

Supplementary Information

Spatial-data preprocessing

Observational data for all species were collated from multiple sources (see Methods) through August 31, 2019. Duplicate observations that co-occurred across databases were removed first. Because large public databases (such as Global Biodiversity Information Facility; GBIF) can contain erroneous data¹, we screened all data using the ‘CoordinateCleaner’ package in R statistical software². Specifically, we flagged coordinates that occurred on land, had equal latitude and longitude or 0-0 coordinates, or were assigned to biological institutions. For each species, we grouped data based on ocean basin (North Atlantic, North Pacific, and Southern Ocean) and time of occurrence (feeding or breeding; see Methods). High-latitude feeding data were subset using all available observations within each ocean basin. To account for individuals that migrate across the equator (e.g., ³), low-latitude breeding data were subset using all available observations within each ocean basin along with observations within neighboring basins up to 15° latitude. The total number of observations for each species by ocean basin and feeding-breeding period is presented in Table S4.

Feeding- and breeding-range distribution polygons

Sophisticated range distribution models for various abiotic and biotic variables exist for whale species^{4,5}. However, such complex distribution models do not exist for our focal whale species at a global scale due to the difficulties in implementing these methods for migrating species that utilize global ocean space and display high levels of route fidelity⁶.

Accordingly, we take a more straightforward approach and estimate range distributions based solely on observational data. The International Union for Conservation of Nature (IUCN) has extensively used this method, which bases its species Extent of Occupancy (EOO) models on observation data only⁷. Here, we estimate feeding and breeding ranges for each species separately using a fixed kernel density estimation⁸. Specifically, we model ranges using the ‘adehabitatHR’ package in R statistical software, which has been used to estimate distribution ranges of numerous marine and terrestrial species, including whales⁹⁻¹¹. The ‘adehabitatHR’ package was developed for use with animal GPS/VHF location data without observation bias. We note that our collated data suffer from nonrandom sampling, which can bias our modelled distribution ranges to sites of greater sampling density (e.g., near shorelines). As a result, we used a 95% kernel density (i.e., 95% probability of finding an observed individual within the boundary) to incorporate as much data as possible, while still excluding uncommon or extralimital observations (e.g., laggard or nonmigratory individuals). Due to possible inaccuracies in the geographic location estimates derived from ship logs of potential low reporting accuracy (e.g., to the nearest half degree), we used a smoothing parameter (h) equal to 1 degree. This parameter helps prevent overfitting of the range distribution model and provides a more conservative estimate of the range area. The ‘adehabitatHR’ package does not consider complex physical barriers to species range distribution, such as land masses. Consequently, we clipped all whale distribution polygons to include marine areas using the NaturalEarth 10m ocean polygon (<https://www.naturalearthdata.com/downloads/10m-physical-vectors/>).

The Robinson projection displays feeding and breeding polygons on a world map (Figs. S1-S5). This projection balances equal-area and conformal projections and has been used to display the global distribution of whales previously¹². We centered maps at 110° W to highlight major regions of whale migratory pathways. All maps were produced in ‘ggplot2’¹³. To calculate the area of each species distribution range, polygons were projected in Behrmann equal area projection. The gArea function from the ‘rgeos’ package¹⁴ was then used to calculate the area in km². To investigate the importance of using a 95% kernel density and smoothing parameter (h) equal to 1 degree, we performed sensitivity analyses of 90% and 99% kernel densities and doubled ($h=2$) and halved ($h=0.5$) the smooth parameter.

The feeding-to-calving ratio represents the overlap between known calving grounds with winter observations, the most constrained of our assumptions. The feeding-to-breeding ratio includes breeding areas found in the literature and thus has a wider distribution. The summer-to-winter ratio includes all data points in the winter. It has the lowest ratio, presumably because it includes whales that do not migrate, arrive late, or depart early, thus extending the winter range.

Calving-area polygons

The distribution ranges described above provide a conservative estimate of spatial distribution. In reality, individuals congregate within these ranges, such as in shallow bays to calve; yet, because of the potential bias in sampling observation data, we don’t have density maps for publicly available databases. To address this limitation, we used the published literature, primarily in peer-reviewed journals, to document the spatial distribution of mother-calf pairs throughout their range for our focal species: gray whales

¹⁵, North Atlantic right whales ¹⁶⁻¹⁸, southern right whales ¹⁹⁻³⁵, and humpback whales ³⁶⁻

⁵¹. Polygons based on the distribution of mother-calf pairs were constructed using QGIS

3.22.7. We also calculated the area that overlaps between the breeding areas and calving areas, to provide the best estimate of where most females and calves reside during the calving grounds. We clipped polygons in R statistical software using the `gIntersection` function in the ‘`rgeos`’ package ⁵² to do this.

Migration

For our calculations, we assumed that the entire population of whales migrates, unless we had evidence to the contrary. This high- to low-latitude movement model has recently been challenged. Geijer et al.⁵³, for example, suggest that mysticete migration consists of a continuum of strategies that have evolved in the face of different selective pressures. Our spatial data should generally reflect that pattern, as it consists of all observations of whales for each population (or ocean basin). Though there may be some bias, with more effort extended in known breeding areas, the range distributions represented here demonstrate our best current understanding of baleen whale distribution and migratory patterns. A detailed focus on individual populations will help illuminate these patterns going forward.

Population updates

Population estimates come from Smith et al.⁵⁴ with the following updates. Populations for the Southern Hemisphere are based on Tulloch et al.⁵⁵ with additional data on 95% CIs from V. Tulloch. In the North Atlantic, present populations of fin and humpback whales have been updated using the IUCN Red List of Threatened Species and references therein^{56,57}. Prehunting population numbers of North Atlantic humpback whales are from

Saurez et al.⁵⁸ The current *E. glacialis* population is from the North Atlantic Right Whale Consortium 2021 report⁵⁹. Historic numbers of humpback whales in the North Pacific are sometimes referenced as approximately 20,000⁵⁴. Current numbers are above these estimates, so we set the range at 25,000 to 40,000 in Table 1 as a reasonable, conservative estimate (Christensen, for example, estimated a 57% depletion in the ocean basin⁶⁰). For contemporary humpback populations in the North Pacific and Hawaii, we relied on estimates from Cheeseman et al., providing a wide range given the recent fluctuations in population⁶¹. Present populations for gray whales are based on population estimates from Stewart et al.⁶² Humpback and gray whales in the North Pacific have exhibited signs of reaching carrying capacity,⁶¹ so we used calculations for stable populations in determining percent mature for these populations.

The population ranges can be found in figshare:

<https://figshare.com/s/69f76e8dcdb0573d9f67>. In cases where confidence intervals or ranges were not available, we set the range at $\pm 30\%$.

Table S1. Yearly movement of biomass and nutrients by mothers and calves from feeding to breeding grounds. Biomass and detritus include carcasses and placentas. All measurements are in tons. Population ranges for whales can be found on Figshare. 95% CIs are in parentheses.

	Total Biomass	Detrital C	Detrital N	Urea N	C fixation from Urea	Total N
North Atlantic						
Humpback	1,142 (909; 1,234)	120 (95; 129)	15 (12; 16)	207 (167; 227)	1,174 (946; 1,286)	222 (178; 242)
Humpback pre hunting	1,506 (1,227; 2,206)	163 (129; 231)	20 (16; 28)	283 (213; 469)	1,604 (1,207; 2,662)	303 (228; 497)
Right	7.4 (6.1; 8.6)	0.8 (0.6; 0.9)	0.1 (0.1; 0.1)	2.6 (2.3; 3.0)	15 (13; 17)	2.7 (2.4; 3.1)
Right pre hunting	432 (350; 514)	45 (37; 54)	5.5 (4.5; 6.6)	155 (126; 185)	881 (715; 1,048)	161 (131; 191)
<i>Total present</i>	1,149 (915; 1,243)	121 (96; 130)	15 (12; 16)	210 (169; 230)	1,189 (959; 1,303)	224 (181; 245)
<i>Total pre hunting</i>	1,992 (1,577; 2,720)	209 (165; 285)	26 (20; 35)	438 (339; 654)	2,485 (1,922; 3,710)	463 (359; 688)
North Pacific						
Gray	1,989 (1,622; 2,120)	209 (170; 222)	26 (21; 27)	302 (257; 319)	1,714 (1,459; 1,812)	327 (278; 346)
Gray pre hunting	2,416 (1,969; 2,640)	253 (206; 277)	31 (25; 34)	367 (307; 408)	2,082 (1,742; 2,314)	398 (332; 441)
Humpback	2,030 (1,732; 2,187)	213 (182; 229)	26 (22; 28)	368 (319; 395)	2,088 (1,813; 2,245)	394 (342; 423)

Humpback pre hunting	1,903 (1,729; 2,232)	199 (181; 234)	24 (22; 29)	345 (326; 427)	1,957 (1,849; 2,424)	369 (348; 456)
Right	8.8 (7.3; 10)	0.9 (0.8; 1.1)	0.1 (0.1; 0.1)	3.1 (2.7; 3.6)	18 (15; 20)	3.3 (2.8; 3.7)
Right pre hunting	423 (351; 495)	44 (37; 52)	5 (5; 6)	152 (131; 173)	862 (741; 981)	157 (135; 179)
<i>Total present</i>	4,028 (2,261; 4,318)	422 (352; 453)	52 (43; 55)	673 (579; 718)	3,819 (3,288; 4,077)	724 (622; 773)
<i>Total pre hunting</i>	4,742 (4,049; 5,366)	497 (424; 562)	61 (52; 69)	863 (763; 1,008)	4,901 (4,332; 5,719)	924 (815; 1,076)
Southern Hemisphere						
Humpback	6,603 (5,369; 7,020)	692 (563; 736)	85 (69; 90)	1,197 (1,012; 1,261)	6,792 (5,745; 7,155)	1,281 (1,081; 1,351)
Humpback pre hunting	10,788 (8,790; 11,414)	1,131 (921; 1,196)	138 (113; 146)	1,955 (1,675; 2,035)	11,097 (9,507; 11,553)	2,093 (1,787; 2,182)
Right	300 (250; 352)	32 (26; 37)	3.8 (3.2; 4.5)	108 (93; 123)	611 (527; 698)	112 (96; 127)
Right pre hunting	4,437 (3,684; 5,170)	465 (386; 542)	57 (47; 66)	1,594 (1,385; 1,799)	9,050 (7,859; 10,209)	1,651 (1,432; 1,865)
<i>Total present</i>	6,903 (5,619; 7,372)	724 (589; 773)	88 (72; 94)	1,304 (1,105; 1,383)	7,403 (6,272; 7,853)	1,393 (1,177; 1,478)
<i>Total pre hunting</i>	15,225 (12,475; 16,584)	1,596 (1,307; 1,738)	195 (160; 212)	3,549 (3,059; 3,834)	20,146 (17,366; 21,762)	3,744 (3,219; 4,046)
Global present	12,080 (9,894; 12,932)	1,266 (1,037; 1,355)	155 (127; 166)	2,187 (1,853; 2,331)	12,412 (10,519; 13,233)	2,341 (1,980; 2,497)
Global pre hunting	21,959 (18,100; 24,671)	2,301 (1,897; 2,586)	281 (232; 316)	4,851 (4,161; 5,495)	27,533 (23,619; 31,191)	5,132 (4,393; 5,811)

Table S2. Yearly movement of biomass and nutrients by mothers and calves from feeding to breeding grounds for blue and fin whales. Detritus includes carcasses and placentas. All measurements are in tons. 95% CIs are in parentheses.

	Total Biomass	Detrital C	Detrital N	Urea N	C fixation from Urea	Total N
North Atlantic						
Blue	45 (36; 48)	4.7 (3.8; 5)	0.6 (0.5, 0.6)	8.7 (7.4; 9.2)	49 (42; 52)	9.3 (7.9; 9.8)
Blue pre hunting	1,264 (1,000; 1,369)	133 (105; 143)	16 (13; 18)	248 (196; 274)	1,405 (1,115; 1,554)	264 (209; 291)
Fin	7,414 (6,028; 7,884)	777 (632; 826)	95 (77; 101)	1,204 (1,019; 1,269)	6,836 (5,781; 7,202)	1,299 (1,096; 1,369)
Fin pre hunting	10,278 (8,693; 11,346)	1,077 (911, 1,191)	132 (111; 145)	1,676 (1,498; 1,885)	9,513 (8,504; 10,698)	1,808 (1,610; 2,029)
<i>Total present</i>	7,459 (6,064; 7,932)	782 (636; 831))	96 (78; 102)	1,213 (1,026; 1,278)	6,886 (5,823; 7,254)	1,309 (1,104; 1,379)
<i>Total pre hunting</i>	11,542 (9,693; 12,715)	1,210 (1,016; 1,333)	148 (124; 163)	1,924 (1,695; 2,159)	10,918 (9,619; 12,252)	2,071 (1,819; 2,320)
North Pacific						
Blue	335 (272; 356)	35 (29; 37)	4.3 (3.5; 4.6)	65 (55; 69)	371 (314; 391)	70 (59; 73)
Blue pre hunting	1,012 (798; 1,099)	106 (84; 115)	13 (10; 14)	198 (157; 220)	1,123 (889; 1,246)	211 (167; 234)
Fin	2,910 (2501; 3,126)	305 (262; 328)	37 (32; 40)	473 (417; 502)	2,683 (2,369; 2,849)	510 (450; 542)
Fin pre hunting	8,456 (7,042; 9,294)	886 (738; 974)	108 (90; 119)	1,379 (1,139; 1,544)	7,827 (6,436; 8,765)	1,487 (1,230; 1,663)

<i>Total present</i>	3,245 (2,773; 3,482)	340 (291; 365)	42 (36; 45)	538 (473; 571)	3,053 (2,683; 3,239)	579 (508; 615)
<i>Total pre hunting</i>	9,468 (7,840; 9,234)	992 (822; 1,089)	121 (100; 133)	1,577 (1,295; 1,763)	8,951 (7,353; 10,010)	1,698 (1,397; 1,894)
Southern Hemisphere						
Blue	506 (411; 539)	53 (43; 57)	6.5 (5.3; 6.9)	99 (84; 104)	560 (474; 591)	105 (89; 111)
Blue pre hunting	39,822 (32,454; 42,204)	4,173 (3,401; 4,423)	540 (415; 540)	7,794 (6,675; 8,120)	44,240 (37,891; 46,091)	8,304 (7091; 8,660)
Fin	4,461 (3,616; 4,729)	468 (379; 496)	57 (46; 61)	725 (612; 762)	4,113 (3,474; 4,325)	782 (659; 822)
Fin pre hunting	60,169 (49,002; 63,637)	6,306 (5,135; 10,261)	770 (627; 815)	9,812 (8,396; 10,202)	55,693 (47,659; 57,908)	10,582 (9,024; 11,018)
<i>Total present</i>	4,967 (4,026; 5,268)	521 (422; 552)	64 (52; 67)	823 (696; 866)	4,673 (3,948; 4,915)	887 (748; 933)
<i>Total pre hunting</i>	99,991 (81,456; 105,841)	10,479 (8,537; 11,092)	1,280 (1,043; 1,280)	17,606 (15,072; 18,322)	99,932 (85,550; 103,999)	18,885 (16,115; 19,678)
Global present	15,671 (12,864; 16,682)	1,642 (1,348; 1,748)	201 (165; 214)	2,574 (2,194; 2,715)	14,612 (12,453; 14,612)	2,775 (2,360; 2,927)
Global pre hunting	121,001 (98,990; 128,949)	12,681 (10,374; 13,514)	1,549 (1,267; 1,651)	21,106 (18,062; 22,244)	119,801 (102,521; 126,261)	22,655 (19,331; 23,894)

Table S3. Yearly movement of biomass and nutrients by all migrating whales from feeding to breeding grounds for blue and fin whales. Biomass and detritus include carcasses and placentas. All measurements are in tons. 95% CIs are in parentheses.

	Total Biomass	Detrital C	Detrital N	Urea N	C fixation from Urea	Total N
North Atlantic						
Blue	279 (227; 297)	29 (24; 31)	3.5 (2.9; 3.7)	16.5 (14; 17.4)	94 (80; 99)	20 (17; 21)
Blue pre hunting	5,431 (4,296; 5,878)	569 (450; 616)	68 (54; 73)	386 (307; 427)	2,192 (1,740; 2,426)	454 (361; 500)
Fin	47,138 (38,322; 50,127)	4,940 (4,016; 5,253)	595 (484; 633)	2,165 (1,831; 2,281)	12,288 (10,392; 12,946)	2,760 (<u>2,316; 2,911</u>)
Fin pre hunting	48,204 (40,770; 53,216)	5,052 (4,273; 5,577)	606 (513; 669)	2,593 (2,318; 2,916)	14,719 (13,157; 16,552)	3,199 (<u>2,834; 3,580</u>)
<i>Total present</i>	47,418 (38,549; 50,424)	4,969 (4,040; 5,285)	599 (487 637)	2,181 (1,845; 2,298)	12,382 (10,472; 13,045)	2,780 (2,333; 2,933)
<i>Total pre hunting</i>	53,634 (45,066; 59,094)	5,621 (4,723; 6,193)	674 (566; 742)	2,979 (2,625; 3,343)	16,911 (14,897; 18,977)	3,653 (3,195; 4,80)
North Pacific						
Blue	2,095 (1,702; 2,227)	220 (178; 233)	26 (21; 28)	124 (105; 131)	704 (595; 741)	150 (126; 159)
Blue pre hunting	4,344 (3,429; 4,722)	455 (359; 495)	54 (43; 59)	309 (255; 343)	1,754 (1,388; 1,945)	363 (288; 402)
Fin	18,497 (115,900; 19,874)	1,939 (1,666; 2,083)	234 (201; 251)	850 (750; 902)	4,822 (4,258; 5,121)	1,083 (952; 1,152)
Fin pre hunting	39,661 (33,029; 43,588)	4,157 (3,461; 4,568)	499 (415; 548)	2,134 (1,762; 2,389)	12,110 (10,000; 13,561)	2,632 (2,179; 2.934)

<i>Total present</i>	20,593 (17,602; 22,100)	2,158 (1,845; 2,316)	260 (222; 279)	974 (855; 1,033)	5,526 (4,854; 5,526)	1,233 (1,078; 310)
<i>Total pre hunting</i>	44,006 (36,457; 48,310)	4,612 (3,820; 5,063)	553 (458; 607)	2,443 (2,006; 2,732)	13,864 (11,388; 15,505)	2,995 (2,467; 3.335)
Southern Hemisphere						
Blue	3,163 (2,567; 3,368)	332 (269; 353)	40 (32; 42)	187 (158; 197)	1,120 (1,062; 1,121)	227 (191; 240)
Blue pre hunting	171,040 (139,396; 181,270)	17,925 (14,609; 18,997)	2,137 (1,741; 2,264)	12,165 (10,419; 12,674)	69,051 (59,142; 71,941)	14,302 (12,161; 14,939)
Fin	28,363 (22,988; 30,066)	2,973 (2,409; 3,151)	358 (290; 380)	1,303 (1,100; 1,370)	7,394 (6,244; 7,774)	1,661 (1,392; 1,747)
Fin pre hunting	282,199 (229,825; 298,466)	29,574 (24,086; 31,279)	3,547 (2,889; 3,752)	15,181 (12,991; 15,784)	86,167 (73,738; 89,595)	18,728 (15,878; 19,538)
<i>Total present</i>	31,527 (25,554; 33,434)	3,304 (2,678; 3,510)	398 (323; 422)	1,490 (1,259; 1,570)	8,456 (7,144; 8,894)	1,888 (1,583; 1,987)
<i>Total pre hunting</i>	453,239 (369,222; 479,737)	47,499 (38,694; 50,276)	5,684 (4,630; 6,016)	27,346 (23,410; 28,458)	155,219 (132,880; 161,535)	33,029 (29,039; 34,474)
Global present	99,537 (81,705; 105,959)	10,432 (8,563; 11,105)	1,257 (1,032; 1,338)	4,645 (3,958; 4,898)	26,364 (22,469; 27,801)	5,901 (4,995; 6,230)
Global pre hunting	550,880 (450,745; 587,140)	57,732 (47,238; 61,532)	6,910 (5,654; 7,365)	32,767 (28,041; 34,533)	185,994 (159,165; 196,018)	39,678 (33,700; 41,890)

Table S4. Feeding and breeding areas of baleen whales, including dates and number of observations for each species and ocean basin. Start and end dates are approximate, and individuals will arrive earlier and later than the dates that appear below.

Species	Binomial	Mode	Start (month)	End (month)	Observations
North Atlantic					
Humpback	Megaptera novaeangliae	Feeding	4	10	36,445
		Breeding	12	2	1,494
North Atlantic right	Eubalaena glacialis	Feeding	3	11	8152
		Breeding	12	2	772
Fin	Balaenoptera physalus	Feeding	5	9	36,236
		Breeding	12	2	781
Blue	Balaenoptera musculus	Feeding	5	11	1,414
		Breeding	12	2	15
North Pacific					
Gray	Eschrichtius robustus	Feeding	6	10	2,236
		Breeding	1	3	8,336
Humpback	Megaptera novaeangliae	Feeding	4	11	14903
		Breeding	12	3	4890

North Pacific right	<i>Eubalaena japonica</i>	Feeding	6	9	4,917
		Breeding	12	2	16
Fin	<i>Balaenoptera physalus</i>	Feeding	5	9	2,367
		Breeding	12	2	424
Blue	<i>Balaenoptera musculus</i>	Feeding	5	11	4,467
		Breeding	12	2	275
Southern Hemisphere					
Humpback	<i>Megaptera novaeangliae</i>	Feeding	12	4	49,686
		Breeding	7	10	10,213
Southern right	<i>Eubalaena australis</i>	Feeding	12	4	4,170
		Breeding	7	9	3,768
Fin	<i>Balaenoptera physalus</i>	Feeding	12	4	1,382
		Breeding	5	8	749
Blue	<i>Balaenoptera musculus</i>	Feeding	12	2	556
		Breeding	6	8	68

Table S5. Values used in the Monte Carlo sensitivity analysis for estimating uncertainty in five key model parameters: (1) population size, (2) time on winter ground, (3) adult body mass, (4) percentage of the population migrating, and (5) percentage of adult females lactating. For ocean basin: North Atlantic (NA), North Pacific (NP), and Southern Hemisphere (SH).

Species	Ocean basin	Date	Population size (n)			Winter grounds (days)			Adult mass (kg)			Migrating (%)			Lactating (%)		
			Lower	Best	Upper	Lower	Best	Upper	Lower	Best	Upper	Lower	Best	Upper	Lower	Best	Upper
Blue whale	NA	current	360	400	440	63	90	117	84	105	126	0.5	1	1	0.2	0.4	0.6
		prehunting	5250	7500	9750	63	90	117	84	105	126	0.5	1	1	0.2	0.4	0.6
	NP	current	2700	3000	3300	63	90	117	84	105	126	0.5	1	1	0.2	0.4	0.6
		prehunting	4200	6000	7800	63	90	117	84	105	126	0.5	1	1	0.2	0.4	0.6
	SH	current	4076	4529	4982	63	90	117	84	105	126	0.5	1	1	0.2	0.4	0.6
		prehunting	236098	236224	236347	63	90	117	84	105	126	0.5	1	1	0.2	0.4	0.6
Fin whale	NA	current	71100	79000	86900	63	90	117	45.48	56.85	68.22	0.5	1	1	0.225	0.45	0.675
		prehunting	79000	79000	102700	63	90	117	45.48	56.85	68.22	0.5	1	1	0.225	0.45	0.675
	NP	current	27900	31000	34100	84	90	117	45.48	56.85	68.22	0.5	1	1	0.225	0.45	0.675
		prehunting	45500	65000	84500	84	90	117	45.48	56.85	68.22	0.5	1	1	0.225	0.45	0.675
	SH	current	42782	47535	52289	63	90	117	45.48	56.85	68.22	0.5	1	1	0.225	0.45	0.675
		prehunting	458340	462488	463408	63	90	117	45.48	56.85	68.22	0.5	1	1	0.225	0.45	0.675
Gray whale	NP	current	18700	20580	22870	63	90	117	21.936	27.42	32.904	0.5	1	1	0.25	0.5	0.75
		prehunting	20580	25000	32500	63	90	117	21.936	27.42	32.904	0.5	1	1	0.25	0.5	0.75
Humpback whale	NA	current	11250	15000	18750	63	90	117	21.24	26.55	31.86	0.5	1	1	0.21	0.42	0.63
		prehunting	9964	20488	57030	63	90	117	21.24	26.55	31.86	0.5	1	1	0.21	0.42	0.63
	NP	current	22470	26662	30850	84	90	117	21.24	26.55	31.86	0.5	1	1	0.21	0.42	0.63
		prehunting	25000	25000	40000	84	90	117	21.24	26.55	31.86	0.5	1	1	0.21	0.42	0.63
	SH	current	78074	86749	95424	63	90	117	21.24	26.55	31.86	0.5	1	1	0.21	0.42	0.63
		prehunting	141324	141724	142126	63	90	117	21.24	26.55	31.86	0.5	1	1	0.21	0.42	0.63

Right whale	NA	current	302	336	370	63	90	117	29.248	36.56	43.872	0.25	0.5	0.75	0.125	0.25	0.375
		prehunting	9800	14000	18200	63	90	117	29.248	36.56	43.872	0.25	0.5	0.75	0.125	0.25	0.375
	NP	current	360	400	440	63	90	117	29.248	36.56	43.872	0.25	0.5	0.75	0.125	0.25	0.375
		prehunting	12322	13691	15060	63	90	117	29.248	36.56	43.872	0.25	0.5	0.75	0.125	0.25	0.375
	SH	current	12322	13691	15060	63	90	117	29.248	36.56	43.872	0.25	0.5	0.75	0.125	0.25	0.375
		prehunting	139389	143760	148100	63	90	117	29.248	36.56	43.872	0.25	0.5	0.75	0.125	0.25	0.375

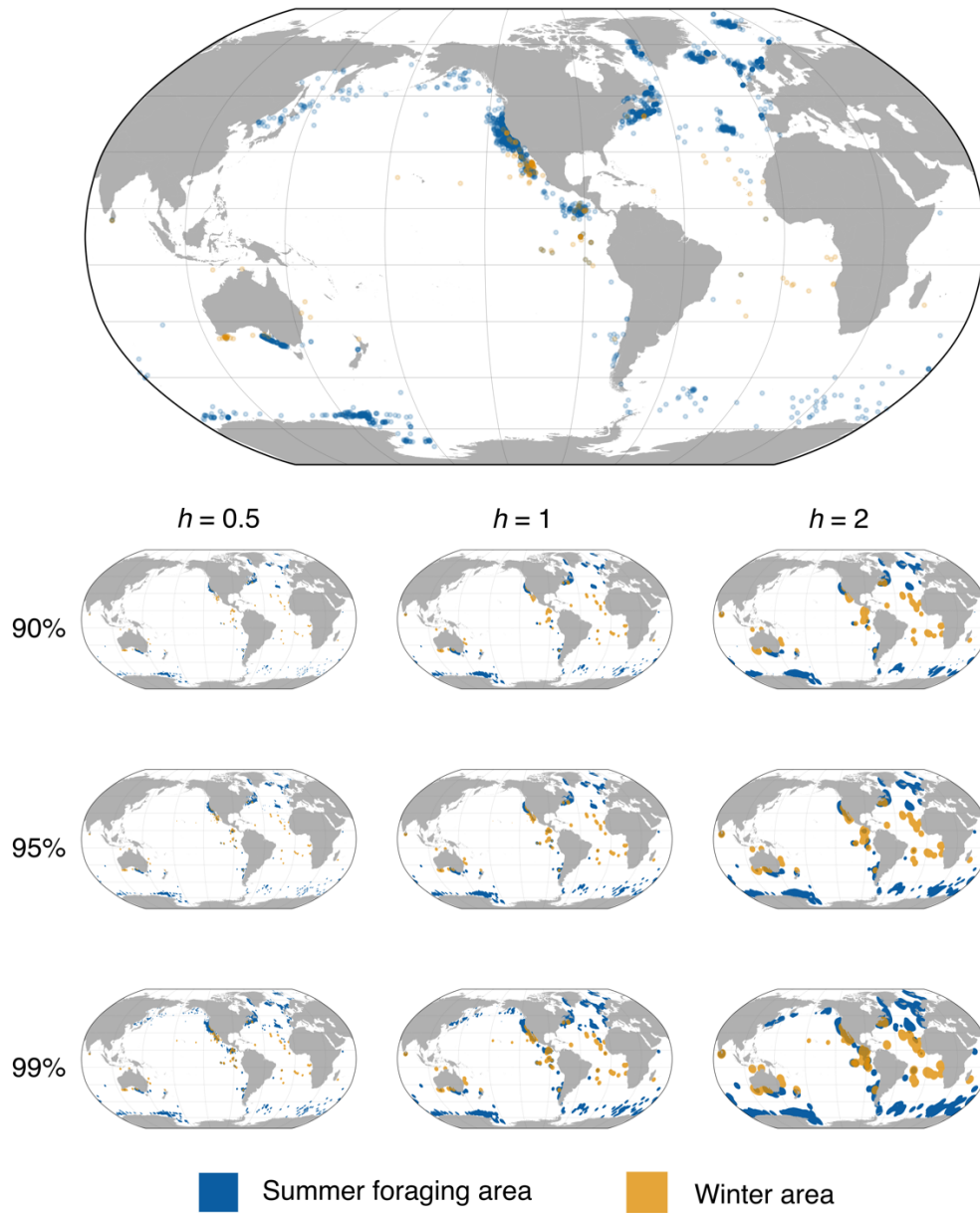


Figure S1. Blue whale observations (top) and maps constructed under varying h parameters. Sources include nineteenth-century whaling data (whalinghistory.org) and contemporary databases such as OBIS-SEAMAP and Global Biodiversity Information Facility.

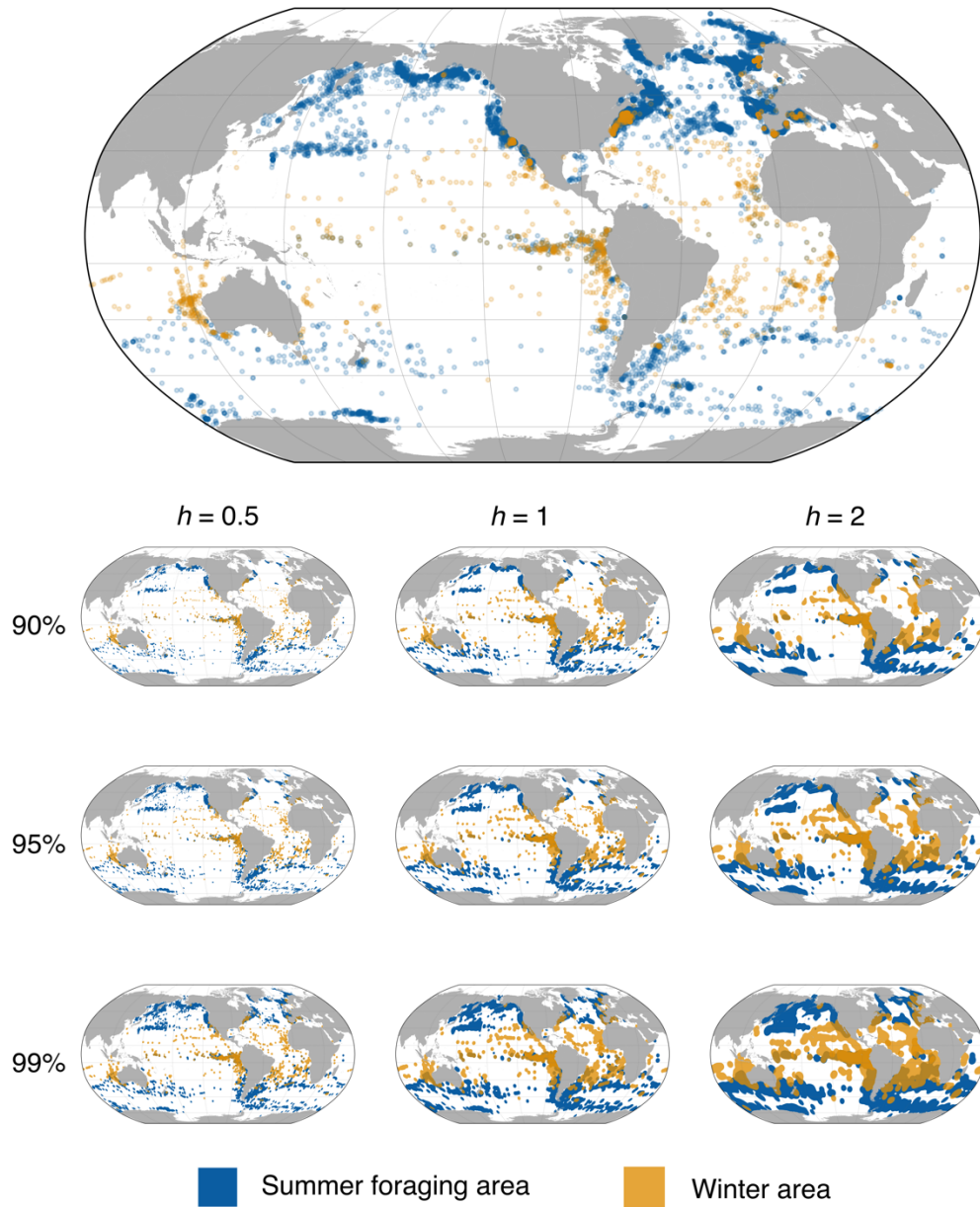


Figure S2. Fin whale observations (above) and maps constructed under varying h parameters. Sources include nineteenth-century whaling data (whalinghistory.org) and contemporary databases such as OBIS-SEAMAP and Global Biodiversity Information Facility.

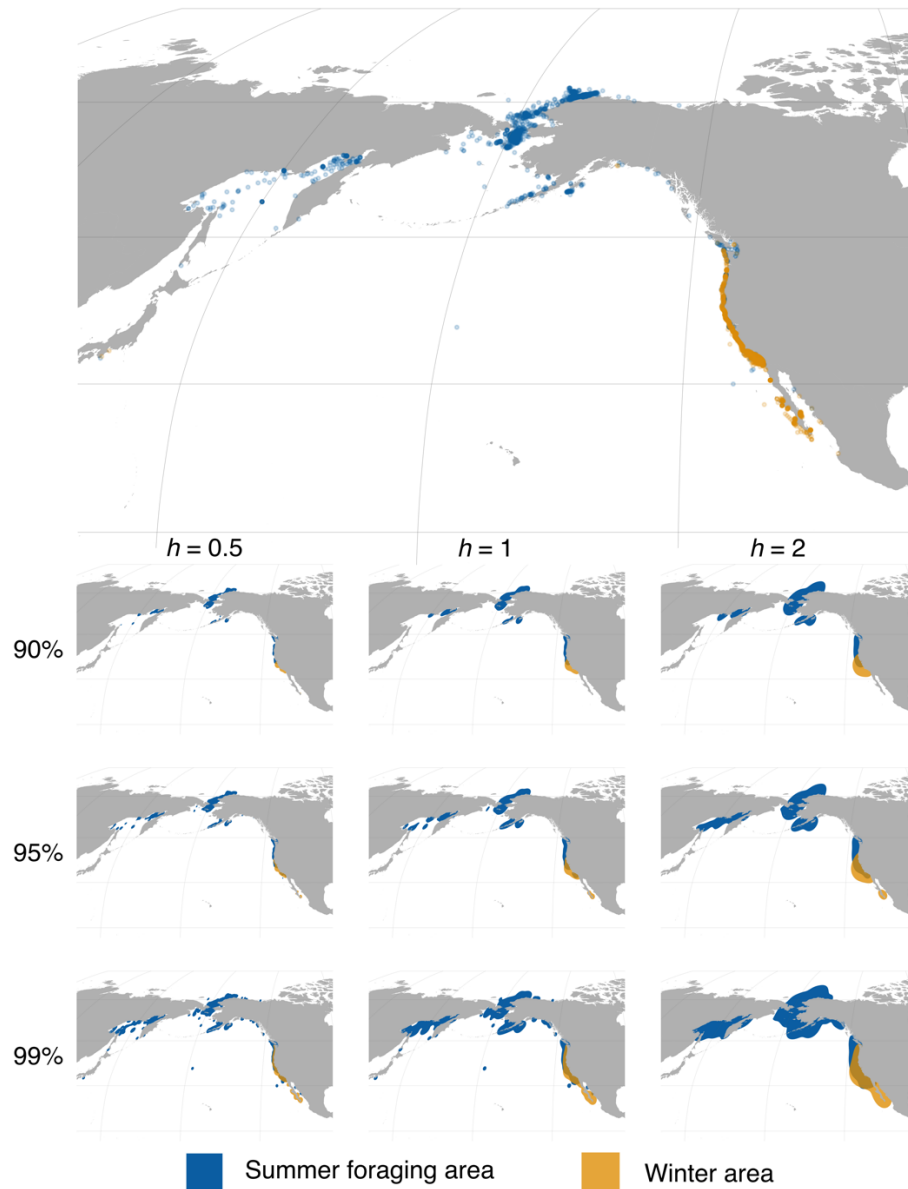


Figure S3. Gray whale observations (top) and maps constructed under varying h parameters. Sources include nineteenth-century whaling data (whalinghistory.org) and contemporary databases such as OBIS-SEAMAP and Global Biodiversity Information Facility.

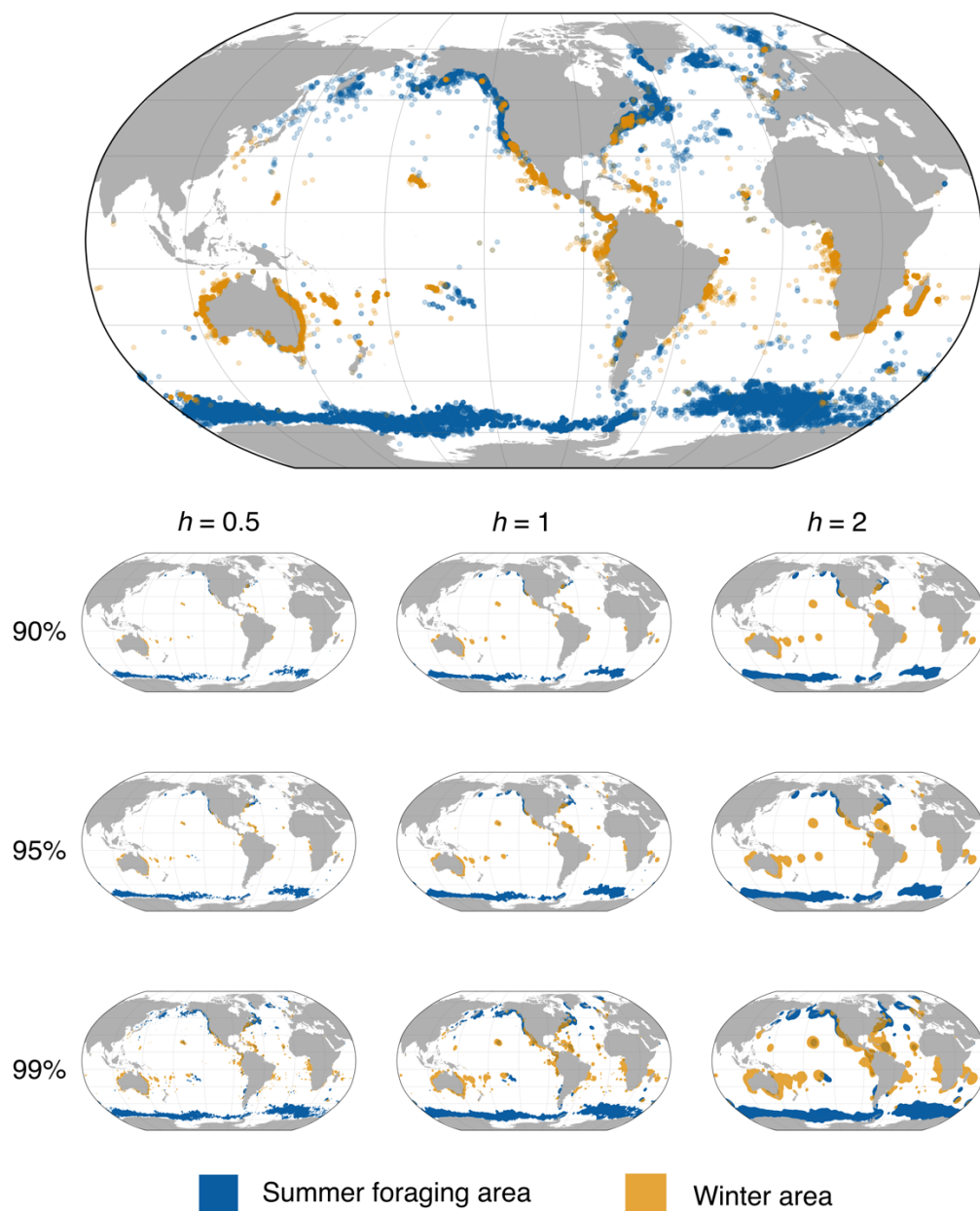


Figure S4. Humpback whale observations (above) and maps constructed under varying h parameters. Sources include nineteenth-century whaling data (whalinghistory.org) and contemporary databases such as OBIS-SEAMAP and Global Biodiversity Information Facility.

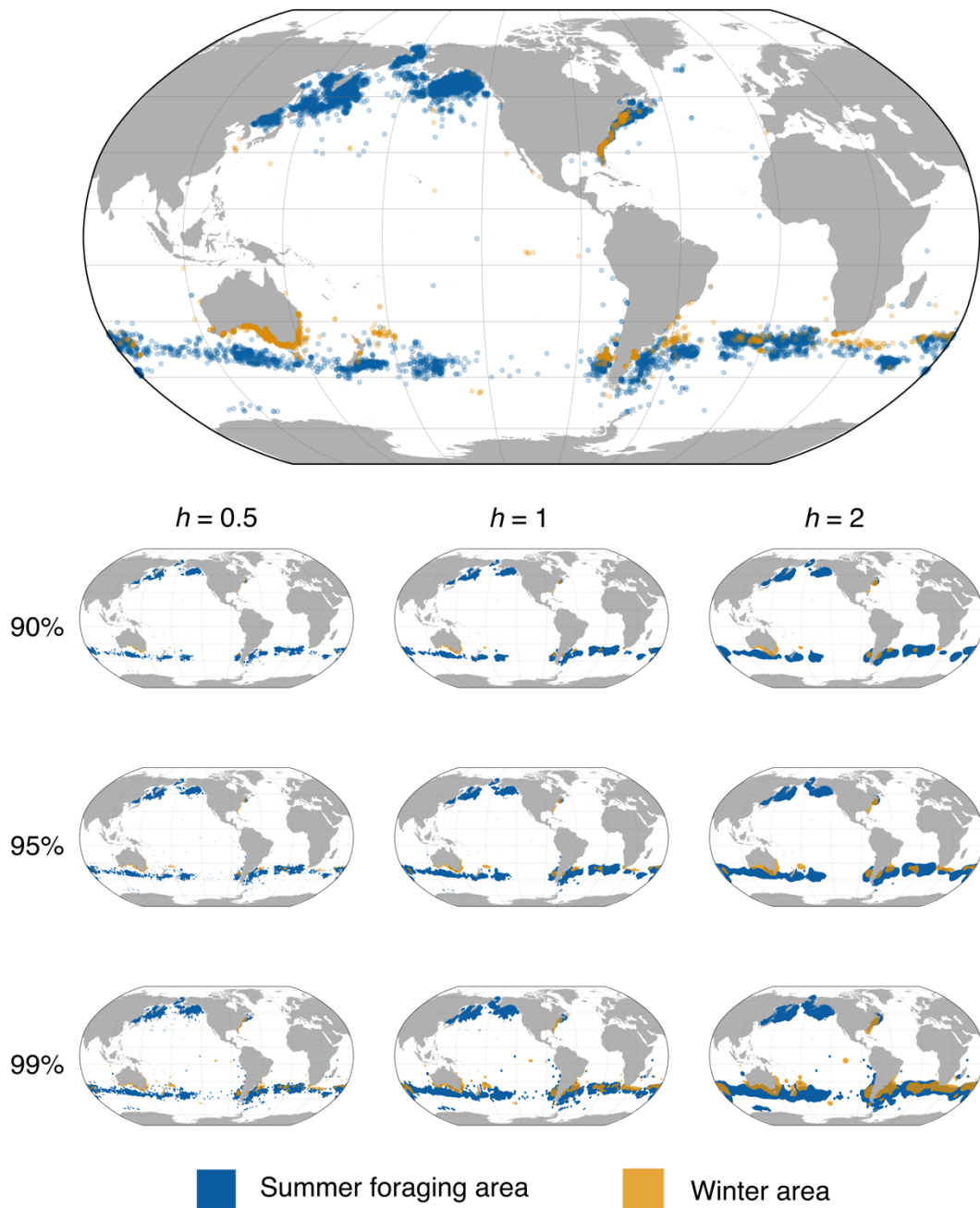


Figure S5. Right whale observations (above) and maps constructed under varying h parameters. Sources include nineteenth-century whaling data (whalinghistory.org) and contemporary databases such as OBIS-SEAMAP and Global Biodiversity Information Facility.

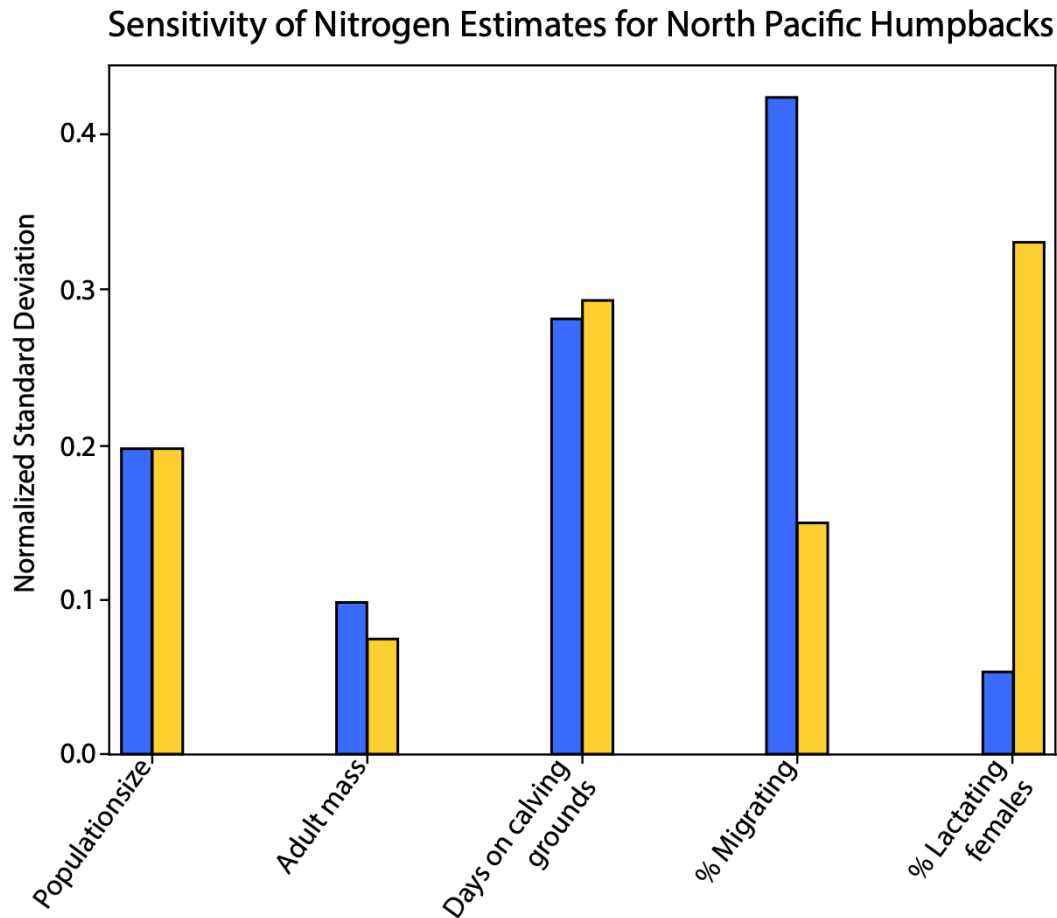


Figure S6. Sensitivity of nitrogen estimates for North Pacific humpbacks to uncertainty in model inputs, including population size, adult mass, days on winter grounds, percent migrating, and percent lactating females. Deadfall N (blue) is most sensitive to percent of population migrating. Urea N (yellow) is most sensitive to population size, days on calving ground, and percentage of lactating females. Source data are provided as a Source Data file.

Supplementary References

- 1 Maldonado, C. *et al.* Estimating species diversity and distribution in the era of Big Data: to what extent can we trust public databases? *Global Ecol. Biogeogr.* **24**, 973-984 (2015).
- 2 Zizka, A. *et al.* CoordinateCleaner: Standardized cleaning of occurrence records from biological collection databases. *Methods Ecol. Evol.* **10**, 744-751 (2019).
- 3 Rasmussen, K., *et al.* Southern Hemisphere humpback whales wintering off Central America: Insights from water temperature into the longest mammalian migration. *Biol. Lett.* **3**, 302-305 (2007).
- 4 Stephenson, F. *et al.* Modelling the spatial distribution of cetaceans in New Zealand waters. *Divers. Distrib.* **26**, 495-516 (2020).
- 5 Pérez - Jorge, S. *et al.* Environmental drivers of large - scale movements of baleen whales in the mid - North Atlantic Ocean. *Divers. Distrib.* **26**, 683-698 (2020).
- 6 Horton, T. W. *et al.* Thermal imaging and biometrical thermography of humpback whales. *Frontiers in Marine Science* **4**, 424 (2017).
- 7 IUCN Standards and Petitions Committee. Guidelines for Using the IUCN Red List Categories and Criteria. Version 14. Prepared by the Standards and Petitions Committee. Downloadable from <http://www.iucnredlist.org/documents/RedListGuidelines.pdf>. . (2019).
- 8 Lichti, N. I. & Swihart, R. K. Estimating utilization distributions with kernel versus local convex hull methods. *The Journal of Wildlife Management* **75**, 413-422 (2011).
- 9 Irvine, L. M. *et al.* Spatial and temporal occurrence of blue whales off the US West Coast, with implications for management. *Plos One* **9**, e102959 (2014).
- 10 Palacios, D. M. *et al.* Tracking North Pacific humpback whales to unravel their basin-wide movements. (2019).
- 11 Scales, K. L. *et al.* Should I stay or should I go? Modelling year - round habitat suitability and drivers of residency for fin whales in the California current. *Divers. Distrib.* **23**, 1204-1215 (2017).
- 12 Smith, T. D. & Reeves, R. R. Spatial and seasonal distribution of American whaling and whales in the age of sail. *Plos One*, 7(4): e34905. doi:34910.31371/journal.pone.0034905 (2012).
- 13 Wickham, H. *Package 'ggplot2': Elegant Graphics for Data Analysis*. (Springer Verlag, 2016).
- 14 Bivand, R. *et al.* rgeos: interface to geometry engine—open source ('GEOS'). 2019. URL <http://CRAN.R-project.org/package=rgeos>. *R package version 0.3-14* (2019).
- 15 Brownell Jr, R. A review of gray whales (*Eschrichtius robustus*) on their wintering grounds in Mexican waters. *J. Cetacean Res. Manage* **5**, 281-295 (2003).
- 16 Keller, C. A., Garrison, L., Baumstark, R., Ward-Geiger, L. I. & Hines, E. Application of a habitat model to define calving habitat of the North Atlantic right whale in the southeastern United States. *Endangered Species Research* **18**, 73-87 (2012).

- 17 Soldevilla, M. S., Rice, A. N., Clark, C. W. & Garrison, L. P. Passive acoustic monitoring on the North Atlantic right whale calving grounds. *Endanger. Species Res.* **25**, 115-140 (2014).
- 18 Kenney, R. D., Mayo, C. A. & Winn, H. E. Migration and foraging strategies at varying spatial scales in western North Atlantic right whales: a review of hypotheses. *J. Cetacean Res. Manage.*, 251-260 (2020).
- 19 Vernazzani, B. G., Cabrera, E. & Brownell Jr, R. L. Eastern South Pacific southern right whale photo-identification catalog reveals behavior and habitat use patterns. *Mar. Mamm. Sci.* **30**, 389-398 (2014).
- 20 Santillán, L., Roca, M., Apaza, M., Oliveira, L. & Ontón, K. New record of mother-calf pair of southern right whale, *Eubalaena australis*, off the Peruvian coast. *Latin Am. J. Aquat. Mammals* **3**, 83-84 (2004).
- 21 Bannister, J. Status of southern right whales (*Eubalaena australis*) off Australia. *J. Cetacean Res. Manage. Special Issue* **2**, 103-110 (2001).
- 22 Zerbini, A. N. *et al.* Winter distribution and abundance of humpback whales (*Megaptera novaeangliae*) off Northeastern Brazil. *J. Cetacean Res. Manage.* **6**, 101-107 (2004).
- 23 Charlton, C. *et al.* Southern right whales (*Eubalaena australis*) return to a former wintering calving ground: Fowlers Bay, South Australia. *Mar. Mamm. Sci.* **35**, 1438-1462 (2019).
- 24 Best, P. B., Schaeff, C., Reeb, D. & Palsbøll, P. J. Composition and possible function of social groupings of southern right whales in South African waters. *Behaviour*, 1469-1494 (2003).
- 25 Carroll, E. L. *et al.* Reestablishment of former wintering grounds by New Zealand southern right whales. *Mar. Mamm. Sci.* **30**, 206-220 (2014).
- 26 Dombroski, J. R., Parks, S. E., Groch, K. R., Flores, P. A. & Sousa-Lima, R. S. Vocalizations produced by southern right whale (*Eubalaena australis*) mother-calf pairs in a calving ground off Brazil. *The Journal of the Acoustical Society of America* **140**, 1850-1857 (2016).
- 27 de Oliveira Santo, M. C., Siciliano, S., de Souza, S. P. & Pizzorno, J. L. A. Occurrence of southern right whales (*Eubalaena australis*) along southeastern Brazil. *J. Cetacean Res. Manage.*, 153-156 (2020).
- 28 Elwen, S. H. & Best, P. B. Female southern right whales *Eubalaena australis*: Are there reproductive benefits associated with their coastal distribution off South Africa? *Mar. Ecol. Prog. Ser.* **269**, 289-295 (2004).
- 29 Gibbons, J., Capella, J. J., Kusch, A. & Cárcamo, J. in *An. Inst. Patagonia*. 75-80.
- 30 Pirzl, R., Patenaude, N. J., Burnell, S. & Bannister, J. Movements of southern right whales (*Eubalaena australis*) between Australian and subantarctic New Zealand populations. *Mar. Mamm. Sci.* **25**, 455-461 (2009).
- 31 Rayment, W., Davidson, A., Dawson, S., Slooten, E. & Webster, T. Distribution of southern right whales on the Auckland Islands calving grounds. *N. Z. J. Mar. Freshwat. Res.* **46**, 431-436 (2012).
- 32 Seyboth, E., Groch, K. R., Secchi, E. R. & Dalla Rosa, L. Habitat use by southern right whales, *Eubalaena australis* (Desmoulins, 1822), in their main northernmost calving area in the western South Atlantic. *Mar. Mamm. Sci.* **31**, 1521-1537 (2015).

- 33 Watson, M., Stamation, K. & Charlton, C. Calving rates, long-range movements and site fidelity of southern right whales (*Eubalaena australis*) in south-eastern Australia. *J. Cetacean Res. Manage.* **22**, 17-28 (2021).
- 34 Rowntree, V. J., Payne, R. S. & Schell, D. M. Changing patterns of habitat use by southern right whales (*Eubalaena australis*) on their nursery ground at Península Valdés, Argentina, and in their long-range movements. *J. Cetacean Res. Manage.*, 133-143 (2020).
- 35 Zeh, J. M., Dombroski, J. R. & Parks, S. E. Preferred shallow-water nursery sites provide acoustic crypsis to southern right whale mother–calf pairs. *Royal Soc. Open Sci.* **9**, 220241 (2022).
- 36 Steiger, G. H., Calambokidis, J., Sears, R., Balcomb, K. C. & Cubbage, J. C. Movement of humpback whales between California and Costa Rica. *Mar. Mamm. Sci.* **7**, 306-310 (1991).
- 37 Craig, A. S. & Herman, L. M. Habitat preferences of female humpback whales *Megaptera novaeangliae* in the Hawaiian Islands are associated with reproductive status. *Mar. Ecol. Prog. Ser.* **193**, 209-216 (2000).
- 38 Kiszka, J., Vely, M. & Breysse, O. Preliminary account of cetacean diversity and humpback whale (*Megaptera novaeangliae*) group characteristics around the Union of the Comoros (Mozambique Channel). (2010).
- 39 Rossi-Santos, M. R. *et al.* Occurrence and distribution of humpback whales (*Megaptera novaeangliae*) on the north coast of the State of Bahia, Brazil, 2000–2006. *ICES J. Mar. Sci.* **65**, 667-673 (2008).
- 40 Mikhalev, Y. A. Humpback whales *Megaptera novaeangliae* in the Arabian Sea. *Mar. Ecol. Prog. Ser.* **149**, 13-21 (1997).
- 41 Cartwright, R. *et al.* Between a rock and a hard place: habitat selection in female-calf humpback whale (*Megaptera novaeangliae*) pairs on the Hawaiian breeding grounds. *Plos One* **7**, e38004 (2012).
- 42 Smith, J. N. *et al.* Identification of humpback whale breeding and calving habitat in the Great Barrier Reef. *Mar. Ecol. Prog. Ser.* **447**, 259-272 (2012).
- 43 Rasmussen, K. *et al.* Southern Hemisphere humpback whales wintering off Central America: insights from water temperature into the longest mammalian migration. *Biol. Lett.* **3**, 302-305 (2007).
- 44 Stevick, P. T. *et al.* Migratory destinations and timing of humpback whales in the southeastern Caribbean differ from those off the Dominican Republic. *J. Cetacean Res. Manage.* **18**, 127-133 (2018).
- 45 Herman, L. M. *et al.* Resightings of humpback whales in Hawaiian waters over spans of 10–32 years: Site fidelity, sex ratios, calving rates, female demographics, and the dynamics of social and behavioral roles of individuals. *Mar. Mamm. Sci.* **27**, 736-768 (2011).
- 46 Carvalho, I. *et al.* Does temporal and spatial segregation explain the complex population structure of humpback whales on the coast of West Africa? *Mar. Biol.* **161**, 805-819 (2014).
- 47 Rasmussen, K., Calambokidis, J. & Steiger, G. H. Distribution and migratory destinations of humpback whales off the Pacific coast of Central America during the boreal winters of 1996–2003. *Mar. Mamm. Sci.* **28**, E267-E279 (2012).
- 48 Webster, I., Cockcroft, V., Cadinouche, A. & Huggins, A. Cetacean diversity of Mauritius. *J. Cetacean Res. Manage.* **21**, 45-58 (2020).

- 49 Minton, G. *et al.* Seasonal distribution, abundance, habitat use and population identity of humpback whales in Oman. *J. Cetacean Res. Manage.*, 185-198 (2020).
- 50 Whitehead, H. & Moore, M. J. Distribution and movements of West Indian humpback whales in winter. *Canadian Journal of Zoology* **60**, 2203-2211 (1982).
- 51 Dulau-Drouot, V., Fayon, J., Mouysset, L. & Boucaud, V. Occurrence and residency patterns of humpback whales off Réunion Island during 2004–10. *J. Cetacean Res. Manage.* **12**, 255-263 (2012).
- 52 Bivand, R. & Rundel, C. rgeos: Interface to Geometry Engine. Open Source. R package version 0.5-2. <https://CRAN.R-project.org/package=rgeos>. (2019).
- 53 Geijer, C. K. A., Notarbartolo di Sciara, G. & Panigada, S. Mysticete migration revisited: Are Mediterranean fin whales an anomaly? *Mamm. Rev.* **46**, 284-296 (2016).
- 54 Smith, C., Roman, J. & Nation, J. B. A metapopulation model for whale-fall specialists: the largest whales are essential to prevent species extinctions. *J. Mar. Res.* **77**, 283–302 (2019).
- 55 Tulloch, V. J., Plagányi, É. E., Brown, C., Richardson, A. J. & Matear, R. Future recovery of baleen whales is imperiled by climate change. *Global Change Biol.* **25**, 1263-1281 (2019).
- 56 Cooke, J. G. *Balaenoptera physalus*. The IUCN Red List of Threatened Species 2018: e.T2478A50349982. <https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T2478A50349982.en>. Accessed on 15 April 2022. (2018).
- 57 Cooke, J. G. *Megaptera novaeangliae*. The IUCN Red List of Threatened Species 2018: e.T13006A50362794. <https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T13006A50362794.en>. Accessed on 15 April 2022. (2018).
- 58 Suárez-Menéndez, M. *et al.* Wild pedigrees inform mutation rates and historic abundance in baleen whales. *Science* **381**, 990-995 (2023).
- 59 Pettis, H. M., Pace, R. M., III & Hamilton, P. K. North Atlantic Right Whale Consortium 2021 Annual Report Card. <https://www.narwc.org/>. (2022).
- 60 Christensen, L. B. Marine mammal populations: reconstructing historical abundances at the global scale. (Fisheries Centre, University of British Columbia, Vancouver, 2006).
- 61 Cheeseman, T. *et al.* Bellwethers of change: population modeling of North Pacific humpback whales from 2002 through 2021 reveals shift from recovery to climate response. *R. Soc. Open Sci.* **11**, 231462 (2024).
- 62 Stewart, J. D. & Weller, D. W. Abundance of eastern North Pacific gray whales 2019/2020. (2021).