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ABSTRACT Last year, we presented a simple and preliminary population model on North Pacific humpback whales. Following suggestions from SC and others, we here present an updated and more complex assessment. We ran three scenarios related to the assignment of the historical catches in the Asia and CA_OR regions. The data on current abundance and exchange rates were the same for all scenarios. The results were not notably sensitive to the choice of catch series, and population trajectories were produced for each feeding and breeding area. Estimates of pre-exploitation abundance for the total North Pacific ranged from 13,000 to 20,000, depending on the catch scenario used. The model was able to mimic the central tendency of the estimates of abundance and in one case (the Asian breeding ground) mimics the trend inferred from the abundance estimates. However, the model was unable to mimic the change in abundance for the Hawaiian and Mexican breeding grounds and the GOA feeding ground. Two of the breeding stocks (Russia and Central America) are estimated to have been severally depleted but to be recovering or recovered. Unexpectedly, the reductions in the Hawaiian and Mexican breeding stocks were estimated to be limited, which is a key reason the model cannot mimic the trends in the abundance estimates for these breeding grounds.

INTRODUCTION

Humpback whales (*Megaptera novaeangliae*) are common in all oceans and conduct long seasonal migrations between winter breeding areas in the tropics and summer feeding grounds in high latitudes (Clapham & Mead 1996). In the North Pacific (NP) they are found along all coastal areas of Asia and North America (Mackintosh 1946). Currently, it is believed that NP humpback whales exist in at least five breeding sub-populations stretching from coastal Mexico to Asia; these are connected to various feeding areas in the northern NP, from the western coast of the United States through British Columbia and Alaskan waters to Russia in the east.

In part because the catch record has until recently been incomplete, NP humpback whales have never been the focus of a Comprehensive Assessment by the International Whaling Commission (IWC). Such assessments use estimates of abundance and trend together with a historical catch series to assess the pre-exploitation size of the population, and its current status relative to that benchmark. Recently, the catch record for NP humpbacks has been updated to include new information on extensive illegal takes by the USSR (Ivashchenko *et al.* 2013). In addition, there is now considerable new information on the current abundance and population structure of NP humpbacks, derived from the multi-national photo-identification and genetic study known as Structure Levels of Abundance and Status of Humpback Whales (SPLASH) (Calambokidis *et al.* 2008; Barlow *et al.* 2011; Baker *et al.* 2013).

Last year, we presented a preliminary assessment of NP humpback whales (Ivashchenko *et al.* 2015), in which a single stock model results was not consistent with observed growth rates. Suggestions were made by the SC regarding ways to improve the model, and intersessional work has been undertaken in this regard. Here, after reiterating some basic background information regarding this population, we provide the results of that subsequent work.

BACKGROUND

For the sake of convenience, we briefly summarize below background information presented last year on NP humpback whales. Further detail is available in Ivashchenko *et al.* (2015).

Whaling history

Whaling for humpback whales in the NP existed for centuries, with known hunting locations including Japan, North America, the Aleutian Islands and Chukotka (Reeves & Smith 2006). Three main periods are described based upon the methods and materials used in the hunt and the extent of the operations: aboriginal, historical and modern whaling. For a more detailed summary of whaling on this species see Ivashchenko *et al.* (2015).

The IWC database contains detailed records for the majority of humpback whale catches made in the NP during the 20th century (Allison, 2015), except for recently corrected Soviet catches for the period 1963-71(Ivashchenko *et al.*, 2013). With these additional catches, the total number of humpbacks killed in the NP during the 20th century is now estimated to be 29,103 whales. Catch records before 1900 are incomplete (Omura, 1986; Reeves & Smith, 2010), and any estimate of the overall total catch for humpback whales in this ocean will vary depending upon the assumptions one makes with regarded to missing information.

Population structure

Current understanding of humpback whale population structure in the NP developed through use of photo-identification, genetics and satellite tagging. The current most complete picture of humpback whale population structure in the NP comes from the multi-national photo-identification and genetic study known as Structure of Populations Levels of Abundance and Status of Humpback Whales (SPLASH) (Calambokidis *et al.* 2008; Barlow *et al.* 2011; Baker *et al.* 2013). The study showed a complicated mixing pattern between breeding and feeding grounds, with the majority of whales showing strong site fidelity to both specific feeding and breeding areas. Currently four breeding populations have been identified:

- the Western NP, including Okinawa and Philippines (Asia)
- Hawai'i
- Mexico (mainland and the offshore waters of the Revillagigedo Islands)
- Central America.

Relatively low match rates between whales feeding in the Aleutian Islands and these four breeding areas indicate the likely existence of a fifth breeding population whose location is presently unknown; for the purpose of management, the U.S. National Marine Fisheries Service recently lumped this unidentified stock with the Western North Pacific. The SPLASH results also highlighted six main feeding areas:

- California-Oregon (CA-OR)
- northern Washington-southern British Columbia (NWA-SBC)
- northern British Columbia-Southeast Alaska (NBC-SEAK)
- Aleutian Islands-Bering Sea (Al-BS)
- the eastern coast of Kamchatka (Russia) (Barlow *et al.* 2011; Baker *et al.* 2013)

The selection of the boundaries for this sub-populations was based upon breaks in humpback whale distribution, observed exchange rates from photo-id matches, and genetic differentiation. Data from Russian waters were collected from three areas: the Commander Islands, the eastern coast of Kamchatka, and the Gulf of Anadyr, although the Commander Islands and Gulf of Anadyr were subsequently placed together with the Aleutians-Bering Sea region.

Estimates of abundance

Rice (1978) estimated that before 1905 the NP humpback whale population was around 15,000 whales; this was based upon the catch history, which was then incomplete. To date, this is the only estimate of the population size in the NP prior to the advent of modern whaling. An estimate of 1,200-1,400 remaining humpbacks in the NP by the end of modern whaling on this species in 1966 was given by Gambell (1976) and Johnson and Wolman (1984). All of these estimates likely involve considerable uncertainty. The most current estimate of the NP population as a whole comes from SPLASH, which used photo-identification mark-recapture to estimate total population size at 21,808 (CV= 0.027) (Barlow *et al.* 2011).

A number of local studies have provided estimates for different sub-populations on feeding or breeding grounds over the last 35 years. These include: Asia, Hawaii, Mexico, USA west coast/California-Oregon, Southeast Alaska, and western Alaska (which includes the Alaska Peninsula and the eastern Aleutian Islands). Many of the estimates from the same regions come from different projects with variable survey coverage and effort, which makes the estimates difficult to use in assessing trend. Wade *et al.* (2016) used recent data to calculate abundance for individual feeding and breeding areas, and exchange rates between each of them. The abundance estimates for this and previous studies, which were used in the modeling reported here, are summarized in Table 1.

METHODS AND MATERIALS

Catches

Catch information was taken from various sources. The IWC database was used for humpback whale catches made by different countries for the period 1906-2006, except for Soviet catches from 1962 through 1972. Earlier catches (by Japan and land stations along the western coast of North America) were taken from the published literature. For 17th century catches in Japan, catch records are incomplete but there exists a list of land stations operating at this time; using this information, we took known catch numbers and either doubled or tripled these for various scenarios.

Details of Soviet catches were reconstructed using formerly secret internal whaling industry reports (primarily those written by fleet scientists and whaling inspectors) that provided details of the distribution and number of catches (Ivashchenko *et al.* 2013). Using these reports together with geo-referencing of maps given by Doroshenko (2000), we were able to assign positions to 3,271 Soviet humpback whale catches made after 1962.

Definitions of Breeding and Feeding areas

We have adopted the locations of humpback whale breeding and feeding areas from the SPLASH project. To define the boundaries of each region, we first drew a 100-nm buffer from the 1000-m isobath. Many catches were distributed much farther offshore of this designated buffer, and some of the regions were expanded offshore or additional regions were created (Figure 1) (see description below).

<u>Breeding areas</u>
Five breeding areas have been described for the North Pacific (Barlow *et al.* 2011). Since no pelagic catches were made on the breeding grounds, we describe the breeding area boundaries as wider ovals and include the Philippines and Okinawa, Hawaii, Mexico, Central America and the Unknown Breeding Area. Coastal whaling catches were made only in the Philippines/Okinawa area and off Mexico.
<u>Feeding areas</u>

Currently six different feeding regions are recognized in the NP (Figure 1):

- **Russia** (= eastern Kamchatka): an area which follows the contour of a 100-nm buffer zone from the southern tip of Kamchatka to the northern end of Karaginskiy Gulf.
- **Aleutians/Bering Sea** (Al-BS). The Aleutian Islands chain includes the Commander Islands. This feeding area is defined as beginning halfway between the Kamchatka coast and the closest of the Commanders, with an eastern extent at False Pass (Alaska Peninsula); the region extends north to include the Bering Sea and Chukchi Sea. The southern boundary initially follows the 100-nm buffer zone, but we include the area below the Aleutian chain to 45° N to include catches that were distributed south of this region.
- **Gulf of Alaska** (GOA). During SPLASH data collection this region was separated into two areas: western and northern GOA. The southern boundary follows the 100-nm buffer zone and the eastern end terminates at longitude 141° W.
- **Southeast Alaska** (SEAK) and **northern British Columbia** (NBC). This region is placed between the GOA and the northern part of British Columbia, with a southern boundary passing close to 50° N. Along the coast it follows the 100-nm buffer line.
- **Southern British Columbia** (SBC) and **northern Washington** (WA). This region continues south to the southern boundary of Washington state at latitude 46° N, while to the west it follows the 100-nm buffer zone.
- **California** (CA) and **Oregon** (OR). This region's boundaries follow the 100-nm buffer line from the northern end of Oregon to the southern end of California, covering the coastal area from 46° N to 32° 30'N.

Additional areas were designated in order to assign catches, as follows:

- **Pelagic Gulf of Alaska** (pelagic GOA): this region includes offshore waters south of the GOA and SEAK regions with a southern boundary along latitude 52°N. This designation was created to incorporate pelagic catches in the GOA.
- **Pelagic North Pacific** (pelagic NP): this region covers the area south of the GOA and west of British Columbia, Washington and part of Oregon. The southern boundary follows latitude 43°N, with the eastern margin at longitude 160°W.
- **Japan, Ogasawara** and **Baja**: these are considered migration routes, with Baja and Ogasawara possibly representing a mixing of whales from two or more feeding/breeding grounds.

<u>Allocation of catches</u>

After all the regions described above were defined in GIS, all modern catches with individual positions could be assigned to a particular region. Known coastal catches were assigned based upon the locations of coastal whaling stations. The majority of the catches were made in feeding areas, but a significant number of whales were killed on the breeding grounds (Mexico, Philippines, and Okinawa) and on migration routes (notably the coast of Japan, as well as Ogasawara and Baja California). All catches from coastal Japan were assigned to the Russian feeding region or Asia breeding ground. We suggest that, based on the SPLASH photo-id exchange rates observed with the feeding regions, the Ogasawara catches, should be split 30%, 47% and 23% between Russia, Al-BS and GOA, respectively. Catches from the start of the 20th century off Baja California are assumed to come from the breeding population in Mexico, although a small percentage were likely whales migrating from Central America. Mexico has been shown to have connections to all known feeding grounds.

Catches from the pelagic regions were assigned in different ways. Pelagic GOA catches were divided based upon the boundary proportion of neighboring feeding regions: 75% to GOA and 25% to SEAK_NBC. Humpback whale catches made in the pelagic North Pacific region were split into equal parts (1/3 each) between AL_BS, GOA and SEAK_NBC. A very small number of catches made around the Kuril Islands were assign as follows: 50% to Al-BS and 50% to the Russian feeding region.

Two areas have major uncertainties in catch totals: California catches during the period 1856-1900, and Japanese coastal catches from 1656 through 1900. We suggest three catch allocation scenarios for each of these two areas, with values for minimum, median and maximum catch totals in years where the total catches are not well known. For Japanese catches the minimum (base) can be represented by known (recorded) catches; however, given that catch data are available from only some of the stations that were known to have existed, we also recommend using values that are double and triple the base numbers. In total, there are three scenarios that were used in the modeling (Table 2). Humpback whale catch records from Japan before 1850s often come as a summary number for a period of years (10-50 years), and for the purpose of the yearly catch database the totals were evenly split between all years for the period covered (for example: during 1748-57 a total of 48 humpback whales were caught, so the catch database assigns 5 whales each year with two years of 4 whales). A final list of catches is shown in Table 3.

Modeling

Basic population dynamics

The number of animals in breeding stock *i* (equivalent to the number of animals using breeding ground *i*) at the start of year *y*+1, N^i_{y+1}, is a function of the catches on the breeding ground of stock *i*, the catches on the feeding grounds of stock *i*, and the impact of density-dependence, i.e.:

$$N^i_{y+1} = N^i_y + r^i \tilde{N}^i_y (1 - \tilde{N}^i_y / K^i) \qquad \tilde{N}^i_y = N^i_y - C^{b,i}_y - C^{f,i}_y \tag{1}$$

where $\tilde{N}^i_y$ is the number of animals in breeding stock *i* after the removal of the catches during year *y*, r^i is the intrinsic rate of growth for breeding stock *i*, K^i is the carrying capacity of breeding stock *i* ($N^i_{1656} = K^i$), $C^{b,i}_y$ is the catch from breeding ground *i* during year *y*, $C^{f,i}_y$ is the catch of animals from breeding stock *i* from the feeding grounds, i.e.:

$$C^{f,i}_y = \sum_j \tilde{C}^j_y \frac{X^{i,j}(N^i_y - C^{b,i}_y)}{\sum_k X^{k,j}(N^k_y - C^{b,k}_y)} \tag{2}$$

$\tilde{C}^j_y$ is the catch from feeding ground *j* during year *y*, and $X^{i,j}$ is the proportion of breeding stock *i* on feeding ground *j* ($\sum_j X^{i,j} = 1$).

Parameter estimation

The parameters of the model are the carrying capacities of each of the breeding stocks, the intrinsic rate of growth (assumed to be same for all stocks), and the parameters of the mixing matrix **X**. The carrying capacities are estimated in log-space while the entries of mixing matrix are zero for breeding ground-feeding ground combinations for which the data indicate that no animals of a breeding ground occur in that feeding ground. In addition, it is only necessary to estimate $n^i - 1$ mixing matrices entries for breeding stock *i* given that constraint $\sum_j X^{i,j} = 1$ where n^i is the number feeding grounds in which animals of breeding ground *i* can be found.

The data available to estimate the parameters of the model are estimates of absolute and relative abundance as well are data on mixing proportions.

The contribution of the estimates of absolute abundance to the negative of the log-likelihood function is:

$$-\ell n L^i = \sum_y \frac{1}{2\sigma^i_y} \left(\ell n N^{obs,i}_y - \ell n \hat{N}^i_y \right)^2 \tag{3}$$

where $N^{obs,i}_y$ is the abundance estimate for feeding / breeding ground *i*, σ^i is the standard error of the logarithm of $N^{obs,i}_y$ (approximated by the CV of $N^{obs,i}_y$), and $\hat{N}^i_y$ is the model-prediction corresponding to $N^{obs,i}_y$, i.e.:

$$\hat{N}_y^i = \begin{cases} N_y^i & \text{If } i \text{ is a breeding ground} \\ \sum_j X^{j,i}(N_y^j - C_y^{b,j}) & \text{If } i \text{ is a feeding ground} \end{cases} \tag{4}$$

The contribution of the estimates of relative abundance to the negative of the log-likelihood function is:

$$-\ell nL^i = \sum_y \frac{1}{2\sigma_y^i}\left(\ell n N_y^{obs,i} - \ell n q^i \hat{N}_y^i\right)^2 \tag{5}$$

where q^i is the catchability coefficient for data series *i* (set to its analytical maximum likelihood estimate). When abundance estimates pertain to a range of years, the model-prediction is the average abundance over the year range concerned.

The data on mixing proportions are assumed to be normally distributed (a Dirichlet likelihood would be better, but this is something for future work). The contribution of the mixing proportions to the negative of the log-likelihood function is:

$$-\ell nL^i = \sum_i \sum_j \frac{1}{2(\tau_y^{i,j})^w}\left(X_y^{obs,i,j} - \hat{X}_y^{i,j}\right)^2 \tag{6}$$

where $X_y^{obs,i,j}$ is the observed proportion during year *y* of breeding stock *i* in feeding ground *j* / proportion during year *y* of animals on feeding ground *j* that are from breeding stock *i*, $\tau_y^{i,j}$ is the standard error of $X_y^{obs,i,j}$, and $\hat{X}_y^{i,j}$ is the model-prediction corresponding to $X_y^{obs,i,j}$, i.e.:

$$\hat{X}_y^{i,j} = \begin{cases} X^{i,j} & \text{if the data relate to breeding stock } i \\ X^{i,j}(N_y^i - C_y^{b,i}) / \sum_k X^{k,j}(N_y^k - C_y^{b,k}) & \text{if the data relate to feeding ground } j \end{cases} \tag{7}$$

Example application

The example application is based on four breeding stocks (Asia, Hawaii, Mexico and Central America) and six feeding grounds (Russia, Bering-Sea Aleutian Islands (BS-AI), Gulf of Alaska (GOA), Southeast Alaska-Northern British Columbia (SA-NBC), Southern British Columbia-Washington (SBC-WA), and Oregon-California (OR-CA)). Table 1 lists the estimates absolute and relative abundance, Table 2 the three scenarios used, and Table 3 the catches by breeding and feeding ground. Table 4 lists the feeding grounds that animals from each breeding stock can be found in, and Table 5 the data on mixing proportions.

RESULTS AND DISCUSSION

We ran three scenarios related to the assignment of the historical catches in the Asia and CA_OR regions. The data on current abundance and exchange rates were the same for all scenarios. The results were not notably sensitive to the choice of catch series except for certain areas under Scenario 2. Table 6 shows estimates of pre-exploitation abundance for the different breeding and feeding areas under the three scenarios. Estimates of total North Pacific population size were very similar for Scenario 1 (20,037 whales) and Scenario 3 (19,999 whales). However, the estimate was lower under Scenario 2 (13,037), primarily because of a major difference in the estimates for Central America and (to a lesser extent) Asia.

Total estimates for breeding and feeding grounds are remarkably consistent within each of the three scenarios (Table 6). The combined pre-exploitation totals of approximately 20,000 animals for both Scenarios 1 and 2 is similar to the recent SPLASH estimate of abundance of about 21,000 animals for the entire North Pacific (Barlow *et al.* 2011).

Estimated population trajectories for each feeding and breeding area for scenarios 1-3 are given in Figs. 3-5. The model is able to mimic the central tendency of the estimates of abundance (Figs 3c, 4c and 5c) and in one case (the Asian breeding ground) mimics the trend inferred from the abundance estimates. However, the model is unable to mimic the change in abundance for the Hawaiian and Mexican breeding grounds and the GOA feeding ground. The inability to fit the Mexican abundance estimates is due to the rapid increase from 1987 to 1991 which is not comparable with stability from 1991 to 2006. The model generally fits the proportion data adequately (Figs 3d, 4d and 5d), although there are some systematic mis-fits. These can be attributable to the model attempting to simultaneously fit the abundance estimates and the proportion data, which although in different units must be incompatible to some extent.

Two of the breeding stocks (Russia and Central America) are estimated to have been severally depleted but to be recovering (or in the case of the minimum catches have recovered). The reductions in the Hawaiian and Mexican breeding stocks are estimated to be limited (unexpected given current abundance and the amount of historical catch), which is a key reason the model cannot mimic the trends in the abundance estimates for these breeding grounds.

One of the next steps will be to use exchange rates between feeding and breeding grounds based on genetic match rates. In addition, other catch allocation scenarios and different abundance estimates can be explored if they come with comparable exchange rates. Finally, there may be value in assuming that density-dependence operates on the feeding rather than the breeding grounds.

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Table 1
List of abundance estimates for the whole North Pacific, and regions therein.

stock	year (period)	N	CV	Source
Asia	1990-1993	400	0.12	Calambokidis et al. 1997
Asia	2004-06	1,059	0.084	Wade et al. (SC/66b/IAxx)
Russia	2004-06	1,111	0.371	Wade et al. (SC/66b/IAxx)
Al-BS	2004-06	2,427	0.199	Wade et al. (SC/66b/IAxx)
GOA	1987	830	0.31	Zerbini et al. 2006
GOA	2001	2191	0.34	Zerbini et al. 2006
GOA	2002	2137	0.24	Zerbini et al. 2006
GOA	2003	2425	0.14	Zerbini et al. 2006
GOA	2004-06	2,089	0.089	Wade et al. (SC/66b/IAxx)
SEAK-NBC	2004-06	6,137	0.07	Wade et al. (SC/66b/IAxx)
SBC-NWA	2004-06	307	0.264	Wade et al. (SC/66b/IAxx)
Hawaii	1991-93	4,629	0.13	Calambokidis et al. in prep.
Hawaii	2004-06	11,398	0.042	Wade et al. (SC/66b/IAxx)
CA-OR	1991-94	797	0.04	Calambokidis et al. in prep.
CA-OR	2004-06	3,734	0.107	Wade et al. (SC/66b/IAxx)
Mexico	1987-90	1964	0.09	Calambokidis et al. in prep.
Mexico	1987	989	0.26	Urban et al. 1999
Mexico	1988	994	0.23	Urban et al. 1999
Mexico	1989	1,435	0.16	Urban et al. 1999
Mexico	1990	1,726	0.17	Urban et al. 1999
Mexico	1991	2,727	0.17	Urban et al. 1999
Mexico	2004-06	3,264	0.058	Wade et al. (SC/66b/IAxx)
Central America	2004-07	411	0.3	Wade et al. (SC/66b/IAxx)

Table 2
Scenarios used in the model.

Scenario	Asia catches	CA-OR catches	Abundance estimates & exchange rates
1	Maximum	Maximum	Wade et al. (SC/66b/IAxx)
2	Minimum	Minimum	Wade et al. (SC/66b/IAxx)
3	Maximum	Median	Wade et al. (SC/66b/IAxx)

Table 3
List of catches of humpback whales in the North Pacific, by year and area. Hawaii and Central America had no catches and considered as all "zeros" in the model.

Year	Asia min	Asia med	Asia max	Ogasawara	Russia	Al-BS	GOA	SEAK-NBC	NWA-SBC	CA-OR med	CA-OR min	CA-OR max	Baja-MX
Total	5573	8216	10859	822	259	7192	4529	4527	3987	4622	3850.8	5401.6	2236
1656	1	2	3										
1657													
1658	2	4	6										
1659													
1660	1	2	3										
1661													
1662	2	4	6										
1663	1	2	3										
1664	1	2	3										
1665	1	2	3										
1666	1	2	3										
1667	1	2	3										
1668													
1669	2	4	6										
1670													
1671	2	4	6										
1672													
1673	2	4	6										
1674	1	2	3										
1675	1	2	3										
1676	1	2	3										
1677	2	4	6										
1678													
1679	1	2	3										
1680	2	4	6										
1681	2	4	6										
1682	1	2	3										
1683													
1684	1	2	3										
1685	1	2	3										
1686	1	2	3										
1687													
1688	2	4	6										
1689	1	2	3										
1690	1	2	3										
1691	1	2	3										
1692													
1693	2	4	6										
1694													

Year	Asia min	Asia med	Asia max	Ogasawara	Russia	Al-BS	GOA	SEAK-NBC	NWA-SBC	CA-OR med	CA-OR min	CA-OR max	Baja-MX
1695	2	4	6										
1696	1	2	3										
1697	1	2	3										
1698	10	20	30										
1699	10	20	30										
1700	11	22	33										
1701	10	20	30										
1702	9	18	27										
1703	12	24	36										
1704	9	18	27										
1705	10	20	30										
1706	11	22	33										
1707	11	22	33										
1708	10	20	30										
1709	11	22	33										
1710	11	22	33										
1711	11	22	33										
1712	10	20	30										
1713	12	24	36										
1714	10	20	30										
1715	11	22	33										
1716	11	22	33										
1717	11	22	33										
1718	10	20	30										
1719	12	24	36										
1720	11	22	33										
1721	11	22	33										
1722	11	22	33										
1723	12	24	36										
1724	10	20	30										
1725	11	22	33										
1726	11	22	33										
1727	11	22	33										
1728	9	18	27										
1729	10	20	30										
1730	10	20	30										
1731	11	22	33										
1732	10	20	30										
1733	10	20	30										
1734	10	20	30										
1735	10	20	30										
1736	10	20	30										
1737	12	24	36										
1738	9	18	27										
1739	10	20	30										

Year	Asia min	Asia med	Asia max	Ogasawara	Russia	Al-BS	GOA	SEAK -NBC	NWA-SBC	CA-OR med	CA-OR min	CA-OR max	Baja-MX
1740	10	20	30										
1741	10	20	30										
1742	9	18	27										
1743	11	22	33										
1744	9	18	27										
1745	11	22	33										
1746	10	20	30										
1747	10	20	30										
1748	6	12	18										
1749	6	12	18										
1750	4	8	12										
1751	7	14	21										
1752	5	10	15										
1753	6	12	18										
1754	5	10	15										
1755	6	12	18										
1756	4	8	12										
1757	5	10	15										
1758	5	10	15										
1759	6	12	18										
1760	7	14	21										
1761	6	12	18										
1762	7	14	21										
1763	8	16	24										
1764	5	10	15										
1765	6	12	18										
1766	6	12	18										
1767	8	16	24										
1768		0	0										
1769	1	2	3										
1770		0	0										
1771	1	2	3										
1772		0	0										
1773	2	4	6										
1774		0	0										
1775	1	2	3										
1776	1	2	3										
1777	1	2	3										
1778		0	0										
1779	1	2	3										
1780		0	0										
1781	2	4	6										
1782		0	0										
1783	1	2	3										
1784		0	0										

Year	Asia min	Asia med	Asia max	Ogasa wara	Russia	Al-BS	GOA	SEAK -NBC	NWA-SBC	CA-OR med	CA-OR min	CA-OR max	Baja-MX
1785	1	2	3										
1786	1	2	3										
1787	1	2	3										
1788		0	0										
1789	1	2	3										
1790		0	0										
1791	1	2	3										
1792		0	0										
1793	1	2	3										
1794		0	0										
1795	1	2	3										
1796		0	0										
1797	1	2	3										
1798		0	0										
1799	1	2	3										
1800	5	10	15										
1801	5	10	15										
1802	11	22	33										
1803	20	40	60										
1804	32	64	96										
1805	22	44	66										
1806	26	52	78										
1807	29	58	87										
1808	33	66	99										
1809	15	30	45										
1810	14	28	42										
1811	22	44	66										
1812	27	54	81										
1813	23	46	69										
1814	9	18	27										
1815	43	86	129										
1816	10	20	30										
1817	16	32	48										
1818	23	46	69										
1819	19	38	57										
1820	15	30	45										
1821	16	32	48										
1822	11	22	33										
1823	28	56	84										
1824	28	56	84										
1825	34	68	102										
1826	16	32	48										
1827	25	50	75										
1828	18	36	54										
1829	20	40	60										

Year	Asia min	Asia med	Asia max	Ogasa wara	Russia	Al-BS	GOA	SEAK -NBC	NWA-SBC	CA-OR med	CA-OR min	CA-OR max	Baja-MX
1830	29	58	87										
1831	26	52	78										
1832	20	40	60										
1833	16	32	48										
1834	8	16	24										
1835	15	30	45										
1836	7	14	21										
1837	6	12	18										
1838	5	10	15										
1839	7	14	21										
1840	0	0	0										
1841	8	16	24										
1842	9	18	27										
1843	9	18	27										
1844	8	16	24										
1845	8	16	24										
1846	9	18	27										
1847	8	16	24										
1848	10	20	30										
1849	21	42	63										
1850	25	50	75										
1851	34	68	102										
1852	20	40	60										
1853	33	66	99										
1854	19	38	57							23	13	33	
1855	19	38	57							36	16	56	
1856	17	34	51							29	18	40	
1857	23	46	69							34	20	48	
1858	16	32	48							46	32	60	
1859	14	28	42							48	33	63	
1860	27	54	81							48	33	63	
1861	9	18	27							71	44	98	
1862	20	40	60							60	38	82	
1863	12	24	36							67	45	89	
1864	25	50	75							59	29	89	
1865	12	24	36							48	27	69	
1866	8	16	24							50	28	72	
1867	5	10	15							49	28	70	
1868	4	8	12							51	29	73	
1869	3	6	9							55	33	77	
1870	5	10	15							45	22	68	
1871	3	6	9							45	22	68	
1872	4	8	12							45	22	68	
1873	3	6	9							42	21	63	
1874	9	18	27							44	22	66	

Year	**Asia min**	**Asia med**	**Asia max**	**Ogasawara**	**Russia**	**Al-BS**	**GOA**	**SEAK -NBC**	**NWA-SBC**	**CA-OR med**	**CA-OR min**	**CA-OR max**	**Baja-MX**
1875	10	20	30							44	22	66	
1876	17	34	51							43	21	65	
1877	28	56	84							48	23	73	
1878	22	44	66							47	22	72	
1879	26	52	78							51	26	76	
1880	27	54	81							42	21	63	
1881	21	42	63							43	21	65	
1882	52	104	156							44	22	66	
1883	49	98	147							38	21	55	
1884	38	76	114							39	22	56	
1885	38	76	114							27	16	38	
1886	44	88	132							22	11	33	
1887	51	102	153							24	11	37	
1888	58	116	174							24	11	37	
1889	32	64	96							24	11	37	
1890	24	48	72							11	2	20	
1891	22	44	66							11	2	20	
1892	4	8	12							11	2	20	
1893	14	28	42							11	2	20	
1894	24	48	72							11	2	20	
1895	41	82	123							11	2	20	
1896	61	122	183							5	0	13	
1897	34	68	102							5	0	13	
1898	4	8	12							5	0	13	
1899	2	4	6							2	2	2	
1900	1	1	1										
1901	12	12	12										
1902													
1903													
1904													
1905													
1906									139				
1907								231					
1908								242	201				
1909								262	335				
1910	29	29	29					352	389				
1911	60	60	60					619	576				
1912	68	68	68			148		469	422				
1913	138	138	138					222	397				
1914	165	165	165			109		122	160				476
1915	105	105	105			117		115	252				
1916	92	92	92			82		143	137				
1917	31	31	31			23		81	205				
1918	24	24	24			58		98	129				
1919	55	55	55		2	126		70	122	225	225	225	

Year	Asia min	Asia med	Asia max	Ogasa wara	Russia	Al-BS	GOA	SEAK -NBC	NWA-SBC	CA-OR med	CA-OR min	CA-OR max	Baja-MX
1920	83	83	83			67		8	106	380	380	380	
1921	100	100	100		1			72	15	157	157	157	35
1922	82	82	82		1	87		57	124	502	502	502	
1923	68	68	68		1	156		78	99	376	376	376	
1924	69	69	69	86	2	72		47	98	197	197	197	150
1925	72	72	72	86	2	266		40	21	43	43	43	403
1926	57	57	57	53		150	236	24		21	21	21	499
1927	80	80	80	14	1	98	455	21					472
1928	65	65	65	25	1	42	178	21		10	10	10	179
1929	69	69	69	5		45	169	10		7	7	7	16
1930	60	60	60	2		13	178	12					
1931	42	42	42	27	1								
1932	53	53	53	34		2	128						
1933	44	44	44	48		26	114			65	65	65	
1934	29	29	29	28	6	72	139	13					
1935	42	42	42	34	1	246	37	1		1	1	1	6
1936	26	26	26	53	23	57	95	14					
1937	21	21	21	50	20	102	43	7		3	3	3	
1938	22	22	22	44	16	40		4					
1939	20	20	20	60	15	54				59	59	59	
1940	33	33	33		12	129		2		19	19	19	
1941	16	16	16	22	5	8		11		16	16	16	
1942	14	14	14	14	5	9		16		12	12	12	
1943	10	10	10	57	10	19		7		5	5	5	
1944	5	5	5	59						1	1	1	
1945	11	11	11		1								
1946	8	8	8	12	3	6							
1947	8	8	8	1	3	7				13	13	13	
1948	8	8	8	3	6	7		115		16	16	16	
1949	0	0	0	4	3	4		76		11	11	11	
1950	5	5	5		10	12		95					
1951	4	4	4		4	5		51		4	4	4	
1952	2	2	2	1	14	51		61					
1953	9	9	9		4	55		47					
1954	12	12	12		14	151		106					
1955	20	20	20		14	136		37					
1956	14	14	14		8	70		28		133	133	133	
1957	32	32	32		18	34		49		199	199	199	
1958	294	294	294		8	29		40		115	115	115	
1959	238	238	238		4	75		27		140	140	140	
1960	170	170	170		4	56				67	67	67	
1961	95	95	95		11	333				62	62	62	
1962	25	25	25		1	1181	657	16		39	39	39	
1963	3	3	3		3	1098	1532	147	5	55	55	55	
1964	1	1	1		1	1025	320	10	26	27	27	27	

Year	Asia min	Asia med	Asia max	Ogasa wara	Russia	Al-BS	GOA	SEAK -NBC	NWA-SBC	CA-OR med	CA-OR min	CA-OR max	Baja-MX
1965	4	4	4			300	210	79	9	4	4	4	
1966	5	5	5			52	6	13					
1967						65	14	22	5				
1968						8	15	14	9				
1969						2			3				
1970						3	3	3	3				
1971													
1972						4							

Table 4
Which feeding grounds animals from each of the four breeding stocks can be found in (1=Yes; 0=No)

Breeding ground	Feeding ground					
	Russia	BS-AI	GOA	SA-NBC	SBC-WA	OR-CA
Asia	1	1	0	0	0	0
Hawaii	0	1	1	1	1	0
Mexico	0	1	1	1	1	1
Central America	0	0	0	0	1	1

Table 5
Exchange rates between (a) feeding to breeding and (b) breeding to feeding grounds (Wade et al., in prep.)

a)

Area moving from/to	Asia	CV	Hawaii	CV	Mexico	CV	Central America	CV
Russia	1.000	0.01	0.000	0.00	0.000	0.00	0.000	0.00
AI-Bering	0.022	0.49	0.865	0.02	0.113	0.25	0.000	0.00
GOA	0.005	0.00	0.890	0.01	0.105	0.16	0.000	0.00
SE-NBC	0.000	0.00	0.939	0.17	0.061	0.03	0.000	0.00
SBC-WA	0.000	0.00	0.529	0.15	0.419	0.14	0.520	0.91
OR-CA	0.000	0.00	0.000	0.00	0.896	0.16	0.104	0.45

b)

Area moving from/to	Russia	CV	AI-Bering	CV	GOA	CV	SE-NBC	CV	SBC-WA	CV	OR-CA	CV
Asia	0.936	0.04	0.064	0.05	0.000		0.000		0.000		0.000	
Hawaii	0.000		0.062	0.26	0.078	0.19	0.849	0.14	0.010	0.39	0.000	
Mexico	0.000		0.091	0.40	0.096	0.38	0.052	0.24	0.025	0.43	0.736	0.06
Central America	0.000		0.000		0.000		0.000		0.086	0.12	0.914	0.06

Table 6
Estimated pre-exploitation abundance for breeding and feeding grounds under the three different catch scenarios (see Table 1)

Region	**Catch scenario**		
	1 (Asia and CA-OR maximum)	**2 (Asia and CA-OR minimum)**	**3 (Asia maximum, CA-OR median)**
Asia	3,681	1,072	3,684
Hawaii	9,849	9,849	9,912
Mexico	2,126	1,892	2,090
Central America	4,308	224	4,312
Total breeding grounds	*20,037*	*13,037*	*19,999*
Russia	3,447	1,003	3,449
BS-AI	1,918	1,665	2,015
GOA	1,875	1,927	1,927
SA-NBC	7,101	6,993	6,993
SBC-WA	606	244	599
OR-CA	5,087	1,204	5,020
Total feeding grounds	*20,037*	*13,037*	*19,999*

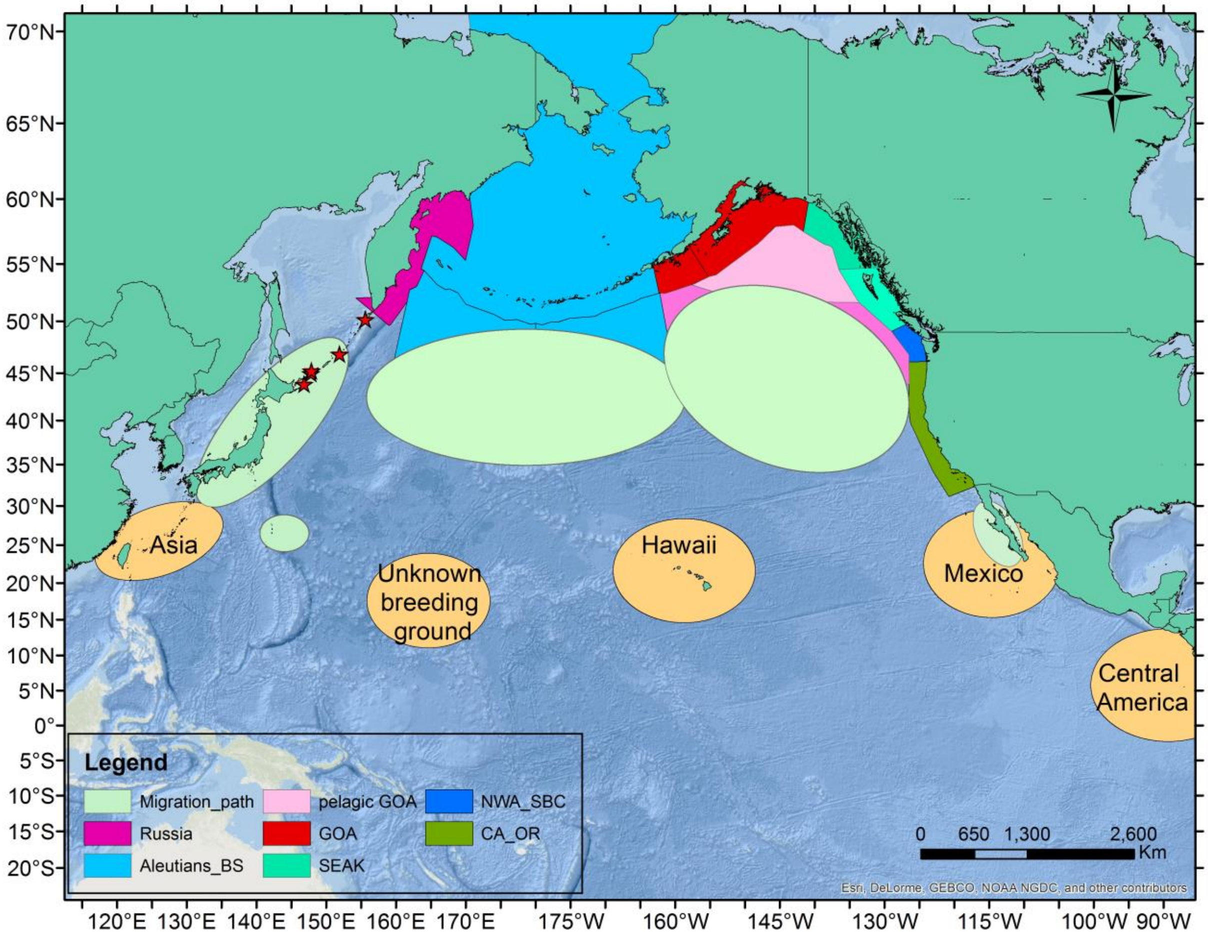

Figure 1. Feeding and breeding regions for the North Pacific humpback whale population.

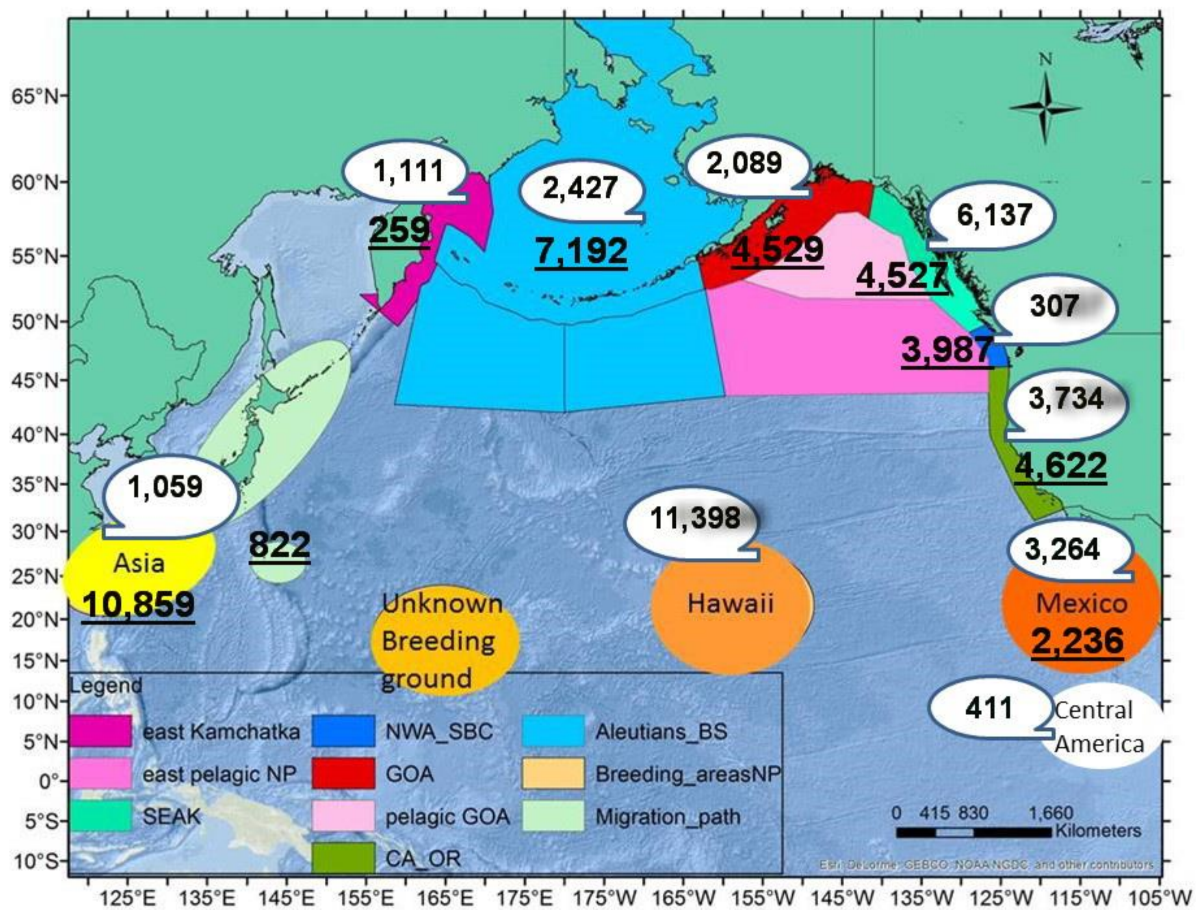

Figure 2. Abundance and catches for each breeding/feeding area (scenario 3). Underlined numbers show the amount of catches made in the area accourding to catch scenario and numbers in the white call-outs are current abundance estimates for each area.

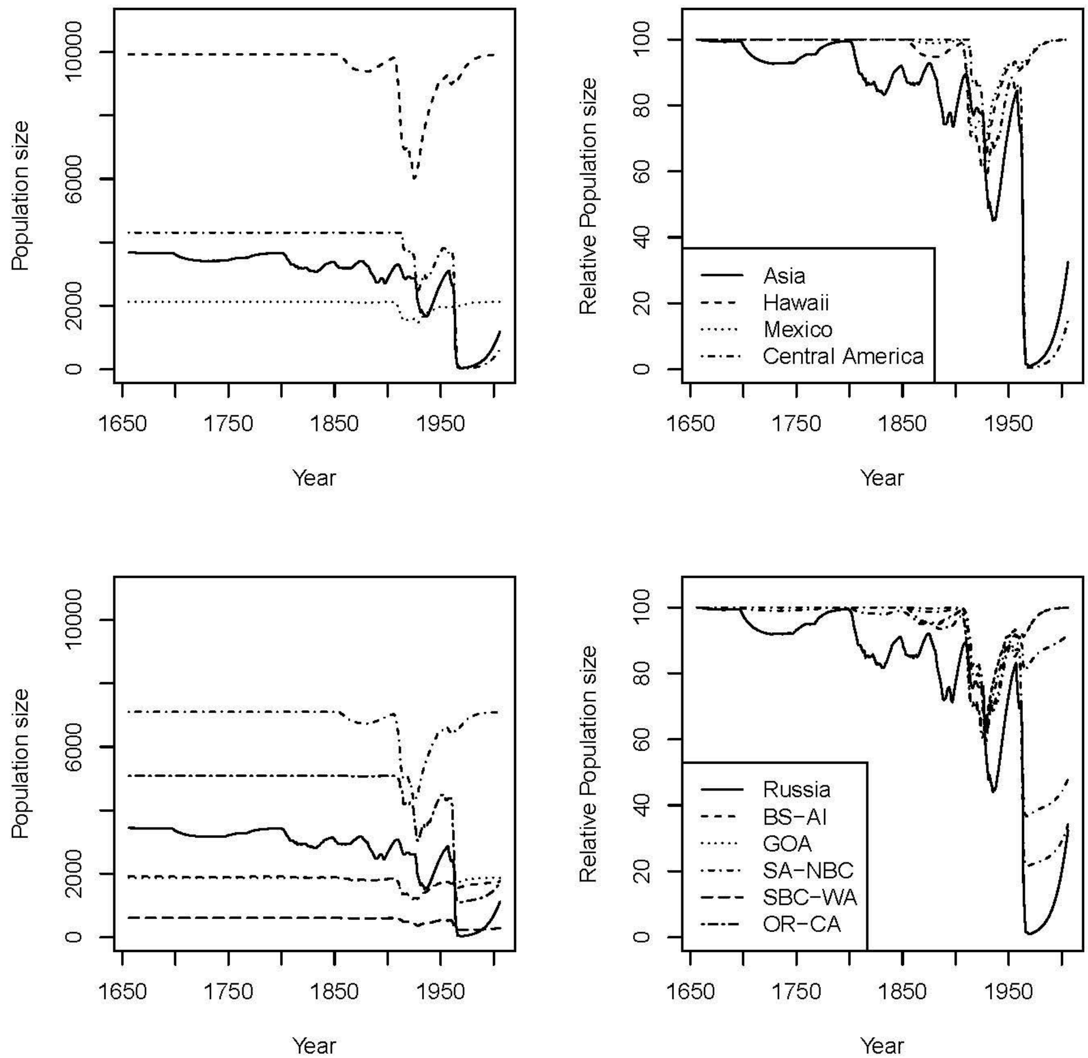

Fig 3a. Time-trajectories of population size in absolute terms (left panels) and relative to carrying capacity (right panels). Results are shown by breeding stock in the upper panels and by feeding ground in the lower panels. The results in this plot pertain to the maximum catches (Scenario 1).

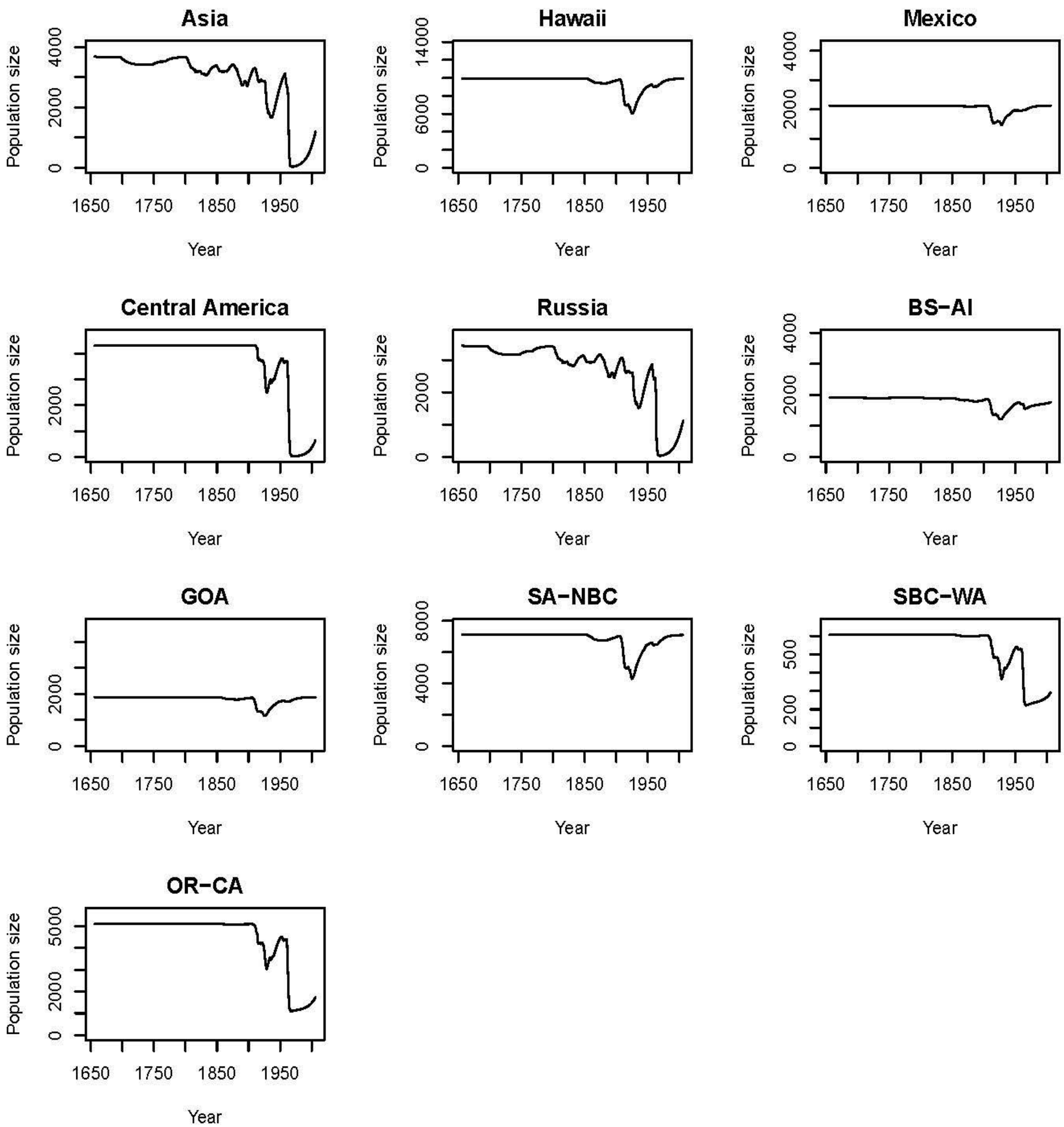

Fig 3b. Time-trajectories of population size by breeding stock and feeding ground. The results in this plot pertain to the maximum catches (Scenario 1).

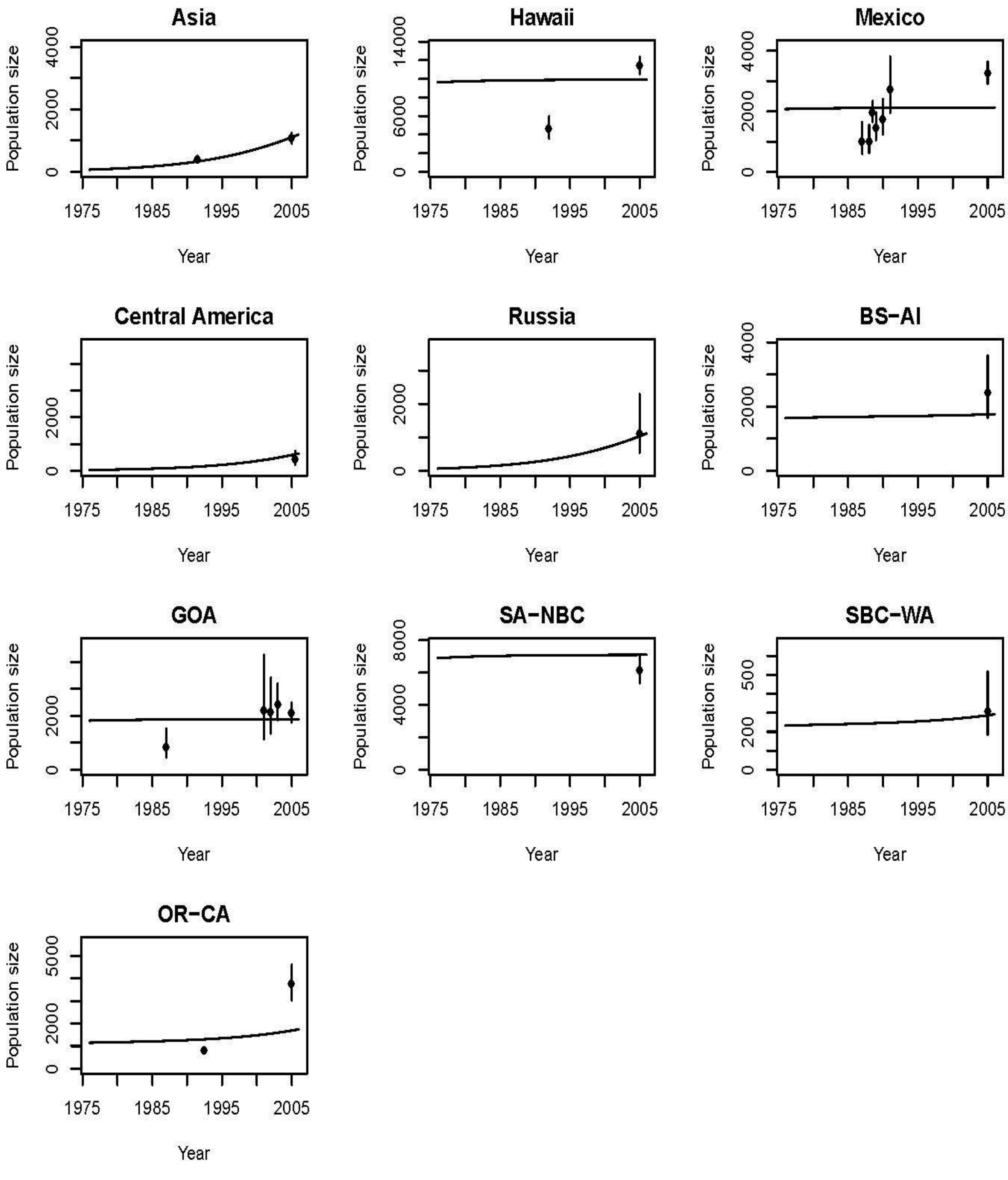

Fig. 3c. Observed (solid dots) estimates abundance (with 90% sampling intervals) by breeding and feeding ground. The solid lines indicate the model predictions when the model is fitted using the maximum catches (Scenario 1).

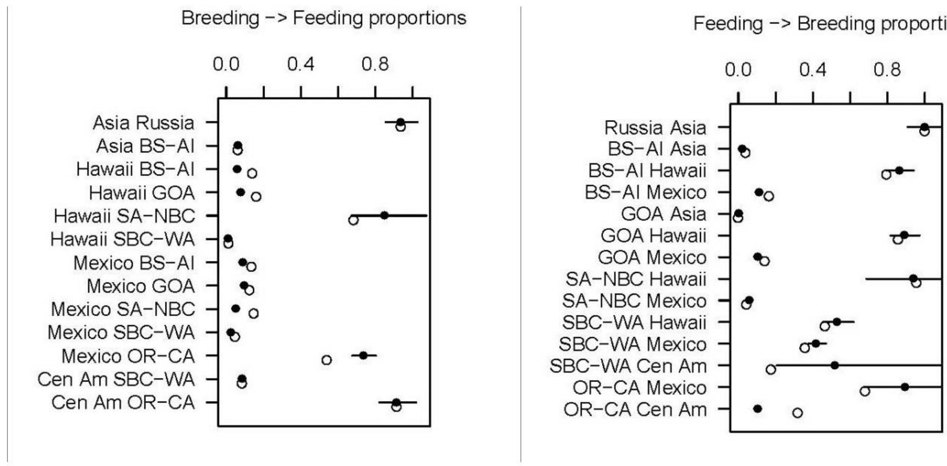

Fig. 3d. Observed (solid dots) and model-predicted (open circles) mixing the proportions. The left panel shows the data and fits to the proportion of each breeding stock in each feeding group and the right panel shows the proportion of each feeding ground made up of each breeding stock. The results in this plot pertain to the model fitted assuming the maximum catches (Scenario 1).

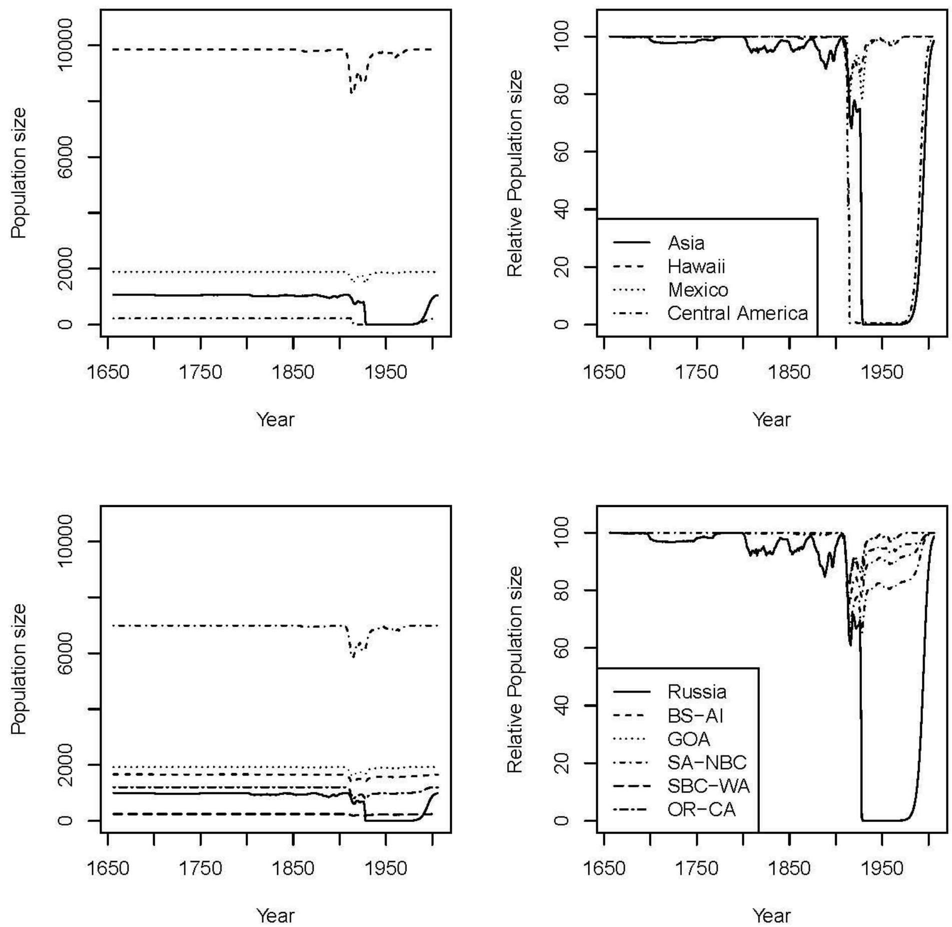

Fig. 4a. Time-trajectories of population size in absolute terms (left panels) and relative to carrying capacity (right panels). Results are shown by breeding stock in the upper panels and by feeding ground in the lower panels. The results in this plot pertain to the minimum catches (Scenario 2).

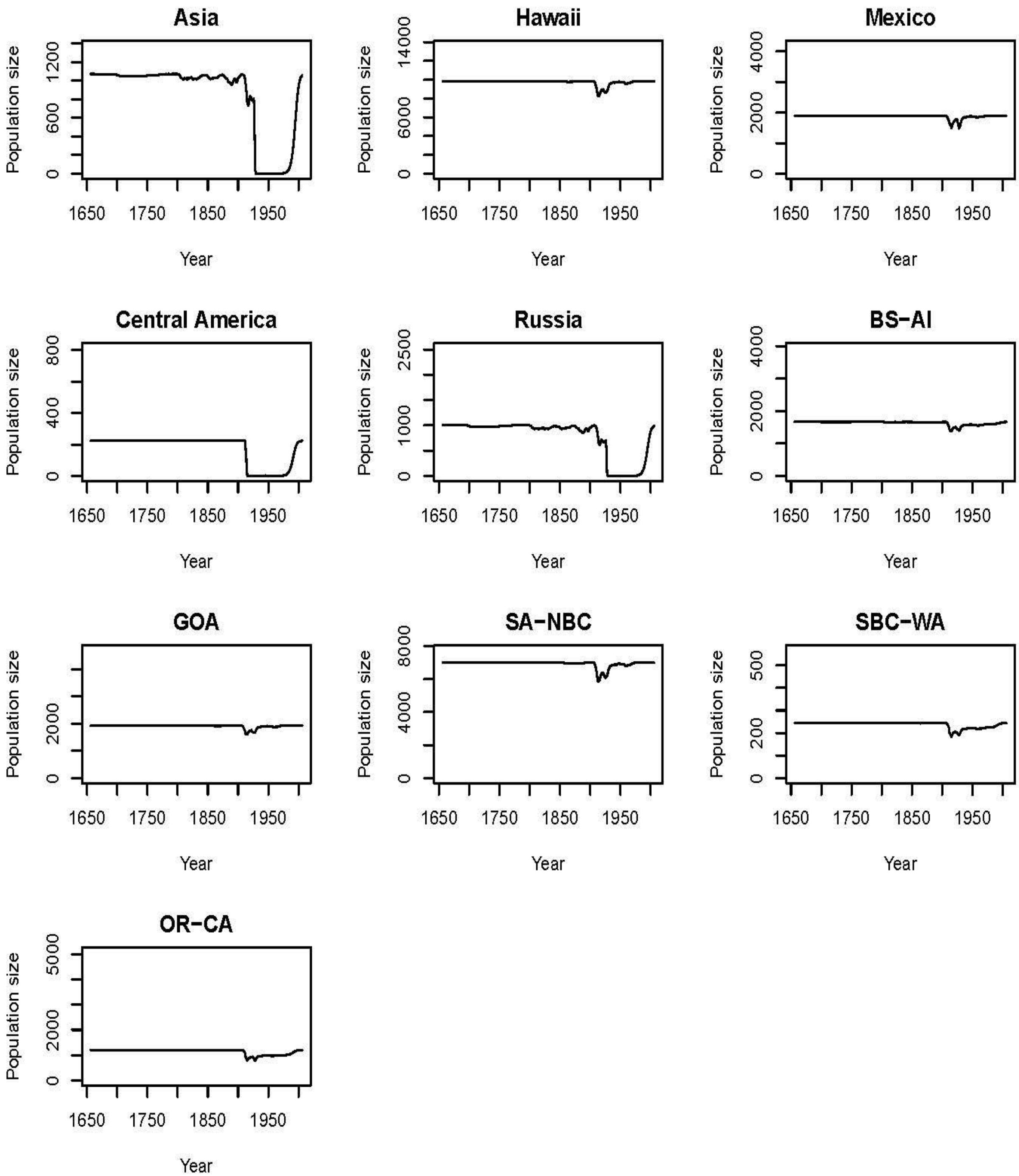

Fig. 4b. Time-trajectories of population size by breeding stock and feeding ground. The results in this plot pertain to the minimum catches (Scenario 2).

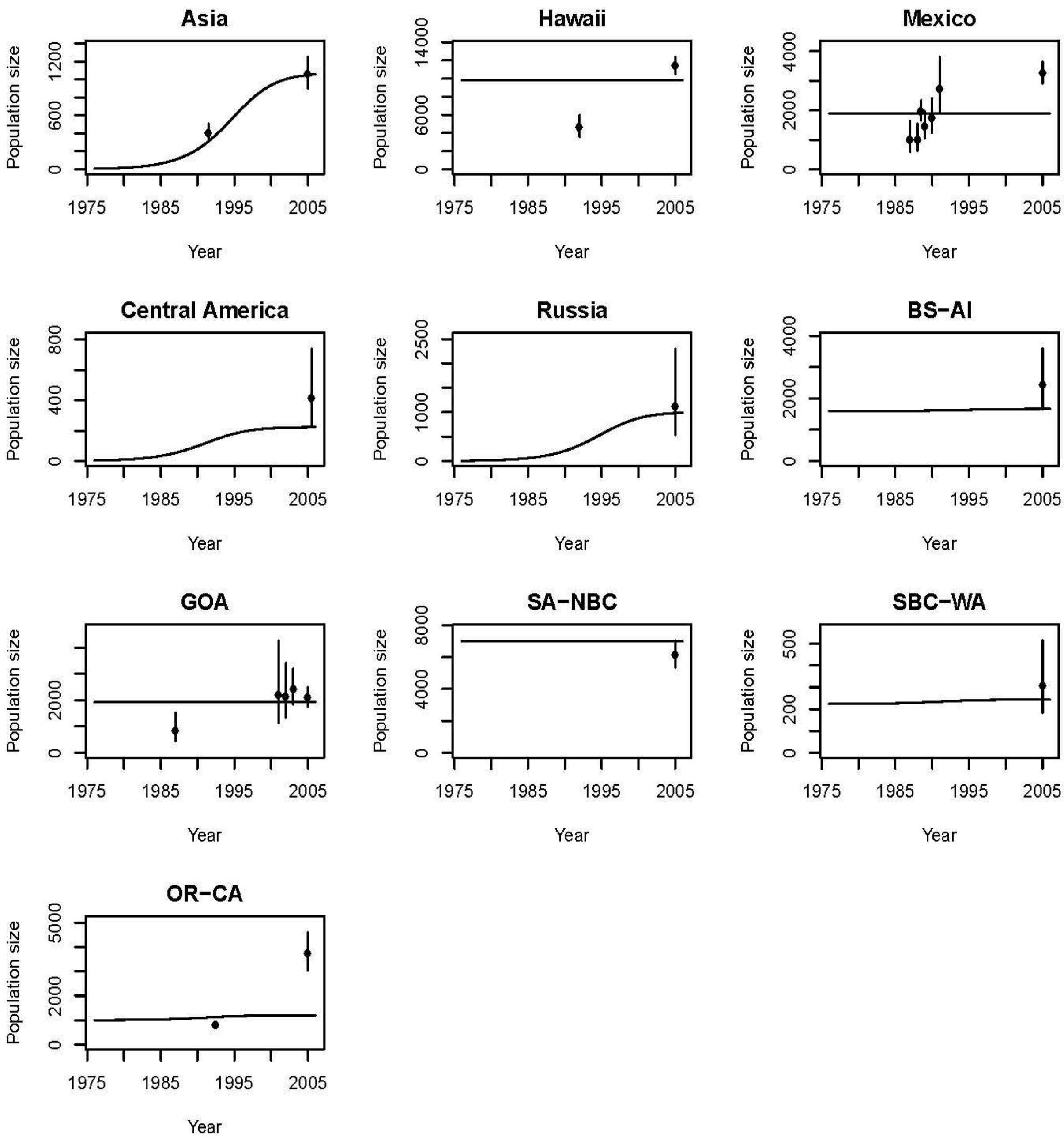

Fig. 4c. Observed (solid dots) estimates abundance (with 90% sampling intervals) by breeding and feeding ground. The solid lines indicate the model predictions when the model is fitted using the minimum catches (Scenario 2).

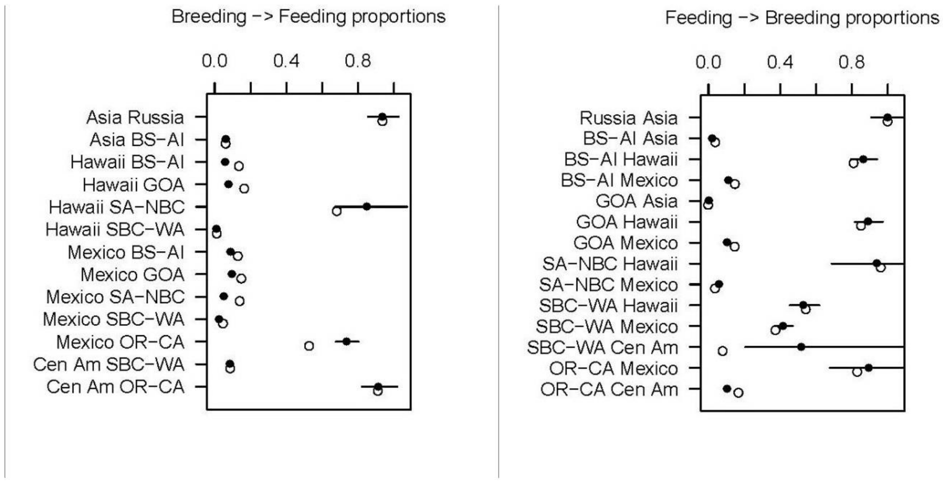

Fig. 4d. Observed (solid dots) and model-predicted (open circles) mixing the proportions. The left panel shows the data and fits to the proportion of each breeding stock in each feeding group and the right panel shows the proportion of each feeding ground made up of each breeding stock. The results in this plot pertain to the model fitted assuming the minimum catches (Scenario 2).

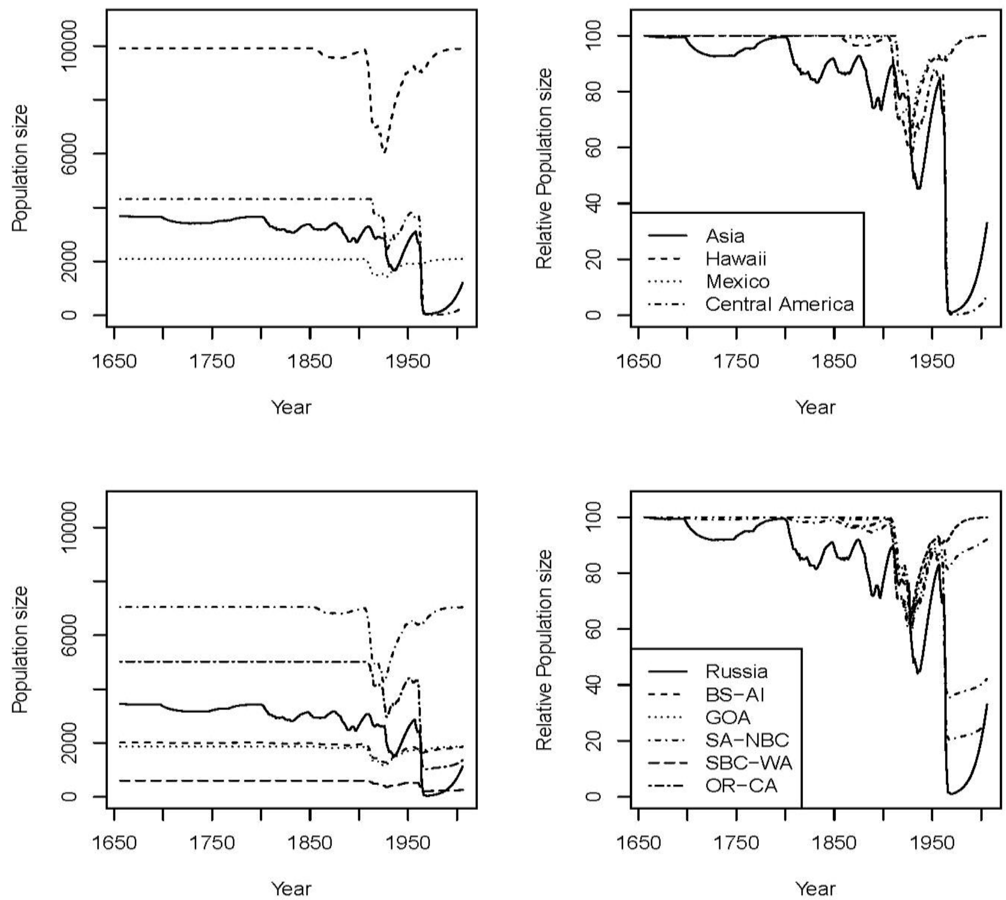

Fig. 5a. Time-trajectories of population size in absolute terms (left panels) and relative to carrying capacity (right panels). Results are shown by breeding stock in the upper panels and by feeding ground in the lower panels. The results in this plot pertain to Scenario 3.

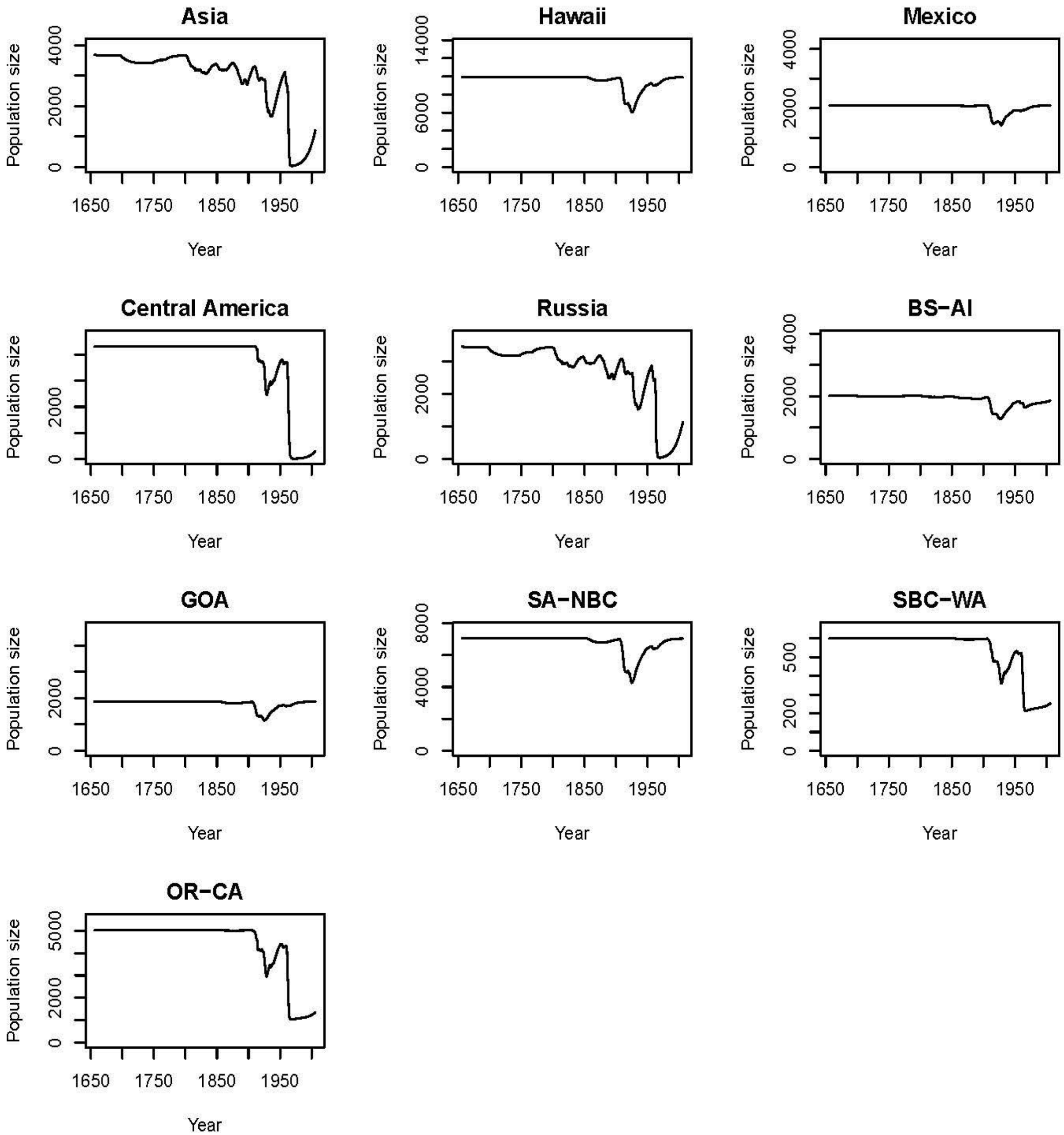

Fig. 5b. Time-trajectories of population size by breeding stock and feeding ground. The results in this plot pertain to Scenario 3.

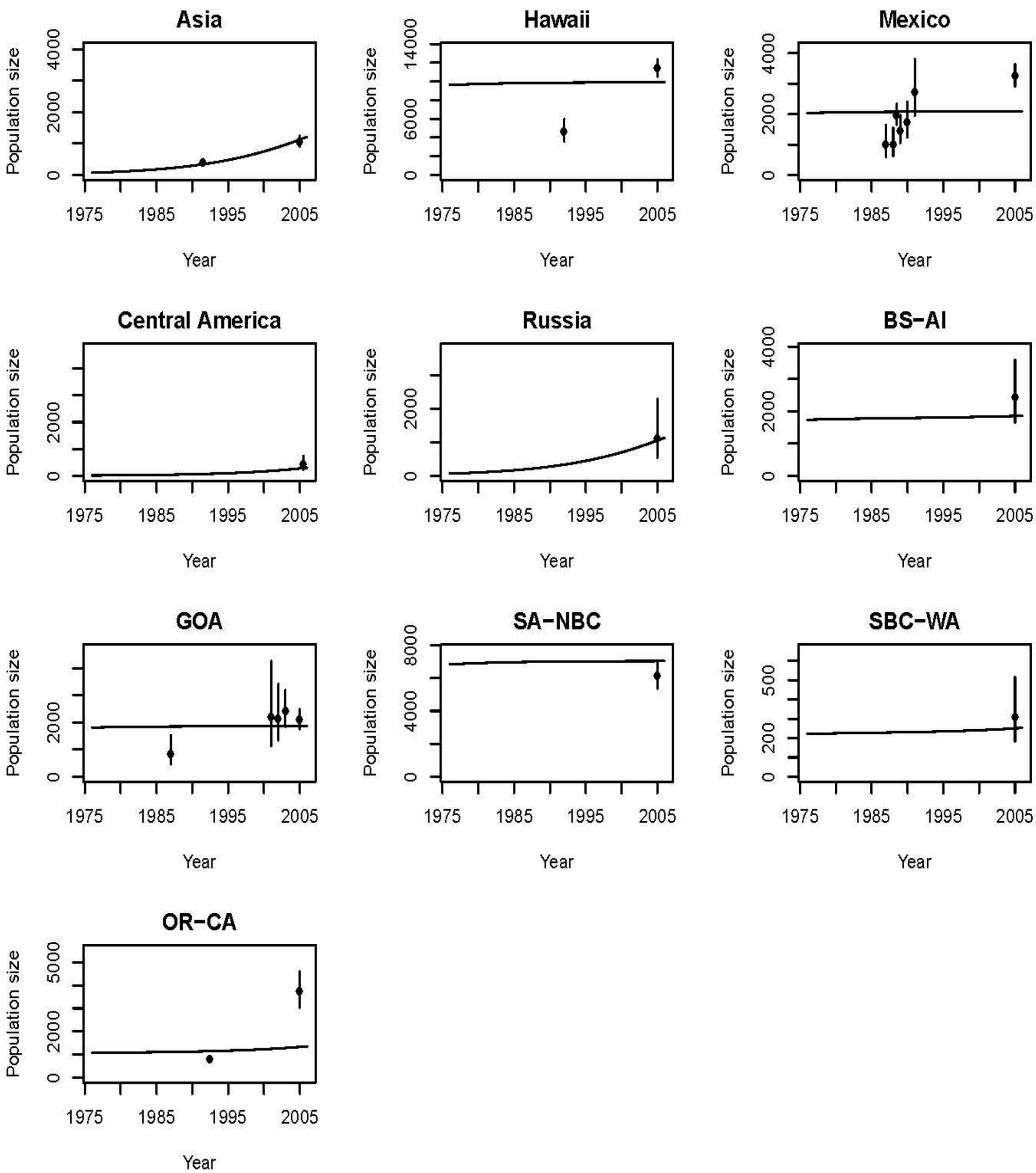

Fig. 5c. Observed (solid dots) estimates abundance (with 90% sampling intervals) by breeding and feeding ground. The solid lines indicate the model predictions when the model is fitted using Scenario 3.

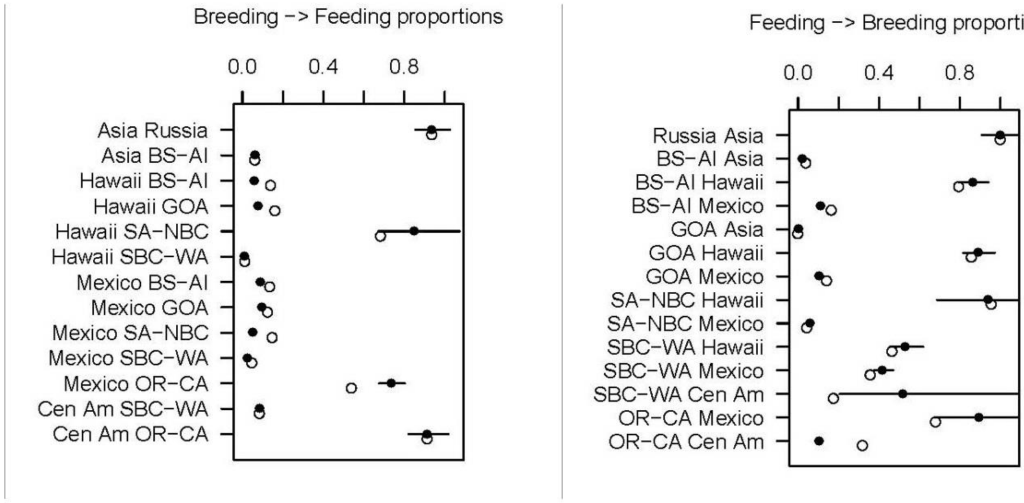

Fig. 5d. Observed (solid dots) and model-predicted (open circles) mixing the proportions. The left panel shows the data and fits to the proportion of each breeding stock in each feeding group and the right panel shows the proportion of each feeding ground made up of each breeding stock. The results in this plot pertain to the model fitted assuming catch allocation Scenario 3.