

AN INCIDENTAL CATCH MODEL FOR PORBEAGLE ASSESSMENT AND STATUS EVALUATION

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SUMMARY

*Fisheries landings and associated biological data collection for porbeagle shark (*Lamna nasus*) declined substantially following CITES Appendix II trade restrictions in 2013. This document describes a new stock assessment method that can be used when length-frequency data and CPUE series are not available or reliable to index changes in abundance. The Incidental Catch Model (ICM) is based on the same general premise as data-poor, length-based assessments, in that it uses life history information and equilibrium assumptions to derive a theoretical age-structured population in the absence of fishing. In the ICM, the effect of historical fishing pressure on productivity is taken into account prior to evaluating fishery removals and abundance relative to reference points. The Northwest Atlantic stock was used to demonstrate the method, which can be easily adapted to assess stocks in the Northeast Atlantic, Southwest and Southeast Atlantic by changing life history inputs.*

KEYWORDS

Alternative assessment approaches, Incidental Catch Model, Porbeagle Shark, status

1. Introduction

A fundamental assumption underlying traditional fisheries assessment is that at least one of the data inputs (e.g. catch per unit effort; CPUE) indexes abundance. In situations where there have been profound changes in data indices that are independent of changes to abundance, such models (e.g. Surplus Production, Statistical Catch at Age, Virtual Population Analysis) will not provide information on population size or status relative to current fishery removals (Maunder et al. 2006). Similarly, data-poor approaches like length-based assessments rely on having a representative length-frequency distribution from the catches to compare with the equilibrium length distribution of the population (based on life history characteristics) to estimate fishing mortality (Hordyk et al. 2015a; Hordyk et al. 2015b). For the porbeagle stocks assessed by ICCAT, recent changes to CPUE series and relatively limited data from which to estimate length-frequency means that a new approach to stock assessment is needed.

Here, we propose an Incidental Catch Model (ICM) that can be used to evaluate historical abundance, estimate reference points, determine status (i.e. overfished), and quantify stock response to various levels of future fishing mortality. It incorporates variability in life history inputs (Cortés and Semba 2020) and in the assessment of status relative to SPR_{MER} reference points (Brooks et al. 2010). We demonstrate the model by fitting it to data from the Northwest Atlantic porbeagle stock. We chose this example because the predicted abundance trajectory from the ICM could be directly compared to predictions from a fully-integrated Statistical Catch at Age model (Campana et al. 2010) to help with validation of the approach.

2. Methods

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The ICM is a simulation model with two main parts: (1) a backward-projecting component, used to predict the historical abundance trajectory given the actual time series of removals, and (2) a forward-projecting component that accounts for any reduction in productivity from fishing pressure to assess current status as well as the scope for future removals. The ICM accounts for uncertainty in our understanding of porbeagle life history by simulating over a distribution of values for population productivity. This distribution comes from a Leslie matrix approach to get the theoretical maximum capacity for population growth in the absence of fishing (r_{max}). This type of modeling approach has been previously applied to demographic analyses of cetaceans (Caswell et al. 1998; Dans et al. 2003), basking shark (Campana et al. 2008) and white shark (Bowlby and Gibson 2020). This is the first application of this type of simulation model for stock assessment at ICCAT.

2.1. Simulation Model

It is very likely that porbeagle in the Northwest Atlantic are at low abundance, so we used a simple exponential growth model in the backwards projections to predict changes in population size (N) from the current year (y) to the previous year ($y-1$), accounting for removals (R):

$$(1) N_y = e^r N_{y-1} - R_{y-1}$$

which can be rearranged as:

$$(2) N_{y-1} = \frac{(N_y + R_{y-1})}{e^r}$$

The time series of removals from Task 1 data informs R , spanning the years 1961 to 2018 for the Northwest Atlantic. Thus, the backwards projections start in 2018 and end in 1961. For this example, we used the median weight at capture (39.34 kg) from Canadian landings to transform Task 1 biomass into numbers. This simplification means it is not necessary to know the selectivity pattern of the fishery.

The backwards projections occur on an annual time step where population increase happens first and removals take place afterwards. This makes the analysis more precautionary as it slightly exaggerates the effects of removals by modeling them as a discrete rather than a continuous process. Note that we used the population's capacity for growth in the absence of fishing (r_{max}) in these backwards projections. This means that the effect of removals in each year (i.e. the level of exploitation) was calculated relative to the population's theoretical capacity for growth at equilibrium, which is the same premise that underlies length-based assessment approaches (Hordyk et al. 2015a; Hordyk et al. 2015b).

In an age-structured population, fishing mortality (F) and exploitation rates (u) are a function of survival at age (l_x), fisheries selectivity, removals and abundance. Survival at age is conditional on natural mortality (M) and instantaneous fishing mortality (F).

$$(3) l_x = \prod_{i=0}^{x-1} e^{-(M_i + F_i)}$$

In the backward projections as well as the assessment of status (below), we found the value for F using minimization of the sum of squared residuals between observed removals (R_y) and predicted removals. From the basic relationship between an annual exploitation rate (u) and instantaneous fishing mortality (F):

$$(4) u = 1 - e^{-F}$$

The number of animals in the population in a given year (N_y) that are vulnerable to the fishery becomes:

$$(5) \text{vulnerable} = N_y \frac{\sum_{x=sel}^A l_x}{\sum_{x=0}^A l_x}$$

where sel is the age at which animals are fully selected to the fishery and A represents maximum age. Here we have approximated a dome-shaped selectivity function by assuming constant fishing mortality rates on juveniles and no fishing mortality on adults. This reflects the length composition data from various fleets, where the vast majority of fisheries captures are immature. We set F to zero above the age at maturity in the calculation of (l_x) and $sel = 1$. Predicted removals are simply $\text{vulnerable} * u$.

We used a simple logistic growth model for the forward projections of the simulation, assuming a carrying capacity (K) of 20 million animals (i.e. very weak density dependence) in the Northwest Atlantic.

$$(6) \quad N_{t+1} = e^r N_t \left(1 - \frac{N_t}{K}\right)$$

This was done to ensure that the future projections could not grow without bound and thus produce overly optimistic results on the potential for population recovery. We assumed the same selectivity pattern as in the backwards projections and we accounted for the reduction to r_{max} from fisheries removals ($r < r_{max}$) by substituting the estimated value of F into Equation 3. We projected the model forwards for 50 years (to 2069) which is roughly 2.5 generation times for porbeagle (generation time ~20 years).

2.2. Model parameterization

We obtained life history parameters for females from previously published data (refer to Table 1 in Cortés and Semba 2020). The growth equation came from Natanson et al. (2002) and information on reproductive biology, including the shape of the maturity ogive, litter size, and gestation period came from Jensen et al. (2002). The maturity ogive was updated to include unpublished data from Canada (Cortés and Semba 2020). An estimate of natural mortality (M) is required to determine survival at age. We calculated six different estimators for M (see details in Cortés and Semba 2020) and took the lowest of the suite in a particular iteration to calculate survivorship.

Using the life history parameters, we applied the age-structured Leslie matrix approach (equivalent to a life table analysis/Euler-Lotka equation) for females described in Cortés and Semba (2020) to generate a distribution of r_{max} values for input into the ICM. In brief, we used Monte Carlo sampling from predefined statistical distributions for multiple life history parameters to generate the maturity ogive and survivorship at age, as well as values for age at maturity and lifespan. The number of MC samples matched the total number of simulations run for the ICM ($n = 5000$). Random draws for parameters contributing to the Von Bertalanffy Growth Function (VBGF) and maturity ogive came from a multivariate normal distribution to account for covariance. We used a uniform distribution for lifespan with the observed longevity from vertebral aging as the lower bound and seven half-lives (from the K parameter of the growth function) as the upper bound (Cortés and Semba 2020).

Recent research has suggested a possible biennial reproductive cycle for porbeagle (Natanson et al. 2019). Thus, we present three alternate life history scenarios: one assuming a reproductive periodicity of one year (annual; High Productivity), one assuming a reproductive periodicity of two years (biennial; Low Productivity), and an intermediate scenario that assumes a 50:50 mix of annually-reproducing and biennially-reproducing females (annual + biennial; Medium Productivity).

2.3. Status evaluation

We assessed whether the stock in the Northwest Atlantic is currently overfished using the SPR_{MER} reference point proposed by Brooks et al. (2010): the Spawning Potential Ratio at Maximum Excess Recruitment. This biological reference point is derived entirely from life history data and has been found to accurately predict overfished status relative to Maximum Sustainable Yield (MSY) reference points from traditional stock assessments (Cortés and Brooks 2018). It is calculated as:

$$(7) \quad SPR_{MER} = \frac{1}{\sqrt{\hat{\alpha}}}$$

Where $\hat{\alpha}$ represents the maximum lifetime reproductive rate (Myers et al. 1997, 1999), which is the maximum number of female spawners that can be produced by a female spawner throughout her life (Bowlby & Gibson 2020). It is calculated from the net reproductive rate or spawners per recruit (SPR) multiplied by maximum age-0 survival (Brooks et al. 2010). Overfished status is determined by comparing current abundance with a threshold value. This value typically represents a given proportion (p) of the stock size which is expected to produce MSY. The value of p is recommended to be the larger of $p = 0.5$ or $p = (1-M)$ (Brooks et al. 2010). Similar to US shark assessments, we have used $p = (1-M)$ to be precautionary for species where $M < 0.5$.

The threshold value representing the depletion of spawners and recruits at Maximum Excess Recruitment, assuming a Beverton-Holt stock-recruit relationship, is:

$$(8) \quad \frac{S_{MER}}{S_0} = \frac{\sqrt{\hat{\alpha}} - 1}{\hat{\alpha} - 1}$$

The population is considered overfished if the level of depletion in an abundance index (I) divided by the threshold value in Equation (7) is smaller than the proportion p :

$$(9) \frac{\frac{I_{current}}{I_{unfished}}}{\frac{S_{MER}}{S_0}} < p$$

Here, we have assumed that predicted abundance in 1961 represents unfished population size and that abundance in 2018 represents current abundance. Each iteration of the simulation yields a different value for $\hat{\alpha}$ as well as for current (2018) and unfished population size (1961) due to the manner in which variability is incorporated into the model (MC sampling from distributions). Therefore, solving Equation 8 gives a distribution of values that can be compared to p .

Similarly, the proportion of simulations that are overfished at a given time step in the forward projections can be found by using predicted future abundance as $I_{current}$. We evaluated the forward predictions at 5-year intervals relative to removals scenarios ranging from 0 to 24,000 animals (0 – 944 mt). In each future year, the proportion of trajectories that are overfished becomes the number of simulations $< p$ divided by the total number of simulations.

2.4. Validation

There are no model residuals or deviances output by the ICM that can be used for validation with traditional metrics like AIC or negative loglikelihood (Johnson and Omland 2004). Instead, using different life history parameters or starting the population at a different initial abundance will lead to different results (e.g. higher/lower predicted F). For this reason, we felt it was necessary to compare model output with a more traditional fishery model to determine if the ICM was a reasonable assessment method. Fortunately, a Statistical Catch at Age (SCA) model that used data up to 2009 was developed for porbeagle in the Northwest Atlantic (Campana et al. 2010). The Canadian SCA was a fully integrated assessment, which incorporated the standardization of raw CPUE data within the model. It was sex-based and stage-structured, and partitioned catches according to three different age-length keys, representing catch profiles from three geographic regions. Four model variants were tested, where each incorporated slightly different life history assumptions leading to differences in productivity. Fisheries selectivity for each region was estimated in the model. Although 10 years old, the general structure of the SCA as well as the methods used for fitting (minimization of an objective function via the Laplace approximation in ADMB) are still considered to be among best-practices for data-rich, age-structured assessments (Maunder and Piner 2015).

We qualitatively compared the predicted historical abundance trajectory from the ICM with predictions from the SCA, after standardizing data inputs to the two approaches. The SCA used a time series of removals derived from NAFO reporting (1961-2009) rather than Task 1 data, which was used as the removals series in the ICM for this comparison. The SCA assumed a Beverton-Holt stock recruitment relationship, and the variant called Model 3 had the most similar reproductive assumptions to the ICM. The VBGF growth parameters were identical.

3. Results

3.1. High Productivity Scenario – annual reproduction

The median and 95th percentiles for r_{max} and the SPR_{MER} reference point were 0.079 (0.057, 0.102) and 0.456 (0.339-0.607), respectively (Table 1). The backwards projections of the ICM indicated that maximum abundance occurred in the 1960s, with a median predicted population size of ~650,000 animals (top panel; Figure 1). Declines continued until 2010, reaching a low of ~150,000, before increasing to the assumed 2018 median population size of 200,000 animals. This means that the stock is predicted to have declined by 69% from maximum historical abundance.

If reproduction is annual, the stock is predicted to not be overfished, with only 43.6% of iterations below the critical value of $(1-M)$. From the future projections (top panel; Figure 2), the stock would remain above the overfished threshold with a $> 50\%$ probability until 2069 if removals remained at or below 16,000 animals (Table 2).

3.2. Medium Productivity Scenario – mixture of biennial and annual reproduction

The median and 95th percentiles for r_{max} and the SPR_{MER} reference point were 0.059 (0.036, 0.081) and 0.558 (0.415-0.743), respectively (Table 1). The backwards projections of the ICM indicated that maximum abundance occurred in the 1960s, with a median predicted population size of ~750,000 animals (middle panel; Figure 1). Declines continued until 2010, reaching a low of ~170,000, before increasing to the assumed 2018 median population size of 200,000 animals. This means that the stock is predicted to have declined by 73% from maximum historical abundance.

If reproduction is a mixture of annual and biennial, the stock is predicted to be overfished with a high probability, with 72.3% of iterations below the critical value of $(1-M)$. From the future projections (middle panel; Figure 2), the stock would remain above the overfished threshold with a > 50% probability until 2069 if removals remained at or below 10,000 animals (Table 3).

3.3. Low Productivity Scenario – biennial reproduction

The median and 95th percentiles for r_{max} and the SPR_{MER} reference point were 0.045 (0.022, 0.067) and 0.645 (0.479, 0.858), respectively (Table 1). Maximum abundance occurred in the 1960s, with a median predicted population size of 850,000 animals (bottom panel; Figure 1). Declines continued until 2010, reaching a low of ~180,000, before increasing to the assumed 2018 median population size of 200,000 animals. This means that the stock is predicted to have declined by 76% from maximum historical abundance.

If reproduction is biennial, the stock remains overfished with a high probability. From Equation 8, 94.4% of iterations were below the critical value of $(1-M)$. From the future projections (bottom panel; Figure 2), the stock would remain above the overfished threshold with a > 50% probability until 2069 if removals remained at or below 5000 animals (Table 4).

3.2. Scenario Comparison

The productive capacity of the stock is reduced by 43% under the assumption of biennial reproduction; r_{max} drops from a median of 0.079 (0.057, 0.102) to 0.045 (0.022, 0.067) and the SPR_{MER} reference point increases from 0.456 (0.339-0.607) to 0.645 (0.479, 0.858). Recall that the closer the SPR_{MER} value is to 1, the less exploitation can be permitted (Brooks et al. 2010). As expected, the Medium Productivity scenario produces results in the mid-point of these ranges.

The predicted trends in abundance are similar among the three productivity scenarios, but the maximum size in the 1960s is ~200,000 animals greater in the Low Productivity scenario than in the High Productivity scenario. This was expected because the population has greater ability to recover from exploitation in the High Productivity scenario so a smaller total number can support a given level of removals. In all scenarios, the stock reached minimum abundance around 2010 and was predicted to have been increasing since that time, albeit very slowly in the Low Productivity scenario. Total declines from maximum abundance (i.e. 1961 to 2018) were quite similar among scenarios, at 69%, 73% and 76%, respectively.

There is a high probability that the stock remains overfished, particularly given the recent research that suggests a biennial reproductive cycle for porbeagle in the Northwest Atlantic (Natanson et al. 2019). In all reproductive scenarios, future removals need to remain low to permit population recovery.

3.2. Model Validation

When productivity inputs and the removals series used in the ICM were matched (as closely as was possible) to the Canadian SCA model, the different approaches produced extremely similar historical abundance trajectories. This could only occur if the ICM was producing similar estimates of the annual exploitation rate as compared to the SCA. Predicted starting population size in the 1960s was just over 800,000 animals from both modeling approaches and declined following a very similar pattern (Figure 3). The total predicted decline rate was essentially identical. This is actually quite remarkable given how different the data inputs, estimation method and assumptions are in the SCA as compared to the ICM, and lends validity to our assertion that the ICM is useful for assessment.

4. Discussion and Conclusions

We have presented a relatively simple simulation model that can be used to assess status relative to biological reference points for porbeagle in the Northwest Atlantic. By changing life history parameter input values (e.g.

growth coefficients), this model could be easily adapted to assess other porbeagle stocks of interest to ICCAT. Since the stock in the Northeast Atlantic will not be assessed at this meeting, the working group may choose to apply the ICM to a (most likely single) South Atlantic stock. The only required data inputs are a time series of removals, parameterized as a number of animals, and a value to use for current population size. If current population size is not known, one alternative would be to use trend information from a time period that CPUE data were available to condition the historical trajectory. As in traditional stock assessment, the ICM assumes that the time series of removals is known. However, unlike traditional fisheries assessments, the ICM uses the theoretical productive capacity of the stock at equilibrium to index changes in abundance and to scale historical population size estimates. This means that abundance predictions and fishing mortality rates are not sensitive to recent changes in the fishery that influence indices, such as management restrictions that reduce landings. There is very good correspondence between the abundance predictions of the ICM as compared to a complex, sex-specific and age-structured SCA model. Because of this, we suggest that it is meaningful to use the ICM to derive advice.

It is very likely that porbeagle in the Northwest Atlantic are currently overfished and remain at low abundance. While only 43% of iterations met the overfished criterion if reproduction is annual, while 94.4% of iterations met the criterion if reproduction is biennial. Even if there is only a component of the population that reproduces biennially, there is still a high probability that the stock is overfished (72.3% of iterations $< (1-M)$).

The future projections demonstrate that the stock in the Northwest Atlantic has very little capacity for removals. Keeping removals below 16,000 individuals (High Productivity scenario) to 5,000 individuals (Low Productivity scenario) would convert to biomass of 629 mt and 197 mt, respectively. For comparison, removals from the Task 1 series averaged 43 mt from 2014-2018, 90 mt from 2009-2013 and 191 mt from 2004-2008. The ICM suggests that it is very unlikely that porbeagle in the Northwest Atlantic can sustain the level of removals seen prior to the early 2000s.

The species was listed on Appendix II of CITES in 2013 (<https://www.cites.org/eng/prog/shark/history.php>), which likely contributed to the drop in landings after that time in the Task 1 data due to changes in fleet behavior. Keeping current management restrictions in place will likely allow for porbeagle in the Northwest Atlantic to recover, even if current fisheries removals are slightly underestimated. However, all scenarios suggest that population recovery will be relatively slow.

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Table 1. Summarized demographic rates for the Northwest Atlantic population of porbeagle shark, assuming annual reproduction (High Productivity), a 50:50 mix of annual and biennial reproduction (Medium Productivity) and biennial reproduction (Low Productivity).

Parameter	High Productivity			Medium Productivity			Low Productivity		
	Median	0.025	0.975	Median	0.025	0.975	Median	0.025	0.975
Lambda	1.083	1.059	1.107	1.061	1.037	1.084	1.046	1.022	1.069
rmax	0.079	0.057	0.102	0.059	0.036	0.081	0.045	0.022	0.067
Generation Time	19.317	16.948	20.462	20.116	17.317	21.324	20.769	17.505	22.021
Net Repro Rate	5.281	3.019	9.352	3.520	2.013	6.235	2.640	1.510	4.676
Age-0									
Survivorship	0.912	0.894	0.931	0.912	0.894	0.931	0.912	0.894	0.931
Alpha hat	4.811	2.718	8.705	3.208	1.812	5.803	2.406	1.359	4.352
Steepness	0.546	0.405	0.685	0.445	0.312	0.592	0.376	0.254	0.521
SPR_MER	0.456	0.339	0.607	0.558	0.415	0.743	0.645	0.479	0.858
R	0.554	0.508	0.621	0.603	0.543	0.702	0.649	0.572	0.795

Table 2. Proportion of simulations that are above the critical value $p = (1-M)$ (not overfished) for porbeagle in the Northwest Atlantic, assuming annual reproduction (High Productivity). The highest level of removals that results in $> 50\%$ of the simulations remaining above the overfished threshold until 2069 (the end of 50 years; ~ 2.5 generations) is shown in bold.

Removals	High Productivity										
	2019	2024	2029	2034	2039	2044	2049	2054	2059	2064	2069
0	0.563	0.844	0.990	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1000	0.571	0.829	0.976	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2000	0.573	0.816	0.957	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000
3000	0.555	0.786	0.920	0.984	0.997	0.999	1.000	1.000	1.000	1.000	1.000
4000	0.563	0.777	0.901	0.965	0.989	0.996	0.998	0.999	0.999	0.999	0.999
5000	0.557	0.749	0.868	0.932	0.966	0.983	0.989	0.993	0.996	0.997	0.997
6000	0.561	0.732	0.841	0.901	0.937	0.958	0.971	0.979	0.983	0.986	0.989
7000	0.558	0.709	0.804	0.866	0.907	0.923	0.938	0.949	0.957	0.962	0.966
8000	0.561	0.693	0.779	0.830	0.867	0.890	0.907	0.916	0.922	0.929	0.932
9000	0.554	0.675	0.747	0.790	0.823	0.847	0.860	0.871	0.881	0.888	0.893
10000	0.561	0.660	0.716	0.753	0.780	0.797	0.811	0.823	0.833	0.840	0.846
11000	0.564	0.644	0.691	0.720	0.741	0.757	0.767	0.776	0.783	0.790	0.795
12000	0.569	0.633	0.668	0.689	0.704	0.717	0.723	0.729	0.736	0.739	0.742
13000	0.573	0.617	0.642	0.655	0.667	0.674	0.679	0.685	0.688	0.691	0.693
14000	0.571	0.603	0.617	0.625	0.629	0.632	0.634	0.636	0.638	0.639	0.641
15000	0.549	0.563	0.572	0.577	0.579	0.581	0.583	0.582	0.582	0.584	0.585
16000	0.554	0.551	0.549	0.548	0.546	0.545	0.543	0.542	0.543	0.542	0.541
17000	0.558	0.544	0.529	0.521	0.515	0.508	0.505	0.501	0.497	0.494	0.492
18000	0.552	0.517	0.494	0.479	0.470	0.464	0.457	0.453	0.448	0.442	0.438
19000	0.563	0.509	0.478	0.457	0.440	0.429	0.418	0.410	0.403	0.397	0.392
20000	0.565	0.496	0.457	0.428	0.409	0.393	0.379	0.367	0.358	0.352	0.346
21000	0.576	0.486	0.436	0.402	0.375	0.355	0.339	0.327	0.317	0.311	0.305
22000	0.552	0.456	0.400	0.361	0.331	0.306	0.293	0.281	0.271	0.262	0.255
23000	0.560	0.446	0.380	0.333	0.298	0.277	0.258	0.247	0.236	0.228	0.219
24000	0.557	0.432	0.354	0.302	0.267	0.240	0.222	0.207	0.194	0.186	0.182

Table 3. Proportion of simulations that are above the critical value $p = (1-M)$ (not overfished) for porbeagle in the Northwest Atlantic, assuming a 50:50 mix of annual and biennial reproduction (Medium Productivity). The highest level of removals that results in $> 50\%$ of the simulations remaining above the overfished threshold until 2069 (the end of 50 years; ~ 2.5 generations) is shown in bold.

Removals	Medium Productivity										
	2019	2024	2029	2034	2039	2044	2049	2054	2059	2064	2069
0	0.277	0.541	0.749	0.903	0.969	0.991	0.997	0.998	0.999	0.999	1.000
1000	0.289	0.532	0.715	0.859	0.937	0.974	0.987	0.993	0.995	0.997	0.997
2000	0.295	0.516	0.680	0.813	0.899	0.944	0.966	0.979	0.987	0.991	0.993
3000	0.265	0.475	0.623	0.750	0.838	0.889	0.923	0.943	0.957	0.966	0.972
4000	0.291	0.474	0.604	0.711	0.790	0.844	0.880	0.903	0.918	0.931	0.941
5000	0.270	0.436	0.562	0.655	0.724	0.774	0.816	0.841	0.862	0.879	0.889
6000	0.276	0.429	0.537	0.611	0.670	0.716	0.753	0.780	0.800	0.814	0.827
7000	0.273	0.399	0.497	0.570	0.622	0.658	0.687	0.709	0.728	0.747	0.758
8000	0.277	0.390	0.475	0.528	0.572	0.606	0.629	0.648	0.662	0.676	0.685
9000	0.278	0.370	0.434	0.484	0.518	0.545	0.565	0.583	0.598	0.606	0.614
10000	0.274	0.351	0.406	0.441	0.468	0.491	0.509	0.522	0.532	0.540	0.547
11000	0.283	0.342	0.382	0.407	0.429	0.444	0.454	0.465	0.471	0.479	0.485
12000	0.299	0.331	0.359	0.376	0.389	0.396	0.406	0.410	0.416	0.422	0.425
13000	0.288	0.309	0.323	0.335	0.341	0.352	0.356	0.358	0.359	0.361	0.362
14000	0.294	0.301	0.302	0.301	0.301	0.300	0.302	0.305	0.306	0.309	0.310
15000	0.265	0.254	0.243	0.242	0.244	0.245	0.244	0.246	0.245	0.248	0.249
16000	0.275	0.250	0.230	0.219	0.212	0.207	0.207	0.205	0.204	0.203	0.203
17000	0.282	0.232	0.201	0.185	0.174	0.171	0.166	0.165	0.164	0.161	0.160
18000	0.269	0.216	0.183	0.163	0.147	0.140	0.134	0.132	0.128	0.127	0.125
19000	0.276	0.204	0.164	0.136	0.121	0.111	0.105	0.101	0.098	0.095	0.093
20000	0.289	0.197	0.143	0.115	0.100	0.093	0.084	0.080	0.075	0.073	0.071
21000	0.298	0.185	0.126	0.098	0.079	0.068	0.063	0.059	0.056	0.054	0.053
22000	0.277	0.156	0.097	0.070	0.055	0.046	0.041	0.037	0.034	0.033	0.032
23000	0.291	0.156	0.086	0.058	0.043	0.037	0.034	0.032	0.029	0.027	0.026
24000	0.276	0.135	0.071	0.043	0.029	0.024	0.021	0.019	0.018	0.017	0.016

Table 4. Proportion of simulations that are above the critical value $p = (1-M)$ (not overfished) for porbeagle in the Northwest Atlantic, assuming biennial reproduction (Low Productivity). The highest level of removals that results in > 50% of the simulations remaining above the overfished threshold until 2069 (the end of 50 years; ~ 2.5 generations) is shown in bold.

Removals	Low Productivity										
	2019	2024	2029	2034	2039	2044	2049	2054	2059	2064	2069
0	0.062	0.204	0.393	0.555	0.694	0.797	0.866	0.910	0.935	0.951	0.961
1000	0.066	0.207	0.372	0.513	0.630	0.722	0.797	0.846	0.881	0.905	0.924
2000	0.064	0.190	0.338	0.456	0.563	0.649	0.715	0.768	0.808	0.839	0.862
3000	0.049	0.156	0.269	0.387	0.475	0.549	0.611	0.656	0.704	0.733	0.757
4000	0.062	0.153	0.262	0.356	0.428	0.492	0.544	0.591	0.621	0.652	0.677
5000	0.062	0.131	0.213	0.293	0.364	0.419	0.461	0.497	0.526	0.551	0.572
6000	0.047	0.116	0.184	0.254	0.314	0.358	0.396	0.427	0.453	0.473	0.492
7000	0.050	0.104	0.161	0.215	0.259	0.298	0.327	0.348	0.369	0.389	0.402
8000	0.056	0.099	0.142	0.183	0.218	0.250	0.275	0.293	0.309	0.321	0.334
9000	0.059	0.087	0.115	0.149	0.175	0.198	0.220	0.237	0.252	0.265	0.273
10000	0.061	0.080	0.102	0.123	0.144	0.163	0.178	0.190	0.201	0.212	0.220
11000	0.062	0.068	0.084	0.104	0.119	0.130	0.141	0.147	0.156	0.162	0.169
12000	0.070	0.069	0.079	0.090	0.098	0.107	0.112	0.118	0.123	0.126	0.129
13000	0.059	0.051	0.056	0.065	0.070	0.075	0.078	0.082	0.084	0.087	0.089
14000	0.065	0.050	0.048	0.051	0.053	0.054	0.056	0.058	0.060	0.062	0.065
15000	0.049	0.033	0.028	0.030	0.033	0.034	0.035	0.037	0.038	0.039	0.040
16000	0.058	0.031	0.026	0.026	0.026	0.027	0.028	0.028	0.028	0.030	0.031
17000	0.054	0.024	0.018	0.017	0.017	0.020	0.021	0.021	0.021	0.022	0.023
18000	0.056	0.020	0.014	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
19000	0.058	0.016	0.010	0.008	0.008	0.008	0.007	0.008	0.008	0.008	0.008
20000	0.064	0.015	0.007	0.006	0.005	0.005	0.005	0.005	0.005	0.005	0.005
21000	0.067	0.016	0.007	0.005	0.004	0.004	0.003	0.003	0.004	0.004	0.004
22000	0.054	0.007	0.004	0.002	0.002	0.001	0.002	0.001	0.001	0.001	0.001
23000	0.063	0.007	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
24000	0.063	0.006	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000

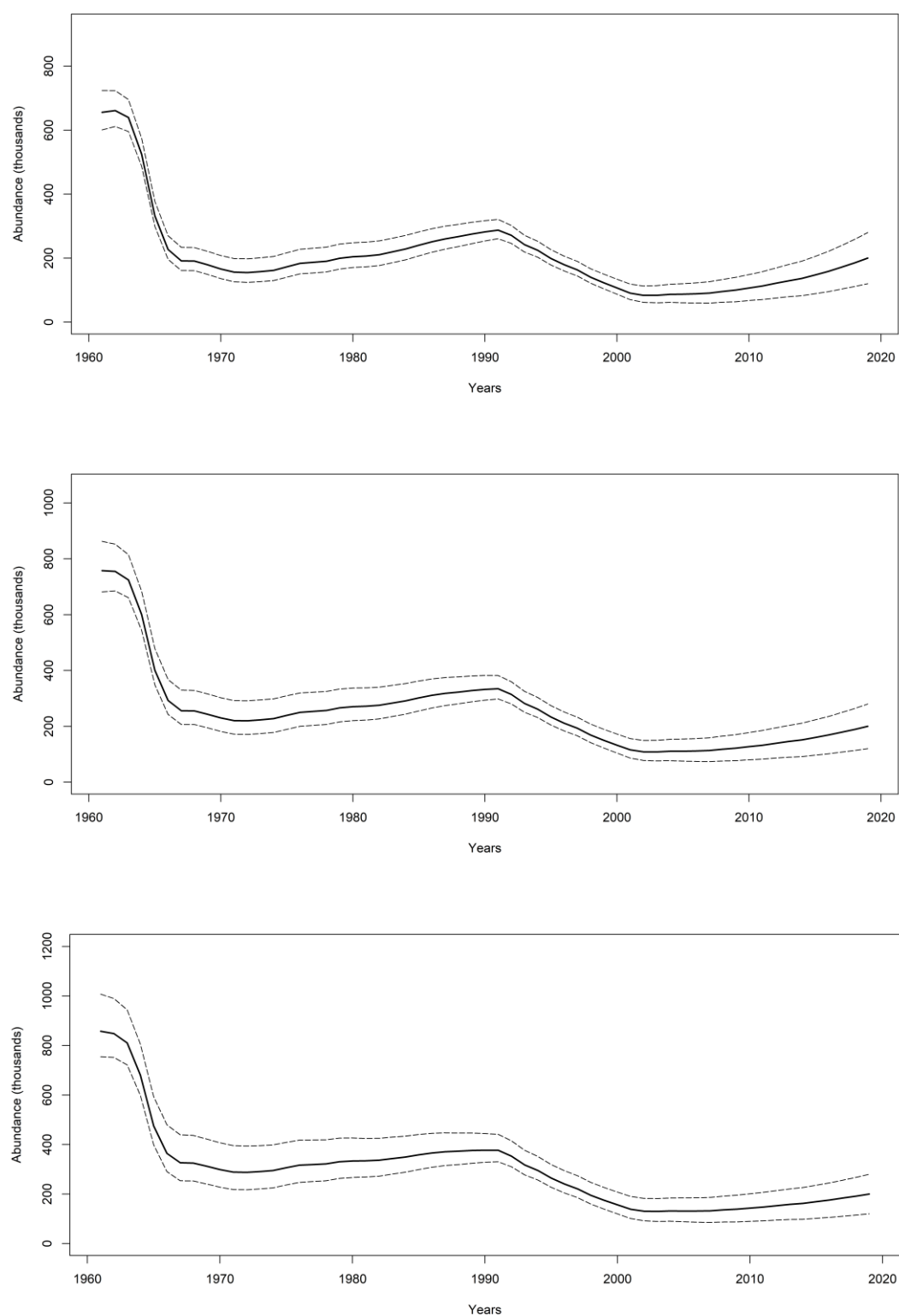


Figure 1. Predicted median abundance trajectory (solid line) and 80th percentiles (dashed lines) for the porbeagle stock in the Northwest Atlantic from 1950 to 2018, assuming annual reproduction (High Productivity; top panel), a 50:50 mix of annual and biennial reproduction (Medium Productivity; middle panel) and biennial reproduction (Low Productivity; bottom panel).

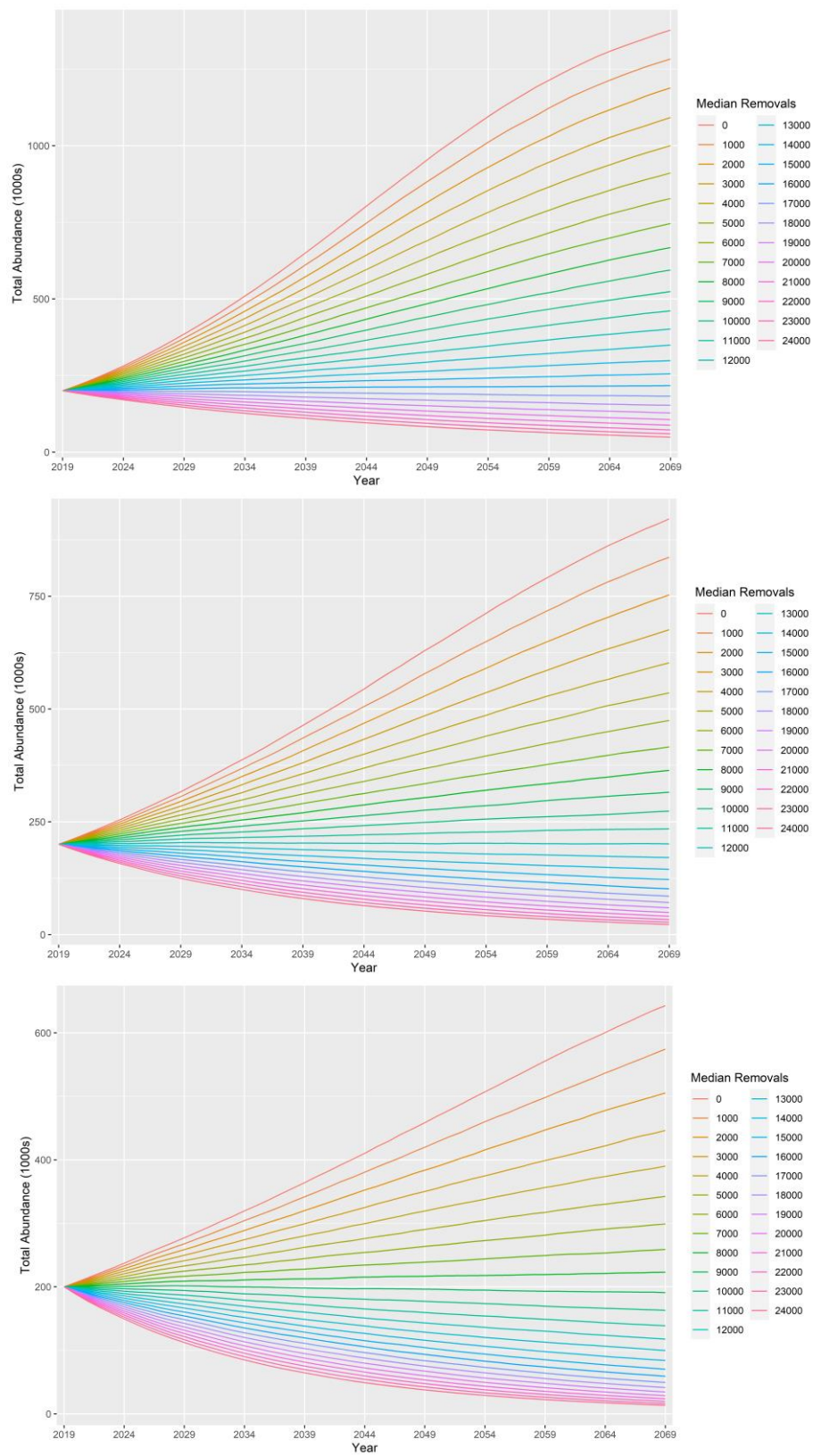


Figure 2. Predicted median abundance under removals scenarios ranging from 0 animals to 24000 animals for porbeagle in the Northwest Atlantic over the next 50 years, assuming annual reproduction (High Productivity; top panel), a 50:50 mix of annual and biennial reproduction (Medium Productivity; middle panel) and biennial reproduction (Low Productivity; bottom panel).

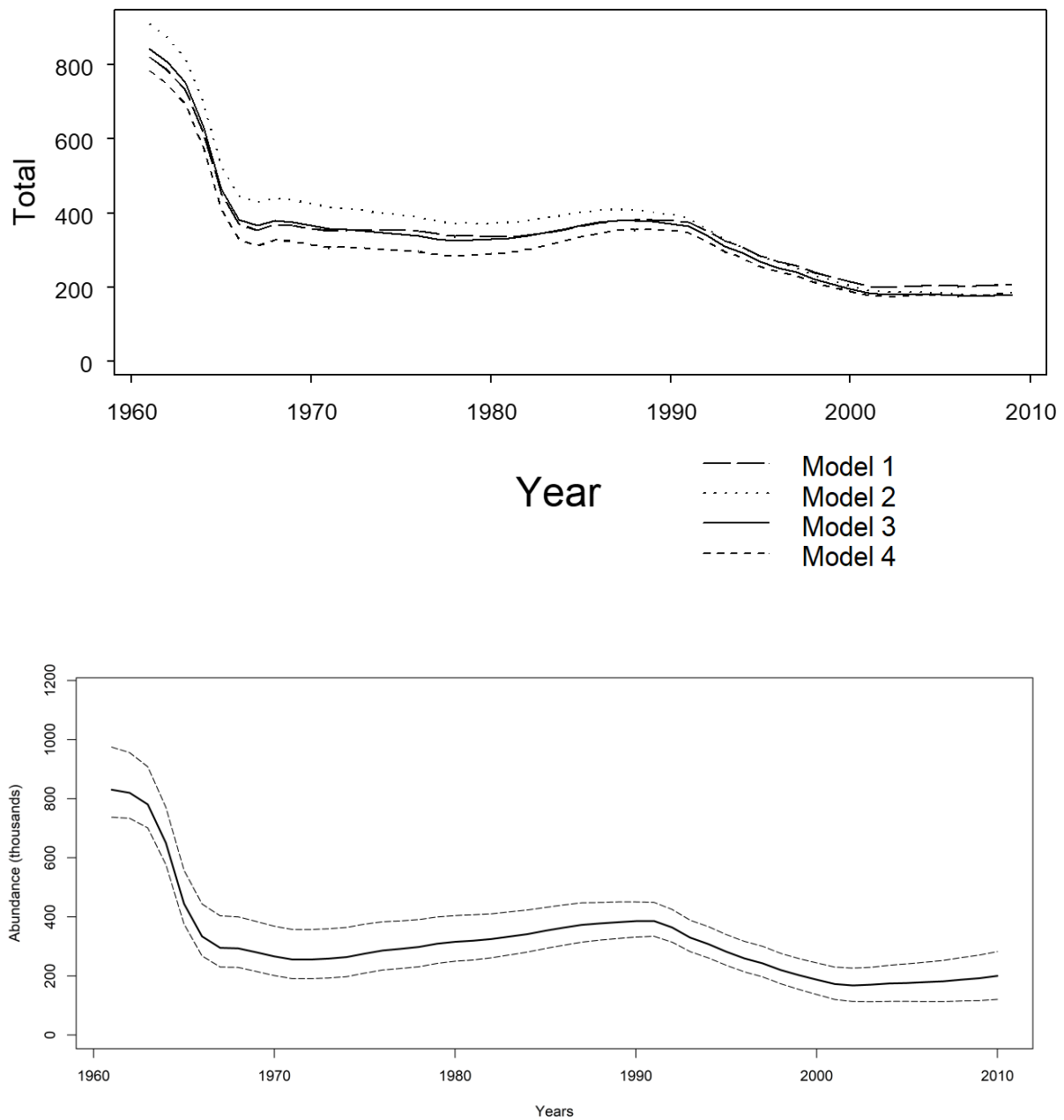


Figure 3. Comparison of the predicted historical abundance trajectories from a Statistical Catch at Age Model (Campana et al. 2010) for Porbeagle in the Northwest Atlantic (top panel) with output from the ICM over the same number of years, using the NAFO series for removals (lower panel).