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Abstract

The models developed and fitted during the Gray Whale Rangewide Review formed the basis for evaluating the performances of the *Gray Whale SLA* and the Makah Management Plan in terms of their ability to achieve the objectives for aboriginal subsistence whaling. Elevated strandings along the eastern North Pacific migration route, and declines in abundance since the completion of the Rangewide Review in 2018 are indicative of a second mortality event starting in 2019. This event may suggest that the set of scenarios used to evaluate the performances of the *Gray Whale SLA* and the Makah Management Plan may need to be revised in order to take into account new information on the expected magnitude and frequency of such events. Although the need for a revision remains an open question, new operating models for the eastern North Pacific gray whales have been developed that include a mortality event during 2019-2022 (continuing into 2023) for the Northern Feeding Group and new abundance data, including for the Pacific Coast Feeding Group. Trials have been conducted for stock structure hypotheses 4a/3a, 4b/3b, 4c/3c, 4e/3e, 7a/5a, and 6b, with sensitivity explored to changes to assumptions related to the frequency of catastrophic events, and allowance for an additional mortality event for the Pacific Coast Feeding Group. These operating models are used to conduct projections under the *Gray Whale SLA* and the Makah Management Plan that use the new scenarios related to possible future mortality events. These models will also be useful for updating the assessment of gray whales for the Scientific Committee's Status of Stocks Website project.

Keywords: Gray whales; Management Strategy Evaluation; Strike Limit Algorithm

INTRODUCTION

The Gray Whale Rangewide Review (GWRR) was conducted over five workshops during 2014 to 2018 (IWC, 2015, 2016, 2017, 2018, 2019a). Outcomes from the GWRR included a set of stock structure hypotheses. The stock structure hypotheses considered whether there was an extant Western Breeding Stock and the locations of three feeding groups within the Eastern Breeding Stock (Western feeding Group [WFG], Northern Feeding Group [NFG], and Pacific Coast Feeding Group [PCFG][1]). Two of the stock structure hypotheses (3a and 5a; Table 1) formed the base case for many of the sensitivity tests. The population dynamics models were based on 11 sub-areas within the north Pacific (Fig. 1; see Annex D of IWC, 2019a) and were used to evaluate the conservation and utilization performance of the Makah Management Plan (IWC, 2019b).

The population dynamics models developed during the GWRR were fitted to: (1) three sources of abundance data (the NOAA time series of population counts off California, the estimates of

[1] WFG: animals that feed regularly off Sakhalin Island according to photo-identification data; PCFG: animals that have been observed in two or more years during the feeding season in the PCFG area (41° N to 52° N along the coast of North America, excluding Puget Sound) according to photo-identification data; NFG: animals found in other areas (and for which there is relatively little information including photo-ID) (IWC, 2019a).

abundance for the PCFG, and the estimates for the WFG / Western Breeding Stock); (2) the proportions of stocks / feeding groups in some of the sub-areas based on photo-identification data, and; (3) data on survival rates for the PCFG and data on bycatch by sub-area. The models also involved assumptions about the immigration rate from the NFG to the PCFG and the proportion of animals killed due to bycatch in fisheries that are included in bycatch reports (Annex D of IWC, 2019a).

Subsequent to the GWRR, new information pertaining to stock structure was reviewed by the Scientific Committee, which determined that hypotheses 4a and 7a should be elevated to high priority for inclusion in the modeling, while hypotheses 3a and 5a should be considered medium priority (IWC 2021, 2022). Of note, however, is that hypotheses 3a and 4a and hypotheses 5a and 7a are functionally equivalent for modelling purposes and thus no new model runs were required to evaluate them.

New data are now available on removals (due to aboriginal takes) and abundance (ENP gray whales from NOAA California counts and estimates of abundance for the PCFG). In 2019, the number of gray whales stranded along the coast of North America increased markedly and led to the declaration of an Unusual Mortality Event in the US[2] (Fauquier et al., 2022). The NOAA population counts off California during the winter of 2019/2020 and 2021/2022 indicated that the abundance had declined by ~40% since 2015 and 2016 (Fig. 2a, Stewart and Weller, 2021; Eguchi et al., 2022). The abundance data for the PCFG are also suggestive of a reduction in abundance starting in 2016 (Fig. 2b; Harris et al. 2022) coincident with a marine heat wave (Peterson et al. 2017) that may have affected body condition of PCFG whales and the availability of their prey (Torres et al., 2022). The original (*Implementation*) trials used to evaluate the *Gray Whale SLA* were based on a single-stock operating model, and considered trials with (a) three mortality events between years 1-75 (with at least two during years 1-50) in which 20% of animals die, and (b) a mortality event during 1999/2000 in which 40% of animals die (trials GE41-50 in IWC, 2005), while those used to evaluate the Makah Management Plan were based on the multi-stock Rangewide operating model, and explored one catastrophic event in years 1-50 and another in year 51-99 of the projection period, with the magnitude equal to that of the mortality rate in 1999 and 2000 (approximately 13% per year). The new abundance data may suggest that the scenarios considered in previous evaluations of *SLA*s and the Makah Management Plan may need to be expanded.

This paper documents how the specifications of the population models, on which the operating models for gray whales are based, can be modified to include additional mortality events. It reports on the results of conditioning a subset of the trials developed during the GWRR but using the modified specifications and the new NOAA California count data and estimates of abundance for the PCFG. The historical period covered by the operating models is extended from 1930 – 2016 (GWRR) to 1930 – 2022. The trials are then used to calculate performance statistics for the *Gray Whale SLA* and the Makah Management Plan under the assumption that the latter is first applied in 2023. The paper concludes with some steps to be conducted if a special *Implementation Review* were to be declared by the Scientific Committee (see Appendix 9 of IWC, 2019b for the details of why a special *Implementation Review* might be declared), given that the updates to the operating models are provisional because not all of the data sources used for conditioning were updated.

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[2] Updated reporting on this event is available at https://www.fisheries.noaa.gov/national/marine-life-distress/2019-2023-gray-whale-unusual-mortality-event-along-west-coast-and

METHODS

New and revised data

Figure 2 compares the most recent ENP population counts from the NOAA California and PCFG abundance estimates with those used in the final GWRR analyses. The GWRR assumed that the NOAA California counts were independent while the analyses of this paper include a variance-covariance matrix for log (abundances) for 2006-2021. Table 2 lists the aboriginal catches for 2010+ used in the trials on which the GWRR was based and those used in the current analyses.

No new abundance estimates for the Western Breeding Stock and WFG were available at the time of writing nor was new information on mixing proportions or bycatch available.

Updated operating model specifications

The specifications for the trials are provided in IWC (2019b). The two changes to the model specifications (apart from extending the modelled period from 1930 to 2016 to 1930 to 2022) were to (a) estimate the annual survival rate for the NFG in 1998 and 1999 for the first UME (it was set to 0.87 in the GWRR trials; based on that estimated in the trials for the original *Implementation*), (b) estimate an annual survival rate for the NFG for 2018 – 2021 for the most recent UME, and (c) estimate an reduction in productivity (model a lower annual survival rate) for the PCFG in 2016[3] (a subset of trials).

Trials considered and exploration of management performance

Table 3 lists the trials considered in this paper. These trials focus on sensitivity to the stock structure hypothesis and how future catastrophic events are modelled. The trials used for GWRR also considered scenarios related to the ratio of actual to reported bycatch, the magnitude of immigration from the NFG to the PCFG in 1999 and 2000, the values for $MSYR_{1+}$, modifications to the base-case stock structure hypotheses given lack of data on whether mixing occurs in some sub-areas, struck and lost rates, and false negative rates for determining if a whale captured in the Makah Usual and Accustomed Area is a PCFG whale.

The *Gray Whale SLA* is documented in IWC (2005) while the Makah Management Plan is documented in Appendix A of this document. The evaluations of management performance were based on 100-year projections where California counts are collected every five years while PCFG estimates of abundance are assumed to be available annually, with a lag of two years (i.e., the application of the Makah Management Plan in 2023 would be based on data until 2021). The first year for application of the Makah Management Plan is 2023 for the analyses of this paper.

Trials with catastrophic events are considered for the two base-case trials (3a0 and 5a0) and the variants thereof that allow for a reduction in the growth rate for the PCFG in 2016 (3a2 and 5a2). These trials are justified and defined as follows.

a. Two periods with UMEs have occurred during the 50ish years with survey estimates of abundance for the ENP population. This is captured in the trials by having two periods with catastrophic events that impact the NFG occurring during each of the first and second 50-year periods of the projection (four events in total). The first and third future UMEs are two years long (mimicking the 1999-2000 event) and the second and fourth UMEs are

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[3] Torres et al. (2022) suggests that PCFG whales had poorer condition during the marine heat wave (although they do not show any data during the event). With poorer condition, more may have perished, but they could have also emigrated to other feeding areas such as Kodiak Island or up to the Arctic and not been available for PCFG abundance estimates.

four years long (mimicking the recent event). The first future UME occurs during one of years 9-13 for two years and the second event occurs 20 years later for four years, with the third event occurring during one of years 59-63 for two years and the fourth event twenty years after the third event for four years. The magnitude of the first and third future UMEs matches that for the 1999-2000 UME as estimated when conditioning the replicate for the trial and the magnitude of the second and fourth UMEs matches that for 2019-2022 UME as estimated when conditioning the replicate. This formulation implies that the sizes of future catastrophic events differ among replicates (trials 3a0, 3a2, 5a0, 5a2).

b. One (potential) event has occurred for the PCFG over 20ish years. This is captured in variants of trials 3a2 and 5a2 by having one catastrophic event that impacts the PCFG randomly in each 20-year block within the projection period (i.e., one event in each of years 0-19, 20-39, etc.), with the size of the event equal to the size of the reduction in productivity estimated for 2016 for the associated replicate (trials 3a2 and 5a2 only).

c. There are impacts on both the NFG and PCFG (combining the effects of "a" and "b") (trials 3a2 and 5a2 only).

The performance statistics used to evaluate the *Gray Whale SLA* and the Makah Management Plan are a subset (1+-based) of the quantitative statistics selected by IWC (2019a), with additional performance statistics to summarize the likelihood of catching western gray whales and the performance of the Makah Management Plan in terms of strikes and landed whales. For each statistic, the median, lower 5th and upper 5th percentiles are shown.

- D1. 1+ Final 1+ depletion, P_T/K by breeding stock / feeding group.
- D2. Lowest depletion: $\min(P_t/K)$: t=0, 1, …, T.
- D8. Rescaled final 1+ depletion, P_T/P_0 by breeding stock / feeding group, where P_0 is the number of 1+ animals had there been no future Makah hunts.
- D10. Relative increase. The ratio of the 1+ population size after 10 and 100 years to that at the start of the projection period by breeding stock / feeding group.
- Need satisfaction. The proportion of the total number of requested strikes that were taken over the first 10 years (Makah hunt) and the entire 100-year period (Russian and Makah hunts).
- Total number of western gray whales taken during hunts over the 100-year projection period.
- Total number of landed whales in the Makah Usual and Accustomed area over the 100-year projection period.
- Total number of struck whales in the Makah Usual and Accustomed Area over the 100-year projection period.

RESULTS

Conditioning results

Not including additional mortality during 2019-2022 led to very poor fits to the NOAA ENP population counts from California (results not shown). Figures 3 and 4 show the fits to the abundance estimates and Figures 5 and 6 the fits to the other data sources. Figure 7 shows the distribution of the estimates of some of the key parameters of the population dynamics model for trials 3a0 and 3a2 and Figure 8 shows the model-predicted bycatch by sub-area over time for trial 3a0 (results are shown for a subset of the trials for the latter two diagnostics as they are visually identical among trials).

All of the trials mimic the NOAA ENP population counts from California well (Figures 3 and 4); although there is some evidence that if the model does not allow for a decline in productivity in 2016, it predicts higher PCFG abundance than recent estimates indicate. In contrast, allowing for a mortality event in 2016 (trials 3a2 and 5a2) leads to better fits to these data (as expected). The fits to the estimates for the western part of the range are poorer but this is consistent with the trials conducted for the GWRR. The trials fit the mixing proportions, the immigration rate and the bycatch data well, with the fit to the survival rates for the PCFG less well (but this was also the case for the GWRR).

The trials infer that the mortality events of ENP whales during 1998-1999 and 2019-2020+ were substantial (15% and 12% annual reductions in abundance on average but note that the 2nd mortality event has been longer so its effect is larger). The effect of the 2016 reduction in productivity on the PCFG is estimated to be about 10% in a single year.

Projection results

Figure 9 shows four time-trajectories of 1+ abundance by breeding stock/feeding group for trials 3a0 and 3a2 and the variants thereof that include future mortality event (3a1, 3a3 and 3a4). The total aboriginal catch is assumed to be bounded by the constant need envelope.

Table 4, 5 and 6 show the values of the performance statistics for the trials with no future mortality events, those for trials 3a0 and 3a2 and variants thereof that include future mortality events, and those for trials 5a0 and 5a2 and variants thereof that include future mortality events.

<u>No future morality events</u>

All breeding stocks / feeding groups are larger than 80% of their (current) carrying capacities after 100 years in the absence of future mortality events with high (>95%) probability (trials 3a0, 3b0, 3c0, 3e0, 5a0, and 6b0) (Table 4). The NFG is about 10% larger than its current size after 100 years for these trials while the PCFG is 93% of its current size or larger. Need satisfaction is high for the ENP gray whales (essentially 100% need satisfaction according to the N9 statistic) while need satisfaction for the Makah hunt is notably lower, with landings ranging between an average of 0.8 to 1.3 animals annually and strikes between 1.3 and 2.0.

<u>With future mortality events</u>

As expected, the NFG and PCFG are at smaller fractions of their carrying capacities after 100 years when future mortality events are assumed (Tables 5 and 6). The final depletion remains above 0.6 with 0.95 probability (D1 statistic) even though there are cases in which population size drops below the current population size (D2 statistic). For these trials, however, the primary driver of population decline is future mortality events and not aboriginal catches, suggesting the value of statistics such as D8, which indicate that PCFG removals are not the main cause for the lower final population size. Need satisfaction for the ENP gray whales as a whole remains high, but the numbers of strikes and landings under the Makah Management Plan are lower, particularly for the scenarios that involve future mortality events in both the NFG and PCFG.

DISCUSSION

The results, while preliminary, provisional and incomplete, suggest that the performances of the *Gray Whale SLA* and the Makah Management Plan are likely robust to the recent UMEs and future mortality events.

The analyses provided in this paper are preliminary because several data sources used during the GWRR have yet to be updated, and are primarily based on recent updates in NOAA California counts, estimates of abundance for the PCFG, and aboriginal catches. In particular, the mixing rates derived from photo-id data have not been updated, nor have the estimates of survival rate for the PCFG, the estimate of abundance for the western part of the range, and bycatch and ship strikes since 2015. All of these data sets need to be updated prior to final conclusions being drawn.

The projections are based on a subset of the model configurations used to test the *Gray Whale SLA* and the Makah Management Plan, with a focus on stock structure uncertainty and the possibility of future mortality events. The full set of sensitivity tests explore the effects of additional sources of uncertainty, in particular, how observed strandings pertain to actual numbers of animals dying due to bycatch and ship strikes. Given a focus on future mortality events, there would be value considering additional performance statistics based on variants of D8 to better understand the relative effects of mortality events and aboriginal catches on future time-trajectories of population size.

Finally, while this document was written primarily to evaluate the impact of the performances of the *Gray Whale SLA* and the Makah Management Plan, its results are also relevant to the Status of Stocks project, given the current agreed assessment of north Pacific gray whales was conducted before the most recent UME for the ENP gray whales.

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Table 1. Summary of the stock structure hypotheses (IWC, 2021). Note that hypotheses 4a (and its variants) and 7a are functionally equivalent to hypotheses 3a (and variants) and 5a, respectively, differing only in that 3a and 5a consider the WFG to be part of the Eastern Breeding Stock (EBS).

Stock structure hypothesis	**Key features**
4a*	Whales exhibit matrilineal fidelity to feeding grounds. Two breeding stocks exist: an eastern breeding stock (EBS) that includes the Northern Feeding Group (NFG) and Pacific Coast Feeding Group (PCFG), and a second breeding stock that includes Western Feeding Group (WFG) whales that mate largely with each other while migrating to Mexico (M). Although a third breeding stock (the WBS) may once have existed, the WBS is assumed to have been extirpated. Southern Kamchatka and Northern Kuril Islands (SKNK) is used by both the WFG whales and the NFG whales.
4b	Identical to hypothesis 4a, except that NFG whales do not feed off SKNK. In addition, a western breeding stock exists that overwinters in Vietnam-South China Sea (VSC) and feeds in the Okhotsk Sea (OS) (but not Sakhalin Island (SI)) and SKNK. Thus, SKNK is used by both the WFG whales and the whales of the Western breeding stock.
4c	Identical to 4a, except that on occasion whales migrating between the Sakhalin feeding region and Mexico travel through the Northern Bering and Chukchi Sea (BSCS) sub-area
4e	Identical to hypothesis 4a, except that the western breeding stock is extant and feeds off both coasts of Japan and Korea and in the northern Okhotsk Sea west of the Kamchatka Peninsula but not off Sakhalin Island (i.e., all of the whales feeding off Sakhalin overwinter in the eastern North Pacific).
7a*	Three breeding stocks exist: EBS and WBS and an unnamed stock of WFG whales that largely breed with each other while on migration to M. The EBS includes two feeding groups: PCFG and NFG. The WBS whales feed in Sakhalin Island (SI), OS, and SKNK and then migrate to VSC to overwinter. SKNK is used by the WFG, the NFG, and the feeding whales that are part of the WBS.
6b	This hypothesis assumes that the WFG does not exist, but that whales feeding in the SI sub-area represent an extant western breeding stock that utilizes two wintering grounds (VSC and M). This hypothesis differs from hypothesis 7a, in that 1) all removals off China and Japan are assumed to be western breeding stock animals, and 2) the abundance estimates for Sakhalin are assumed to relate only to the western breeding stock.

* Base-case model

Table 2. Aboriginal catches for 2010+ from the GWRR and the analyses of this paper. The split of the catches to sex is assumed to be 45:55 male:female for 2017 onwards.

Year	**GWRR**	**This paper**	**Year**	**GWRR**	**This paper**
2010	118	118	2017	N/A	120
2011	130	130	2018	N/A	108
2012	143	143	2019	N/A	137
2013	127	127	2020	N/A	136
2014	124	124	2021	N/A	127
2015	125	125	2022	N/A	127*
2016	120	120			

* Assumed.

Table 3. The trials. All trials assumed $MSYR_{1+}$=0.045, have an immigration rate of 2 per year into the PCFG, assume that a pulse of 20 whales per year moved from the NFG to the PCFG in 1999 and 2000, and assume that actual bycatch is four times the observed number.

Trial	Stock hypothesis	Catastrophic events
3a0	4a/3a	None
3b0	4b/3b	None
3c0	4c/3c	None
3e0	4e/3e	None
5a0	7a/5a	None
6a0	6b	None
3a2	4a/3a	None; but a mortality event is estimated for the PCFG in 2016
5a2	7a/5a	None; but a mortality event is estimated for the PCFG in 2016
3a1	4a/3a	As for 3a0, except with future NFG events
3a3	4a/3a	As for 3a2, except with future PCFG events
3a4	4a/3a	As for 3a2, except with future NFG and PCFG events
5a1	7a/5a	As for 5a0, except with future NFG events
5a3	7a/5a	As for 5a2, except with future PCFG events
5a4	7a/5a	As for 5a2, except with future NFG and PCFG events

Table 4. Performance statistics for the trials in which there are no future mortality events.

	D1 (1+) (10)				D1 (1+) (100)				D2 (1+) (100)				D8 (1+) (100)				D10 (1+) (10)				D10 (1+) (100)				N9(N)	N(P)	N9(P)	WG	UL	US
	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	100	100	10	100	100	100
Trial 3a0																														
5%	1.00	0.99	0.90	0.83	1.00	0.90	0.69	0.75	0.98	0.75	0.50	0.75	1.00	1.00	0.96	0.96	1.00	1.13	1.12	0.93	1.00	1.19	1.17	1.01	1.00	0.54	0.36	0	86	134
Med	1.00	0.99	0.91	0.87	1.00	0.93	0.78	0.79	0.98	0.81	0.60	0.79	1.00	1.00	0.98	0.97	1.01	1.14	1.18	0.95	1.02	1.22	1.39	1.04	1.00	0.68	0.80	1	105	171
95%	1.00	0.99	0.91	0.89	1.00	0.94	0.86	0.83	1.00	0.83	0.73	0.83	1.01	1.10	1.21	1.06	1.01	1.19	1.21	0.98	1.02	1.31	1.60	1.07	1.00	0.82	0.88	3	127	204
Trial 3b0																														
5%	0.96	0.99	0.90	0.83	0.92	0.95	0.69	0.75	0.85	0.83	0.50	0.75	0.98	1.00	0.96	0.96	1.01	1.09	1.12	0.93	0.98	1.13	1.16	1.01	1.00	0.56	0.36	0	83	140
Med	0.98	0.99	0.90	0.86	0.98	0.95	0.78	0.80	0.93	0.85	0.61	0.79	1.00	1.00	0.98	0.97	1.06	1.12	1.18	0.95	1.05	1.17	1.37	1.04	1.00	0.68	0.80	1	105	171
95%	0.99	1.00	0.91	0.89	1.02	0.96	0.87	0.83	0.97	0.88	0.74	0.83	1.03	1.08	1.20	1.06	1.07	1.14	1.21	0.98	1.09	1.19	1.58	1.07	1.00	0.82	0.88	3	126	204
Trial 3c0																														
5%	1.00	0.88	0.90	0.83	1.00	0.70	0.68	0.75	0.98	0.51	0.49	0.75	1.00	0.96	0.96	0.96	1.00	1.19	1.11	0.93	1.00	1.28	1.15	1.01	1.00	0.52	0.36	0	83	131
Med	1.00	0.89	0.91	0.86	1.00	0.77	0.78	0.80	0.98	0.60	0.61	0.79	1.00	0.98	0.98	0.97	1.01	1.28	1.18	0.95	1.02	1.49	1.37	1.03	1.00	0.67	0.80	1	105	168
95%	1.00	0.90	0.91	0.89	1.00	0.83	0.87	0.83	1.00	0.70	0.75	0.83	1.01	1.25	1.18	1.06	1.01	1.35	1.21	0.98	1.02	1.74	1.62	1.07	1.00	0.82	0.88	3	126	204
Trial 3e0																														
5%	0.95	0.99	0.90	0.83	1.14	0.84	0.68	0.75	0.95	0.64	0.49	0.75	0.81	1.00	0.96	0.96	0.88	1.20	1.12	0.93	0.64	1.32	1.16	1.01	1.00	0.53	0.36	0	83	133
Med	0.99	0.99	0.90	0.87	1.18	0.87	0.78	0.79	0.99	0.69	0.60	0.79	0.98	1.00	0.98	0.98	0.93	1.26	1.18	0.95	0.78	1.44	1.39	1.04	1.00	0.67	0.80	1	105	168
95%	1.00	0.99	0.91	0.89	1.33	0.91	0.87	0.83	1.00	0.75	0.75	0.83	1.00	1.23	1.19	1.06	0.94	1.31	1.21	0.98	0.83	1.55	1.63	1.07	1.00	0.82	0.88	3	125	204
Trial 5a0																														
5%	1.00	0.98	0.90	0.84	1.11	0.73	0.68	0.76	1.00	0.57	0.49	0.76	0.84	1.00	0.96	0.96	0.96	1.17	1.12	0.93	0.81	1.35	1.15	1.01	1.00	0.52	0.36	0	82	130
Med	1.00	0.98	0.91	0.87	1.16	0.80	0.78	0.80	1.00	0.65	0.60	0.79	0.98	1.01	0.98	0.98	0.97	1.23	1.18	0.95	0.84	1.51	1.37	1.04	1.00	0.68	0.80	1	107	171
95%	1.00	0.98	0.91	0.89	1.19	0.86	0.87	0.83	1.00	0.74	0.75	0.83	1.00	1.39	1.23	1.06	0.98	1.29	1.21	0.98	0.87	1.72	1.61	1.07	1.00	0.81	0.88	3	125	203
Trial 6b0																														
5%	1.02	0.98	0.90	0.83	1.11	0.95	0.69	0.76	1.02	0.89	0.50	0.75	0.52	1.00	0.96	0.96	0.82	1.05	1.12	0.93	0.37	1.07	1.16	1.01	1.00	0.55	0.40	0	85	138
Med	1.20	0.99	0.90	0.86	2.19	0.97	0.78	0.79	1.20	0.91	0.61	0.79	0.88	1.00	0.98	0.98	0.82	1.06	1.18	0.95	0.46	1.08	1.37	1.03	1.00	0.69	0.80	1	109	172
95%	1.28	0.99	0.91	0.88	2.75	0.97	0.87	0.83	1.28	0.92	0.74	0.83	1.00	1.04	1.23	1.06	0.92	1.07	1.21	0.98	0.85	1.10	1.58	1.06	1.00	0.82	0.88	3	125	204

Table 5. Performance statistics for the trials 3a0 and 3a2 and variants thereof in which there are future mortality events.

	D1 (1+) (10)				D1 (1+) (100)				D2 (1+) (100)				D8 (1+) (100)				D10 (1+) (10)				D10 (1+) (100)				N9(N)	N(P)	N9(P)	WG	UL	US
	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	100	100	10	100	100	100
Trial 3a0																														
5%	1.00	0.99	0.90	0.83	1.00	0.90	0.69	0.75	0.98	0.75	0.50	0.75	1.00	1.00	0.96	0.96	1.00	1.13	1.12	0.93	1.00	1.19	1.17	1.01	1.00	0.54	0.36	0	86	134
Med	1.00	0.99	0.91	0.87	1.00	0.93	0.78	0.79	0.98	0.81	0.60	0.79	1.00	1.00	0.98	0.97	1.01	1.14	1.18	0.95	1.02	1.22	1.39	1.04	1.00	0.68	0.80	1	105	171
95%	1.00	0.99	0.91	0.89	1.00	0.94	0.86	0.83	1.00	0.83	0.73	0.83	1.01	1.10	1.21	1.06	1.01	1.19	1.21	0.98	1.02	1.31	1.60	1.07	1.00	0.82	0.88	3	127	204
Trial 3a1																														
5%	1.00	0.99	0.63	0.72	1.00	0.90	0.69	0.75	0.98	0.75	0.43	0.72	1.00	1.00	0.83	0.91	1.00	1.13	1.12	0.93	1.00	1.19	1.06	0.89	1.00	0.43	0.32	0	63	108
Med	1.00	0.99	0.73	0.77	1.00	0.93	0.78	0.79	0.98	0.81	0.54	0.77	1.00	1.00	1.00	0.95	1.01	1.14	1.18	0.95	1.02	1.22	1.11	0.93	1.00	0.65	0.80	1	101	163
95%	1.00	0.99	0.82	0.81	1.00	0.94	0.86	0.83	1.00	0.83	0.64	0.81	1.01	1.10	1.31	0.98	1.01	1.19	1.21	0.98	1.02	1.31	1.17	0.95	1.00	0.77	0.88	3	121	192
Trial 3a2																														
5%	1.00	0.99	0.89	0.83	1.00	0.90	0.69	0.73	0.98	0.75	0.50	0.72	1.00	1.00	0.96	0.96	1.00	1.13	1.12	0.95	1.00	1.19	1.15	1.03	1.00	0.54	0.36	0	83	134
Med	1.00	0.99	0.90	0.87	1.00	0.93	0.78	0.78	0.98	0.82	0.61	0.77	1.00	1.00	0.98	0.98	1.01	1.14	1.18	0.99	1.02	1.22	1.36	1.10	1.00	0.69	0.80	1	106	172
95%	1.00	0.99	0.91	0.89	1.00	0.94	0.87	0.82	1.00	0.84	0.75	0.82	1.01	1.10	1.20	1.10	1.01	1.20	1.21	1.04	1.02	1.32	1.58	1.18	1.00	0.82	0.88	3	127	204
Trial 3a3																														
5%	1.00	0.99	0.89	0.75	1.00	0.90	0.69	0.68	0.98	0.75	0.50	0.58	1.00	1.00	0.96	0.89	1.00	1.13	1.12	0.89	1.00	1.18	1.15	0.98	1.00	0.50	0.32	0	78	126
Med	1.00	0.99	0.90	0.83	1.00	0.93	0.78	0.77	0.98	0.82	0.61	0.72	1.00	1.00	0.98	0.97	1.01	1.14	1.18	0.97	1.02	1.22	1.36	1.05	1.00	0.65	0.80	1	101	162
95%	1.00	0.99	0.91	0.87	1.00	0.94	0.87	0.81	1.00	0.84	0.75	0.81	1.01	1.10	1.20	1.09	1.01	1.20	1.21	1.03	1.02	1.32	1.58	1.12	1.00	0.81	0.88	3	124	202
Trial 3a4																														
5%	1.00	0.99	0.64	0.67	1.00	0.90	0.69	0.65	0.98	0.75	0.45	0.58	1.00	1.00	0.82	0.88	1.00	1.13	1.12	0.87	1.00	1.19	1.05	0.88	1.00	0.30	0.32	0	47	75
Med	1.00	0.99	0.74	0.75	1.00	0.93	0.78	0.77	0.98	0.82	0.55	0.68	1.00	1.00	1.00	0.95	1.01	1.14	1.18	0.96	1.02	1.22	1.11	0.94	1.00	0.56	0.80	1	91	141
95%	1.00	0.99	0.82	0.80	1.00	0.94	0.87	0.82	1.00	0.84	0.65	0.78	1.01	1.10	1.31	1.06	1.01	1.20	1.21	1.04	1.02	1.32	1.16	1.04	1.00	0.74	0.88	3	116	185

Table 6. Performance statistics for the trials 5a0 and 5a2 and variants thereof in which there are future mortality events.

	D1 (1+) (10)				D1 (1+) (100)				D2 (1+) (100)				D8 (1+) (100)				D10 (1+) (10)				D10 (1+) (100)				N9(N)	N(P)	N9(P)	WG	UL	US
	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	WB	WF	NF	PC	100	100	10	100	100	100
Trial 5a0																														
5%	1.00	0.98	0.90	0.84	1.11	0.73	0.68	0.76	1.00	0.57	0.49	0.76	0.84	1.00	0.96	0.96	0.96	1.17	1.12	0.93	0.81	1.35	1.15	1.01	1.00	0.52	0.36	0	82	130
Med	1.00	0.98	0.91	0.87	1.16	0.80	0.78	0.80	1.00	0.65	0.60	0.79	0.98	1.01	0.98	0.98	0.97	1.23	1.18	0.95	0.84	1.51	1.37	1.04	1.00	0.68	0.80	1	107	171
95%	1.00	0.98	0.91	0.89	1.19	0.86	0.87	0.83	1.00	0.74	0.75	0.83	1.00	1.39	1.23	1.06	0.98	1.29	1.21	0.98	0.87	1.72	1.61	1.07	1.00	0.81	0.88	3	125	203
Trial 5a1																														
5%	1.00	0.98	0.63	0.73	1.11	0.73	0.68	0.76	1.00	0.57	0.43	0.72	0.84	1.00	0.82	0.92	0.96	1.17	1.12	0.93	0.81	1.35	1.05	0.90	1.00	0.37	0.32	0	56	93
Med	1.00	0.98	0.74	0.78	1.16	0.80	0.78	0.80	1.00	0.65	0.54	0.77	0.98	1.01	1.00	0.95	0.97	1.23	1.18	0.95	0.84	1.51	1.11	0.93	1.00	0.65	0.80	1	102	163
95%	1.00	0.98	0.83	0.83	1.19	0.86	0.87	0.84	1.00	0.74	0.66	0.82	1.00	1.39	1.32	0.98	0.98	1.29	1.21	0.98	0.87	1.72	1.17	0.97	1.00	0.81	0.88	2	126	202
Trial 5a2																														
5%	0.99	0.98	0.89	0.84	1.14	0.74	0.69	0.74	0.99	0.56	0.50	0.72	0.83	1.00	0.96	0.96	0.96	1.19	1.12	0.95	0.78	1.38	1.15	1.03	1.00	0.54	0.36	0	82	134
Med	1.00	0.98	0.90	0.87	1.17	0.79	0.78	0.78	1.00	0.63	0.61	0.77	0.98	1.01	0.98	0.98	0.96	1.25	1.18	0.99	0.82	1.57	1.36	1.10	1.00	0.67	0.80	1	106	169
95%	1.00	0.99	0.91	0.89	1.22	0.85	0.87	0.82	1.00	0.72	0.75	0.82	1.00	1.42	1.21	1.10	0.97	1.31	1.21	1.04	0.84	1.74	1.59	1.19	1.00	0.82	0.88	3	124	205
Trial 5a3																														
5%	0.99	0.98	0.89	0.72	1.14	0.74	0.69	0.65	0.99	0.56	0.50	0.60	0.83	1.00	0.96	0.89	0.96	1.19	1.12	0.89	0.78	1.38	1.15	0.98	1.00	0.47	0.32	0	78	117
Med	1.00	0.98	0.90	0.83	1.17	0.79	0.78	0.77	1.00	0.63	0.61	0.71	0.98	1.01	0.98	0.97	0.96	1.25	1.18	0.97	0.82	1.57	1.36	1.05	1.00	0.64	0.80	1	101	161
95%	1.00	0.99	0.91	0.87	1.22	0.85	0.87	0.82	1.00	0.72	0.75	0.80	1.00	1.42	1.21	1.10	0.97	1.31	1.21	1.04	0.84	1.74	1.59	1.11	1.00	0.80	0.88	3	123	201
Trial 5A4																														
5%	0.99	0.98	0.64	0.65	1.14	0.74	0.69	0.66	0.99	0.56	0.44	0.56	0.83	1.00	0.83	0.88	0.96	1.19	1.12	0.87	0.78	1.38	1.05	0.87	1.00	0.26	0.32	0	40	65
Med	1.00	0.98	0.74	0.75	1.17	0.79	0.78	0.77	1.00	0.63	0.55	0.68	0.98	1.01	1.00	0.95	0.96	1.25	1.18	0.97	0.82	1.57	1.11	0.94	1.00	0.57	0.80	1	90	142
95%	1.00	0.99	0.83	0.80	1.22	0.85	0.87	0.82	1.00	0.72	0.66	0.79	1.00	1.42	1.32	1.06	0.97	1.31	1.21	1.04	0.84	1.74	1.16	1.03	1.00	0.75	0.88	3	115	188

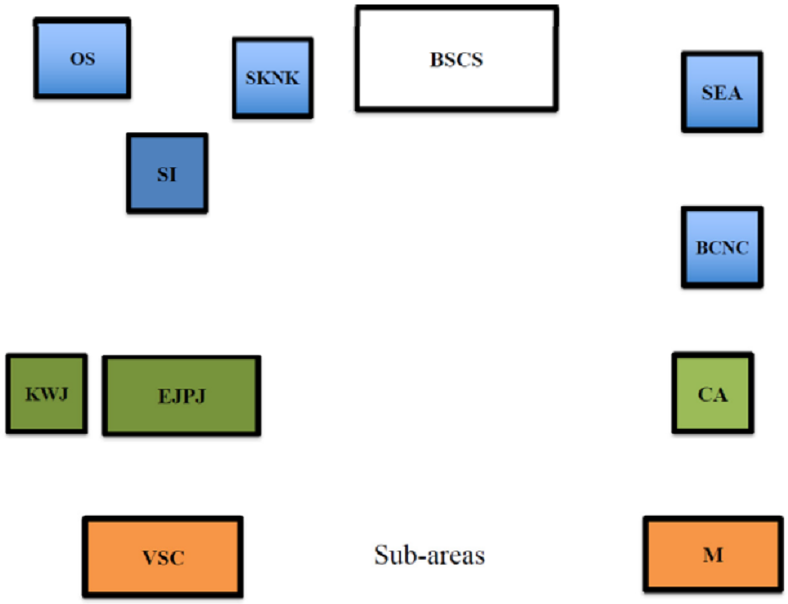


Figure 1. The sub-areas in the operating model (IWC, 2019a). OS = Okhotsk Sea, SI = Sakhalin Island, SKNK = Southern Kamchatka and Northern Kuril Islands, BSCS = Northern Bering and Chukchi Sea, SEA = Southeast Alaska; BCNC = British Columbia to Northern California, KWJ = Korea and the west coast of Japan, EJPJ = east coast of Japan, CA = California, VSC = Vietnam-South China Sea, M = Mexico. Colors indicate: breeding (orange), migration (green), and feeding (blue) grounds.

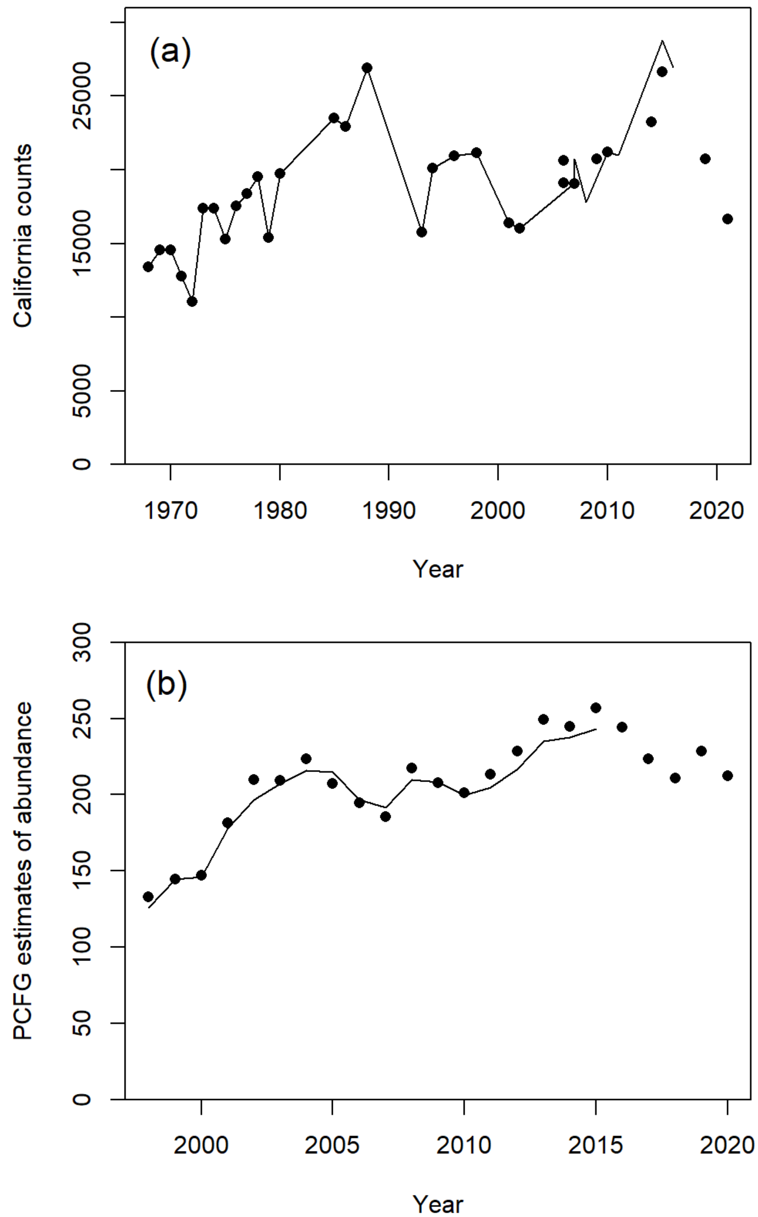


Figure 2. Abundance for California (upper panel) and the PCFG (lower panel). The values used in the Gray Whale Rangewide Review are indicted by lines and new estimates are indicated by dots.

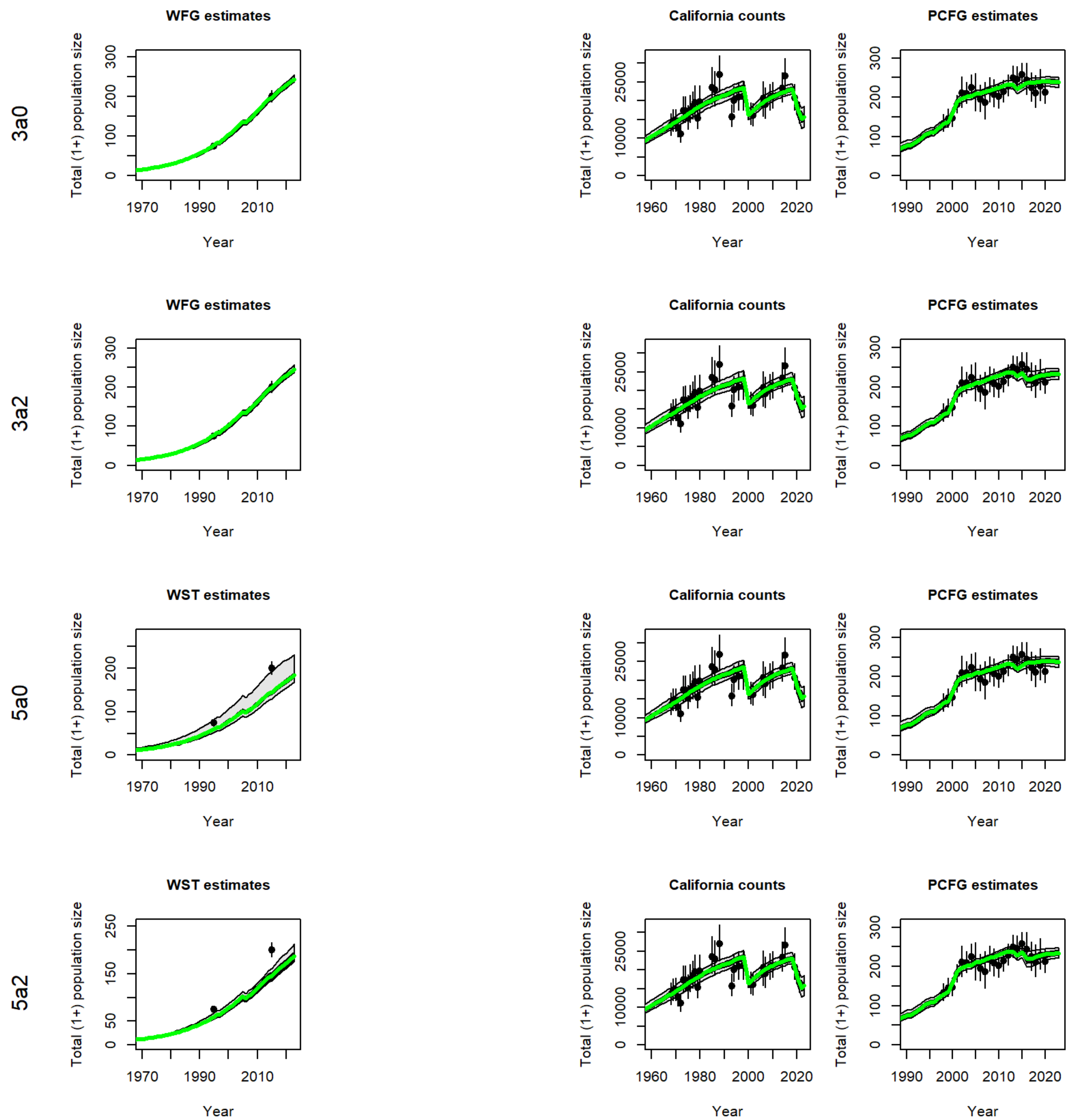
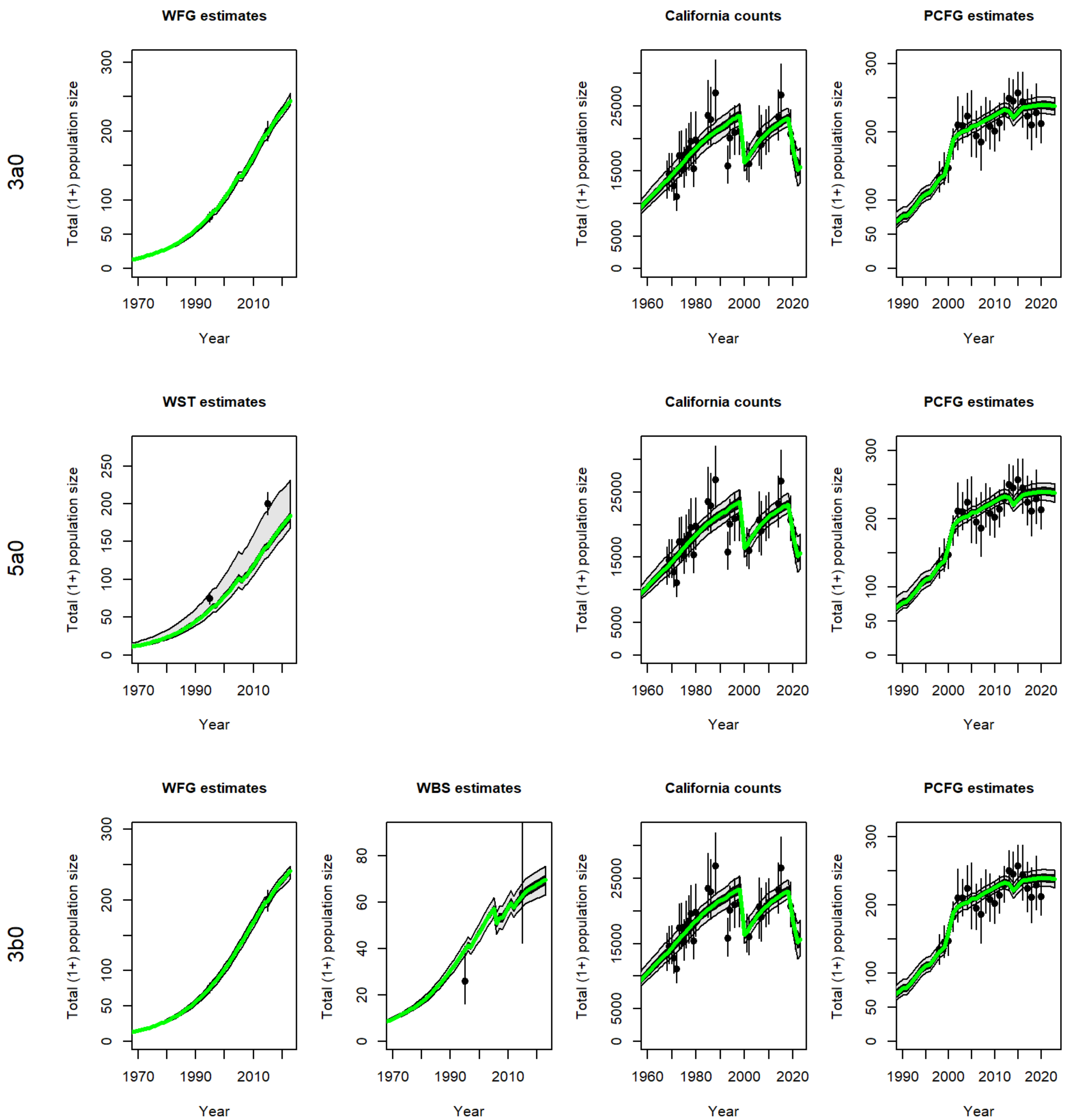


Figure 3. Fits to the abundance estimates for the base-case trials (3a0 and 5a0) and variants thereof that estimate a mortality event for the PCFG in 2016 (3a2 and 5a2). WST denotes the Western Breeding Stock.


3a0
WFG estimates
California counts
PCFG estimates
5a0
WST estimates
California counts
PCFG estimates
3b0
WFG estimates
WBS estimates
California counts
PCFG estimates
Total (1+) population size
Year

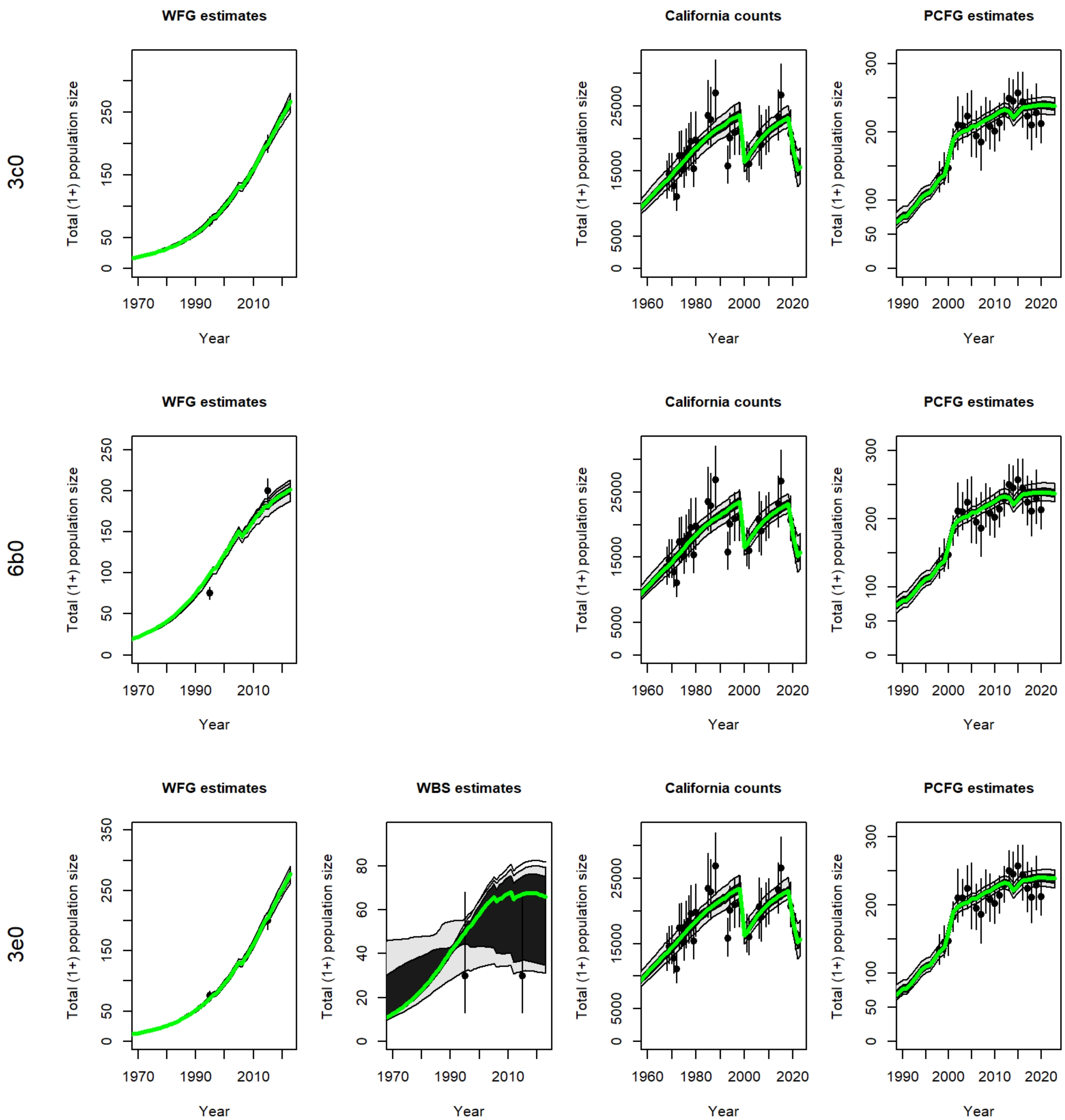


Figure 4. Fits to the abundance estimates for the six trials that explore sensitivity to stock structure uncertainty (3a0, 3b0, 3c0, 3e0, 5a0, and 6b0). None of the models allow for a mortality event in the PCFG.

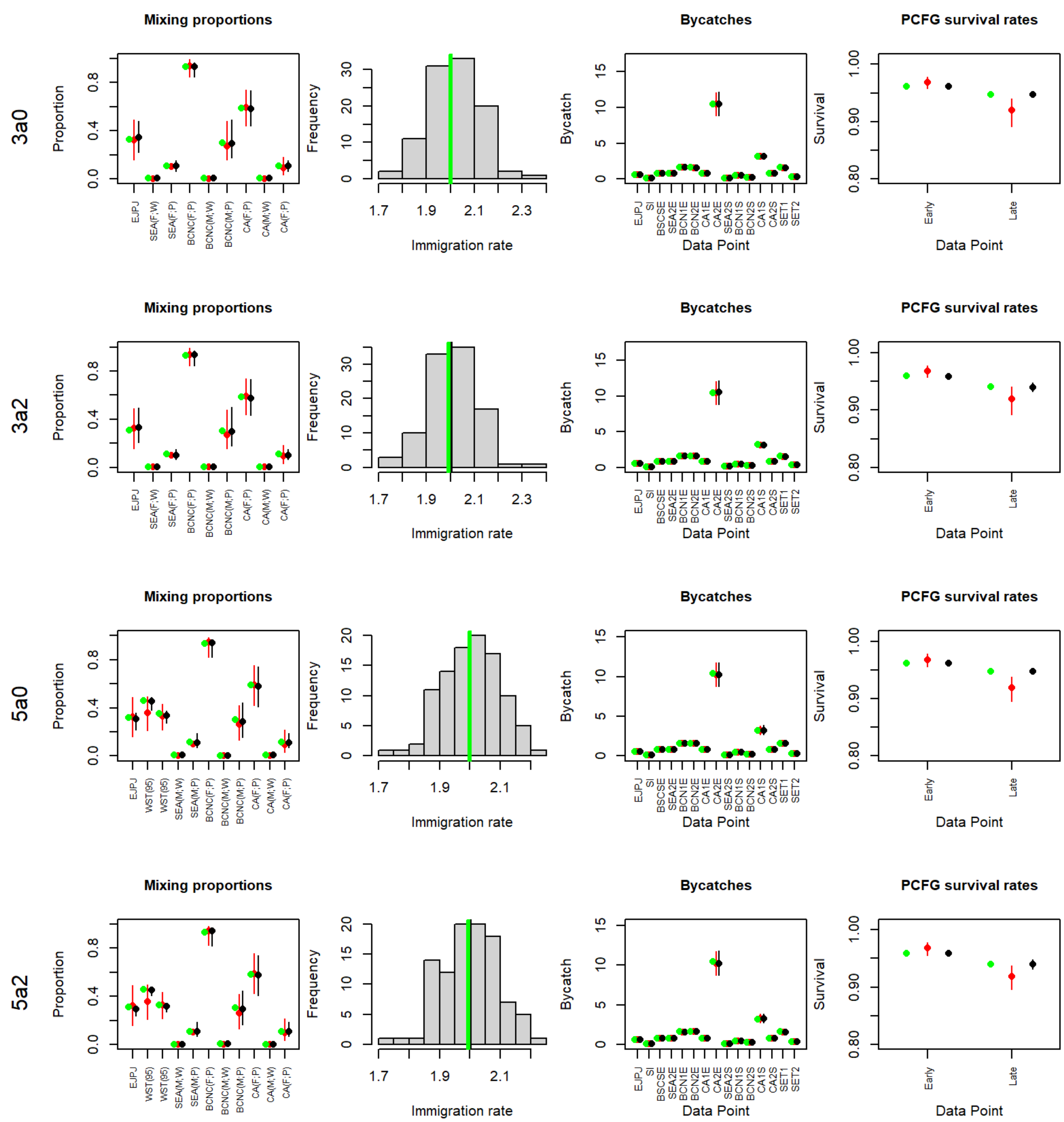
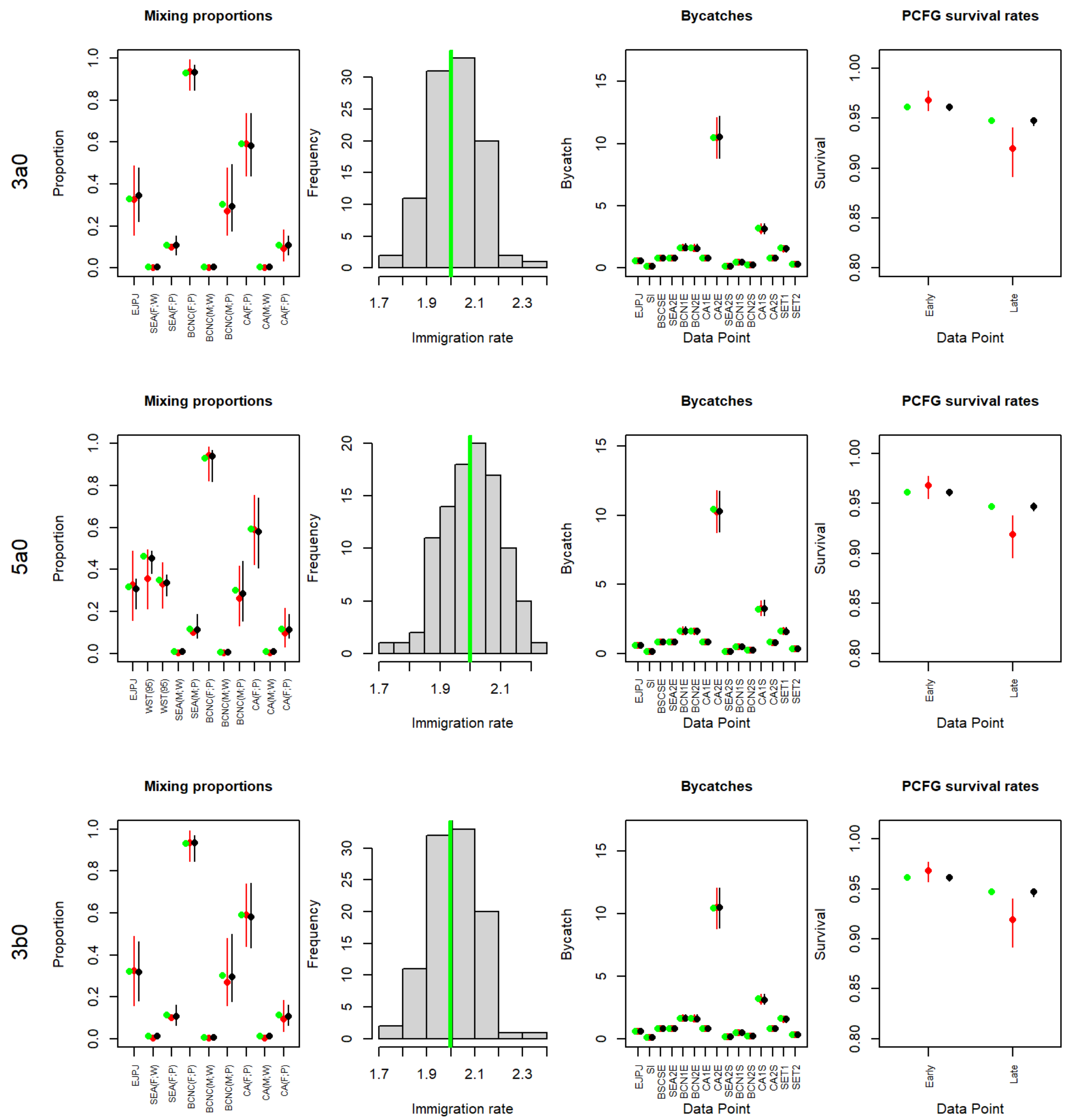


Figure 5. Fits to the mixing proportions (first column), the assumed immigration rate of 2 (second column), the average bycatches (third column), and the PCFG survival rates (fourth column) for the base-case trials (3a0 and 5a0) and variants thereof that estimate a mortality event for the PCFG in 2026 (3a2 and 5a2).


3a0
5a0
3b0
Mixing proportions
Proportion
EJPJ
SEA(F,W)
SEA(F,P)
BCNC(F,P)
BCNC(M,W)
BCNC(M,P)
CA(F,P)
CA(M,W)
CA(F,P)
WST(95)
SEA(M,W)
SEA(M,P)
Frequency
Immigration rate
Bycatches
Bycatch
EJPJ
SI
BSCSE
SEA2E
BCN1E
BCN2E
CA1E
CA2E
SEA2S
BCN1S
BCN2S
CA1S
CA2S
SET1
SET2
Data Point
PCFG survival rates
Survival
Early
Late
Data Point

323

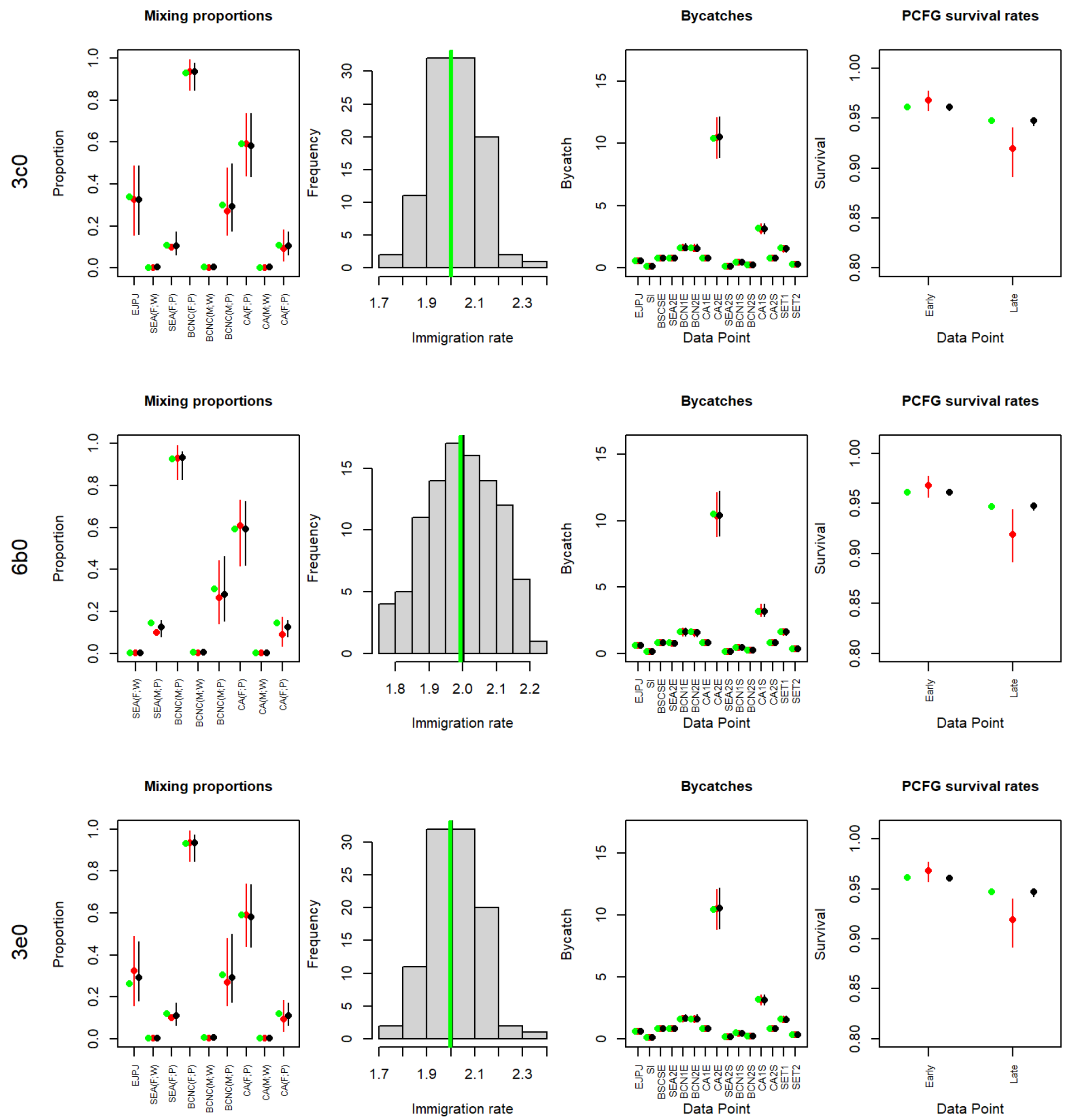
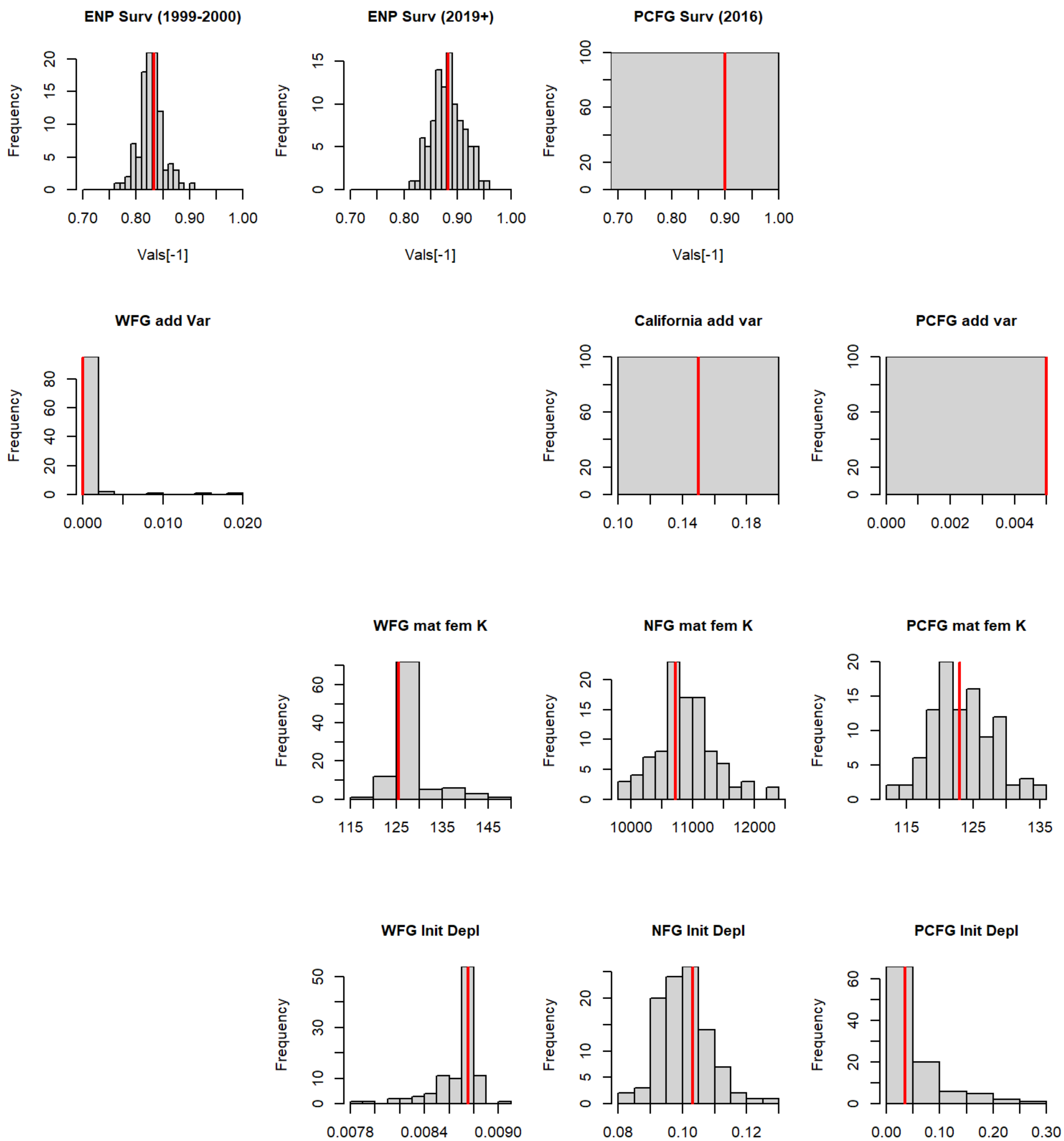


Figure 6. Fits to the mixing proportions (first column), the assumed immigration rate of 2 (second column), the average bycatches (third column), and the PCFG survival rates (fourth column) for the six trials that explore sensitivity to stock structure uncertainty (3a0, 3b0, 3c0, 3e0, 5a0, and 6b0).



3a0

Figure 7(a). Distribution of estimates of (key) parameters for trial 3a0. Note that the mortality rate for the PCFG is not estimated (set to 1), and the additional CVs for the California counts and the PCFG estimates are set to 0.15 and 0.005 respectively. "mat fem K" denotes the number of mature females in the unexploited state while "Init Depl" is the ratio of the 1930 population size to carrying capacity.

3a2

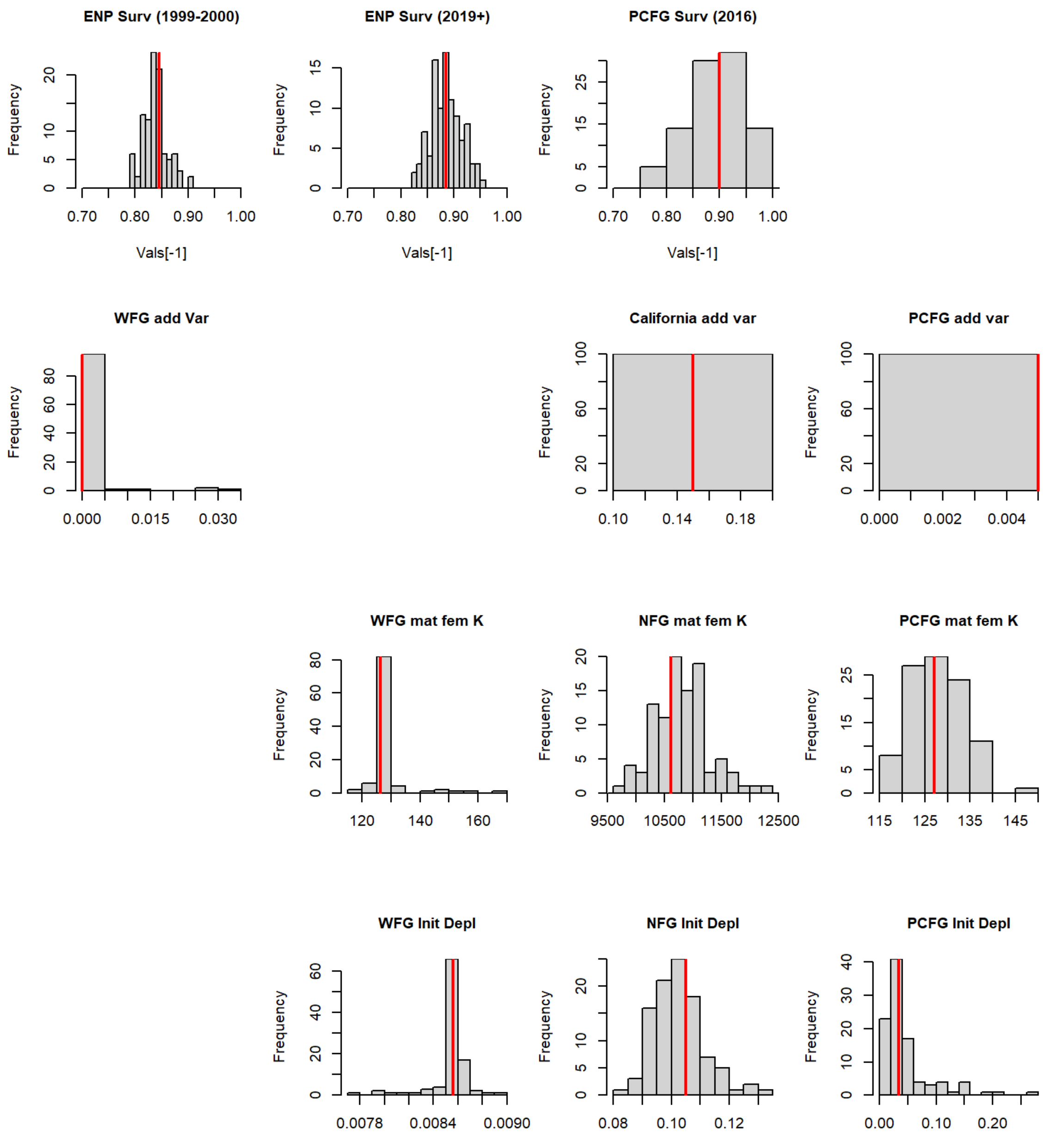


Figure 7(b). Distribution of estimates of (key) parameters for trial 3a2. Note that additional CVs for the California counts and the PCFG estimates are set to 0.15 and 0.005 respectively. “mat fem K” denotes the number of mature females in the unexploited state while “Init Depl” is the ratio of the 1930 population size to carrying capacity.

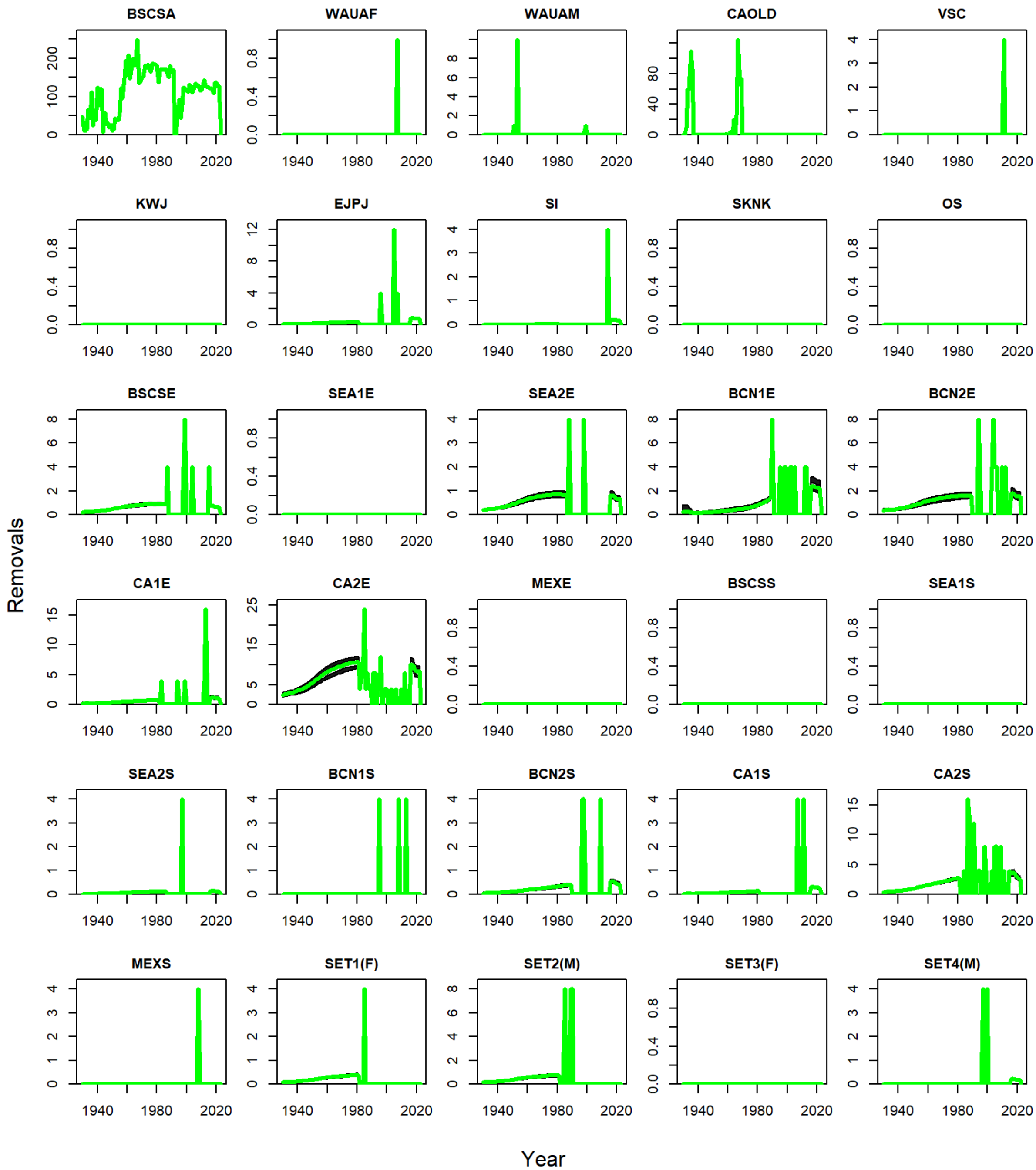


Figure 8. Time-trajectories for estimates of bycatch by sub-area for trial 3a0.

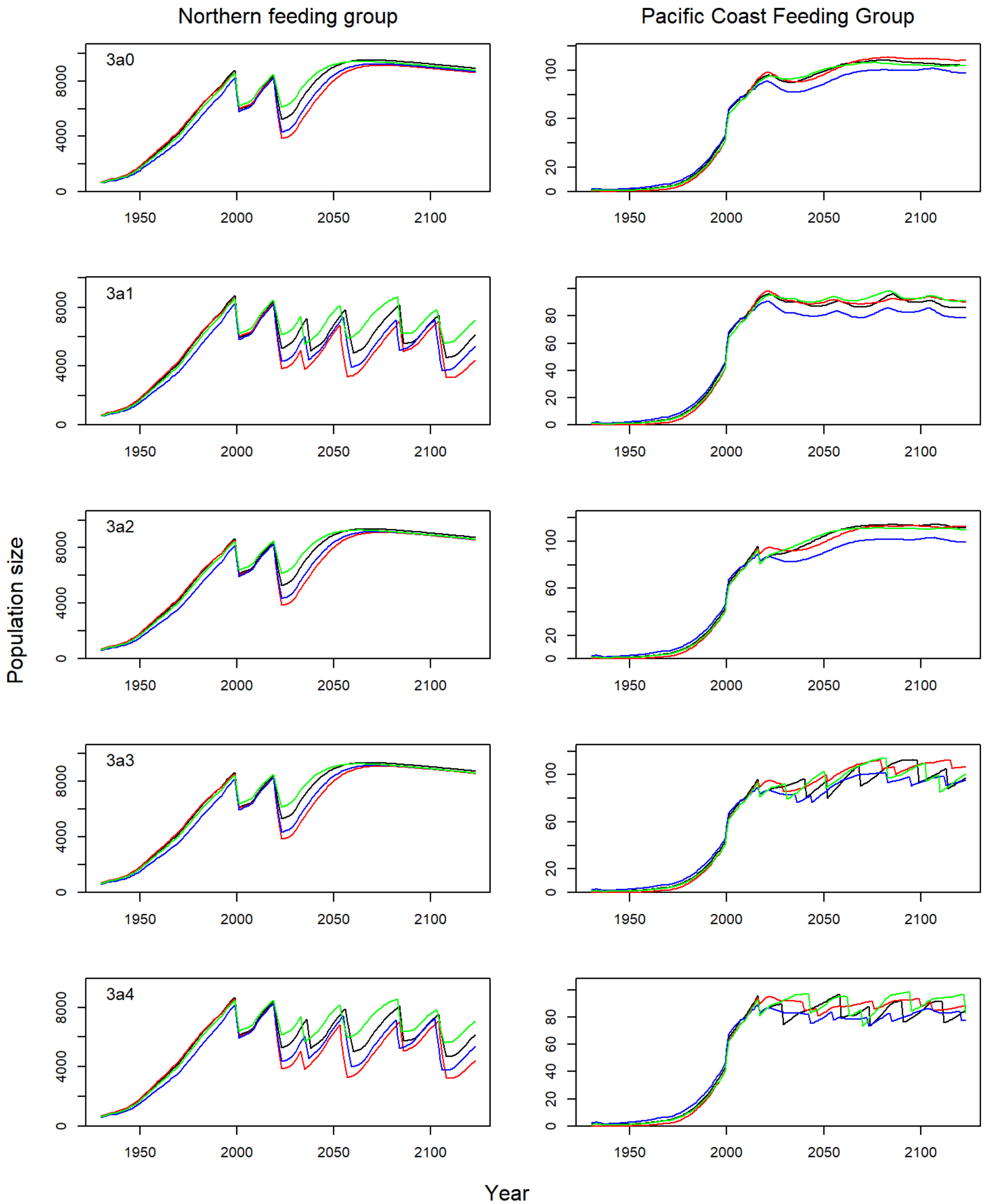


Figure 9. Four example time-trajectories of 1+ numbers for the NFG and PCFG for trials 3a0, 3a1, 3a2, 3a3, and 3a4. The projection allows for aboriginal catches in the Russian hunt but no future Makah hunt.

Appendix A

The Makah Management Plan (source: IWC, 2019a, pg 598)