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A hybrid stock synthesis—Virtual population analysis model of Pacific bluefin tuna

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ABSTRACT

The fishery selectivity or availability of younger ages of highly mobile species can be strongly influenced by changes in environmental conditions or fishery targeting, and may not conform to the parametric selectivity curves commonly used in integrated assessment models such as stock synthesis (SS), which could lead to unreliable results. In contrast, a virtual population analysis (VPA) makes no assumptions regarding selectivity of ages younger than those used to link cohorts, and should provide a reliable solution for those ages, without adverse impacts on other aspects of the assessment. We propose a "hybrid" model where young ages are disconnected from the integrated model's selectivity curves for older fish, and are modeled as a VPA. Catches of young fish are removed from the individual fishery landings and are aggregated to form "artificial" single-age fisheries with unit selectivity, so that fishing mortality rates can be estimated directly, thus emulating a VPA for the youngest ages. This is especially useful when there are a large number of independent fleets. Applying this exploratory model to an SS assessment of Pacific bluefin tuna (*Thunnus orientalis*) with 10 fleets indicates that fishing mortality rates since 1990 may be higher than are estimated by the currently accepted integrated model, and that current spawning biomass may be lower by nearly half. Estimated annual recruitments from the two models are nearly identical.

1. Introduction

The parametric selectivity curves used in integrated assessment models such as stock synthesis (SS) are a powerful tool for creating "separable" models of fishing mortality, an approach originally proposed for VPA by Doubleday (1976) and elaborated in the context of an integrated assessment by Fournier and Archibald (1982). In a separable approach, variability of fishing intensity is modeled using independent and additive year/season and age effects according to a fitted age- or length-specific selectivity curve. However, if true availability or selectivity varies independently of age and year due to environmental variability or shifts in fishery targeting, model results may become unreliable without giving the analyst a clear indication of the problem. It is common in integrated assessments such as SS to address variable selectivity of young fish by use of year-specific parameter values, such as for the length at 50% selection. In contrast, virtual population analysis (VPA) provides direct estimates of fishing mortality rates (F) by age and season, without requiring a fitted selectivity curve.

Past experience with VPA provides ample evidence that the estimated F of young fish can be highly variable, especially in the case of mobile species such as pelagic fish. An example, taken from a VPA of Pacific sardine, *Sardinops sagax*, shows that the F at ages 2 and 3 cannot be predicted reliably from the annual F estimated for fish aged 4 and older that are assumed to be fully selected (Fig. 1, reproduced from MacCall, 1979). The initial drop in availability of age-2 fish is believed to be associated with a progressively more southerly and distant origin of cohorts as the spawning stock in southern California waters became depleted, and the high values in 1960 are due to a northerly population shift associated with the strong El Niño of 1958–59.

Sampson and Scott (2012) examined selectivity patterns implied by VPA in 15 recent stock assessments. They concluded in every case that selectivity shows substantial to extreme temporal variation, and that the patterns do not conform to conventional parameterizations of annual shifts in length at 50% selection. These variable selectivity patterns are clear from a VPA assessment, but can be problematic in an integrated assessment that uses conventional selectivity curves, even with year-specific parameters.

The problem of modeling inter-annual variability in selectivity becomes especially complicated if there are multiple fisheries in the model. Each fleet would require its own series of year-specific parameters to describe inter-annual variability, and covariance due to common environmental or biological causes may not be recognized. Parametric selectivity curves also cause inter-annual variability at young ages to be propagated to older ages

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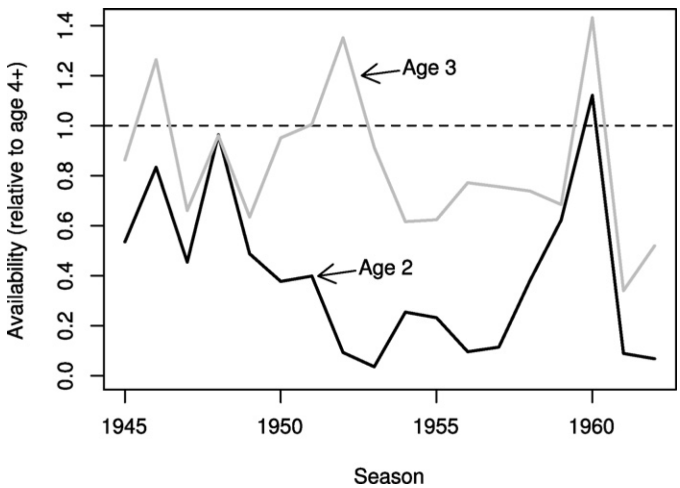

Fig. 1. VPA estimates of annual fishery selectivity of young Pacific sardines. Redrawn from MacCall (1979).

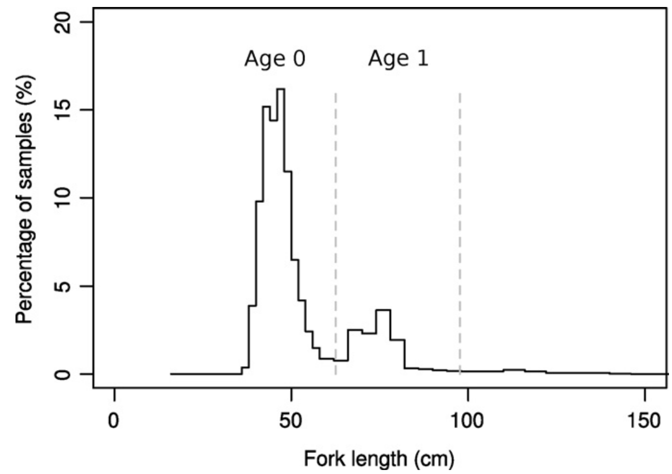

Fig. 2. Composite length composition of the Small Pelagic Purse Seine fishery in season 3 from 1996 to 2007. Dashed gray lines indicate estimated class boundaries of age 0 and age 1.

whether or not it is appropriate to the circumstances causing the variation.

This paper explores a resolution to the problem of highly variable selectivity by freeing integrated model constraints on selectivity at young ages, and implements an example in SS. The need to reconsider parameterization of young fish selectivity is motivated by the recent SS assessment of Pacific bluefin tuna (PBF, *Thunnus orientalis*), conducted by the Pacific Bluefin Tuna Working Group (PBFWG) of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC). The assessment (ISC, 2008), which we refer to as the "base model", indicates an increase in recruitment during the past decade. However, an increase in targeting of young fish is suspected due to the rapid growth of the pen-rearing industry, and the consequent need for small PBF as input to these operations. Possible increased targeting of young fish presents an alternative hypothesis: the model's estimated increase in recruitment is an artifact resulting from the use of constant selectivity curves that fail to recognize an increase in targeting. Although the SS model used for the PBF assessment is capable of exploring time-varying parameters to reflect alternative selectivity hypotheses, eight of the ten modeled fisheries catch young fish, and would require time-varying selectivity parameters. It would be difficult to judge statistically which time-varying parameterization is more appropriate. Our proposed hybrid approach avoids this difficulty.

Under a VPA approach, as was used for PBF assessments prior to 2007, estimated annual *F*s for young fish are free to take the value that explains the time series of catches from a cohort (Murphy, 1965). In VPA, older age classes are linked by a selectivity assumption, usually that of equal selectivity at adjacent ages. If cohorts are linked properly at older ages, a VPA approach should lead to objective values of *F* for young fish, and would easily recognize a shift toward targeting of young fish. In this paper, we introduce this capability in a new hybrid approach to modeling in stock synthesis. We describe this model of PBF as "exploratory" to distinguish it from the base model, which is the official assessment accepted by the ISC. In our hybrid model, a conventional SS integrated model with parametric selectivity curves applies to fish aged 2 and older and provides a cohort linkage analogous to that used in VPA. However, fish aged 0 and 1 are disconnected from the selectivity curves so that *F* for the youngest ages conform to a backward VPA solution given the "terminal" *F* values at age 2 estimated by SS, using selectivity curves for the older ages.

2. Materials and methods

Most integrated assessment packages should be capable of specifying a hybrid model. Our example of a hybrid assessment for PBF uses a standard SS executable (v3.10b; available from the NOAA Fisheries Toolbox, http://nft.nefsc.noaa.gov), but requires modifications to the base model structure and data files (SS control and data files; Appendix A). PBF is assumed to be a single well-mixed stock, and the base model is a single-sex, seasonal model with 10 fleets, 6 surveys (CPUE), and a fixed growth curve. The data in the base model range from 1952 to 2007, but estimation of annual recruitments starts in 1946. We emulate a VPA by reassigning catches-at-age to respective "artificial fisheries" that catch only a single age. In this present example of PBF, we want to retain the conventional use of fishery-specific selectivity curves for ages 2 and older, which are progressively more difficult to distinguish in the length compositions. We therefore create artificial "fisheries" for easily distinguished ages 0 and 1. Catches of these two age groups are removed from the existing fisheries (see Fig. 2 for an example) and are re-assigned to the two new fisheries, "AGE0" and "AGE1." By assigning unit selectivity to each single-age fishery, SS calculates F directly for these two ages. The age selectivities and length composition samples for ages 0 and 1 are set to zero since catches of ages 0 and 1 are removed from existing fisheries. The length selectivities for all fisheries are fixed and left unchanged from the base model. Model specifications are given in Appendix A.

3. Results

3.1. Spawning stock biomass and recruitment

The initial conditions are roughly equivalent for the base and hybrid models. The overall likelihoods of the two models cannot be compared because the catch and length composition data differ. However, the CPUE indices are the same for both models and their likelihood components can be compared. The negative log-likelihood of the CPUE component of the hybrid model is 14.5 log-likelihood units better than that for the base model, although the statistical significance of this difference cannot be ascertained due to the use of non-binary likelihood weighting (lambda) factors in both models. Importantly, the time trajectories of spawning stock biomass (SSB) are similar (the hybrid model tends to be a little lower) until the early 1990s, where they diverge (Fig. 3a). The estimate of 2007 SSB is 56% of that from the base model.

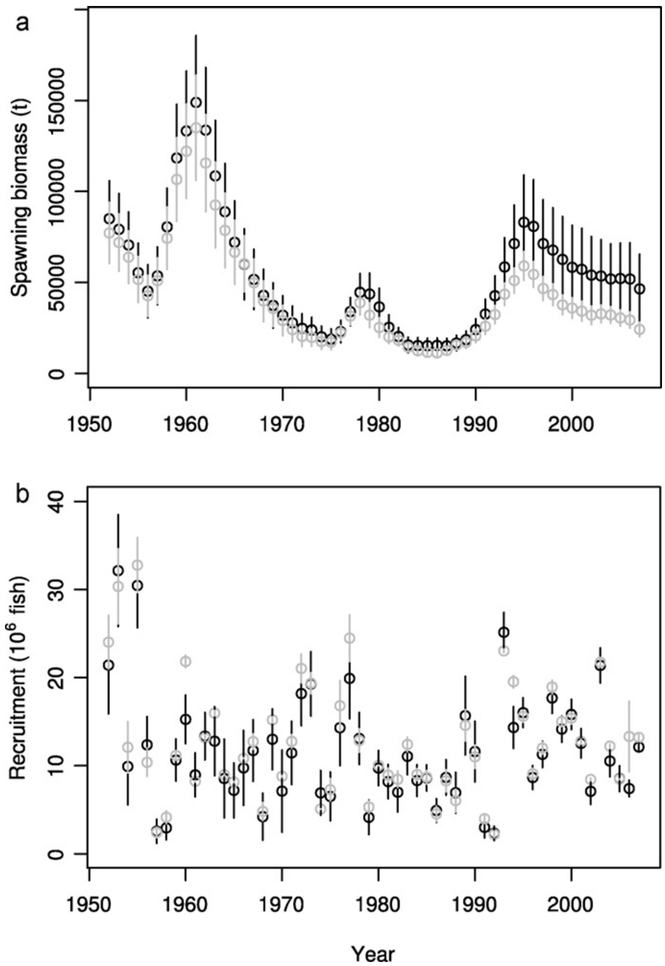

Fig. 3. Estimated time-trajectories of spawning stock biomass (a) and recruitment (b) from base (black) and hybrid (gray) models. Vertical bars indicate asymptotic 95% confidence intervals.

The constant expected recruitment is about 9% larger than in the base model (Fig. 3b). Estimated annual recruitments agree in the first few years, and are remarkably similar after 1952 (the start year of data, and first year for which the model provides a confidence interval), with the hybrid model giving slightly larger recruitments before the mid-1980s, but nearly identical recruitments since then. Both models agree that recruitment has increased since the early 1990s. Clearly, the difference in recent SSB values is not due to a difference in estimated recruitment alone.

3.2. Fishing mortality rate

Histories of F are shown for young fish (ages 0–3) in Fig. 4a–d and for combined intermediate (ages 4–6) and older fish (ages 7–10) in Fig. 4e and f. VPA-based values of F for age 0 fish increased relative to the base model since about 1980, and recently have been higher than the base model estimates by about 0.2 year^{-1}. Though they are freely estimated by the VPA approach, F values for age 1 are nearly identical to those in the base model. Values of F for ages 2 and older are constrained by selectivity curves, but the hybrid model nonetheless leads to higher F values for age 2, with a strong trend of increasing relative F since the late 1980s. Still, the difference in estimated F on age 2 fish is nearly 0.4 year^{-1} in recent years. Ages 3 and older all show increased F in recent years. The increased estimated F at ages 0 and 2 is enough to account for the recent decline in estimated biomass. The increase in F at older ages is consistent with the given catch and lower estimated biomass.

4. Discussion

There seem to be two entrenched camps of fish stock assessment modeling: those who favor use of VPA, which is a relatively transparent accounting approach, and those who favor use of statistical, likelihood-based integrated approaches, such as SS, which can be quite complex. A hybrid SS-VPA model addresses some weak areas of both of these approaches to stock assessment and may have benefits relative to conventional assessments using either method alone, especially if young age classes are subject to unpredictable fluctuations in availability or selectivity.

4.1. General

The cohort linkage used to establish terminal F in VPA usually consists of an assertion that two or more adjacent ages of older fish experience the same fishing mortality rate in a given year (i.e. they have equal selectivity), and this linkage is accomplished by means of "plus-group" aggregations of catches of fish older than a nominal age of full selectivity. Both Patterson's (1998) VPA and the selectivity curves used in integrated analyses provide greater flexibility in linking cohorts, and do not require equal selectivity of linked cohorts. Notably, adjacent ages seldom have exactly the same F (equal selectivity) in SS, but rather they have a statistically predictable relationship to each other according to a parameterized age- or length-based selectivity curve. In the case of VPA, assuming equal selectivity in cases where true selectivities differ in a consistent manner leads to systematic error in the assessment, and may contribute to a retrospective pattern. The standard VPA packages provide no diagnostics for optimal specification of the cohort linkage function, which, if considered at all, is usually based on an ad-hoc inspection of alternatives.

Conventional use of SS specifies selectivity values at all ages. Although flexibility is provided by allowing year-specific parameters in the selectivity functions, the patterns of variability such as were described by Sampson and Scott (2012) would require multiple year-specific parameters which would be difficult to justify or estimate in the normal course of developing an SS assessment. Also, year-specific selectivity parameters in SS propagate the variability into the selectivities at older ages, which may be undesirable. The hybrid approach of beginning the selectivity curves at an age (or size) above which selectivity-at-age patterns become more stable provides a useful alternative to the more conventional SS specification of time-varying selectivity at younger ages. The ages that can be treated as a VPA are limited only by the ability to quantify the catches by age – the same constraint that exists for conventional VPA. Our bluefin tuna example is based on lengths, so only very young fish can be assigned reliable ages. For most VPA assessments, age determination allows many more young age groups to be distinguished. In direct analogy to specification of plus-groups in conventional VPA, a comparison of apparent selectivity at age given alternative ages of the integrated model – VPA transition should allow for the identification of the transition age for a hybrid model. Integrated models such as SS provide a rich statistical basis for evaluating alternative model specifications, and we expect that quantitative guidance for implementing a hybrid approach will emerge with future experience. We believe that the hybrid model is a statistically robust approach: if catches are accounted for properly, and because F-estimates for young ages are free to take their true values, there seems to be little or no potential error introduced by a hybrid approach. In contrast, the selectivity curves used in conventional integrated models pose a relatively high risk of model error (Sampson and Scott, 2012).

Aside from statistical optimization, the VPA portion of the hybrid model, like conventional VPA, requires data in the form of catches-at-age, and choice of a transition age is constrained by our

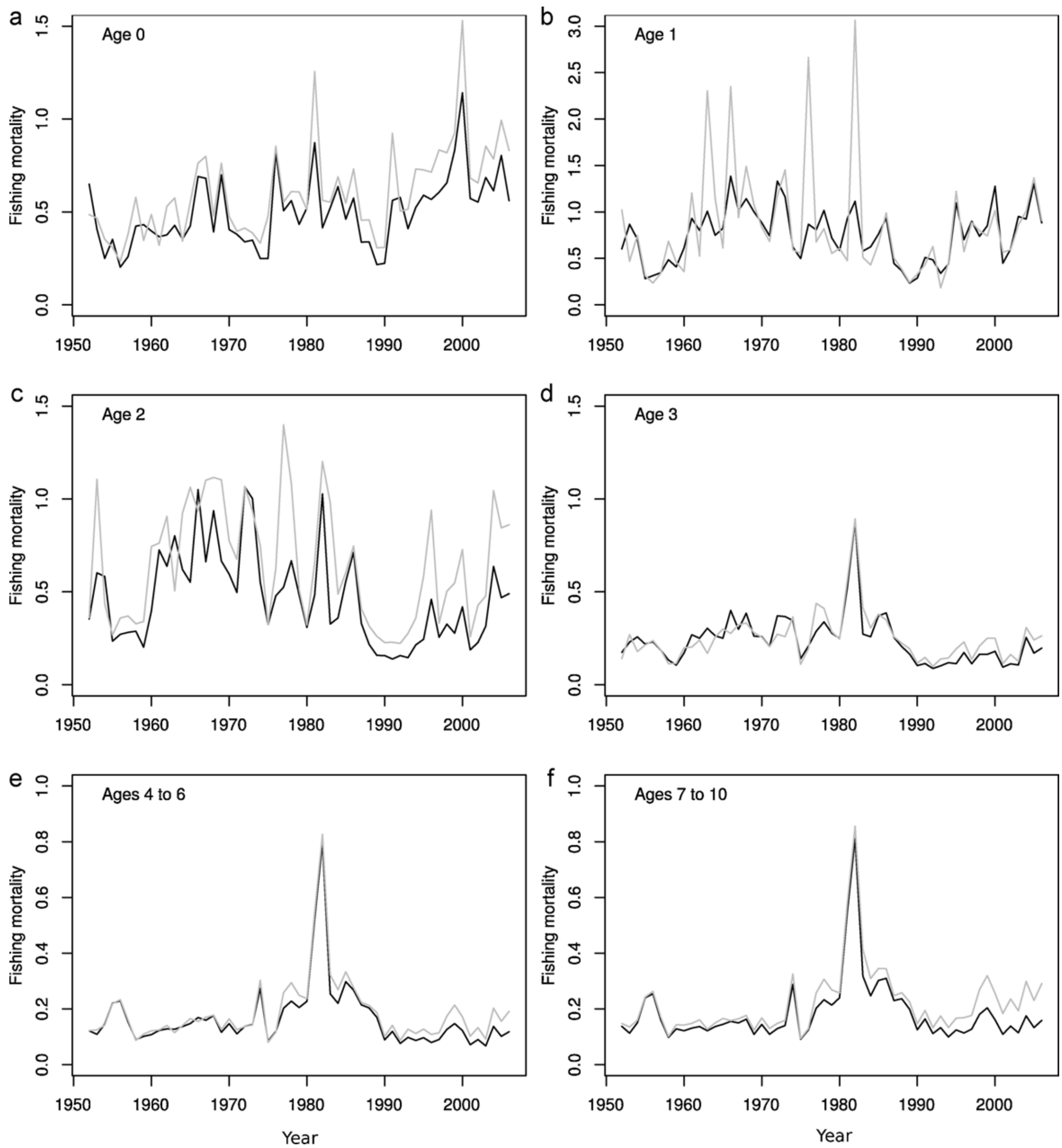

Fig. 4. Time-trajectories of *F*-at-age from base (black) and hybrid (gray) models.

ability to separate out the age-specific catches of the younger age groups. Direct age determination, such as from counts of otolith annuli, is desirable, and such ages tend to be most precise for younger individuals. As in most assessment approaches, the age determination problem is more difficult if there is only length composition information. Growth modes may provide a basis for allocating catches to age groups for length-based assessments, allowing use of approaches such as normal curve separation, or cohort slicing as we did for PBF (Fig. 2). For the purpose of defining single-age fisheries, there is presently no internal way to utilize the SS features associated with imprecise age determinations other than by using the 'CATCH_AT_AGE' and 'BIOLOGY_AT_AGE' components of the original SS report file from an initial SS model as a first approximation. Indeed, this iterative approach may be as good as can be hoped for, since SS is able to account for error in length-to-age conversion as well as approximate selectivity patterns, neither of which is addressed well by external methods. In addition, since the total catch is assumed to be without error in SS, the quantity of catch assigned to the young ages is also appropriately constrained.

4.2. *Pacific bluefin tuna*

The results for PBF indicate a substantial difference between the base and hybrid versions of the assessment, with the hybrid model indicating a substantially lower recent abundance and higher recent fishing mortality rates. Some other recent exploratory analyses of PBF have produced similar results to those of the hybrid model. For example, Piner et al. (2011) obtained a similar trend in recent abundance from a two-area spatial model of PBF, including migration between fishing grounds on the eastern and western sides of the North Pacific. Piner et al. (2011) showed that that one likely reason for this is the treatment of selectivity for tuna on the eastern side of the North Pacific. A benefit of the hybrid model is that explicit spatial modeling of young fish distribution is not needed.

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Appendix A. Preparation of SS data files

A.1. Data file

A hybrid SS-VPA is relatively easy to construct if age-specific catches are available. If there is significant imprecision in age determinations, or if only length compositions are available (as is the case for PBF), calculation of age-specific catches can be difficult. Conversions of length compositions (or imprecise ages) to age distributions contain an implicit, or more rarely explicit, assumption of a prior probability distribution of ages (Kimura, 1977). The data used in this study were modified from the SS data file (Data08_20100611ver7.SS) used in the Pacific Bluefin Tuna Working Group (PBFWG) update of PBF status in July 2010 (ISC, 2008). The main modifications are: (1) catches of age-0 and age-1 fish were removed from all fisheries except the Japan and Taiwan longline fisheries, which catch negligible numbers of age-0 and age-1 fish; (2) two artificial fisheries (AGE0 and AGE1) were created to contain the age-0 and age-1 catches that were removed; and (3) length compositions in bins corresponding to age-0 and age-1 fish were set to zero for all fisheries except the two longline fisheries. The CPUE indices in the data file were not modified. Besides the original data file, all of the auxiliary data (e.g. catch-at-age, length-at-age) used in this study were extracted or derived from quantities in the original SS report file from ISC (2008).

Catches from all fisheries were in weight (mt) in the base data file. Although age-0 and age-1 catches could be easily supplied as catches in numbers, maintaining them as catches in weight assures that the total catches in the base and hybrid models are identical. Age-0 and age-1 catches (mt) were estimated by multiplying the number of age-0 and age-1 fish (easily identifiable as modal groups in the length composition) caught by each fishery for each season and year, with the retained weight of age-0 and age-1 fish for their respective fishery and season. The number of age-0 and age-1 fish and the retained weight were extracted from the 'CATCH_AT_AGE' and 'BIOLOGY_AT_AGE' components of the base SS report file (this is a convenience of working iteratively from a previous conventional SS model and should give values equivalent to those that would be calculated externally). The catches of age-0 and age-1 fish from all fisheries, except for Japan and Taiwan longline, were summed and placed into the "AGE0" and "AGE1" fisheries, respectively and were removed from their respective original fisheries. Length-bin boundaries for age-0 and age-1 fish were estimated using cohort slicing (Lassen and Medley, 2000) for all fisheries, except Japan and Taiwan longline, and length frequencies in those bins were set to zero. The seasonal length-bin boundaries, l_{ij}, between adjacent age classes i and j were estimated by $l_{ij} = \mu_i + [\sigma_i/(\sigma_i + \sigma_j)] \times (\mu_j - \mu_i)$, where μ and σ are the mean and standard deviation (SD) of length for each age class by season, and $j = i + 1$. Length frequencies in bins that were smaller than l_{12} were set to zero for each season. The means and SDs of seasonal age-class lengths were extracted from the 'BIOLOGY_AT_AGE' component of the report file. Length composition data for the Japan pole and line fishery were eliminated due to having only two lines of data remaining after the modifications.

In addition, the initial conditions for this study are slightly different from those in the base model. Initial catches in the base data file were defined for the Japan longline, tuna purse seine, and Japan troll fisheries. We estimated the initial catches of age-0 and age-1 fish from reported initial catch-at-age and retained weight because we were unable to determine how the initial catches in the base data file were derived. Similar to the procedure described above, we removed the estimated initial age-0 and age-1 catches from the tuna purse seine and Japan troll fisheries and put them into the initial catches for the AGE0 and AGE1 fisheries. The removed catch was larger than the base initial catch for the Japan troll fishery, so we set the initial catch for that fishery to zero. The most likely reason for this discrepancy is that the assumed initial catches in the base model were relatively poor assumptions and did not correspond well to model estimates of initial conditions.

A.2. Control file

The SS control file for the hybrid model was modified from the base control file (Control08.SS). The modifications were: (1) age selectivities for age-0 and age-1 were set to unit value for the AGE0 and AGE1 fisheries respectively, and length selectivities for the AGE0 and AGE1 fisheries were turned off, (2) length selectivities for CPUE indices were not mirrored to their respective fisheries, but were instead set to fixed values extracted from the original report file (i.e. estimated in the base model), and (3) the age selectivities for age-0 and age-1 were set to zero for all fisheries except Japan and Taiwan longline. The length selectivities for all fisheries in the base model were dome-shaped, except for the Japan and Taiwan longline fisheries, which were both logistic-shaped. Length selectivity parameters in the hybrid model were set to fixed values extracted from the base report file and the length selectivity patterns were therefore identical to those estimated in the base model. All other parameters remained the same as in the original control file.

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