A Supplementary Materials Online

A.I Habitats

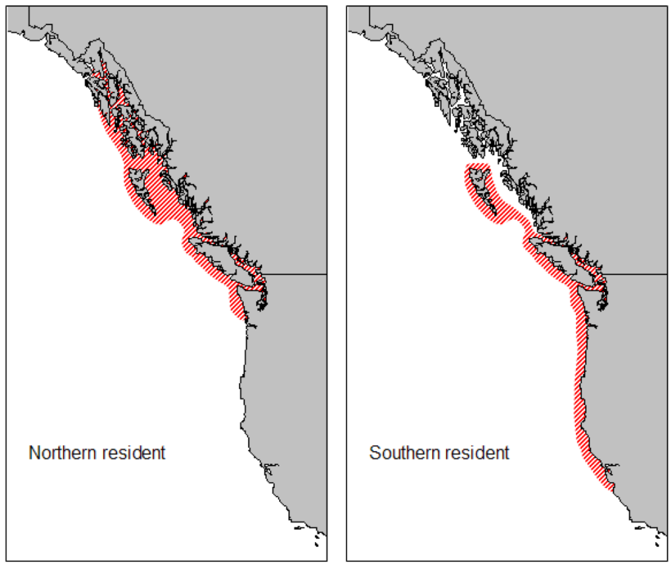

Figure A.1: Northern and Southern Overlapping Habitats
Known geographical ranges of northern (left) and southern (right) resident killer whales. Extent of movement offshore is unknown. Source: Figure 1. in Ford (2006)

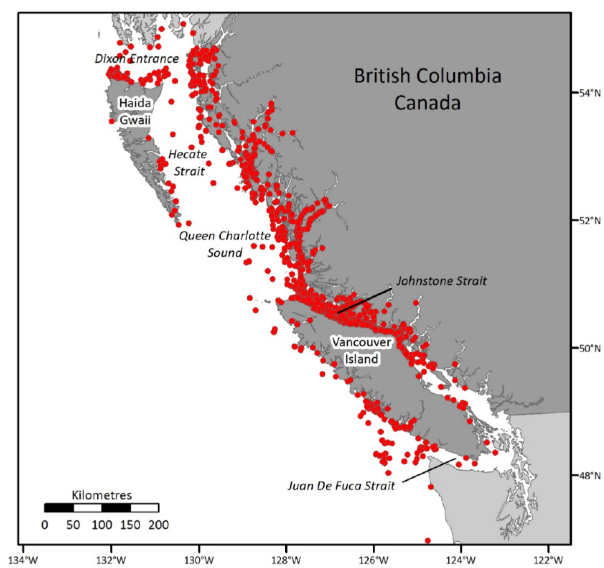

Figure A.2: Locations of sightings and encounters with Northern Resident Killer Whales, 1973–2014. Source: Figure 1. in Ford et al. (2017)

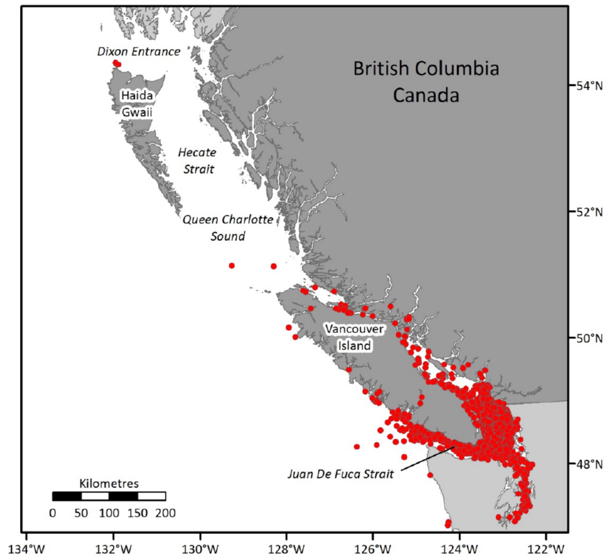

Figure A.3: Distribution of sightings and encounters with Southern Resident Killer Whales. Source: Figure 2. in Ford et al. (2017)

A.II List of 31 Ports of Interest

Table A.1: Ports in the Critical Habitat

Port	Longitude	Latitude	Port	Longitude	Latitude
Vancouver (CAN)	-123.1120	49.2847	Anacortes	-122.6170	48.5167
Fraser River Port	-122.9170	49.2000	March Point	-122.5670	48.5000
Richmond (CAN)	-123.1260	49.1978	Esquimalt	-123.4330	48.4333
Nanaimo	-123.9330	49.1667	Victoria (CAN)	-123.3830	48.4167
Harmac	-123.8500	49.1333	La Conner	-122.5060	48.3739
Roberts Bank	-123.1355	49.0270	Port Angeles	-123.4170	48.1333
Ladysmith	-123.8260	49.0063	Port Townsend	-122.7920	48.0927
Chemainus	-123.7000	48.9167	Everett (WA)	-122.2170	47.9833
Crofton	-123.6330	48.8667	Point Wells	-122.4000	47.7833
Cherry Point	-122.7500	48.8667	Bainbridge Island	-122.5210	47.6222
Ferndale	-122.7170	48.8333	Seattle	-122.3555	47.5900
Cowichan Bay	-123.6000	48.7500	Bremerton	-122.6170	47.5667
Bellingham	-122.5000	48.7500	Manchester (USA)	-122.5330	47.5500
Sidney	-123.3830	48.6500	Tacoma	-122.3993	47.2649
Orcas Is.	-122.9577	48.6296	Olympia	-122.9145	47.0554
Roche Harbour	-123.1782	48.6214			

A.III Map of Routes from Sea Routes

Figure A.4: Incoming and outgoing routes

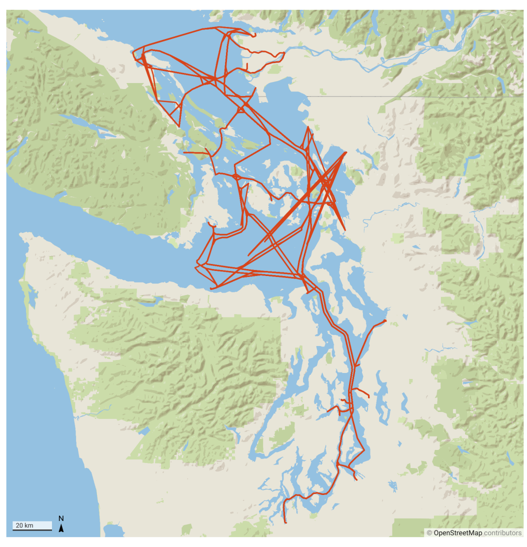

Figure A.5: Routes within the critical habitat

A.IV KW Demographic Data

As described in the main text, the two resident populations, especially the Northern one, are tallied every few years. The population surveys of the residents were the basis of our demographic data. The surveys are particularly useful because instead of giving a list of the animals they are organized into family trees that reflect genealogical relationships and include information on gender, year of birth, and year of death, if known.

Consecutive surveys also helped to pinpoint ages and genders of animals that were previously too young. As the survey effort extended towards the turn of the century, information on familial relationships became more precise. Combining multiple surveys allowed us to track major life events of individual animals, such as births. Given that each KW birth is highly valued from a preservation and ecological stand point, regular surveying also helps keep track of the survival of calves. This was more difficult for the SRKW because only two population census could be used for them: the one in 1999 and the one in 2019. Consequently, animals that were born after the former and perished before the latter were missing from both. Similarly, information on the death of animals between the two census was missing.

Part of this missing information could be amended by scouring the Center for Whale Research's historical website records. Their website provided family trees for the SRKW in 2010. Still, that meant long gaps between reliable surveys. Luckily, the KW are highly popular subjects among whale watchers. The SRKW were observed by whale watchers between 1999 and 2019 countless of times and the records of their various sightings were published online. The Orca Network proved particularly useful in this regard because they list dated sightings all around the Salish Sea and their records go back until 2003.[59]. Moreover, the Network validates photos sent in by whale watchers which makes the list of animals appearing in a sighting report more reliable. The Center for Whale Research also records its own encounters with the KW starting 2016.[60] Information from these sources helped to determine missing dates of births and deaths. They also helped to augment missing information for the NRKW.

[59]These are available here: https://indigo-ukulele-jm29.squarespace.com/sightings-report-archive

[60]These encounter reports are available here: https://whaleresearch.wixsite.com/archives

A.V Fertility, Mortality, and KW Age

It is well known that female whales reach sexual maturity by their mid-teens and remain potentially reproductive into their early forties.[61] The profile of KW fertility rises steeply at first, reaches a peak near the age of 20, and then falls. This feature of their reproduction is shown graphically below and, then more concretely, in table form. The fecundity of KW is maximized near the age of 20 when almost twenty percent of females in this age category will succeed in giving birth. Fecundity falls off dramatically after the age of 40 with a lengthy period of senescence starting in their late 20s.

Figure A.V reinforces these findings. There are only 2 births across the sample of 1645 female whale-years when whales are aged 0-9, and 26 births post the age of 40 across 1262 female whale-years. To capture this highly non-linear, and asymmetric, fertility profile of KW, we employ a higher-order polynomial in age.

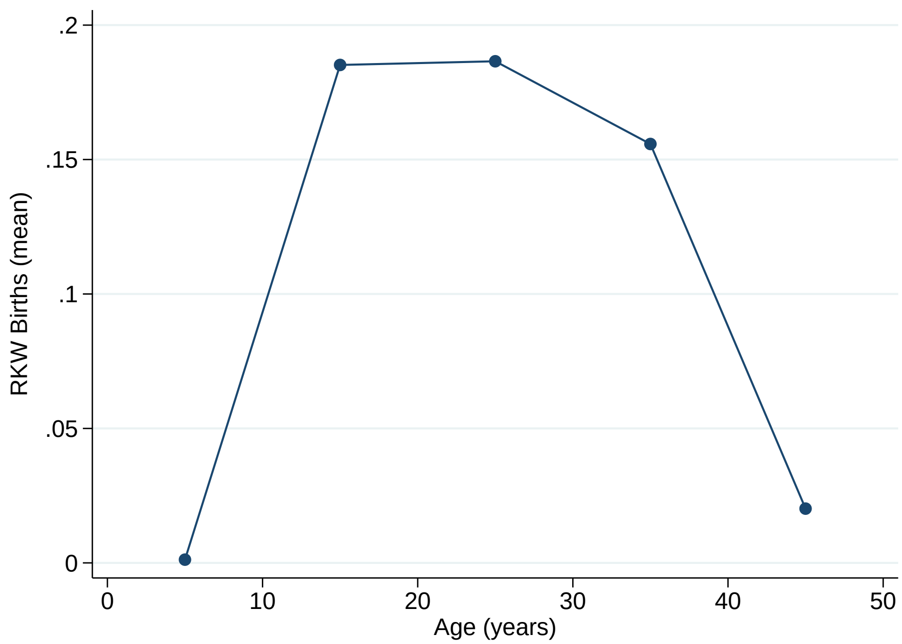

Figure A.6: Percentage of females with births by age in the pooled RKW populations, 1979-2019

[61] See the life table analyses by Olesiuk, Ellis and Ford (2005*a*), Olesiuk, Ellis and Ford (2005*b*) and Olesiuk, Bigg and Ellis (1990).

Table A.2: Births in the pooled RKW populations by age, 1979-2019

		Birth		
Age group	n	without	with	Mean
0 − 9	1645	1643	2	0.001
10 − 19	1215	990	225	0.185
20 − 29	922	750	172	0.187
30 − 39	751	634	117	0.156
40 −	1288	1262	26	0.020
Total	5821	5279	542	0.093

In Figure A.7, we present the mean death rate at various ages. Since deaths early in life are very common the 0-9 year window has been divided above and below the age of 4. As shown there is significant neonatal fatality which declines quite quickly so that by a whale's mid-teens mortality is at its lowest. Thereafter mortality rises with age with an especially steep increase post-40. Although there are some very old whales in our sample, the age axis is cut off at age 50 for presentation. This same information is presented in tabular form in Table A.3 where it is easier to see that mortality does not rise to the neonatal level until whales are past 40 years of age. The figure and table again suggest a specification for deaths with a higher-order polynomial in age.

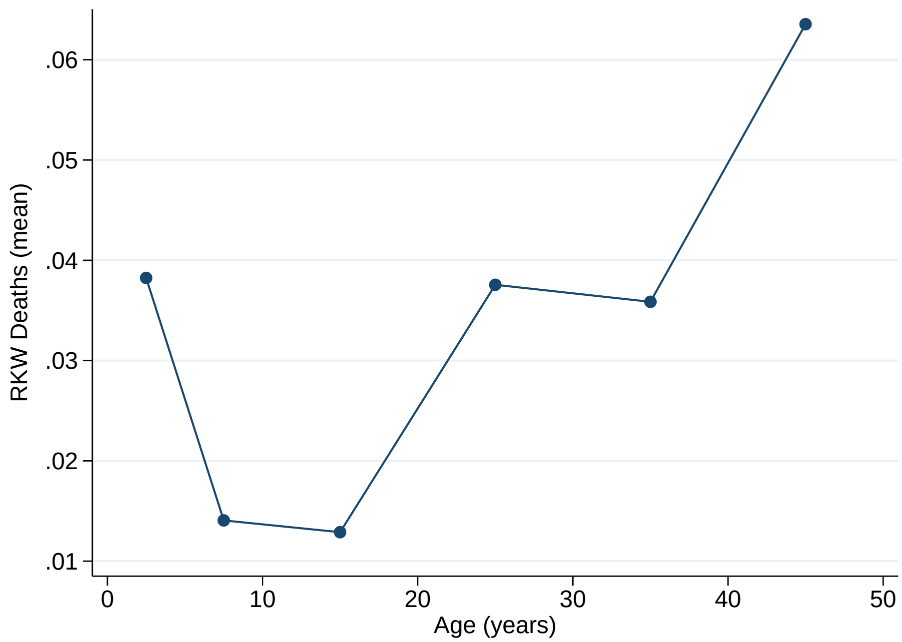

Figure A.7: Percentage of deaths by age in the pooled RKW populations, 1979-2019

Table A.3: Deaths in the pooled RKW populations by age, 1979-2019

Age group	n	Death No	Death Yes	Mean
0 – 4	2432	2339	93	0.038
5 – 9	2062	2033	29	0.014
10 – 19	2716	2681	35	0.013
20 – 29	1917	1845	72	0.038
30 – 39	1199	1156	43	0.036
40 –	1432	1341	91	0.064
Total	11758	11395	363	0.031

A.VI Fertility, Mortality Plots

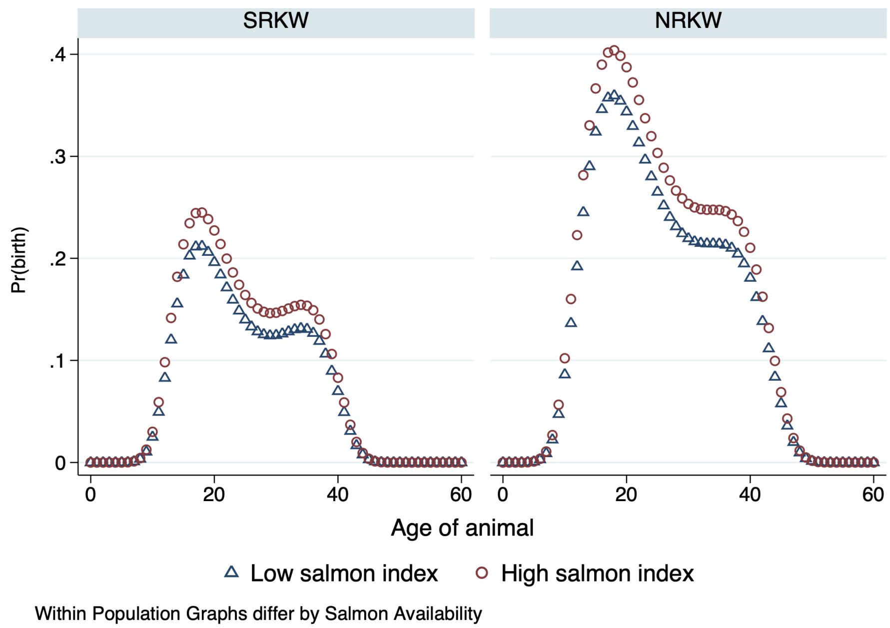

Figure A.8: Fertility Profiles

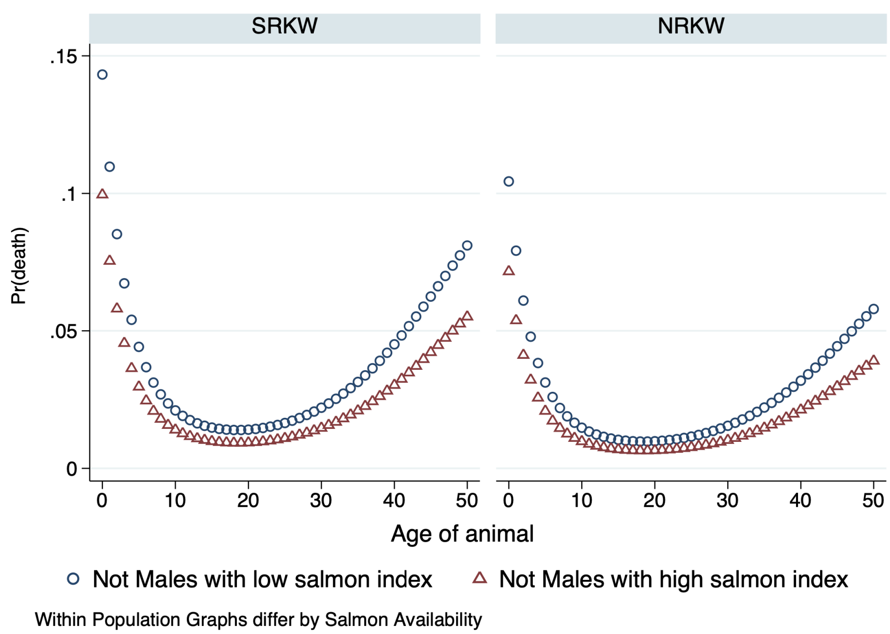

Figure A.9: Mortality Profiles

A.VII Matriline FE regressions: Pod level Clustering

The following six tables replicate the procedures in the text but now estimate the models using conditional logit assuming matriline fixed effects. The differences are slight and highlighted in the text with footnotes where appropriate.

Table A.4: Baseline Demographic Determinants of Fertility with matriline FE

	I.	II.	III.	IV.	V.
Age	2.80	2.82	2.83	2.85	3.98
	0.000	0.000	0.000	0.000	0.000
Age^2	−0.16	−0.16	−0.16	−0.16	−0.24
	0.000	0.000	0.000	0.000	0.000
Age^3	0.004	0.004	0.004	0.004	0.006
	0.000	0.000	0.000	0.000	0.000
Age^4	−0.00004	−0.00004	−0.00004	−0.00004	−0.00005
	0.000	0.000	0.000	0.000	0.000
L1.Salmon abundance		0.36	0.32	0.29	0.28
		0.005	0.011	0.023	0.031
L1.Within competition			−0.003	−0.004	−0.003
			0.004	0.002	0.003
L1.Across competition				−0.01	−0.01
				0.000	0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes
NRKW × Age	No	No	No	No	Yes
N	5527	5379	5379	5379	5379
Log-likelihood	-1268.75	-1242.09	-1238.79	-1234.29	-1231.48
Groups dropped	20	21	21	21	21

Table A.5: Baseline Demographic Determinants of Mortality with matriline FE

	I.	II.	III.	IV.	V.
Age	−0.30	−0.30	−0.30	−0.31	−0.46
	0.000	0.000	0.000	0.000	0.000
Age^2	0.01	0.01	0.01	0.01	0.02
	0.000	0.000	0.000	0.000	0.000
Age^3	−0.0001	−0.0001	−0.0001	−0.0001	−0.0002
	0.004	0.004	0.004	0.005	0.000
Age^4	0.000001	0.000001	0.000001	0.000001	0.000001
	0.021	0.023	0.022	0.028	0.000
L1.Salmon abundance		−0.67	−0.63	−0.59	−0.57
		0.017	0.021	0.029	0.040
L1.Within competition			0.003	0.004	0.002
			0.061	0.046	0.198
L1.Across competition				0.005	0.007
				0.028	0.002
Matriline FE	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes
NRKW × Age	No	No	No	No	Yes
N	12223	12001	12001	12001	12001
Log-likelihood	-1284.92	-1266.48	-1264.68	-1262.63	-1253.78
Groups dropped	34	34	34	34	34

In Table A.4 and A.5, standard errors are clustered at the pod level. P-values appear under the coefficient.
N records the number of female-whale-years
Groups dropped: "clogit" drops animals with an outcome variable that is either 0 or 1 for all their observations.

Table A.6: First difference Impacts on Births with matriline FE

	I.	II.	III.	IV.	V.
Age	3.91	3.88	3.86	3.79	3.89
	0.000	0.000	0.000	0.000	0.000
Age^2	−0.23	−0.23	−0.23	−0.22	−0.23
	0.000	0.000	0.000	0.000	0.000
Age^3	0.01	0.01	0.01	0.01	0.01
	0.000	0.000	0.000	0.000	0.000
Age^4	−0.0001	−0.0001	−0.0001	−0.0001	−0.0001
	0.000	0.000	0.000	0.000	0.000
L1.Salmon abundance	0.29	0.28	0.26	0.30	0.26
	0.028	0.030	0.041	0.016	0.044
L1.Within competition	−0.004	−0.004	−0.003	−0.003	−0.003
	0.003	0.002	0.004	0.009	0.004
L1.Across competition	−0.01	−0.01	−0.01	−0.01	−0.01
	0.000	0.000	0.000	0.000	0.000
L1.Δ Total Vessel km	−0.68				
	0.000				
L1.Δ Total Vessel km × NRKW	0.84				
	0.004				
L1.Δ Other Vessel km		0.83			
		0.268			
L1.Δ Other Vessel km × NRKW		−0.404			
		0.657			
L1.Δ Unitised km		−4.01	−3.25	−3.32	−0.13
		0.006	0.000	0.000	0.844
L1.Δ Unitised km × NRKW		3.55	3.12	3.18	
		0.042	0.004	0.003	
Δ Unitised km				−1.31	
				0.101	
Δ Unitised km × NRKW				0.42	
				0.682	
L1.Δ Unitised km × J pod					−4.53
					0.000
L1.Δ Unitised km × K pod					−0.47
					0.489
L1.Δ Unitised km × L pod					−3.58
					0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes
N	5379	5379	5379	5379	5379
Log likelihood	-1230.61	-1227.8	-1228.68	-1227.5	-1228.12
Groups dropped	21	21	21	21	21

Standard errors are clustered at the pod level. P-values appear under the coefficient.
N records the number of female-whale-years
Groups dropped: "clogit" drops animals with an outcome variable that is either 0 or 1 for all their observations.

Table A.7: First difference Impacts on Deaths with matriline FE

	I.	II.	III.	IV.	V.
Age	−0.46	−0.46	−0.46	−0.46	−0.46
	0.000	0.000	0.000	0.000	0.000
Age^2	0.02	0.02	0.02	0.02	0.02
	0.000	0.000	0.000	0.000	0.000
Age^3	−0.0002	−0.0002	−0.0002	−0.0002	−0.0002
	0.000	0.000	0.000	0.000	0.000
Age^4	0.000001	0.000001	0.000001	0.000001	0.000001
	0.000	0.000	0.000	0.000	0.000
L1.Salmon abundance	−0.55	−0.55	−0.56	−0.55	−0.57
	0.051	0.052	0.041	0.048	0.043
L1.Within competition	0.002	0.002	0.002	0.002	0.002
	0.213	0.221	0.199	0.187	0.187
L1.Across competition	0.01	0.01	0.01	0.01	0.01
	0.002	0.002	0.002	0.002	0.002
L1.Δ Total Vessel km	0.66				
	0.021				
L1.Δ Total Vessel km × NRKW	−0.54				
	0.302				
L1.Δ Other Vessel km		0.40			
		0.321			
L1.Δ Other Vessel km × NRKW		−0.23			
		0.725			
L1.Δ Unitised km		1.25	1.59	1.62	
		0.002	0.001	0.003	
L1.Δ Unitised km × NRKW		−1.22	−1.43	−1.44	
		0.194	0.166	0.176	
Δ Unitised km				1.78	−0.43
				0.014	0.511
Δ Unitised km × NRKW				−2.22	
				0.018	
Δ Unitised km × J pod					3.55
					0.000
Δ Unitised km × K pod					−1.28
					0.049
Δ Unitised km × L pod					2.77
					0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes
N	12001	12001	12001	12001	12001
Log likelihood	-1252.86	-1252.76	-1252.94	-1251.74	-1252.71
Groups dropped	34	34	34	34	34

Standard errors are clustered at the pod level. P-values appear under the coefficient.
Distances are measured in million km.
Δ denotes first differences.
N records the number of female-whale-years for births; all whale years for deaths.
Groups dropped: "clogit" drops animals with an outcome variable that is either 0 or 1 for all their observations.

Table A.8: Noise-weighted distance effects on fertility with matriline FE using conditional logit

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Age	3.88	3.77	3.91	3.88	3.77	3.91
	0.000	0.000	0.000	0.000	0.000	0.000
Age^2	−0.23	−0.22	−0.23	−0.23	−0.22	−0.23
	0.000	0.000	0.000	0.000	0.000	0.000
Age^3	0.006	0.006	0.006	0.006	0.006	0.006
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	−0.00005	−0.00005	−0.00005	−0.00005	−0.00005	−0.00005
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Salmon abundance	0.28	0.30	0.28	0.28	0.30	0.27
	0.032	0.016	0.034	0.033	0.016	0.035
L1.Within competition	−0.003	−0.003	−0.004	−0.003	−0.003	−0.004
	0.004	0.008	0.004	0.004	0.008	0.004
L1.Across competition	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Δ Distance weighted by noise	−0.46	−0.49	0.03	−0.40	−0.42	0.03
	0.000	0.000	0.737	0.000	0.000	0.753
L1.Δ Distance weighted by noise × NRKW	0.50	0.53		0.43	0.45	
	0.001	0.000		0.001	0.000	
Δ Distance weighted by noise		−0.37			−0.31	
		0.005			0.006	
Δ Distance weighted by noise × NRKW		0.26			0.21	
		0.210			0.223	
L1.Δ Distance weighted by noise × J pod			−0.76			−0.65
			0.000			0.000
L1.Δ Distance weighted by noise × K pod			−0.24			−0.22
			0.022			0.016
L1.Δ Distance weighted by noise × L pod			−0.48			−0.41
			0.000			0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	5379	5379	5379	5379	5379	5379
Log likelihood	-1229.77	-1228.46	-1229.54	-1229.72	-1228.43	-1229.51
Groups dropped	21	21	21	21	21	21

Standard errors are clustered at the pod level. P-values appear under the coefficient.
Distances are measured in million km.
Δ denotes first differences.
N records the number of female-whale-years for births; all whale years for deaths.
Groups dropped: "clogit" drops animals with an outcome variable that is either 0 or 1 for all their observations.

Table A.9: Noise-weighted distance effects on mortality with matriline FE

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Age	−0.46	−0.46	−0.46	−0.46	−0.46	−0.46
	0.000	0.000	0.000	0.000	0.000	0.000
Age^2	0.02	0.02	0.02	0.02	0.02	0.02
	0.000	0.000	0.000	0.000	0.000	0.000
Age^3	−0.0002	−0.0002	−0.0002	−0.0002	−0.0002	−0.0002
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	0.000001	0.000001	0.000001	0.000001	0.000001	0.000001
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Salmon abundance	−0.55	−0.53	−0.56	−0.55	−0.53	−0.56
	0.048	0.063	0.051	0.047	0.062	0.051
L1.Within competition	0.002	0.003	0.003	0.002	0.003	0.003
	0.216	0.170	0.157	0.212	0.166	0.156
L1.Across competition	0.01	0.01	0.01	0.01	0.01	0.01
	0.002	0.003	0.003	0.002	0.002	0.003
L1.Δ Distance weighted by noise	0.35	0.35		0.29	0.29	
	0.001	0.002		0.002	0.003	
L1.Δ Distance weighted by noise × NRKW	−0.26	−0.25		−0.23	−0.21	
	0.228	0.256		0.220	0.256	
Δ Distance weighted by noise		0.24	−0.21		0.21	−0.18
		0.003	0.158		0.003	0.154
Δ Distance weighted by noise × NRKW		−0.46			−0.40	
		0.005			0.004	
Δ Distance weighted by noise × J pod			0.64			0.57
			0.000			0.000
Δ Distance weighted by noise × K pod			0.04			0.03
			0.798			0.813
Δ Distance weighted by noise × L pod			0.51			0.44
			0.001			0.001
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	12001	12001	12001	12001	12001	12001
Log likelihood	-1252.48	-1251.07	-1252.01	-1252.58	-1251.16	-1251.95
Groups dropped	34	34	34	34	34	34

Standard errors are clustered at the pod level. P-values appear under the coefficient.
Distances are measured in million km.
Δ denotes first differences.
N records the number of female-whale-years for births; all whale years for deaths.
Groups dropped: "clogit" drops animals with an outcome variable that is either 0 or 1 for all their observations.

A.VIII Lloyd's List Data

The data obtained from Lloyd's list is contained in two related subsets. One subset of data contains, 'previous movements'. The 'previous movements' data contains information on the current port of arrival and the last two ports visited, for vessels making a landing at one of 121 ports on the west coast of North America from 1977 to 2019. We refer to this set of ports as the Ports of Interest (PoI). Each entry includes the port of landing, the count of vessels landing, their vessel class, and the month/year of the landing. Vessel classes include fishing vessels, research vessels, dredging vessels, tugs, passenger, and military vessels but most importantly, it contains a set of vessels commonly employed in international trade: these are, two types of tankers, two types of bulk carriers, and three classes of cargo vessels. In total, the data contains approximately 1.8 million current landings, which combined with information on their past two landings, yields information on over 5 million vessel movements.

The remaining subset is the 'vessel characteristics' set. It contains average vessel characteristics for the same vessel landings by ports/vessel type/month/year. The characteristics recorded include dead-weight tonnage, vessel length, year of build, and several measures of container capacity (when relevant). These data provide a little over 100,000 additional, but related, observations by month/year/port/vessel type. The two subsets of data report information on the same set of trips, and therefore provide an internal consistency check on the data itself. Every individual vessel landing recorded in the previous movement data, must also be present in the counts recorded in the vessel characteristics data.

If all vessel trips were simple one-stop voyages arriving at a port in the critical habitat from outside and exiting similarly, then the landing data could be easily matched with route distances to calculate the distance traveled in the critical habitat. However, many vessels make several stops in the critical habitat before exiting; some vessels stay within the critical habitat and never leave; some vessels traverse the critical habitat without ever landing at any port within; and others leave the critical habitat and then re-enter before turning towards the Pacific. Therefore, the number of port landings is at best a very gross measure of vessel traffic.

To solve this problem, Taylor (2021a) develops a form of *Vessel Arithmetic* exploiting concepts from both National Income Accounting and general equilibrium theory. A vessel trip is identified by its origin (previous port) and its destination (landing port). He divides these annual vessel trips into one of five, mutually exclusive and exhaustive, trip categories: incoming, within, outgoing, pass-through, and irrelevant. Incoming trips are vessel trips originating outside the (critical habitat) CH but landing in the CH; trips with origin and destination ports within the CH are defined as within trips; outgoing trips are trips originating within the CH, but having destinations outside the CH; and finally pass through trips originate and terminate outside the CH, but whose voyage traverses the CH.

A.IX Presence/Absence and Intensity of Use

In Table A.10 below we use the monthly presence-absence data to examine whether the SRKW has become more or less resident in the Salish. This table is based on data from The Whale Museum (2019) and it shows three things. One, J pod is resident most of the year and quite a bit more than either K or L pods. J pod was resident all months of the year for all years prior to 1999; it was resident for 95% of those months subsequently. Two, there are very small changes in the presence of J pod over time. For example, J pod may be using the Salish less (.08 less over the 42 years), but the magnitude of this effect is minuscule. Three, K, and L pods appear to be using the Salish much more. This is evident from the difference in means over the two periods, or by the coefficient on the time trend in the entire sample. In this case, the magnitudes of these changes are much larger (.29 and .42 more over the 42 years). We are leery about reading too much into these trends because the Whale Museum sightings come from platforms of opportunity and are therefore affected by effort, boat activity, interest, etc. As a result, the rising presence of K and L may be due to effort and interest changing, not whale behavior.

The intensity of use is represented by two figures taken from Thornton et al. (2022). They show the intensity of use by geographic area. The first combines data taken from the Department of Fisheries and Oceans Canada with data from the Whale watching community. We used this first graphic to develop Fact 8 in the text. The second uses data from platforms of opportunity - that is, sightings by individuals from boats, land, etc. reported to the sightings network. It is clear from the shipping lanes depicted in Fact 8 that very high-use areas for KW often fall along shipping lanes.

Table A.10: J, K & L-Pods Annual Residence and its Time Trend in the Salish Sea (1978-2019)

	(1) J-Pod	(2) K-Pod	(3) L-Pod
Panel A. 1978-1998			
Annual Average Fraction of Residence	1	0.488	0.405
Standard Deviation	0	0.113	0.103
Panel B. 1999-2019			
Annual Average Fraction of Residence	0.952	0.675	0.679
Standard Deviation	0.056	0.111	0.106
Difference of average between two periods	-0.048	0.187	0.274
N	21	21	21
Panel C. Time Trend of the Whole Sample			
Year	-0.002***	0.007***	0.010***
	(0.000)	(0.002)	(0.002)
N	42	42	42

Standard errors in parentheses
*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

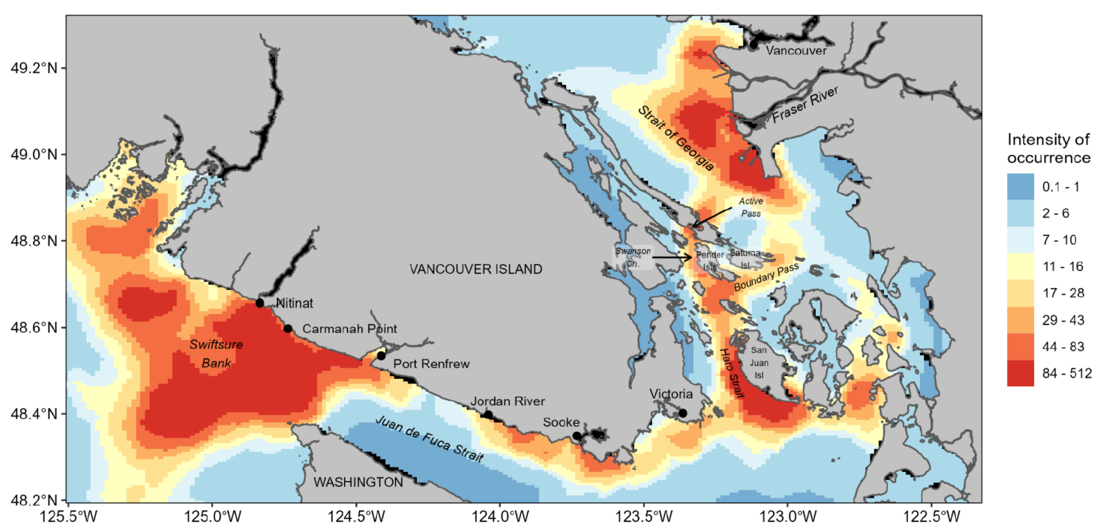

Figure 11. Annual SRKW intensity of occurrence as estimated by the SRKW occurrence model using combined WW and DFO data for May to October, 2009—2020.

Figure A.10: Intensity of Use, DFO and Whale Watch Data

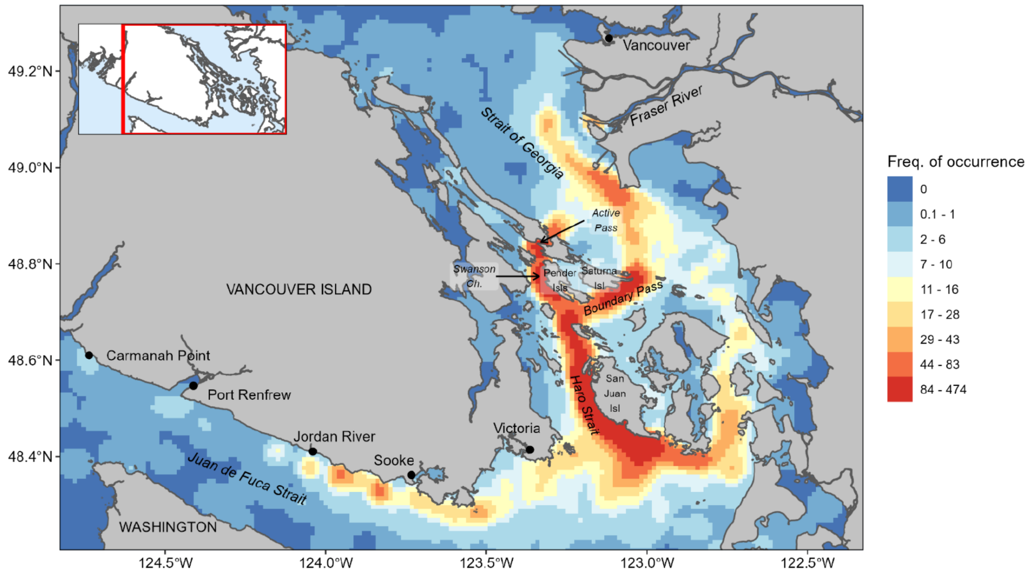

Figure 9. Annual frequency of SRKW occurrence from May to October as predicted by the 2009-2018 platform of opportunity (BC Cetacean Sightings Network/OrcaMaster) sightings fit to a Kernel Density model.

Figure A.11: Intensity of Use, Platforms of Opportunity Data

A.X Pacific Salmon Commission

The PSC works to uphold the Pacific Salmon Treaty signed by the U.S. and Canada and therefore closely monitors the Pacific Salmon populations. One of its technical committees focuses exclusively on collecting, evaluating, and publishing data on the various Chinook populations that spawn in the rivers of Western shores of North America.

The Joint Chinook Technical Committee publishes reports on an annual basis in which it records various measures of the Chinook salmon populations it monitors. A particularly useful measure of the health of the Chinook population is the abundance index which tracks the abundance of a number of indicator stocks. These are then aggregated into three indexes for the three aggregated abundance-based management (AABM) fisheries across the Western coast of North America. The three fisheries are the Southeast Alaska (SEAK), the Northern British Columbia (NBC), and the West Coast Vancouver Island (WCVI) troll fisheries. Between the three total indexes there are thirty stocks measured, each distinguished by their spawning location and in some cases by the age of the fish considered.

In our analysis, we use the unweighted sum of the three total indices and refer to this aggregate in our tables as salmon abundance. This seems appropriate as the indices themselves are unweighted sums of their totals, and as we mentioned previously the indices are all very highly correlated.

A.XI Vessel Noise

Data on ship noise comes from two sources. Most of the data was collected by Veirs, Veirs and Wood (2016) which we augmented with data published in McKenna et al. (2012). Both of these data sets were collected in a similar manner and with a very similar goal: to describe how various ship types contribute to underwater noise and how ship characteristics explain the noisiness of vessels.

Both studies collect ship sounds with the help of a seafloor-mounted hydrophone. They combine the recordings of a ship with information about the ship's passage from AIS to calculate how loud it is. The authors then use the AIS-provided ship identifier to collect further vessel characteristics. McKenna et al. (2012) use Lloyd's list for this purpose and Veirs, Veirs and Wood (2016) relies on Marine Traffic.

McKenna et al. (2012) focus on modern commercial vessels and record ships passing the Santa Barbara Channel in California in April 2009. They provide details about 29 ships in their study. They measure the underwater noise of each ship as it approaches and then pass the hydrophone to assess noise over a broader range of distances. Importantly for our research, they report the source level noise of ships which they calculate from the noise received by the hydrophone and the distance of the ship from the recording device. They also record the speed at which the vessels travel, as well as the length, gross tonnage, year of build, and vessel type. They divide the recorded commercial ships into seven vessel categories which closely match the commercial vessel classes of the vessel traffic data provided by Lloyd's.

Veirs, Veirs and Wood (2016) record ships passing in the Haro Strait which is located inside the critical habitat of the SRKW. The scope of their data collection is much wider in both time covered and ship types recorded than that of McKenna et al. (2012). They record all ships with at least 65 feet in overall length that pass their hydrophone in the northbound shipping lane of Haro Strait. Apart from ship length, the authors limited the study in one more way: they recorded only ships that passed the hydrophone in isolation to make sure noise signatures can be identified. They took recordings between March 2011 and October 2013 which resulted in a rich data set even after the necessary removal of recordings from a period of equipment reparation.

Similarly to McKenna et al. (2012) Viers and coauthors combined the received sound parameters with ships' distance from the hydrophone – learned from AIS – to calculate the source level noise of the passing vessels. Both papers measured source level noise in decibels (dB) referred to 1μPa at a distance of 1 m. Veirs, Veirs and Wood (2016) also record speed, dead weight, ship length, year of build, and vessel category for each ship in their data. As speed comes from direct observation of a ship's passage, it is never missing. Ship characteristics, however, show some missing details depending on data availability in Marine Traffic. We augmented these details in as many cases as possible to avoid losing observations to missing information.

As Veirs, Veirs and Wood (2016) is less focused on modern commercial ships than McKenna et al. (2012), they differentiate between 12 wide ship categories. In the case of commercial ships, they further differentiate smaller groups based on ship length. Even so, the data of the two studies are easy to combine due to the common characteristics recorded and the common units of measurement used in them.

The observations were collected over the 2011-2013 period and therefore include contemporary vessels. We requested vessel-specific sound data collected by the ECHO program but were refused access.[62] Instead we were given aggregate summary statistics which we use as a partial check on our results. Since the ECHO program only measured vessel noise from vessels that voluntarily entered the program to have their sound level recorded, self-selection is likely to be a considerable problem for this data. In contrast, our primary source for data ($> 90\%$ of the observations) was collected from a random selection of vessels moving through Haro Strait over six different time periods. Vessel characteristics include 15 vessel categories, length, dead weight tons DWT, speed (knots), and the year of build. A set of summary statistics for the relevant data is presented in Table A.11 below.

The numbers in the name of vessel classes refer to the range of lengths in the class. For example, "Bulk carrier 200-250" contains bulk carrier ships which are at least 200 m and less than 250 m long. The number of recorded ships varies across classes. The least often observed ships were Research vessels with 14 observations, and the most often recorded ones were Bulk carriers that are less than 200 m long.

Source level noise varies both within and across vessel types. On average the largest type of Container ships were the loudest with 180.3 dB at source level, while the second largest type of Container ships were the second loudest (178.7 dB) and the largest Bulk carrier ships the third loudest (177.3dB). Non-commercial ships (these are all ship categories listed after

[62] See https://www.portvancouver.com/environmental-protection-at-the-port-of-vancouver/maintaining-healthy-ecosystems-throughout-our-jurisdiction/echo-program/projects/

Table A.11: Mean and Standard deviations of Vessel Noise by Class

Vessel class	Source level (dB)	Speed (km/h)	LOA (m)	Dead weight (t)	Age	N
Bulk carrier	173.6	25.3	206.0	67,321.9	6.9	971
	[5.2]	[2.7]	[36.2]	[42,621.8]	[7.6]	
Cargo	175.3	26.6	184.1	41,183.9	12.3	311
	[5.1]	[4.2]	[45.2]	[25,048.2]	[9.6]	
Container ship	178.4	35.6	276.7	67,527.3	7.9	535
	[4.0]	[3.6]	[48.8]	[25,739.6]	[4.9]	
Tanker	174.7	25.5	171.6	38,218.7	6.9	158
	[4.6]	[2.6]	[40.3]	[27,414.6]	[5.4]	
Vehicle carrier	175.7	31.3	187.1	17,392.7	12.6	191
	[2.6]	[3.3]	[12.8]	[6,879.4]	[9.9]	

Vehicle carriers) are generally less noisy than commercial ones.

Commercial ships are not just more noisy than their non-commercial counterparts but also faster. The three categories of Container ships are on average the fastest across all the observed classes with average speeds ranging between 34.1 and 36.5 km/h. The only other class with an average speed over 30 km/h is the Vehicle carrier. The lowest average speed among commercial ships belongs to the shorter cargo vessels (24.8 km/h). Non-commercial ships have an average speed below 24 km/h except for passenger ships that passed the recording device in Haro Strait on average at 26.6 km/h. The slowest ships in the sample are Tug ships with an average of 15.2 km/h.

In terms of length and dead weight commercial ships also outstrip non-commercial ones with a few exceptions. On average all commercial vessels are over 100 m long, while non-commercial ships are typically shorter than that. The only exceptions are passenger ships which are on average 221.3 m long. In terms of dead weight, all commercial ships are on average over 10,000 tons. Non-commercial ships are usually much lighter, except for Military vessels. Although dead weight was available only for a single military ship.

Lastly, commercial ships tend to be younger relative to non-commercial ships. The average age is under 10 years in each commercial category, except for Vehicle carriers and for the two Cargo classes. Even in these three groups, the average is lower than 13 years. Non-commercial ships, especially Tugs are much older. Only Military ships have an average age under 10 years, and Pleasure crafts get close with an average age of 10.1 years. The next youngest group is that of Passenger ships with an average of 16.4 years.

The summary statistics suggest that commercial ships are on average noisier, faster, larger, and younger than non-commercial ships in the sample. This makes determining how vessel features contribute to ship noise an interesting exercise. There is however only very limited time-series variation in the data, and hence the year of the build is effectively the same as vessel age and we will employ vessel age in all our empirical work.

We use these data in a very straightforward cross-sectional regression linking a vessel's SL measure to its characteristics. We consider three increasingly detailed specifications allowing for differences across vessel classes and sizes as we proceed. Since our dependent variable is measured on a log 10 scale, we transform all continuous regressors (except age) similarly. This decision is consistent with the functional form of existing theoretical models of vessel noise which are almost always multiplicative in key characteristics. Although vessel length is available as an independent variable in our data, so too are very fine vessel categories defined by length (bulk $<$ 200 meters, container $>$ 320, etc.). Accordingly, we consider two possible methods to account for length. We either choose very broad vessel categories (Container, Cargo, etc.) and let length enter as an independent variable; or we choose narrower vessel categories defined by length and class (Container $<$ 200, etc). The benefit of the former is that we estimate the independent impact of length; the benefit of the latter is that we put less structure on the estimation. Our preference is for the second method.

The results from estimating these different specifications are shown in Table A.12 below. Column I contains the simplest specification linking noise levels to basic vessel characteristics but not differentiating across vessel classes. Speed, dead weight, and age all appear to be important determinants of the noise created, while vessel length enters negatively but with a large standard error. Speed in particular appears to be a very strong indicator of vessel noise, entering with a coefficient of 18.90. This strong speed-to-noise relationship and the somewhat strangely signed length coefficient soon disappear when we differentiate among vessel classes.

The results across the last two columns where we adopt either broad (II) or narrow vessel classes (III), are quite similar. In column II where we employ broad vessel categories and allow vessel length to appear as an independent variable, we find speed and dead weight are positively related to vessel noise while length enters positively but with little significance. This is perhaps not surprising, because a ship's length and dead weight are highly correlated even across vessel classes. In column III we allow the impact of length to vary across vessel classes. Here we find that length matters within vessel classes, and in all cases, but one, longer and hence larger vessels are noisier than their smaller counterparts. In both columns, we also find that once vessel class is accounted for, the coefficient on speed falls tremendously. The simple explanation is of course omitted variable bias because the fastest and noisiest of

Table A.12: Ship noise regressions

	I.	II.	III.
Constant	140.01	144.98	157.51
	0.000	0.000	0.000
Log speed (km/h)	18.99	9.22	8.85
	0.000	0.000	0.000
Log vessel length	−1.99	2.48	
	0.330	0.323	
Log vessel dead weight	2.51	2.06	0.72
	0.000	0.014	0.313
Vessel age	0.07	0.02	0.02
	0.000	0.070	0.088
Bulk carrier 200-250			−0.97
			0.024
Bulk carrier 250+			3.37
			0.000
Cargo (all)		2.15	
		0.000	
Cargo 150-			1.50
			0.033
Cargo 150+			1.91
			0.000
Container (all)		3.05	
		0.000	
Container ship 250-			1.56
			0.002
Container ship 250-320			3.81
			0.000
Container ship 320+			5.24
			0.000
Tanker (all)		1.88	
		0.000	
Tanker 165-			0.41
			0.497
Tanker 165+			2.21
			0.000
Vehicle carrier		2.38	1.69
		0.000	0.000
Tug		5.07	0.60
		0.000	0.705
Fishing		−1.87	−5.62
		0.511	0.059
Military		−8.89	−9.07
		0.000	0.000
Miscellaneous		−5.80	−8.60
		0.000	0.000
Passenger		−4.70	−5.81
		0.000	0.000
Pleasure craft		0.59	−4.39
		0.740	0.061
Research		−0.60	−4.53
		0.694	0.015
N	2319	2319	2323
R^2	0.17	0.25	0.28
Adjusted R^2	0.17	0.25	0.27

p-values appear under their corresponding parameters instead of standard errors.
Speed is measured in km/h, dead weight in tons, and length in meters.

ships are containers. When we pool all vessels in column I, we confuse an across-vessel-class noise impact for one tied to their speed.

Even accounting for speed and dead weight differences, vessels of different categories create different disturbances. For example, in column II the omitted category is Bulk ships. The coefficients on Cargo, Container, Tanker, and Vehicle carrier all indicate those classes are, on average, noisier. In column III, we refine this finding somewhat. Here the omitted category is Bulk vessels less than 200 meters in length. Therefore, the coefficient on small container ships (250 meters or less) tells us that all else equal, they are noisier than small Bulk ships by 1.82 dB. Similarly, larger container ships (250-300 meters) are slightly noisier than even large 250-meter plus Bulk ships. But large Bulk ships are now found to be more noisy than say even large Cargo vessels (150+) and Vehicle carriers.

Overall, the results show Containers are the noisiest of commercial vessels, with Cargo, Tankers, Vehicle carriers, and large Bulk ships following. Tugs appear to be about as noisy as small Bulkers. In contrast, all of the remaining ships are significantly less noisy. Fishing vessels, passenger, etc. are found to be 4 to 10 decibels quieter than similarly sized commercial vessels. This is a very large difference indeed which suggests our focus on the potentially disturbing impact of commercial ships is likely correct.

These results are consistent with others presented in the (very small) literature. Containers are known to be the noisiest vessels followed by bulk carriers, etc. What is new and somewhat surprising is the magnitude of the speed impact. Given our log 10 specification, the change in SL from a percentage change in vessel speed is equal to the estimated coefficient on log speed divided by ln(10) or approximately 2.3. This implies a 20 percent decrease in vessel speed lowers source level noise by (averaging coefficients across columns) approximately $(8/2.3) \cdot .2 = .7$ dB. This is a very small impact. For example, an often-quoted goal of policy is to reduce ambient or background ocean-level noise by 3 dB. Our estimates suggest a 3 dB reduction in SL noise would require, an over 80% reduction in speed! Therefore, it appears that altering vessel speed, in isolation, is relatively ineffective in altering SL.

A corollary of speed mattering less than previously thought is that vessel class matters much more. For example, using the estimates from the narrow categories we see that a 320-meter plus container ship, all else equal, is 5 dB noisier than a small bulk vessel. It is 3 dB louder than a smaller container ship and 2 dB louder than even a large Bulk carrier. In short, much of the noise impact of vessels is baked in by their class categorization. The vessel class dummies are capturing unmeasured characteristics which make container vessels unique. It could reflect their particular width/length profile, depth in the water, engine type and number, displacement, propeller location, size, and number, etc. - and we know that all of these unmeasured vessel characteristics, which make a container ship a container ship, are significant determinants of its noise impact.

Finally, across all columns, we include a vessel age variable. Its significance and size vary somewhat across columns, but in columns II and III it is found to be approximately .02. Since our data is cross-sectional, we cannot separately identify the impact of vessel age and vintage. Therefore, our .02 coefficient could mean that a vessel 25 years older than its otherwise identical counterpart is .5 of a decibel louder than its younger self; alternatively, it could mean that technological progress over these 25 years has rendered the newer vessel quieter by .5 decibels. Therefore, younger or newer, vessels are quieter. Since much of recorded vessel noise comes from the movement of the propeller, new designs that lessen the stress on propellers and improve their efficiency and productive lifetime, may have reduced the SL disturbances of large vessels significantly. Therefore, technological progress may well be a powerful force quieting ships.

A.XII The Sound Exposure Model

Moving from a knowledge of a vessel's source level noise pollution, SL, and its trip length and speed, to a measure of the average sound exposure of a typical resident killer whale requires us to place considerable structure on the problem. We do so by making three key assumptions: random whale movements, a binary measure of vessel disturbance, and acoustically isolated vessels. We combine these assumptions with well-known physical laws governing sound propagation and transmission losses to generate our sound exposure model (SEM).

The model we construct is entirely novel and very simple. Our goal is to develop a consistent method to transparently link SL emissions to measures of KW exposure using known laws of sound dissipation. Our model could, of course, form the basis for future research relaxing some of our assumptions, but it is important to keep top of mind, current, and probably future, data limitations. The location of killer whales in their critical habitat and beyond is poorly understood. While there are many visual observations, these are limited by season, inclement weather, daylight, distance from shore, and the simple biological fact that much of their time is spent underwater. The SRKW critical habitat is also, of course, a huge area - over 11,000 square km - more than the area of Delaware and Rhode Island combined.

To date, KW tagging and tracking operations have had very limited success; acoustic data is more promising but is also quite limited.[63] Therefore, building a model where detailed knowledge of KW location and movements is a fool's errand. It would be especially suspect given that over the 40-year period we are studying, we know populations, pod numbers, and prey abundance has changed considerably.

Instead, we assume KW locations are randomly and uniformly distributed across their critical habitat at any time t.[64] It's helpful to think of the critical habitat as one very large aquarium with volume V determined in the usual way. Whales move randomly and independently throughout V during a time period of length T which we take to be one year to match our annual data. V could represent the entire critical habitat or some well-defined subset thought to be especially relevant. A vessel trip through V disturbs a fraction of V for a fraction of time T, and hence we measure the size of this disturbance by:

$$D_{it} = [\text{Fraction of V disturbed}] \cdot [\text{Fraction of time V disturbed}] \leq 1 \tag{A.1}$$

Very simply, if a vessel disturbs 50 percent of the volume of the critical habitat over 25 percent of the year, then the vessel's disturbance is 12.5 percent. Our uniformly distributed KW assumption ensures the probability of any one whale falling into this disturbance subset is also 12.5% or .125. Uniformity ensures all KW have uniform exposure, and this assumption is very common, but almost always implicit, in environmental economics where agents in districts, cities, states, and even countries are often assumed to be equally exposed to pollution emissions.[65] In our empirical work we relax this assumption to allow exposure to vary by matriline and pod affiliation.

If a whale does fall within a vessel's disturbance set we say it is disturbed by the vessel.

[63]If the entire Salish Sea could be continually monitored with hydrophones, and the data decoded by experts and cataloged, in theory, we could know a lot more about their movements.

[64]One micro-foundation for this assumption is the following. Suppose every whale follows a random walk and at t they are uniformly distributed across V. During the next interval, they next move either up, down, side-wise, forward, or back with equal probability. Then we can think of whale movement as a symmetric random walk on the three-dimensional lattice defined by the critical habitat with given length, width, and depth. If we ignore boundary issues, then at t+1, the whales are again uniformly distributed through V.

[65]In theoretical work this assumption is almost always unstated because it is so common. In the empirical health and environment literature researchers make specific assumptions about agents' exposure often tied to their place of residence. For example, it is common to assume all agents, living within a given census block/zip code/county/state are equally exposed. It is very unusual to tie exposure to the activity of agents going to their work or school locations. It is extremely rare to actually track individuals by pollution monitors, which would be the equivalent of tracking the KW through their habitat 24/7. When real-time monitoring of humans is available researchers often note it comes from small and often unrepresentative samples - the same critique applies with full force to the existing KW monitoring data.

In doing so we have implicitly assumed a disturbance is an all-or-nothing thing; there is no intense disturbance for whales close to a vessel nor is there a minimal disturbance for those much further away. Disturbance is either zero or one. Despite this simplification, larger and noisier vessels will still create larger disturbances and have potentially greater impacts.

Finally, we have assumed that all vessels are acoustically isolated so that their disturbance subsets do not intersect. This rules out vessels being bunched close together or traveling in caravans. This assumption implies the probability of any one whale being disturbed over the year of length T is given by the simple sum of the disturbances created by many vessels.[66]

To determine when a whale is disturbed, we assume a disturbance occurs whenever a nearby vessel raises the ocean's ambient noise above its typical background level, B (any threshold level will suffice). Since sound dissipates with distance, let $TL(d) < 0$ be the transmission loss occurring over distance d from the vessel. Then the following equality implicitly defines the critical distance d when the source level disturbance becomes, in effect, background noise; i.e., it solves

$$SL + TL(d) = B \tag{A.2}$$

To solve for d explicitly we exploit the fact that sound dissipates with distance according to the famous inverse square law. This law tells us that the transmission loss between an emitting source with SL measured at distance $d_1 = 1$ meters, to another point at distance d_2, is given by:

$$TL = 10 \log_{10}[d_1/d_2]^2 = 10 \log_{10}[1/d_2]^2 \tag{A.3}$$

where the second equality follows because our source level SL is measured at the standard distance of $d_1 = 1$. As is well known, the workings of the inverse square law mean every doubling of distance leads to a sound reduction of approximately 6 decibels.

Now define X as the excess of SL over background noise, B. Then using (A.2) and (A.3) the distance at which this excess – disturbance – becomes indistinguishable from background ocean noise is simply:

$$d_2 = 10^{X/20} \tag{A.4}$$

[66] Acoustic isolation is not a rare phenomenon at all. When researchers estimate a vessel's SL they discard all the data from any vessels that are not acoustically isolated vessels, and therefore this assumption fits nicely with the data we have.

For example, if the background noise of the ocean is 90dB, and the source level at the ship is 150 dB, then X is 60 dB. This sound will be dissipated as it spreads through the water, and reach background dB levels at the distance of 1 km.

To calculate the scale of the noise disturbance, we adopt the spherical spreading model commonly used to study ocean noise. Since noise spreads spherically in three dimensions below a vessel, the volume of habitat disturbed, V_D, is equal to one-half the volume of a sphere with radius, r where r is, of course, the margin of disturbance d_2 we calculated above. Therefore, V_D becomes:

$$V_D = \frac{2}{3}\pi r^3 = \frac{2}{3}\pi[d_2]^3 \tag{A.5}$$

To complete our aquarium analogy, each vessel on top of the water in the tank has underneath it a (half) sphere disturbance bubble with volume V_D. At any time t, if a whale is within the bubble it is disturbed; similarly, any whale outside is not. If there are two or more vessels their disturbance bubbles do not intersect. Larger, faster or older ships have larger bubbles; smaller, slower, or newer ships have smaller bubbles. And hence the magnitude of the disturbance is tied to the magnitude of a vessel's SL even though the disturbance measure itself is binary. Higher SL vessels just have bigger bubbles. Together these calculations allow us to calculate, at any point in time, the ratio of V_D to V: i.e. the fraction of the critical habitat disturbed.

To complete our measurement of D_{it} we need to calculate the time over which the disturbance takes place. We do not have data on the length of vessel trips; we do however have distances covered x and estimates of speed s, and we know distance/speed equals time of the voyage. If our vessel travels a known distance of x, at a constant speed of s, then the time of travel is $t^* = x/s$. If T is a measure of time over one year in the same units (say it's measured in hours), then our original disturbance measure D_{it} for a singular vessel trip is:

$$D_{it} = \left[\frac{V_D}{V}\right] \cdot \left[\frac{t^*}{T}\right] \tag{A.6}$$

where V_D is solved using by (A.2) to (A.5). Since the choice of V and the units of T are arbitrary, we substitute for t^*, and rearrange to find:

$$D_{it} = \Omega V_D \left[\frac{x}{s}\right] \tag{A.7}$$

where Ω is a positive constant reflecting the geography of V and the time frame selected.

Therefore, (A.7) is measurable up to a positive constant.

To find the disturbance created by many such vessels over T, we exploit the acoustically independent assumption and simply add them up. Because a vessel's SL is determined by its own potentially unique characteristics, we need to sum disturbances across N potentially heterogeneous vessel trips, by j (isolated) vessels, on a representative whale i, in year t, by finding:

$$D_{it} = \Omega \sum_{j \in N} \left[\frac{V_{Djt} x_j}{s_j} \right] \tag{A.8}$$

Where V_{Djt} is now indexed by time to allow for year of build (or age effects) across vessels. This equation is again completely determined up to the common constant Ω and could of course replace our previous simple measures of disturbance.

Before we do so, several observations are in order. Note, in particular, that if all of the j vessels were traveling at the same speed, and had the same source level noise, then (A.8) simplifies further to:

$$D_{it} = \Omega' \sum_{j \in N} x_j \tag{A.9}$$

where Ω' is a positive constant. Therefore, our explicit model of vessel disturbance yields a measure of disturbance proportional to the simple sum of vessel km traveled in the critical habitat. Constructing $D_{it} - D_{i,t-1}$ generates a measure of disturbance shocks that, apart from a constant of proportionality, is identical to our previous measure associated with Total km. Alternatively if the only significant differences in the components of (A.8) were between Unitised and all Other vessels, then our formula becomes the simple sum of disturbances across these two aggregated classes - again much like we have done thus far.

It is also important to recognize how (A.8) captures a vessel's time in the water. Faster vessels have lower voyage times which lowers their disturbance. This impact is captured by the x/s term. But faster vessels are also noisier. This impact is also present but implicit because a vessel's V_{Djt} changes with its speed. In principle, the net impact of speed on our disturbance measure could be positive or negative.

To investigate we use our estimates from Table A.12, where the coefficient on log_{10} speed was found to be approximately 8. If we use this number and work through the somewhat tedious algebra from a change in speed to changes in SL and V_D we find that vessel disturbance does in fact rise with vessel speed despite reduced time-in-the-water.

A.XIII How important is Vessel Speed?

To see this, take (A.7) and plug in (A.5) for V_D then (A.4) for d_2 in the resulting equation to express D_it as a function of X, s, and x:

$$D_{it} = \Omega V_D \left[\frac{x}{s}\right] = \Omega \frac{2}{3}\pi[10^{X/20}]^3 \cdot \left[\frac{x}{s}\right] := \tilde{\Omega} \cdot x \frac{10^{3X/20}}{s}$$

where $\tilde{\Omega}$ collects all the constants. Taking first $\log_{10}$ of the equation then taking its total derivative while keeping distance x constant gives the following useful equation:

$$\frac{dD_{it}}{\ln(10)D_{it}} = \frac{3dX}{20} - \frac{ds}{\ln(10)s} \tag{A.10}$$

To get to dX, plug in X for $TL(d)$ into (A.2), rearrange the equation for X, and take its total derivative while remembering that the background noise level is constant and that source level noise depends on speed ($SL(s)$):

$$dX = d(SL(s) - B) = SL'(s) \cdot ds.$$

Plugging the above into (A.10) gives:

$$\frac{dD_{it}}{\ln(10)D_{it}} = \frac{3}{20}SL'(s) \cdot ds - \frac{ds}{\ln(10)s}.$$

This expression can be rearranged into:

$$\frac{dD_{it}}{ds}\frac{s}{D_{it}} = \frac{3\ln(10)}{20}SL'(s) \cdot s - 1. \tag{A.11}$$

To get to $SL'(s)$ take the derivative of our regression equation $SL = \alpha + \beta \log_{10}(s)$ with respect to speed which gives $dSL/ds = \beta/\ln(10)s$. Plugging this into (A.11) and using our estimate for $\beta = 8$ gives:

$$\frac{dD_{it}}{ds}\frac{s}{D_{it}} = \frac{3}{20} \cdot 8 - 1 = 4/20 > 0.$$

The last inequality confirms that disturbance rises with speed.