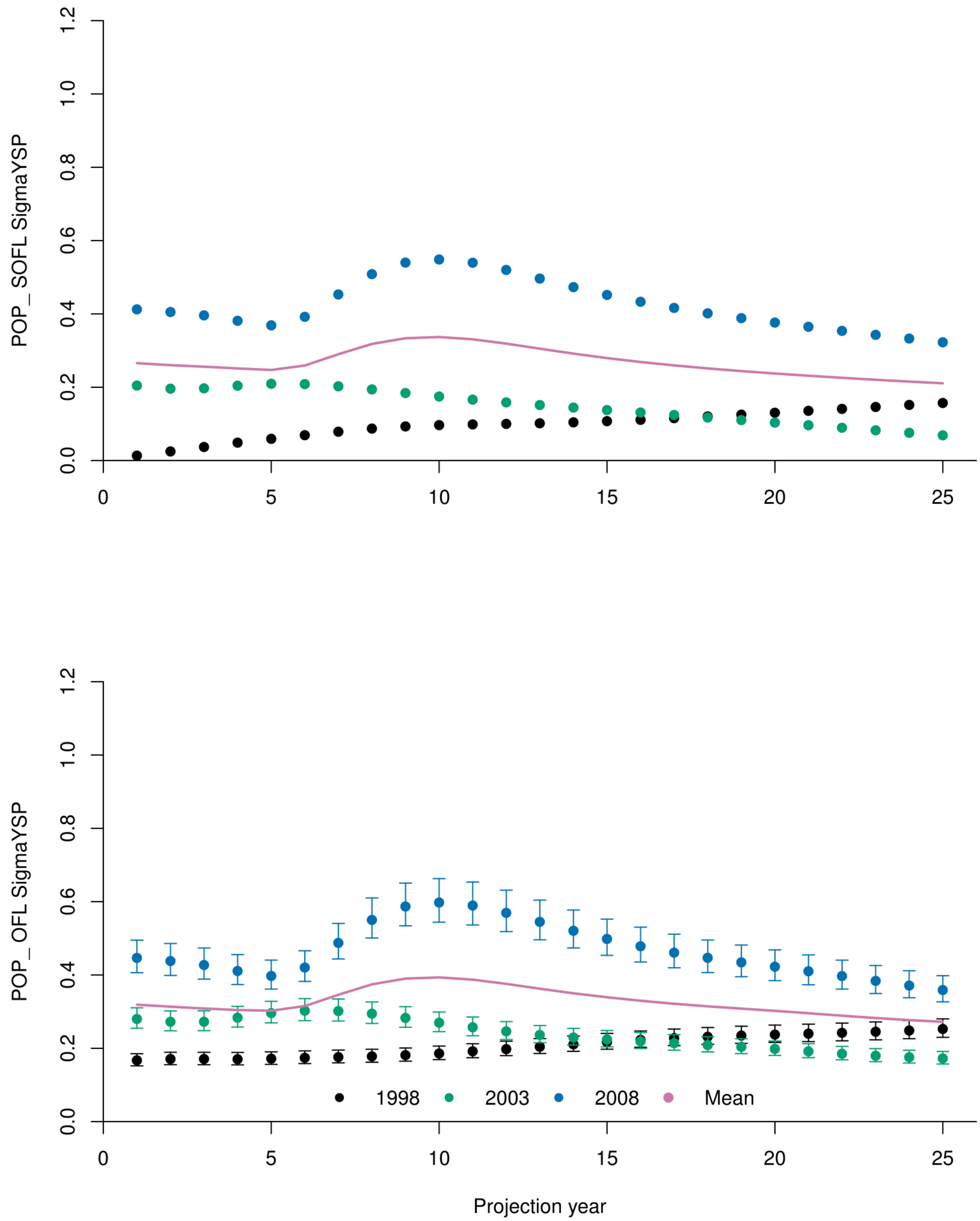

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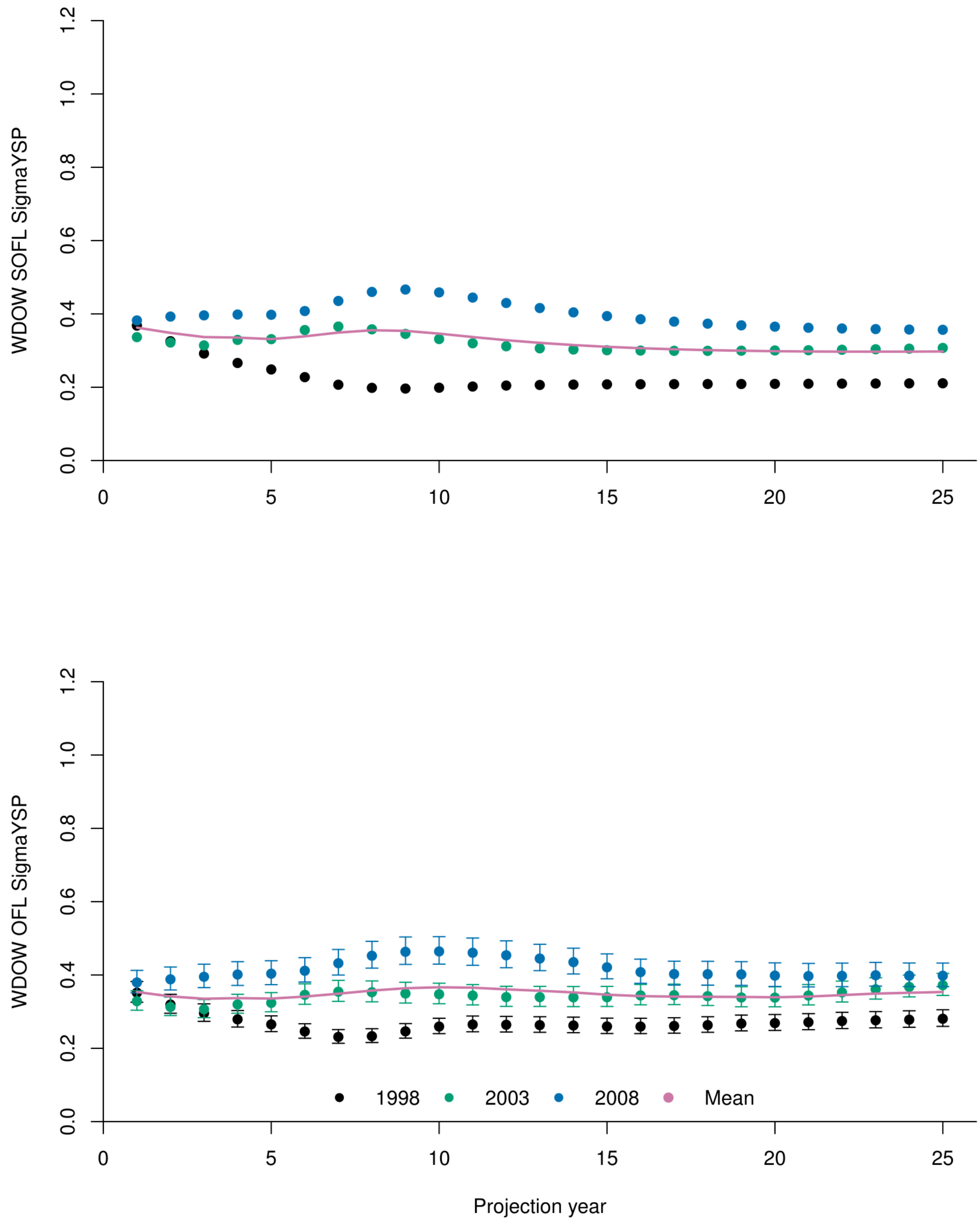

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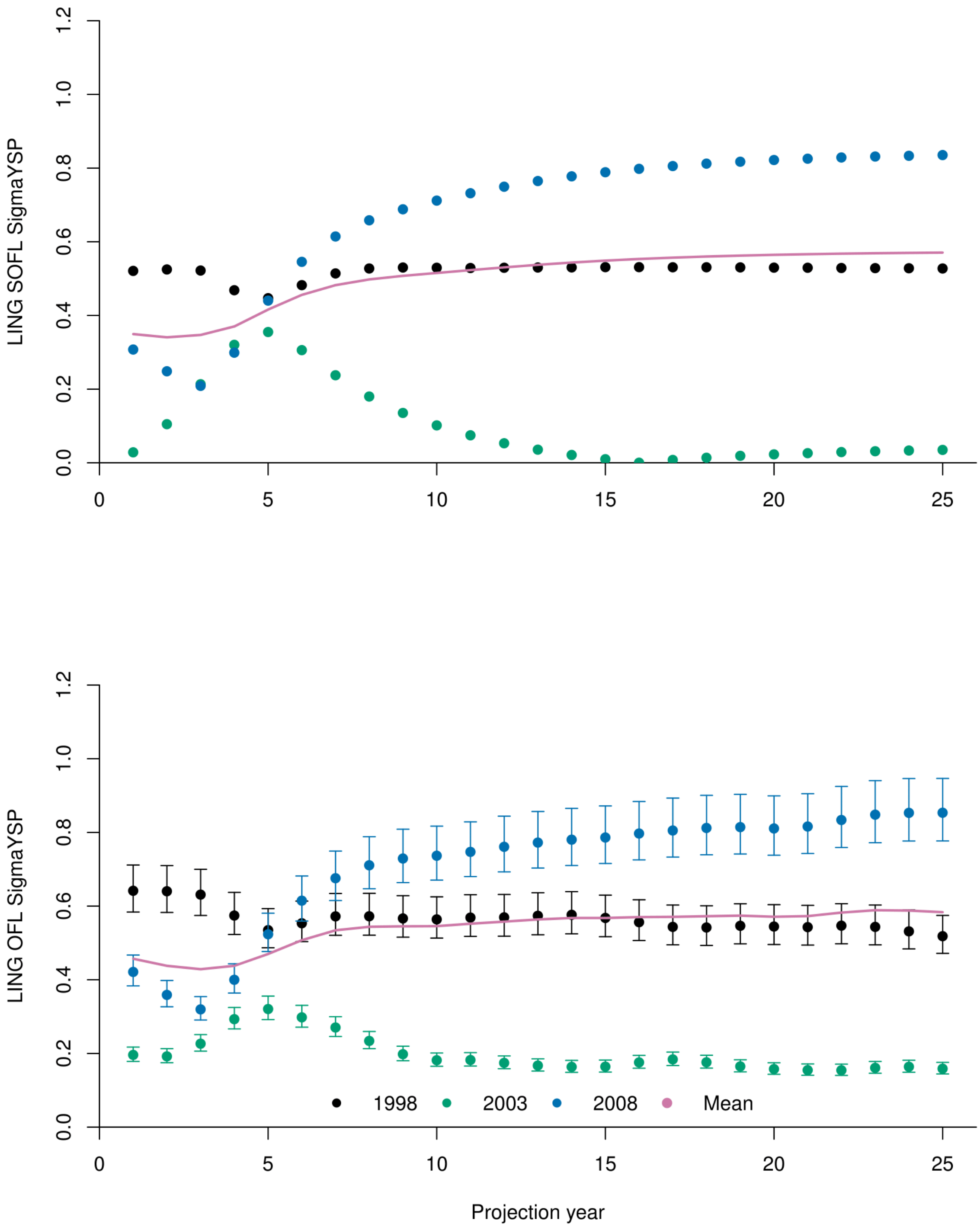

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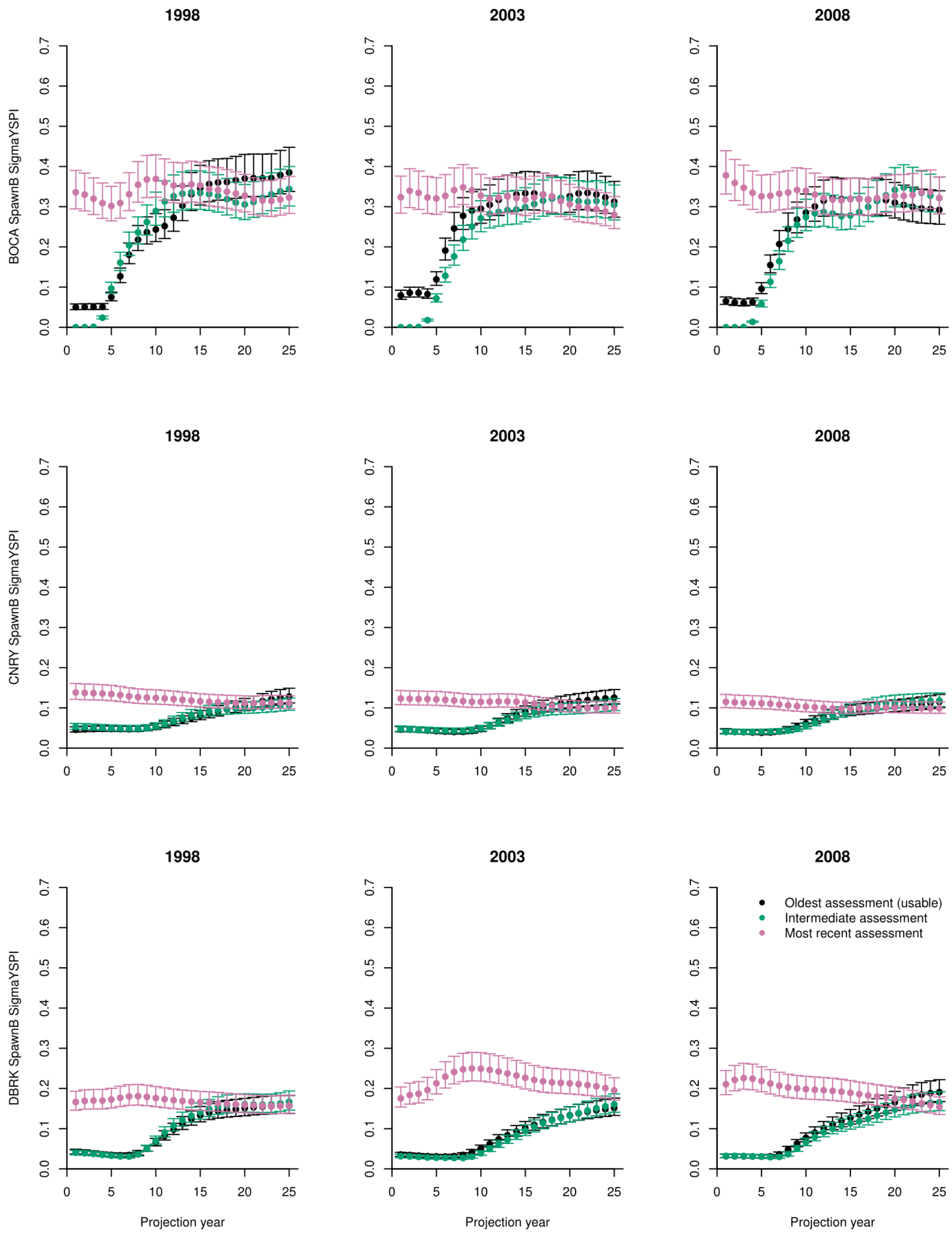
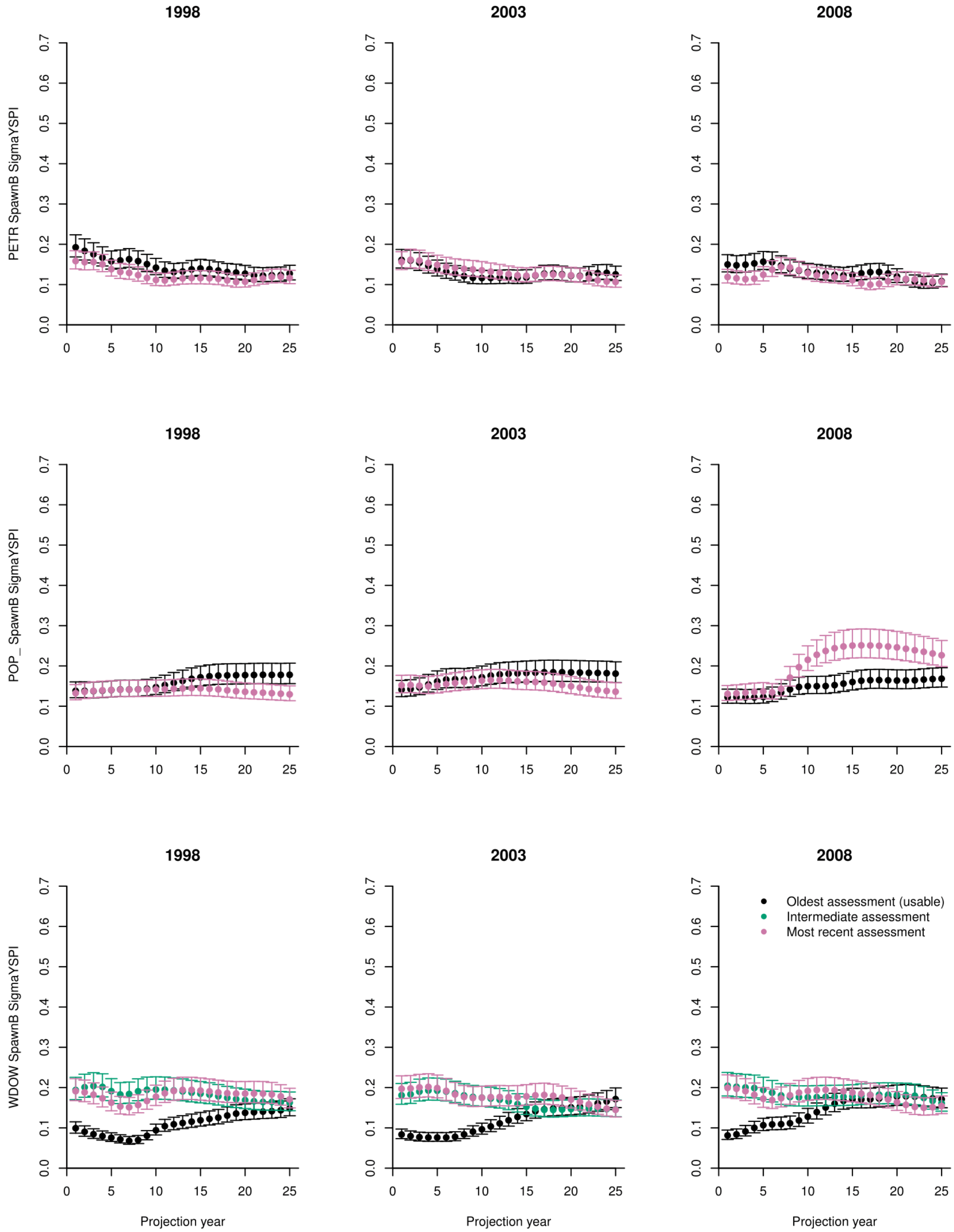


Supplementary Figure 11. Values of species-specific within-assessment σ based on spawning biomass. Results are shown for stochastic analyses by start year and by assessment. The whiskers indicate 95% confidence intervals.



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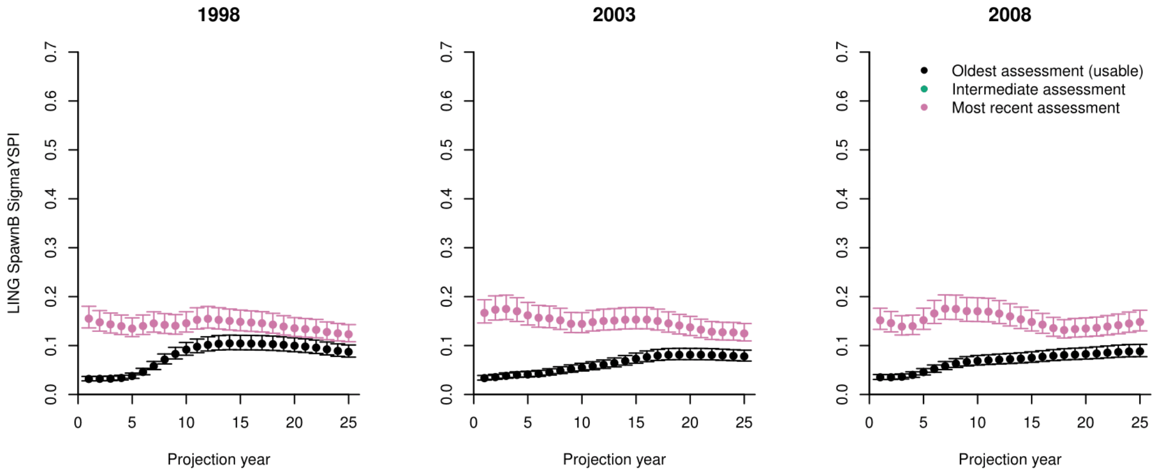

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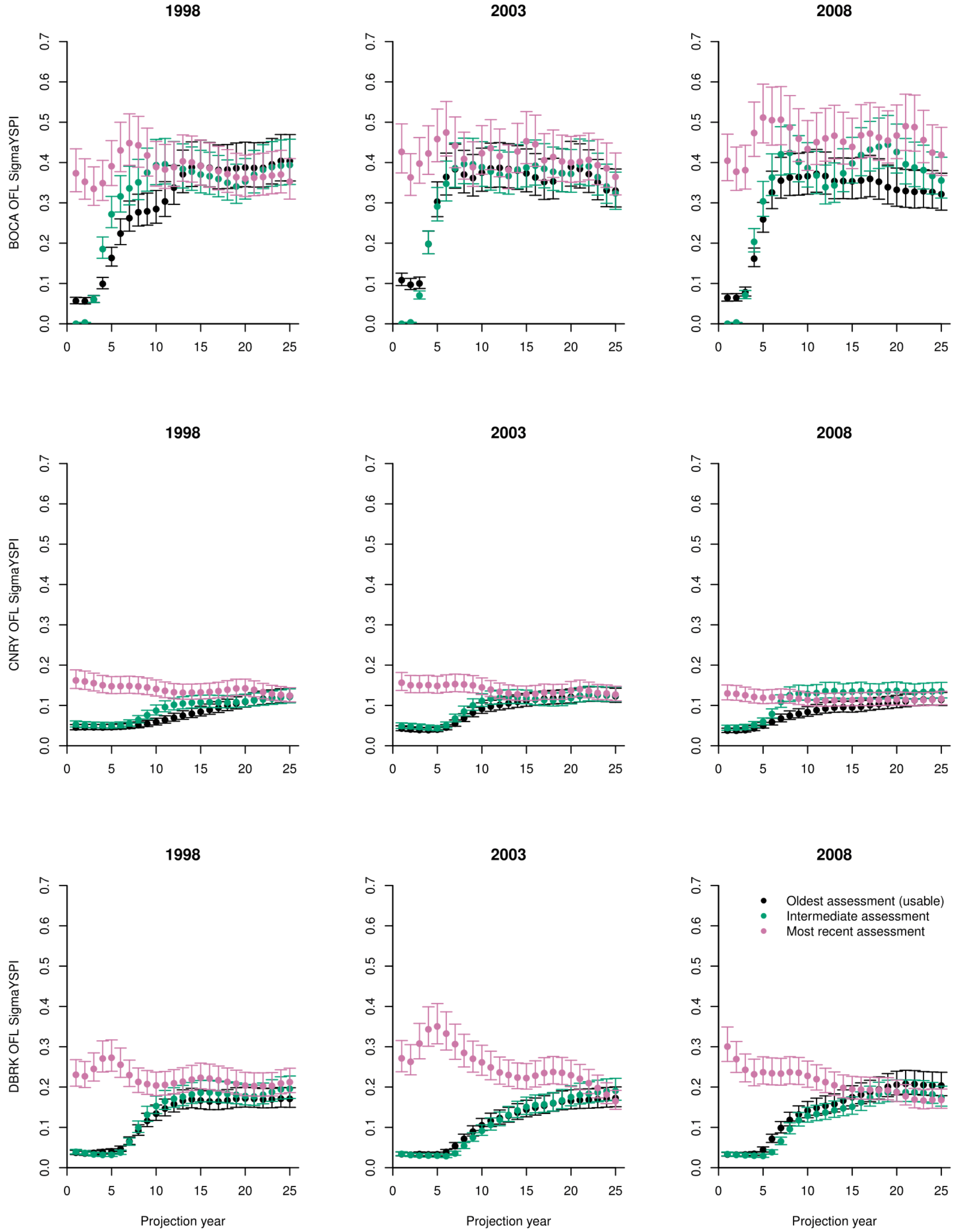
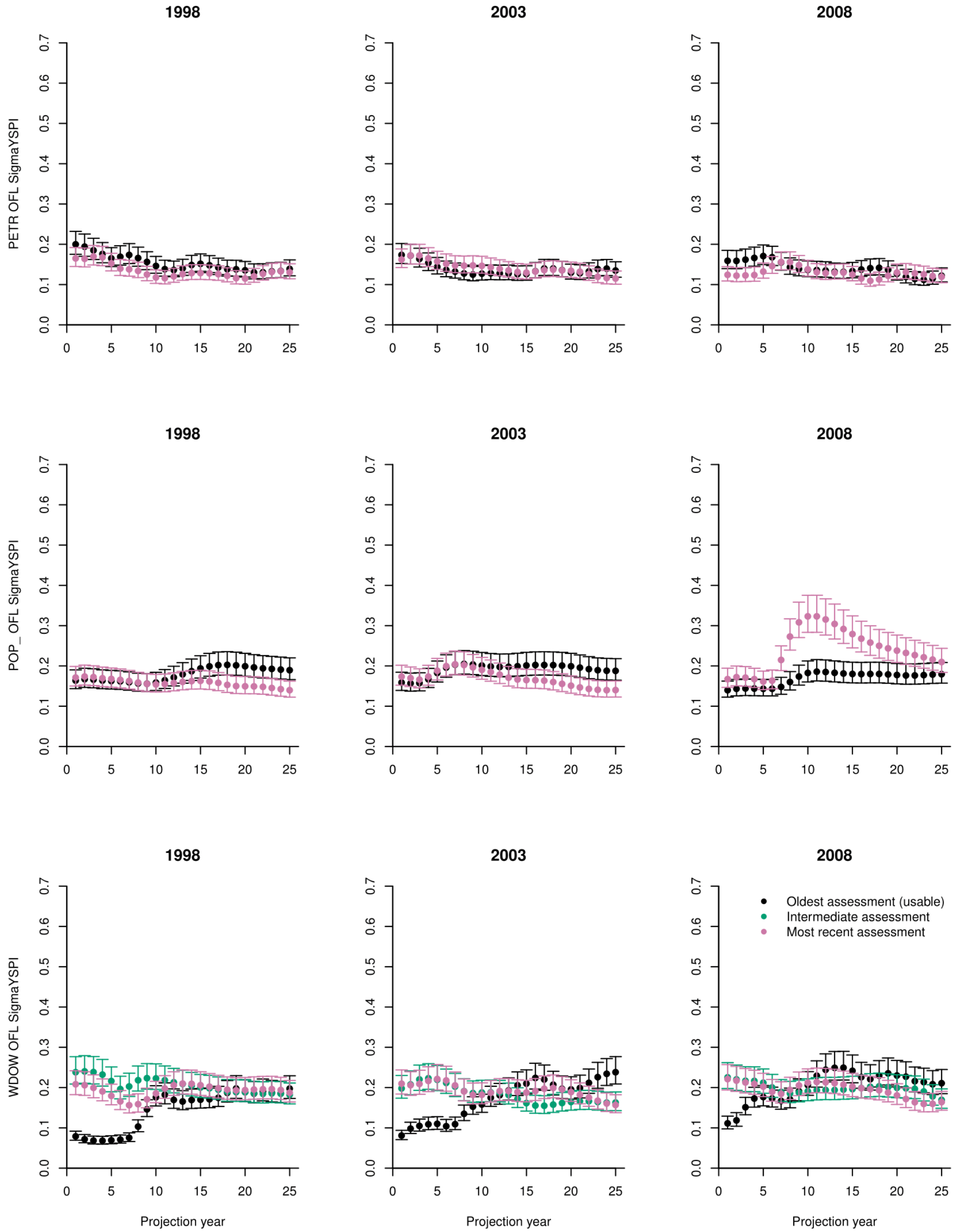


Supplementary Figure 12. Values of species-specific within-assessment σ based on OFL. Results are shown for stochastic analyses by start year and by assessment (2009, 2011, and 2015). The whiskers indicate 95% confidence intervals.



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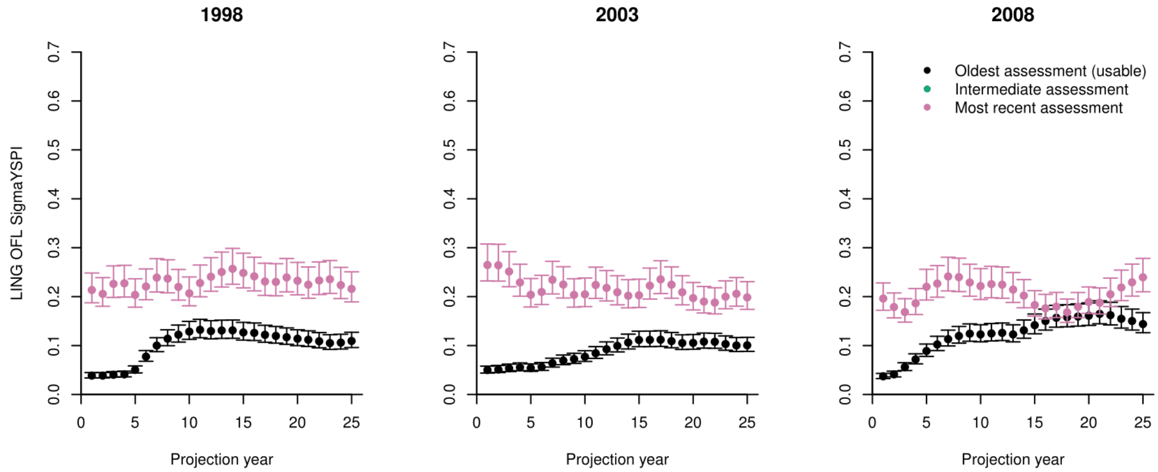

Supplementary Figure 12 continued.