NOISY TRADE:

THE IMPACT OF SHIPPING NOISE ON MARINE MAMMALS

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Abstract

Although no longer at risk from industrial whaling, marine mammals now face a new and growing threat - noise pollution. Hearing is whales' most important sense, and human activity, primarily shipping, has radically altered their acoustic environment. While physical scientists have struggled to establish a direct link between noise pollution and whale health, we employ quasi-experimental methods drawn from Economics to discover noise from international shipping vessels has lowered the fertility and raised the mortality of one very important endangered population - the Southern Resident Killer whales found in the Pacific Northwest. We provide a new method for identifying the health effects of noise pollution on marine mammals and a least-cost solution to save this endangered population. JEL: F18, Q27, Q52, Q53; WC $\approx 20,000$

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I Introduction

Although no longer at risk from industrial whaling, marine mammals face a new and growing threat - noise pollution. Hearing is whales' most important sense, and human activity, primarily shipping, has radically altered their acoustic environment. New and planned investments in deep ocean mining and offshore wind installations will raise ambient noise levels further, with, at present, unknown effects on these majestic creatures. We draw on tools from Environmental Economics to provide a method for estimating the impact of noise pollution on marine mammals. These estimates allow us to develop a least-cost solution for saving one severely endangered population: the Southern Resident Killer whales (SRKW).

Killer whales (Orcinus Orca) are the world's largest predator, and simultaneously a significant tourist asset and cultural icon for much of the Pacific Northwest. In the past twenty-five years, the Southern Resident Killer Whale population (SRKW) has declined by more than 25% and is now on a slow-motion path toward extinction. Despite extensive scientific inquiry, several government task forces, and millions of dollars of research money being spent, there is no consensus as to why. Limitations in prey, disturbance by whale watching vessels, and contamination by PCBs all feature prominently in the current discussion, but it is unclear which of these is the most significant driver. Surprisingly, other Orca populations have not fared as poorly. For example, the Northern Resident Killer whales (NRKW), whose range overlaps with the South, has grown over this period.

Our least-cost solution involves a combination of salmon management (to affect prey availability) and noise abatement to improve their acoustic environment. Some salmon restoration is ongoing, but our results suggest these efforts are futile without limiting noise pollution. We argue for pricing noise pollution and show that altering vessel vintage, speed, length, technology in place or even, in some cases, vessel class (bulk vs containers for example) can reduce noise significantly. Adjustments at the fleet level include shifting newer, quieter vessels to whale-sensitive routes. Previous policy responses have focused on salmon restoration or limiting speed (technology

standards). No one has suggested the obvious economic choice - pricing noise pollution. The reason is clear: without evidence that noise pollution harms whales, policymakers have been reluctant to regulate. This is true despite the fact that US plus CDN citizens may value the recovery of this whale population in the billions of dollars per year (see Section VI for a discussion).

The reason for inaction is the lack of evidence that noise pollution matters, and this is not surprising, given the physical context in which whales and ships interact. Whales do, of course, divert from ships' paths and alter their diving and socializing behavior. Ship noise also makes communication more difficult and may make hunting via echolocation less successful. Broadly speaking, noise creates new energetic costs for whales, but biologists have been unable to provide a direct link between rising noise pollution and measures of a population's health such as fertility and mortality.[1]

Our ability to go further stems from access to novel long-term data on ship movements, our knowledge of earlier work in economics linking quasi-experimental variation in industrial pollution to human health outcomes, and, frankly, blind luck. The SRKW happens to be the world's most intensively studied whale population; their critical habitat happens to coincide with several of the world's busiest ports; and these ports happen to have experienced a rapid change in the composition and scale of their vessel traffic over the last 40 years as the United States and Canadian trade turned increasingly to Asia. This lucky happenstance provides us with a setting where a very well-documented killer whale population, that is largely resident in a defined space, has been exposed to quasi-experimental variation in noise pollution.

Using this quasi-experimental variation, we find consistent evidence that shipping noise has lowered their fertility and raised their mortality. The effects we estimate are large. For example, if noise pollution had remained at its early 1980s average, rather than grown by over 100% to its level today, our estimates suggest the SRKW population would be 30% higher than otherwise. This

[1] The state of the art is summarized by (Merchant, 2019, Page 1) "While the risks to marine ecosystems are clear, quantifying the ecological cost of noise pollution remains challenging ... quantifying the link between noise exposure and large-scale effects is complex due to the many other factors which influence populations and ecosystems, and gathering direct evidence of large-scale effects is not expected to be possible in the near term."

change would largely undo the last twenty-five years of population decline. We also find that no feasible level of salmon enhancement - alone - can offset the negative impacts of noise pollution. Instead, our economic analysis of least-cost methods for conservation suggests policymakers may be spending too much on salmon restoration - to the detriment of sport fishers and the salmon fishing industry - because of too little effort constraining noise pollution. Our new economic approach to estimation, valuation, and policy design may help us meet the challenge of restoring the more than 100 threatened and endangered whale populations worldwide.

Providing this evidence required us to overcome several challenges. Our first challenge was to obtain long-term data on KW demographics and potential vessel disturbances. We acquired a complete inventory of all Southern and Northern resident whales from the very first exploratory whale census in the 1970s to 2020. It represents a complete accounting of all killer whale births and deaths for either population for every year. This data is the work of a large scientific community spanning professional government scientists, whale enthusiasts, and a large community-driven whale spotting network.

To this we added data on vessel movements. We started with over 40 years of commercial vessel landings data at over 120 ports on the West Coast of North America. The richness of this data (over 5 million landings) allows for the calculation of yearly vessel km traveled, by various large vessel types, within the SRKW critical habitat. Combining this with estimates of trip length provided by a commercial logistics provider (*SeaRoutes*), generates estimates for the km traveled in the critical habitat (for details see Taylor (2021)). This data provides us with information on potential vessel disturbance decades before the Automated Identification System (AIS) and satellite tracking of vessels made similar calculations possible.[2] The change in vessel traffic over our sample period is very large: the *annual* vessel km traveled, by large commercial vessels within the critical habitat,

[2]The methods described in Taylor (2021) allow researchers to estimate the distance traveled by commercial vessels in a particular habitat from the late 1970s onwards. Although satellite data that tracks vessels through their automated identification system (AIS) could be used to calculate similar estimates, this data is only available, at best, from 2009 and has limited geographic coverage. Since the decline of the SRKW population began in the 1990s our retrospective 40-year study period is critical to identifying the cause of their decline.

rose from approximately 1.5 million km in 1977 to over 3.5 million in 2019.

Our second challenge was to measure the noise pollution generated by vessel trips. We start with a *naive* approach, assuming noise pollution is proportional to vessel km traveled. This is likely to result in significant measurement error because it fails to account for differences across vessel types, their speed, or vintage. While this measure is both simple and transparent, commercial vessels are known to differ greatly in the noise they radiate. Consequently, we also construct a *sophisticated* measure that weighs vessel km by their likely noise disturbance. To do so we exploit data from the handful of studies that document recorded noise from commercial vessels. Most of our data comes from Veirs, Veirs and Wood (2016), which we augment with data published in McKenna et al. (2012).[3] The result is a data set consisting of 2,828 observations on commercial vessels that cover a broad range of vessel classes. Importantly, Veirs, Veirs and Wood (2016) record ships passing in the Haro Strait which is located inside the critical habitat of the SRKW; and, in both studies, vessels were tracked opportunistically, making selection into the samples random.

Our third challenge is ensuring that exposure to noise pollution is as good as randomly assigned. It should be clear that variation in our noise disturbance measures are exogenous to KW behavior. Vessel km in the critical habitat are driven by changes in economic activity in the U.S., Canada, and their numerous trading partners thousands of miles away. Exposure, however, may reflect choices; therefore, treatment may be correlated with whale attributes linked to health. We deal with this challenge using well-known methods. We focus on shocks to noise pollution levels to lessen the ability of whales to adjust to heightened exposure. The logic for doing so is simple. If travel patterns are habitual or avoidance takes time to learn, then noise pollution shocks should generate short-run variation in exposure independent of health status. This shock methodology is, of course, commonly employed in studies linking industrial pollution to human health.[4]

[3] Both papers measured source level noise in decibels (dB) relative to the standard pressure and distance of 1 μPa at a distance of 1 m from the vessel.

[4] Our methods are similar to those used in environmental economics. See the reviews by Graff Zivin and Neidell (2013) and Greenstone and Gayer (2009), or related work by Chay and Greenstone (2003), Currie et al. (2009), Hanna and Oliva (2015) and Schlenker and Walker (2016).

We address the potential for bias from longer-term locational sorting by exploiting a particular feature of killer whale society. Whale populations are comprised of pods, which are, in turn, comprised of matrilineal groups. Matrilines are comprised of very closely related whales who share genetics, travel in very close proximity, share food, and have common learned behaviors and language. Some of these features could affect both health and exposure to noise pollution. To eliminate the potential for bias, we include matriline fixed effects. Our matriline fixed effects play the same role as zip code or income class fixed effects in the existing literature. They force us to identify the impacts of pollution shocks on (whale) health using only within-group (matriline) variation.

While economics can be a powerful lever, this paper owes its existence to the hundreds of researchers, academic and otherwise, who have studied the population dynamics of the SRKW over the last fifty years. One early approach was through the construction and use of life tables (Olesiuk, Bigg and Ellis, 1990; Olesiuk, Ellis and Ford, 2005*a*,*b*). More recently, a handful of researchers have tried to explain KW population growth via regression methods. For example, Ward, Holmes and Balcomb (2009) employs data from 1981 to 2007 on both the NRKW and SRKW to evaluate how salmon abundance and climatic factors may affect KW. Their most important finding is that salmon abundance has a large positive effect on fertility, whereas matriline and pod-related variables do not. Salmon abundance has also been found to be important by Ford et al. (2010) and Ford, Ellis and Olesiuk (2005). Related work has examined the stress hormone responses of KW to summer traffic pulses in the Salish Sea (Ayres et al., 2012), while many others have documented behavioral changes arising from vessel traffic and associated noise (e.g. Williams et al. (2014)).

Our work is similar in that we condition on salmon abundance and adopt the same discrete choice framework favored by natural scientists, but is unique in every other way - in terms of our identification strategy, our construction of a new noise disturbance measure, our use of a theoretical framework to guide estimation and provide counterfactuals, and our novel policy prescriptions. Within Economics, our work is a contribution to the large and growing literature examining the environmental consequences of international trade (See Copeland, Shapiro and Taylor (2022)).

The rest of the paper proceeds as follows. Section II presents a short history and relevant biology of the SRKW. In section III, we present eight facts to frame our argument while introducing data sources. We develop our research design in section IV. Our main empirical results are in section V, followed by policy options in section VI. A short conclusion ends the paper. An online Supplementary Appendix contains considerable detail on methods and data, a formal analysis of parameter identification, and a full set of estimates generated using a linear probability model.

II An Introduction to Killer Whales (Orcinus Orca)

Killer whales are the world's largest predator; the world's most cosmopolitan whale species with populations in all seven seas; and probably the world's most recognizable whale given their striking black and white coloration. While today almost everyone knows something about killer whales, before the early 1960s, very little was known. During this time, killer whales were viewed as a pest to commercial fishing and a danger to humans.[5] Not surprisingly, KW were often shot by fishermen, boaters, and sometimes by the US airforce.[6] Following the initial (and inadvertent) capture of a live killer whale off the BC coast in the early 1960s, the display and live capture industry was born with the Vancouver Aquarium taking a leading role. The industry is still in existence today.[7]

In response to booming demand for display specimens, and the lack of regulation on capture, both US and Canadian authorities started to fund research studying killer whales. Initially, the goal was to calculate what might be a "sustainable" harvest for the display industry but soon grew into a much broader research agenda studying marine mammals. Almost all of our current scientific knowledge comes from research post-1970.

[5] A quote by well-known US naturalist William Temple Hornaday (Hornaday, 1914, p.148) from the turn of the century was still commonly held wisdom sixty years later: "The Killer Whale, or Orca, is the demon of the seas. This creature has the appetite of a hog, the cruelty of a wolf, the courage of a bulldog, and the most terrible jaws afloat. Its teeth are surpassed in size only by those of the sperm whale. It attacks whales of the largest size, and devours sea-lions, seals, and small porpoises as a hungry longshoreman destroys saddle-rock oysters."

[6] See "Air Force Guns to Shoot Whales", Seattle Times, October 16, 1955.

[7] For the full story, see the video of the captive, Moby Doll, available at https://youtu.be/U39Dc87G2yo

A killer whale census began in the early 1970s and continues to this day. It covers whales from both the Northern Resident population, those KW mostly resident in Canada, and whales from the Southern Resident population, those KW mostly resident in the U.S.. Using novel techniques developed by Canadian fisheries scientist Michael Bigg, researchers could identify individual whales, and soon discovered killer whales have life long attachments to their matrilineal group which in turn is tied, again for life, to larger groupings they named pods. Far looser associations of pods constitute what we now call the NRKW and SRKW populations. After more than fifty years of research, the SRKW is arguably the most studied whale population in the world. The NRKW would not be far behind. A map of the habitats for US and Canadian whales together with a frequency of sighting map is in the Supplemental Appendix A.I.

Our detailed knowledge of killer whale society is key to our research design. For example, our study is based on only one eco-type, but there are in fact three different *eco-types* of killer whales. These three differ in their social structure, their size and body structure, and their movement and communication patterns, but it is simplest to define them by their prey. Resident killer whales eat fish; Transient killer whales eat marine mammals (seals, sea lions, whales); and Offshore killer whales eat sharks, squids and rays. Both the SRKW and the NRKW are Resident KW populations, although all three eco-types have been spotted in Canadian and US waters.

Most important to us, is that residency means that, almost every year, every living whale in the resident population is spotted, counted, and recorded in our data. If a whale is continuously absent, it is dead. The only population events missing from the data could be unsuccessful births or neonatal deaths. Our data is therefore a population census and not a sample of these whales.

Second, the NRKW and SRKW do not breed with each other nor interact. Language or calls differ significantly across members of the NRKW and SRKW. The only point of contact between these populations is over their common prey - salmon. Accordingly, we will allow for both within and across-population competition for prey to affect whale fitness and hence outcomes. The critical habitat for the SRKW is primarily, but not exclusively used by southern residents. The critical

habitat for the NRKW is rarely used by southern residents.[8] Commercial vessel traffic in the NRKW critical habitat is also orders of magnitude lower than the traffic in the Salish since it neither contains nor is the entry channel for any deep water port. As a result, we focus on noise disturbance in the Salish Sea because there is very little if any vessel disturbance in the NRKW critical habitat.[9]

Third, the societal structure of a family grouping (pod), consists of several matrilines, each led by a senior female. Matrilines contain all living offspring (both males and females) and their descendants. No whale has ever switched matrilines, and only one orphaned whale has ever changed pods. Calves tend to be born in autumn and winter months, and gestation is 16 to 18 months. These lifelong family connections carry over to their travel patterns and hence exposure to noise, and we exploit these facts in our identification strategy. Our knowledge of birth dates and length of gestation, also implies conception occurs in the important spring and summer months of the preceding year when the whales are often resident in the Salish Sea. Accordingly, we investigate both contemporaneous and one-period lagged values for noise disturbance shocks and salmon abundance.

Fourth, killer whales are very specialized predators. The two resident populations not only specialize in eating almost exclusively members of the salmon family, but they are also highly dependent on Chinook salmon. Estimates of this reliance vary across studies, but salmon make up perhaps 70-80% percent of their diet with Chinook salmon being 70-80% this total. This heavy reliance on salmon, and Chinook in particular, is true for both the NRKW and the SRKW populations. As a result, we employ salmon abundance measures specific to Chinook. Fortunately, these data exist for our entire sample period and come from an authoritative international body (The joint US-Canada Pacific Salmon Commission). Since many of the Chinook intercepted by KW are des-

[8]The NRKW critical habitat lies between the continental mainland of B.C. and Vancouver Island starting just north of East Thurlow Island and covering the entire width of Johnston Strait to a vertex at Numas Island just north of Port McNeil.

[9]One of us (Taylor) has visited the NRKW critical habitat four times in the last six years by either kayak, fishing boat, or cruise ship. Part of the reason for visiting was to gauge the extent of vessel traffic not captured in our data. Interactions with guides and captains confirm what our data, and common sense, told us - with no major port in or near the habitat, and given the difficult passage for large vessels through Seymour Narrows at the end of Georgia Strait, there is very little commercial vessel traffic through the inside passage via Johnson Strait.

tined for the Fraser River this means our very specialized predator has to focus on paths leading to the mouth of the Fraser which is just south of Greater Vancouver Ports. These paths are either very close to or on top of international shipping lanes; as a result, avoiding vessel noise comes at a very high cost, and we exploit this high cost of avoidance in our identification strategy.

Fifth, killer whales spend the vast majority of their lifetime in very dark deep ($\geq$10 m) water; not surprisingly, hearing is by far their primary sense and they have developed very specialized (and different) organs that use sound waves for communication (using low frequencies up to 10Khz that are received by bones in their lower jaws and transmitted to their inner ear) and prey identification and capture via echolocation (using frequencies up to 60kHz emitted and received by vibrating fatty tissues in their snout).[10] Sound, of course, travels much faster in water than air, and typically much further in oceans than over land, which is why some baleen whales can communicate over hundreds if not thousands of miles. Against this backdrop, it's important to recognize that large commercial vessels are surprisingly noisy with decibel levels at the source sometimes exceeding 180dB. To put this in perspective, the US Marine Mammal Protection Act defines level B harassment of a marine mammal to occur when there is persistent exposure to noise exceeding 120dB.

Importantly, some vessels are considerably noisier than others and it may be important to distinguish across vessel types and their vintage.[11] Therefore, we allow for vessel-specific noise signatures. This means that changes in aggregate vessel disturbance come from changes in both the scale and composition of vessel traffic. And since decibels alone are a poor measure of disturbance, we construct a simple sound exposure model (SEM) to translate variation in noise at the vessel source (in decibels) to an area of the critical habitat disturbed.[12]

[10] A very nice review of killer whale hearing is contained in Ford (2017)

[11] For example, McKenna et al. (2012) studies the noise signature of 7 different vessel classes using acoustic data from the Santa Barbara channel finding the acoustic level, frequency (Hz), and spectral shapes, (across dB) vary significantly.

[12] The SEM here plays exactly the same role as does an air pollution dispersion model: it takes variation in source-level emissions and maps them into variation in potential exposure. One very good example in the environment and health literature is Schlenker and Walker (2016).

III Eight Facts to Frame our Argument

We start by presenting eight facts to frame our argument. With one exception they are descriptive statistics. Together, they provide suggestive evidence of a link between noise pollution and the decline of the SRKW population.[13]

III.I The Critical Habitat contains 31 Ports

Killer whales (KW) have been protected in one way or another since the early 1970s. They were protected under the Canadian Fisheries Act in 1970, and in the USA by the Marine Mammal Protection Act since 1972. The capture industry was first regulated in the early 1970s and then banned entirely. The two populations initially grew from their early 1970s numbers, but the recovery of the SRKW has been uneven at best. In response the SRKW were listed as Depleted under the MMPA in 2003; Endangered by Washington state in 2004, and Endangered under the U.S. Endangered Species Act in 2006. The NRKW was listed by the Committee on the Status of Endangered Wildlife in Canada as threatened and the SRKW as Endangered in 2001 due to their low population sizes, low population growth, and recent *unexplained* population declines (Fisheries and Oceans Canada: Canadian Science Advisory Secretariat, 2017). These Canadian listings became law under the Species at risk act (SARA) in 2003.

As a result of these listings both the US and Canadian governments have identified critical habitats for the SRKW (see figure below). These designations occurred in 2009 and 2006 respectively, although they have been subject to review and expansion very recently.[14] In this paper, we employ the original designations of CH. By definition, critical habitat should "include sufficient quantity and quality of prey species, particularly Chinook Salmon, water of a sufficient level so as not to

[13] The first three of these facts also appear in Taylor (2021) and are presented here for the reader's convenience.

[14] In December of 2018, the critical habitat for KW has been recently expanded to include additional areas off the southwest of Vancouver Island. This is an area of prey abundance, and both the NRKW and SRKW have been identified in this area throughout the year.

result in loss of function and an acoustic environment that does not interfere with communication or echolocation" (Fisheries and Oceans Canada: Canadian Science Advisory Secretariat, 2017, p2.).

Figure 1 presents a map of an area of the west coast near Vancouver, Seattle, and Puget Sound, commonly referred to as the 'Salish Sea'. The map shows three shaded areas, and our 31 ports of interest (POI) are shown with a dot. We have drawn in two bold lines to demarcate entrances and exits from what Taylor (2021) refers to as the critical habitat plus. The critical habitat plus (henceforth CH) is the sum of the three shaded areas. Any vessel entering the CH does so in only one of two ways: it could enter via the inside passage down the east side of Vancouver Island or it could enter through the international shipping lanes in Juan de Fuca Strait which separates the Southwest tip of Vancouver Island from the Northwest tip of Washington state. The vast majority of traffic enters and exits via the Juan de Fuca Strait. As a consequence of this geography, vessel trips can be classified into a limited number of types, and their vessel km calculated.

The parts of the Salish Sea trapped by these boundaries are taken to be the area of critical habitat for the purposes of this study. This is a slight overestimate of the actual area since there are small areas that are not included such as bays, some ports, etc. In all cases of significance, getting to these ports requires a vessel to traverse the official critical habitat, and hence we believe the critical habitat plus assumption is innocuous.

In total, there are 31 Ports contained in our CH as shown by the brown dots (a full list of these Ports of Interest (POI) is included in the Supplementary Appendix A.II). While several of these ports are very small and never host large commercial vessels, the Port of Vancouver is Canada's busiest port, and both Seattle and Tacoma are major ports. Even relatively obscure named ports host commercial vessel traffic, and all others are very busy with fishing, government, and pleasure craft as well. Our point is simply that the critical habitat for the SRKW is coincident with a very active portion of the Pacific Northwest coast.

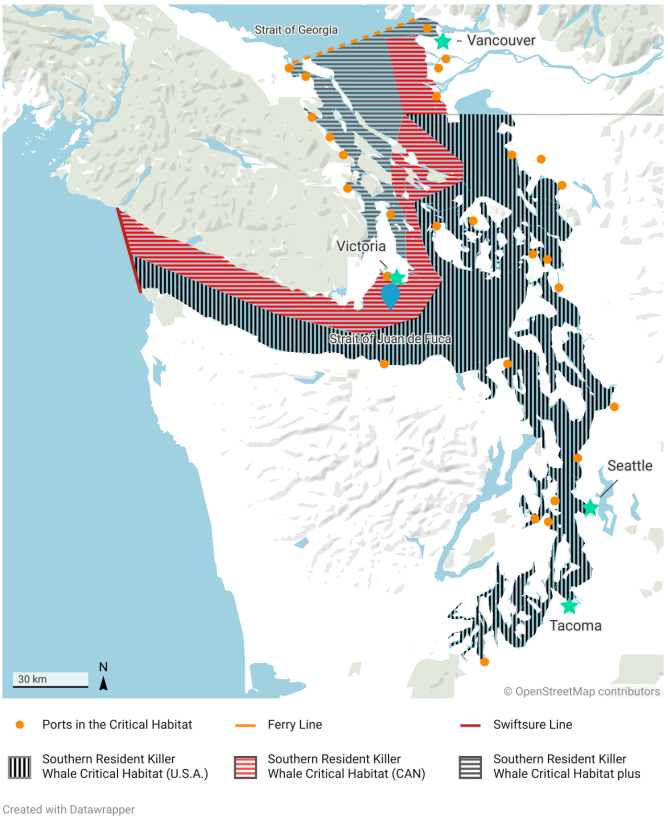


Figure 1: Designated critical habitats for Southern Resident Killer Whales

III.II The Growth in Vessel Traffic is Huge

How active are these 31 Ports of Interest (POI); why are they active, and has their activity level changed over time? To do so, we collected data on vessel landings from Lloyd's of London. Lloyd's of London has been providing data on international shipping since 1778 and is the premier data provider of shipping data worldwide. Unlike the many newer data providers, Lloyd's has vessel traffic data prior to the introduction of the Automated Identification System or AIS. Prior to approximately 2010 (the exact date varies by location and vessel type), Lloyd's relied on human intelligence and terrestrial sightings. Post-2010 these reports are buttressed with AIS readings.[15]

[15] While vessels of a certain size (greater than 500 gross tons for example) or trip type (international/national, passenger carrying) have been subject to requirements on AIS since 2004, AIS data prior to 2009 is very spotty. This is not surprising since AIS is first a ship-to-ship navigation aid, then when in range, a ship-to-shore navigation aid, and only recently has it become a useful tracking data source when it moved to ship-to-satellite.

In Table 1, we provide trip figures for vessels departing from our 31 POI over two time periods. The time periods divide the sample years into two roughly equal time periods and differ greatly in the extent of vessel traffic. We have included in this table only departing trips taken by large commercial vessels: bulk carriers, tankers, cargo ships, etc. since these are well known to be the largest and noisiest ships. Several features stand out.

First, if we sum the two-period totals from column one, the All Departures column, we find there were approximately 300,000 trips by large commercial vessels recorded as departures from CH ports over the entire time period (120,038 + 174,911). The majority of these trips are recorded in the later 1998-2019 period which recorded about 55,000 more trips than the earlier 1977-1997 period. This increase in 55,000 represents a 46% increase in trips. Therefore, in some sense, traffic in the Salish Sea has increased significantly.

Table 1: Departures by commercial vessels* from the ports in the Critical Habitat**, aggregated over 1977-2019

Country	*(1)=(2)+(3)+(4)* All departures	*(2)* Domestic departures[a]	*(3)* International departures to U.S. or Canada[b]	*(4)* International departures to third countries[c]
	b) 1977-1997			
Canada	58,192	19,418	35,584	3,190
U.S.A.	61,846	42,033	18,403	1,410
Total	120,038	61,451	53,987	4,600
	As percentage of (1):			
Canada	100%	33%	61%	5%
U.S.A.	100%	68%	30%	2%
Total	100%	51%	45%	4%
	c) 1998-2019			
Canada	100,276	34,236	25,515	40,525
U.S.A.	74,635	39,508	14,591	20,536
Total	174,911	73,744	40,106	61,061
	As percentage of (1):			
Canada	100%	34%	25%	40%
U.S.A.	100%	53%	20%	28%
Total	100%	42%	23%	35%

*: Commercial vessels: bulk, combined carrier, gas tanker, general cargo, misc. general cargo, tank, unitized.
**: Including Orcas Is. (U.S.A.) and Vancouver Anchorage (Canada).
[a]: Goes from Canada to Canada and from U.S. to U.S.; arrival port may be outside the critical habitat
[b]: Goes from Canada to U.S. and from U.S. to Canada; arrival port may be outside the critical habitat
[c]: Goes from Canada and from U.S. to third country

Columns (2), (3), and (4) tell us where these departures are destined to land. For example, Column two, Domestic departures, represents vessel departures from US (CDN) ports within the CH destined for other ports in the US (Canada). Since these are within-country trips, they are not directly involved in international trade, and their share of total departures fell from 51% of total departures in the first period to 42% in the second. Their absolute number grew however by approximately 12,000 trips.

The last two columns record departures directly tied to international trade. The third column contains departures originating in a US or CDN port within the CH, but bound for a port in the other country. Surprisingly, these within North America (but across the country) trips fell over the period, not only in percentage terms but in absolute numbers from 53,987 to 40,106. Therefore, it appears traffic in the Salish Sea generated by US/Canada trade has been falling.

What is responsible for the 46% growth in trips? Column (4) tells us that departures leaving the CH and (directly) bound for foreign ports have skyrocketed. In percentage terms, they rose from 4% of all departures to 35%. In absolute numbers, they jumped from only 4,600 in the earlier period to 61,061 over the latter. One conclusion is inescapable: commercial vessel traffic in the Salish Sea has grown tremendously over these two time periods, not because of rising US/Canada trade (it fell by almost 14,000 trips), or rising traffic within US or CDN waters (this rose by only approximately 12,000 trips), but because of an explosion of new direct trips outside of North America.[16]

III.III The Composition of Vessel Traffic Changed Dramatically

Not only has vessel traffic in the Salish Sea increased, but the composition of this traffic has changed dramatically. To see this, we present landings by vessel type below.[17]

[16] We cannot identify vessels engaged in trade per se because we do not have individual vessel data and bills of lading. For example, if a vessel went from a CDN (US) port to a US (CDN) port, and then to Asia that vessel trip appears in column 3. Therefore, the growth we see in column four comes from growth in vessel traffic going directly to ports outside of North America.

[17] This table also appears as Table 2 in Taylor (2021).

Table 2: Landings at Critical Habitat ports by Vessel Type

	(1)	*(2)*	*(3)*	*(4)*
	1977-1997		1998-2019	
Vessel type	Landings	Share in total	Landings	Share in total
Bulk	48,020	40.0%	42,417	24.3%
Combined Carrier	353	0.3%	49	0.0%
Gas Tanker	139	0.1%	343	0.2%
General Cargo	21,099	17.6%	14,068	8.0%
Misc. General Cargo	8,901	7.4%	21,835	12.5%
Tank	15,787	13.2%	23,246	13.3%
Unitised	25,739	21.4%	72,953	41.7%
Total commercial	**120,038**	**100.0%**	**174,911**	**100.0%**

Three things are evident. First, the two most common large vessels are Bulk vessels and Unitised (container ships). They account for a little over 60% of all vessel landings in both periods. Second, Bulk vessel traffic has fallen slightly over the period, while Unitised (Container) vessel traffic has almost tripled from 25,739 landings in the pre-1998 period to 72,953 in the post-1998 period! Container ships are now, by far, the most common vessel type landing in CH ports. Third, Gas Tankers and Combined Carriers are only a very small fraction of vessel traffic whereas Tank vessels (those carrying liquid cargo other than gas) are the third largest vessel class and have grown over time. Their share of overall traffic has however remained virtually constant. Therefore, the Salish Sea has become much busier; vessel trips are now more international than previously; and, not surprisingly, this traffic is dominated by an explosion in the use of Container ships.

III.IV The Vessel km Traveled in the CH has more than Doubled

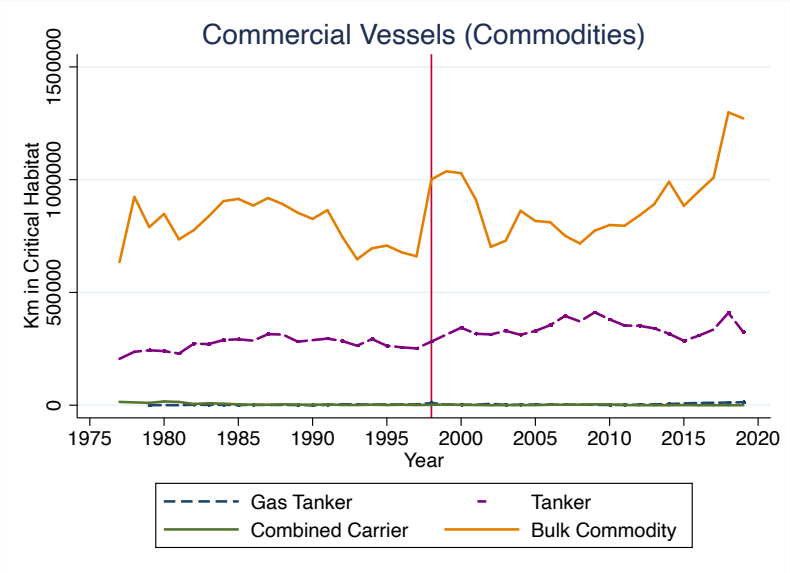


Figure 2: Vessel Km in Critical Habitat by commodities vessels

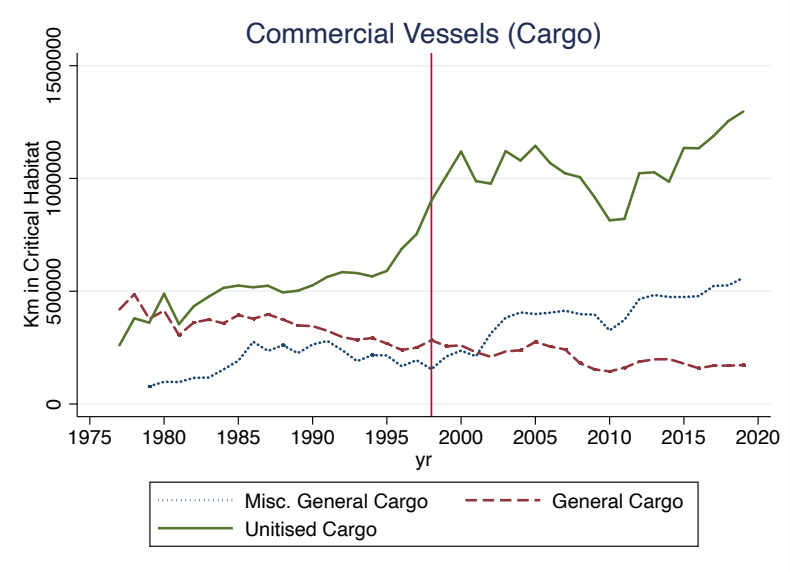


Figure 3: Vessel Km in Critical Habitat by cargo vessels

To generate our third fact we employ the *Vessel Arithmetic* developed in Taylor (2021) to calculate the actual vessel km traveled in the Salish. For each landing observed in the data, we count only the net contribution in terms of km traveled from its previous port to its current landing port. In essence, this sums something akin to value-added (km in the CH) from gross transactions data (all possible landings). The km of the associated trip is collected from the voyage planning company, *Sea Routes*, and entered as the trip distance for that trip type in a given month/year.[18] Aggregating across all trips gives us the km traveled in any given period t. An example of the vessel routes reflected in incoming and outgoing trips together with their destinations/origins is presented in Supplementary Appendix A.III. In Figures 2 and 3 we plot the calculated annual vessel km in the CH, for various vessel types, over the entire time period.

Four features stand out. First, the vast majority of km in the critical habitat comes from Bulk Carriers and Unitised (container) Cargo ships. Gas Tankers and Combined Carriers make up an infinitesimal contribution, followed by Tankers. Second, there appears to be some substitution across cargo vessel types during the period. General Cargo falls throughout being replaced by both Misc. General Cargo and Unitised vessels. Third, the total vessel km grew tremendously over this period more than doubling from a little over 1.5 million km in 1977 to over 3.5 million in 2019. In annual average terms, over the pre-and-post-1998 periods indicated by the vertical line, vessel km in the CH rose from 2.1 million to 2.9 million. This represents an annual average increase of 800,000 km or 38%. Fourth, and finally, it is obvious what is driving most of this increase. It is the change in km traveled by Unitised (container) shipping. Unitized km takes off in the late 1990s and remains very high for almost ten years only to fall during the credit crisis years to then recover and continue its growth entering 2019.[19]

[18] SeaRoutes is a professional tool for route and distance calculation: see, https://www.searoutes.com

[19] In comparison, McWhinnie et al. (2021) tracks vessel hours in the critical habitat for two classes of vessels matching our commercial vessel categories. She finds vessel hours rise from 6,222 (4-month period) in 2013 to 12,192 by 2016. This is broadly consistent with the post-crisis recovery shown in the figure but more extreme perhaps because vessel hours are not km traveled. While there is a strong seasonal component to whale watching, fishing, and cruise ship activity none of these are in our commercial vessel categories which show little seasonal influence.

III.V The Nosiest Vessels are Container Ships

Commercial vessels differ greatly in the noise they generate. Some of these differences come from differences in their average speed, but much more of this variation is explained by fixed vessel class characteristics such as propeller placement, vessel shape, displacement etc. As a result, some vessels are just far more likely to disturb whales than others. To investigate we collected data on vessel noise from two sources. The majority of the data was collected from Veirs, Veirs and Wood (2016) which we augment with data published in McKenna et al. (2012). Both studies collect ship sounds with the help of a seafloor-mounted hydrophone, and both combine the received sound parameters with ships' distance from the hydrophone – learned from AIS – to calculate the source level noise of the passing vessels. The authors then use the AIS-provided ship identifier to collect further vessel characteristics.

In Supplementary Appendix A.XI, we present a table of cross-sectional regressions that link vessel noise measured at the source level in decibels, to vessel characteristics. We explore two specifications that differ in how we define vessel classes. For a variety of reasons, explained in the appendix, we have a slight preference for the narrow vessel class specification. We use estimates from this specification (See column III, Table A.12 in the appendix), to generate predicted source level, SL, by vessel class. These estimates are reported in the first column of Table 3.[20]

Looking at the estimates for source level disturbances we see that within vessel classes, larger (longer) vessels are almost always associated with greater noise disturbance. These within-class differences are however swamped by differences across vessel classes. It's apparent that large container ships are the noisiest of all vessels with source-level emissions at over 180 dB. In contrast, pleasure craft, fishing, and some military vessels are relatively quiet with source level emissions near 165dB. These differences look small (15dB on a scale ranging from 165 to 180), but this is misleading. Source level emissions are measured on a log_{10} scale. A vessel emitting 180dB at the

[20] We use vessel class-specific sample averages for speed, dead weight, and age together with the fitted equation in the table notes. Using the alternative wide-vessel class specification produces similar results.

source level is orders of magnitude noisier than one at 165 dB. And these differences matter because whales may be disturbed whenever a nearby vessel's SL emissions raise the ambient noise of the ocean above some threshold level. The relevant metric is then the size of the disturbance created by a vessel.

In column three we translate our SL estimates in column two, into a relative measure of physical disturbance. To do so we employ a sound exposure model that relates a vessel's SL emissions to a three-dimensional measure of underwater disturbance (model details in Appendix A.XII). The model is based on two physical laws: sound dissipates with distance via a known formula, and it does so by spherical spreading from the source. In theory, all moving vessels create a three-dimensional disturbance bubble that contains an area where ambient noise is greater than a given (chosen) threshold.[21] As a result, what appears to be small differences in column two now map into large differences in column three. To make our vessel comparisons free of physical units, we chose the vessel disturbance of Bulk ships less than 200 meters in length as our numeraire. The results on Relative Disturbances in the last column are striking. A very large Container ship traveling 1 km in the habitat is more than 7 times as disturbing as a small Bulk vessel covering the same distance! Even a medium size Container ship is more disturbing than all other vessel classes and still 4.5 times as disturbing than a somewhat smaller Bulk vessel. Also apparent from the table is that commercial vessels as a class, are just far more disturbing than others. Therefore, our exclusion of km traveled by Tugs, Fishing Vessels, and the like from our analysis seems justified.

III.VI The Availability of Salmon is Cyclical

Since Resident KW are reliant on salmon for prey, it is important we understand how salmon abundance may have changed over time. To do so, we rely on publications from the Pacific Salmon Commission (PSC) for data on the KW's main prey, the Chinook salmon. Specifically, we

[21] We didn't invent the disturbance bubble idea - NOAA documents are replete with graphics showing these bubbles. For example, visit https://www.fisheries.noaa.gov/national/science-data/ocean-noise

Table 3: Relative Vessel Disturbance (1 km)

Vessel type	Predicted source level $\hat{SL}$	Relative Disturbance
Bulk carrier 200-	173.35	1.00
Bulk carrier 200-250	172.58	0.77
Bulk carrier 250+	177.24	3.76
Cargo 150-	174.39	1.46
Cargo 150+	175.62	2.05
Container ship 250-	176.02	1.87
Container ship 250-320	178.72	4.49
Container ship 320+	180.26	7.55
Tanker 165-	173.52	1.05
Tanker 165+	175.65	2.20
Vehicle carrier	175.68	1.81
Tug	171.11	0.77
Fishing	165.35	0.10
Military	163.62	0.03
Miscellaneous	163.15	0.04
Passenger	167.08	0.11
Pleasure craft	166.65	0.11
Research	167.12	0.14

$\hat{SL}_{it} = 157.79 + 7.2 \log_{10}(\text{speed}) + 1.16 \log_{10}(\text{dwt}) + 0.02\text{age}_t + \hat{\beta}_2 \text{vessel type}_i$

rely on the Commission's Joint Chinook Technical Committee's report published in 2021 (Pacific Salmon Commission, 2021), because it provides historical abundance indexes for the 1979-2019 period. The committee provides abundance indexes for three areas relevant to KW foraging: South East Alaska (SEAK); Northern British Columbia (NBC); and the West Coast of Vancouver Island (WCVI).[22] Figure 4 plots these indices over the sample period.

[22] This index is commonly used in research on KW by biologists. For example, see Ward, Holmes and Balcomb (2009).

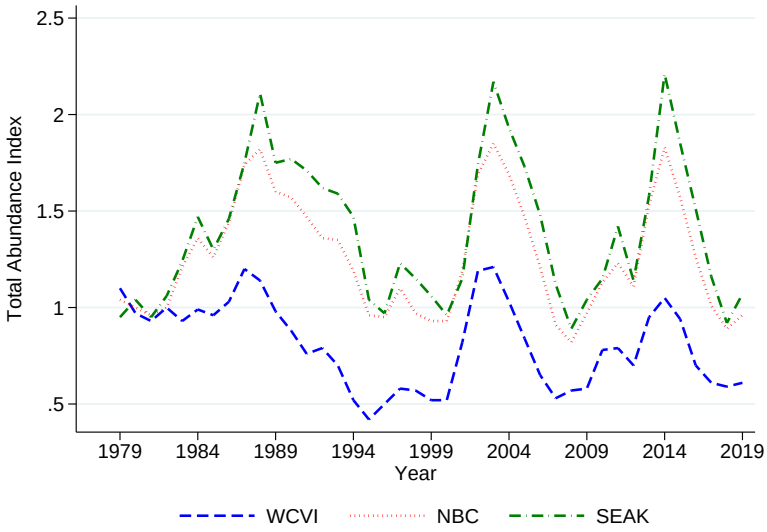


Figure 4: Total abundance indexes of the three AABM fisheries

The indexes (which are all unity in 1979) show the abundance of Chinook salmon periodically peaks and plummets. This feature is consistent with evidence that periodic changes in the abundance of many salmon species are driven by common, and poorly understood, natural processes on the high seas.[23]

Three features of this data are important for our purposes. First, consistent data is available over a long period of time suitable for studying the demographics of long-lived marine mammals. In particular, we note that the dramatic fall in all three indices in the 1990s is coincident with the dramatic decline in the SRKW over the same period (see Figure 5). A commonly held view is that this relationship is causal.

Second, despite some level differences across the indices, their over-time variation is very similar. Z-scores calculated from these three indices have very high ($> .9$) pair-wise correlations. This

[23] While Welch, Porter and Rechisky (2021) finds that the Chinook smolt-to-adult return rate (the ratio of very young fish leaving their natal river that later return to spawn) has fallen by a factor of three over the last fifty years most of this decline occurred before our sample period. Since the decline is common across coastal rivers (some dammed/some pristine), they attribute the decline to the poorly understood ocean phase of a salmon's life.

means, in effect, there is one salmon abundance index and not three. Consequently, we aggregate these indices into one overall salmon abundance measure for our empirical work.

Third, our abundance measure reflects the estimated number of Chinook salmon returning from their 2-7-year hiatus in the ocean to spawn in their natal streams. This number is unaffected by the size of the current KW population in the Salish Sea, and we take salmon abundance as exogenous. A decline in this year's salmon abundance may drive down today's KW numbers, but today's KW numbers only affect the potential number of returning salmon escaping to spawn upstream.[24]

The key feature of the figure is the cyclical nature of abundance. It is apparent that since the large decline in abundance in the 1990s there have been at least two episodes where all of the indices have cycled upwards to levels very close to, or higher, than the highest levels of abundance on record! This cyclical feature of salmon abundance is our sixth fact.

III.VII The SRKW Population Decline is Unique

The SRKW are arguably the most studied whale population in the world - and not surprisingly - there exists very good data on their population as well as that for the NRKW.[25] We obtained the data on the Northern and Southern Resident KW populations mainly from whale census documents. The publications give a summary of the population's status and photos of the individual animal's dorsal fin and saddle patch area. These photos identify individual animals because notches, scars, and coloration are unique to individual whales. Accordingly, each whale has its own name, or tag, which refers to the pod to which it belongs: J1, L15, A32, etc.

The first KW survey was published in 1987 and summarized the past fifteen years' research into

[24] Could this be important over a longer time horizon? Possibly, but salmon lay thousands of eggs (1,000-17,000), with only about 1% of these getting to adulthood. Mortality is very large, and mortality at early life stages (as eggs, alevin, fry, and smolt) is density dependent. This implies if a large population of KW meant fewer salmon escaped upstream, their eggs, alevin, etc. would all face lower mortality because of reduced competition and this lessens any link between today's KW numbers, escapement numbers and eventual recruitment and return 2-7 years hence.

[25] A whale census was made possible by the pioneering work of CDN fisheries scientist Michael Biggs who developed a novel method of whale identification and then spearheaded the very first census in the early 1970s.

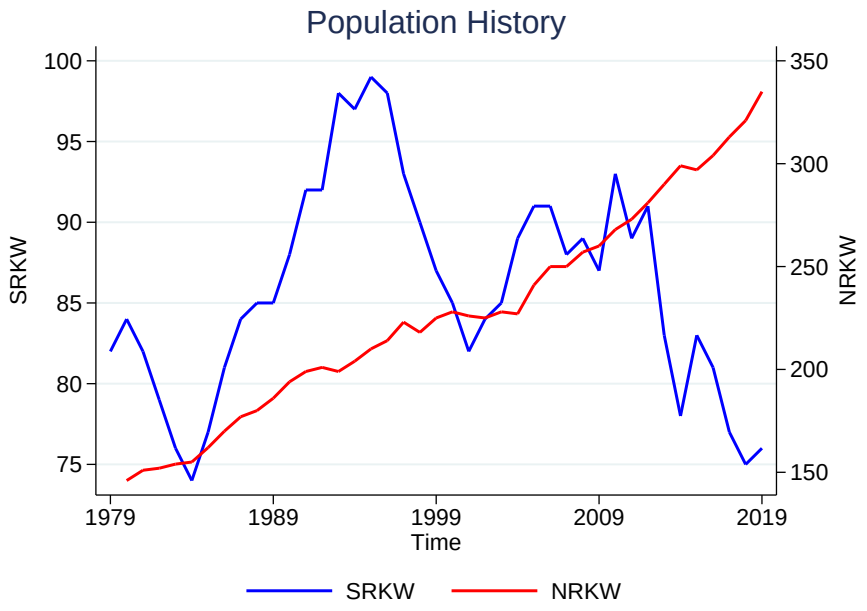


Figure 5: A Tumultuous History

killer whales (Bigg et al., 1987). After 1999 the census of the Northern and Southern populations separated. The Northern Residents were surveyed in 2007 (Ellis, Ford and Towers, 2007), 2010 (Ellis, Towers and Ford, 2011), 2014 (Towers, Ellis and Ford, 2015), and 2019 (Towers et al., 2020). These surveys were published by Fisheries and Oceans Canada. Information on the Southern Residents was less well-published. This population is monitored by the Center for Whale Research in the US. They published a photo identification guide for the SRKW in 2019, which conveyed fairly similar information to the Fisheries and Oceans Canada publications (CWR, 2019).

The resulting data contains each animal's year of birth, their year of death when applicable, their gender, their pod affiliation, and for females the years in which they gave birth and whether their calves survived to the next year. Using this data we constructed a panel data set with 12,793 whale-year observations over the 1979-2019 period. The data is truly a census because every whale, in both the NRKW and SRKW population, appears in this data for the years between its birth and death (details in section A.IV of the Supplementary Appendix).

Using this data we plot the population history of both the Southern and Northern Residents in Figure 5. Since the size of the whale populations is quite different we plot them on separate axes. The overall impression from the figure is divergence. The NRKW started with a relatively small population in the late 1970s but has since grown more or less steadily at an annual average rate above 3% more than doubling over the sample period. In contrast, and despite the protections afforded by an endangered species listing, the SRKW has experienced at best zero growth over the same period. Therefore, the decline of killer whales on the West Coast is far from a universal phenomenon: the NRKW are doing very well thank you, while the SRKW are not. There is also evidence that other killer whale populations - transient killer whales who visit the Salish Sea to hunt for marine mammals - are also doing very well.[26] Consequently, our seventh fact is that the SRKW population decline is unique amongst KW populations on the West Coast.

III.VIII Conflict is Inevitable

Recent work by Fisheries and Oceans Canada (Thornton et al., 2022) has aggregated all available KW sightings data from whale-watching vessels, from volunteers located at *platforms of opportunity*, and from Department of Fisheries research vessels collecting encounter data during fieldwork. Aggregating this data provides measures of the intensity of occurrence of the SRKW in various locations, from May to October, in the Salish Sea. The results from this analysis are best illustrated in graphical form which allows us to superimpose shipping routes of commercial vessels drawn from our data provider *SeaRoutes*. These routes are those used by vessels either exiting or entering the Salish, or transiting between Salish seaports. In Figure 6 we present the intensity of occurrence map constructed by combining whale watching and DFO sightings data.[27] As shown there are several KW hotspots. First, the area of Swiftsure Banks at the entrance to the Juan de Fuca Strait; second

[26] The west coast transient population has been growing at approximately 3.5% since 1975, see Towers et al. (2018).

[27] The data from platforms of opportunity give very similar results for areas close to San Juan Island and the Fraser River. We chose to use this graphic because it includes the important Swiftsure Banks region.

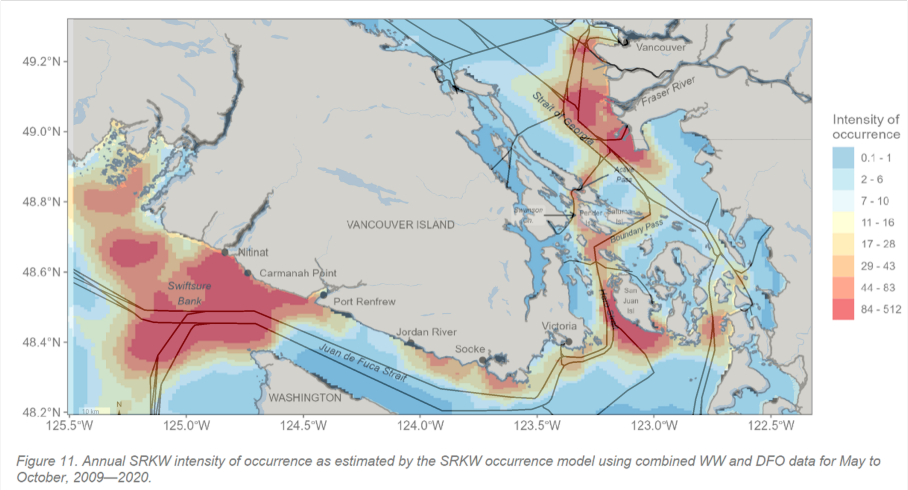


Figure 11. Annual SRKW intensity of occurrence as estimated by the SRKW occurrence model using combined WW and DFO data for May to October, 2009—2020.

Figure 6: Conflict is Inevitable

Haro Strait and Boundary Pass transiting the islands, and then the area proximate to the mouth of the Fraser River near Roberts Bank. All commercial vessels must cross Swiftsure Banks to enter and leave; any vessel heading to CDN ports follows the routes through Haro Strait and Boundary Pass; and all vessels destined for Fraser River docks, or the container port at Roberts Bank must cross the remaining hotspot. It is very clear from the figure that key areas of KW habitat are also very important routes for international shipping - leading to our final fact - conflict is inevitable.

IV Research Design

It is very tempting to weave our eight facts into a suggestive argument: vessel km rise at about the right time; the composition of vessels shifts to just the right ships; and this disturbance happens at largely the right place - because killer whales cannot flee the cacophony without abandoning prime foraging grounds. The leading alternate theory of the decline - falling salmon abundance - has to dismiss these facts as mere coincidence of both time and place - and must also explain why periods of historically high salmon abundance subsequent to their late 1990s decline has failed to halt it.

Our facts provide motive (growing trade with Asia) and opportunity (vessel disturbance in the

critical habitat), but how does the largely unobservable noise disturbance from vessels translate into observable indicators of killer whale health and reproductive success?

IV.I The Causal Connection

Sound to marine mammals is much like eyesight to us - it is their primary means of understanding and exploring the world around them. Sound from vessels disturbs their ability to navigate, socialize, and hunt but finding incontrovertible proof of these effects is not easy, and estimating the magnitude of the disturbance is harder still. Despite these difficulties novel work by ecologists and biologists has established commercial vessels create significant noise in frequencies used by KW for both communication (lower frequencies) and echolocation (higher frequencies). Hall and Johnson (1972) for example provided the first evidence on KW hearing from experiments on a captive KW at Seaworld San Diego. As well, observational studies provide dose-response estimates of behavioral changes when large boats are near, which imply an energetic cost to KW from vessel disturbance.[28] Finally, constant, high amplitude background noise can drive KW from an area (Morton and Symonds, 2002). Taken together this evidence from the natural sciences connects vessel noise to energetic costs and lowered fitness of KW. To understand what might be the observable implications of this loss in fitness, we turn to a very standard model used in resource economics.

Consider a whale population with size N in a constrained environment with carrying capacity K. Their growth is governed by a standard logistic growth equation with an intrinsic rate of growth given by r; that is, our whale population is governed by:

$$dN/dt = rN(1 - N/K) \tag{1}$$

In the absence of any human interference, any initial whale population, $N(0) > 0$, grows to its

[28] There are many observational studies showing avoidance behavior by KW, but fewer explicitly linking the acoustic signature of different nearby vessels to changes in observed behavior. For an example of this latter type, which also includes many references to the former type, see Williams et al. (2014) and Williams, Trites and Bain (2002).

maximum at the carrying capacity K in the very long run. We think of K as being determined by the quality of the acoustic environment, the abundance of salmon, and the extent of competition from other whale populations.

Now view this very standard resource model through a Malthusian lens where separate birth and death processes, both functions of carrying capacity per whale, K/N, add up to (1). K/N - which we think of as a key determinant of average fitness in the population - is the obvious whale analog to Malthus's income per capita.

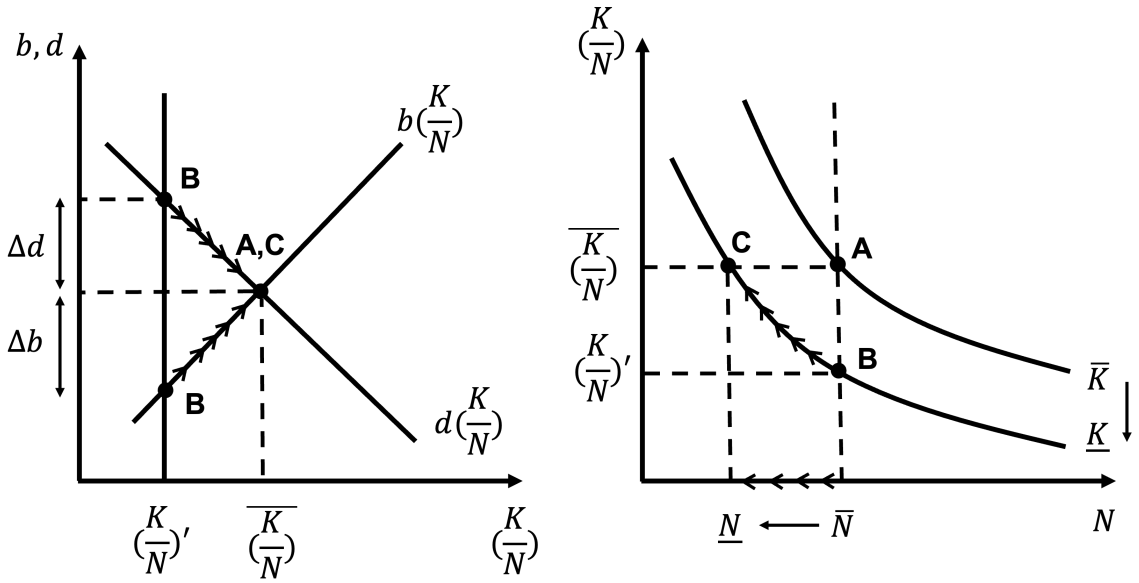


Figure 7: Births, Deaths, and Noise

To make the connection to Malthus precise, divide (1) by N to relate the population's growth rate, g, to the difference between birth, b, and death, d, rates: i.e. $g = b - d$ for some functions b and d of K/N. Two possible birth and death rate functions are shown in the left panel of Figure 7. We have assumed birth rates rises with K/N while death rates falls with K/N. In the right panel, we are simply dividing our environment's carrying capacity into its component parts - K/N and N - which generate the rectangular hyperbola shown. If we start in an undisturbed environment with carrying capacity $K = \overline{K}$, the long run of the system is at the points labeled A in both panels. Births

equal deaths when N has adjusted to ensure $K/N = \overline{K/N}$ (which is 1 in our textbook model).

Vessel noise lowers the productivity of any given environment by masking prey and making socializing and communication more difficult. It increases the energetic costs of everyday whale life. To an economist, this is technological regress. This regress is captured in the right panel by shifting our hyperbola inwards to represent the now degraded carrying capacity given by $\underline{K} < \overline{K}$.

On impact, the shock moves us to the points labeled B in both panels. Since N is fixed in the very short run, the carrying capacity per whale falls below subsistence. Consequently, in the left panel shown by the two points labelled B, death rates rise and birth rates fall. Over time the population falls moving us towards C in both panels. In the very long run, the system restores itself to a stationary state with equal birth and death rates at the now reduced population of $\underline{N}$. This is the long-run effect of vessel noise degrading the whales acoustic environment.

This model, while very simple, is tremendously helpful. To see why, consider the impact of a once-for-all permanent increase in noise pollution. If noise pollution degrades the whales' habitat we should observe, in the short run, a combination of higher death rates and lower birth rates. For any individual whale, we may find its probability of death rising, while female whales may experience a lower probability of birth. In the long run, whale numbers adjust to the new situation, and birth and death rates return to their previous levels. Therefore, the model predicts a long-run negative relationship between the level of noise disturbance and the level of the whale population.

While this levels-on-level logic is a useful theoretical insight, it will prove very difficult to evaluate empirically. It is obvious from the data already presented that vessel traffic rose tremendously over the sample period - especially since 1998 - while the SRKW population has trended downward over almost all of this post-1998 period. Disentangling the impact of rising vessel noise from a host of other potential drivers that also rose (or fell) consistently over this period - the impact of climate, rising NRKW numbers, a rise in whale watching, economic growth in the Pacific Northwest, etc. - will be very difficult if not impossible.

Fortunately, there is an alternative (model suggested) empirical approach which is equivalent.

As we will soon show, vessel noise has not risen steadily over the period. There have been very noisy years; some relatively quiet years; and others with what we might call average noise. The sum total of these noise disturbance shocks has led, over the last 40 years, to an increase in the average noise experienced by KW, but the amplitude of the changes between noisy and quiet years is considerable. We can use this fact to evaluate our theory by linking these temporary noise disturbance shocks to their short-run, and relatively immediate, impact on fertility and mortality. In terms of the figure, think of the movement to $\underline{K}$ as the result of a temporary noise disturbance shock. There are many such movements over time - both inwards (shown) and outwards (not shown). Each of these shocks precipitates immediate changes in births and deaths, represented by the distance BB in the left panel, which we may estimate. The key benefit of exploiting noise disturbance shocks is that they are far less likely to be correlated with other potential confounders, although we would still need to condition on other determinants of births and death responses - such as salmon abundance and the size of any competing whale population. Less obvious is that it will also allow us to estimate the long-run relationship between noise disturbance and population in levels.[29]

IV.II The Quasi-Experiment

Our research design relies on exploiting quasi-experimental variation that is as good as randomly assigned across units (whales) to investigate their health impacts.[30] To do so, we rely on the annual variation in vessel traffic which is significant. While total commercial vessel km traveled in the SRKW critical habitat grew at an annual average rate of over 40,000 km per year, this growth has been anything but constant. The standard deviation of these changes is approximately 185,000 km annually. In one sample year, km fell by 370,000; in another, it grew by 519,000 km. Changes like these provide a very rich source of exogenous variation in noise pollution.

In Figure 8 we present the time series of noise disturbance shocks D_{it} we employ. The shocks

[29] The details are provided in our penultimate section Can Environmental Policy Save the Whales?

[30] See Graff Zivin and Neidell (2013) for an excellent discussion of the health and environment literature.

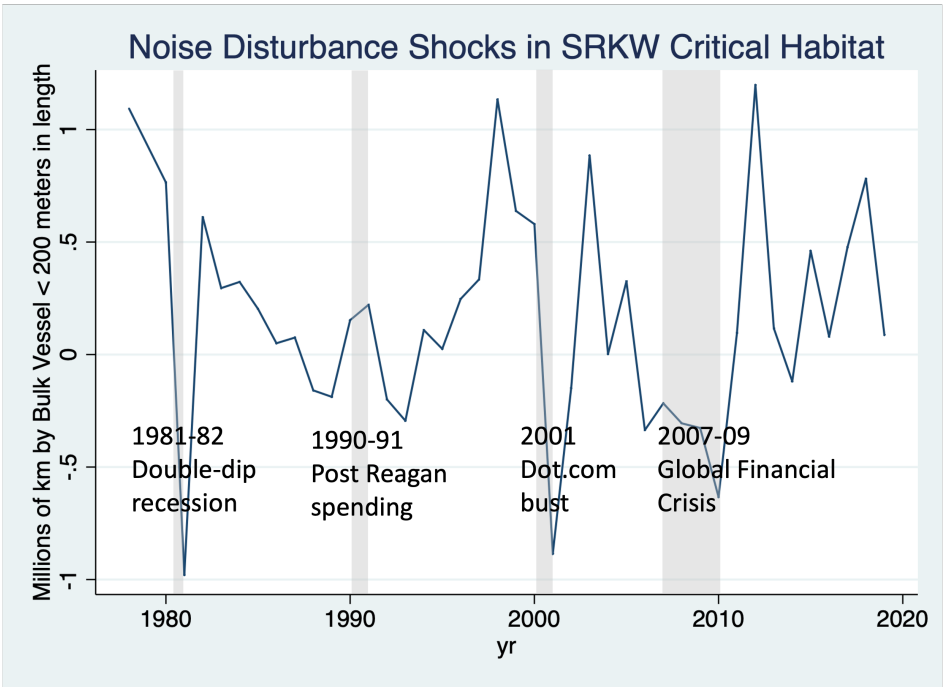


Figure 8: Noise Disturbance & Recessions

are denominated in a common numeraire but represent an aggregation across vessel types taking into account their relative noise disturbance.[31] Three things are apparent. First, both positive and negative shocks are distributed over the sample period. Second, the size of shocks is similar over time despite the growth in overall vessel traffic we documented in facts two and four. And finally, it is apparent what is driving the shocks. It is easy to pick out the impacts of US/CDN and global recessions across the sample period. Every major slowdown has its echo in the figure as shown by the grey bars and text. It is obvious that the scale and timing of these shocks - driven by variations in economic activity worldwide - are unrelated to the comings and goings of KW in the Salish Sea.

[31] Shown is one of our *sophisticated* measures of noise disturbance shocks. We also use a *naive* measure equal to the annual change in, unweighted, commercial vessel km. Its time series is similar.

IV.III The Mode of Inference

The Malthusian model we developed in (1) links population growth rates to birth and death rates; i.e. $g = b - d$ for some functions b and d of K/N. Logit estimation allows us to construct the death rate, d, and birth rate, b, using the relevant predicted probabilities. Using these estimates, we can then parameterize our model to calculate the steady-state impacts of noise disturbance on whale populations. Logit estimation is also the standard tool used by marine scientists and biologists in past, influential work on KW.[32]

An important feature of our identification strategy is the inclusion of matriline fixed effects. Therefore we adopt conditional logit. One potential drawback to conditional logit is that observations with no over-time variation in outcomes (or our treatment variable) are dropped from the estimation. However, this affects less than 5% of our observations. Finally, since economists favor the linear probability model, we present (in our Supplementary Appendix) a parallel set of estimations from an LPM as a robustness check.

Our clustering decision is informed by recent work on design-based models of uncertainty (See in particular Abadie et al. (2020), and Abadie et al. (2023)) while taking into account our special setting where our data contains the entire population of both the SRKW and the NRKW.[33] One lesson from this literature is to cluster at the level of treatment. While we allow for the possibility that treatment varies over the two populations, we believe treatment varies most over the pod and to a lesser extent time dimensions.[34] We cluster at the pod level because it matches our variation in treatment most closely. Two-way clustering over time is ruled out (pod $\times$ time, etc.) given our fixed effects while clustering at more aggregate (populations or clans) levels would not capture the significant variation in treatment we expect for individual pods within these units.[35]

[32] See for example, Ward, Holmes and Balcomb (2009).

[33] See also Xu (2019) and Xu (2021) who extends this work to the class of M-estimators.

[34] We do not want to eliminate the possibility that the NRKW are affected by traffic in the Salish by assumption. Given their travel patterns and the available sightings data, our strong prior is that they should be affected far less if at all but prefer to have the data decide.

[35] Clustering at the pod $\times$ time level while seemingly attractive, is not possible because our matrilineal fixed effects

V The Empirical Implementation

We model life outcomes as discrete and uncertain events. Let $dt = \Delta t$ equal one year and assume births and deaths, which are recorded annually in our data, are Bernoulli random variables. This is captured by:

$$Y_{it} = 1[X'_{it}\beta + \rho_i D_{it} + \epsilon_{it} > 0] \tag{2}$$

where $1[]$ is the indicator function, and the CDF of ϵ is logistic. Whale fitness is an unobservable latent variable whose value determines the probability of a life event.

We proceed in three steps. In step one, we reproduce - using our data and methods - results that are consistent with what is broadly known about KW birth and death processes. Step two adds to this baseline model a naive measure of vessel disturbance shocks. This is simply the year-over-year change in annual km traveled by all commercial vessels. Following this, we construct our sophisticated measure of noise disturbance shocks where vessel km are weighted by their relative disturbance. Using this measure we again examine the impact of these shocks on KW demographics.

V..1 Births

It is well known that female whales reach sexual maturity by their mid-teens and remain potentially reproductive into their early forties.[36] It is of course important to develop a baseline regression model consistent with this knowledge before introducing measures of vessel disturbance. The profile of KW fertility rises steeply at first, reaches a peak near the age of 20, and then falls off dramatically after the age of 40. To capture this highly non-linear, and asymmetric, fertility profile of KW, we employ a higher-order polynomial in age.

In Table 4 below we investigate the basic demographic and environmental determinants of KW

need to be nested within the clusters.

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

births. The most parsimonious and restrictive model appears in the first column, with more general versions following as we move rightwards. Several features are noteworthy. First, the coefficient estimates governing the polynomial in age are stable across all specifications with only small differences in magnitudes as we move from column I to V. These coefficient estimates are also highly significant individually and as a group. From the sign pattern, it is obvious fertility rises steeply at first and eventually falls although the exact shape is a bit unclear.

Second, in columns II onward there is consistent evidence that prey (salmon) abundance matters a great deal to KW fertility. In all instances, we relate the one-year lag of abundance to current fertility, because gestation is 16 to 18 months for KW. And for clarity, we let the prefix Lx denote any variable that is lagged x years. The estimated salmon abundance coefficients show high salmon years raise subsequent fecundity, while low salmon years reduce future births considerably. To understand the magnitude of these effects we calculated the mean and standard deviation of the salmon index, over the entire period, as 1.15 and .28 respectively. Therefore, using the estimated salmon abundance coefficient estimate of .36 from column II, we conclude that a one std. deviation increase in salmon abundance - a good salmon year - raises the odds of a subsequent birth by 10.6%; a great, two std. deviation salmon year raises them 22.3%. These are large effects.

Third, we allow for a full set of NRKW $\times$ Age interactions in column V. There are only small changes to the existing coefficient estimates and only a relatively small change in the log-likelihood. A comparison of north vs. south fertility is shown by a plot, for each population, giving the predicted probability of birth at various ages. This is found in in Appendix A.VI. The NRKW are clearly more fecund than the SRKW, but both follow the pattern described earlier. Why the NRKW are more fecund is unclear at this point.

Fourth, in columns III onward, we find evidence that both within and across population competition matters. The size of its own population measures within competition for a given population. In contrast, across-population competition is measured by the population size of the other whale population. Both elements of competition affect births negatively, which suggests competition for

prey lowers fecundity, consistent with our density-dependent resource growth model.[37] For example, using the estimates from column V, a large 50-whale within-population increase lowers the odds of birth in that population by 14%.

Table 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

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.

V..2 Deaths

The demographic and environmental determinants of death are similar to those for births: age, access to prey, and gender. Deaths early in life are very common, but this declines quickly so that mortality is at its lowest by a whale's mid-teens. Thereafter mortality rises with age with an espe-

[37] As across-population competition increases, the K locus in Figure 7 shifts inwards, raising death rates and lowering birth rates.

cially steep increase post-40.[38] In Table 5 below we investigate the demographic and environmental determinants of KW deaths. Since male KW live far shorter lives than females we allow for gender and gender by age controls. As before, less restrictive models are estimated as we move rightwards.

Table 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

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.

Several features of the table are noteworthy. First, the coefficient estimates governing the polynomial in age are stable across all specifications with only small differences as we move from column I to V. Mortality falls steeply at first and eventually rises although the exact shape is best left to Figure A.9 in the appendix. In all columns, we add interactions of Age with Male. Differences, when they do arise, occur when we introduce a full set of NRKW × Age interactions in Column V.

Second, in columns II onward there is consistent evidence that greater prey availability lowers

[38] A graphical presentation of the KW mortality profile is found in Appendix A.VII.

mortality. Interestingly, the impact of a bad salmon year is much larger than for births. Using column V estimates, a one std. deviation decline in salmon abundance raises the odds of death by approximately 17%.[39] Finally, there is mixed evidence that an increase in within-competition raises deaths. Across-competition remains a significant determinant.

Tables 4 and 5 provide a strong foundation for examining the impact of vessel disturbance.

V.I A Naive Accounting for Vessel Disturbance Shocks

V.I.1 Births

We present in Table 6 a series of results linking disturbance shocks to KW births. We start with our preferred specification for births from column V of Table 4. As we move across columns, the disturbance shocks become more refined. Since these impacts should or could differ across populations, they are interacted with population-level dummies. In column I, our measure of disturbance shocks is the change in total vessel km traveled in the critical habitat. Total vessel km is the sum of km traveled by all commercial vessels in a given year. A period t disturbance shock is given by the difference between period t and period t-1 km. Since KW conception occurs approximately 18 months before births, we lag this disturbance shock one period and attach the prefix L1 as a reminder.

In column I we find this measure of disturbance shocks is negatively related to births of the SRKW. The NRKW is affected, if at all, positively (sum the main and interaction coefficient). Both coefficients are highly significant, while the sign, size, and significance levels of the preferred demographic model for births remain largely unchanged.

[39] Ford et al. (2010) using quite different methods find similar results. They employ life table statistics from 1973 to 1996 to create a steady state expected profile for births and deaths, and then examine how deviations from this average are related to salmon abundance. Using data from 1979 to 2004 they find both births and deaths respond to variation in the salmon index used but the evidence for mortality being related to abundance is much stronger.

Table 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.

In this and all other columns, salmon abundance has a strong and positive effect on births, while negative coefficients on our measures of within and across competition by other whales remain largely unchanged in sign and significance. All of these coefficients are precisely estimated, as is the polynomial in age whose structure is also stable across columns.

It is well known that unitized cargo ships are the fastest, largest, and noisiest of all commercial vessels. Since any one of these characteristics could be driving KW disturbance, in column II we divide the change in Total Vessel km traveled into a disturbance shock coming from the change in km traveled by Unitised vessels and the shock coming from the change in all Other km.

Perhaps not surprisingly, the coefficient estimates across these two (lagged) potential disturbance shocks now differ greatly. The coefficients on Other km and its interaction with NRKW are now insignificant; whereas the coefficient estimates for Unitised km and its NRKW interaction are now much larger, and again, highly significant. Taken at face value these results suggest changes in Unitised vessel km are driving the results found in column I.

Since the coefficient estimates for disturbance shocks from Other km are not significant at conventional levels, we drop them entirely in column III. The results appear to strengthen: the estimates imply the SRKW are strongly affected by the Unitised km disturbance shock while the NRKW are unaffected. The implied magnitude is also important. Since km are measured in units of millions, the coefficient estimate of -3.25 implies a one std. deviation change in vessel traffic (76,000 km) lower the odds of a subsequent SRKW birth by 22%. This is a large effect.

In column IV we investigate whether our prior - that lagged and not contemporaneous disturbances matter to births - is borne out by the data. We add both contemporaneous and lagged disturbance shocks. The results are clear: the inclusion of this year's disturbance shock makes little difference to the coefficient estimates and on its own is not significant. This is consistent with vessel disturbance primarily affecting the success of conception, rather than raising neonatal mortality in the current birthing season.

Finally, in column V we allow the impact of disturbance shocks to vary across the three pods,

J, K, and L pods that constitute the SRKW population as a whole. The impact of these disturbance shocks on the NRKW in this column is now captured by the coefficient on the change in (lagged) Unitised km. This impact is estimated to be small and indistinguishable from zero - consistent with the earlier results. In contrast, the estimated negative impacts on the three whale pods remain negative, although that for the K pod is imprecisely estimated and much smaller than the other two. This may be due to K pod's much smaller size (mean of 20) and less frequent births, or it could reflect real differences in exposure of K pod to vessel disturbance in the Salish.

Overall, the results on births are surprisingly good and very supportive of the view that of all commercial vessel traffic, that coming from large, fast, and noisy Unitised cargo ships are by far the most important to KW fecundity.

V.I.2 Deaths

In Table 7 we investigate the impact of disturbance shocks on KW mortality. We add disturbance shock measures to our preferred demographic model of Deaths from column V of Table 5. In column I, we use the total km traveled by all vessels to construct our disturbance shock. We again find mixed results - much as we did when we used this same measure with births. Following our previous logic, in column II we divide this aggregated shock into its Other and Unitised components. Again consistent with our results for births, the two shocks differ greatly in their impact - both in terms of their magnitudes and significance levels. SRKW mortality rises with our Unitised disturbance shock, while this same shock has a much smaller or statistically zero impact on the NRKW. As shown in column IV, dropping the Other category entirely has only a small impact on the overall results, and does little to improve the significance of the NRKW interaction.

In these first three columns we employed lagged measures of disturbance shocks, but this timing choice is far less clear for deaths. Deaths may occur from the energetic costs of avoiding a contemporaneous disturbance, a lagged disturbance, or both. To investigate in column IV we include both contemporaneous and lagged shocks focusing on the Unitised km disturbance.

Table 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.

Interestingly, contemporaneous shocks appear to matter greatly as shown by the larger size and significance of the key coefficients. Contemporaneous disturbances to the SRKW are large and precisely estimated. The NRKW interaction tells us these shocks are far less important for the other population. At the same time, the lagged shocks retain their sign, size, and significance levels suggesting both contemporaneous and lagged shocks matter. As a result, a one-time disturbance shock raises deaths in both this and the next period. The order of magnitude of this combined effect is also similar to that on births, and again the impact on the NRKW is smaller and indistinguishable from zero.

Finally, in column V we allow the impact to vary by SRKW pod. The main effect, which is that estimated for the NRKW, is small and indistinguishable from zero. The impact on the three pods is again very different. The J and L pod estimates are in line with earlier columns, but the K pod results are again quite different.

Across all columns, the basic demographic determinants of mortality remain largely unchanged. The coefficients on within-competition are similar to those in Table 5, and the across-competition coefficients are positive, significant, and large. Salmon abundance again drives deaths downward and is precisely estimated. The age and main NRKW interactions remain stable across columns. Overall the results across these last two tables are very supportive of our approach. In all cases, the basic demographic and environmental variables hold up very well in terms of sign, significance, and magnitude. The disturbance shocks appear to do just that - provide an unwelcome shock to the KW. This shock is most important to births during their sensitive breeding period one year previous, while deaths respond most strongly to contemporaneous shocks. Interestingly, it is a standard result in the Malthusian approach to human demographics that negative shocks (disease, crop failures, etc.) immediately impact deaths, but only impact births next year. The same pattern appears here - except now the population under study is killer whales.

V.II A Sophisticated Accounting for Noise Pollution Shocks

With the exception of separating Unitized vessel km from all others, we have treated a km traveled by any type and age of vessel as equally disturbing. But as we showed in Fact 5, commercial vessels differ greatly in the noise radiated from them. To move from our naive measure to a more nuanced or sophisticated measure of potential disturbance, we need estimates of vessels' source level noise emissions, SL. This is the noise radiated from the ship.[40] In the Appendix A.XI we develop a simple cross-sectional regression linking noise disturbance measured at the ship source to a set of characteristics known to be important (dead weight tons, length, operating speed, etc.). As mentioned previously, we explore two specifications that differ in how we define vessel classes. We use estimates from both of these specifications to assign SL noise disturbances to vessels in our data. This allows us to associate a different SL to vessels that differ in their class (unitized, bulk, etc.), their operating speed, vessel age, and other common characteristics (length, dead weight). In doing so we are averaging across time, which forces the average age, speed, and dwt characteristics of vessels to remain constant over time. This simplification has minimal effects because changes over time in commercial ships have not come from say 200-meter Bulk vessel average speed moving from 10 to 15 knots, but rather from the introduction of larger bigger vessels (250+) that come with entirely different characteristics. The same is true, in spades, for cargo vessels.

While our estimates of SL emissions are interesting in their own right, they are not direct measures of vessel disturbance. First, the SL measures ignore the length of time a vessel takes to complete its journey - a 10-hour passage through the critical habitat would be treated equivalently to a 3-hour passage if the two vessels SL were the same. Second, SL measures tell us little about

[40] There are some ugly details we are glossing over here. For example, vessels create sounds at various frequencies, and therefore their signature is typically shown as a spectrum plot of amplitude against frequencies. The measures we employ aggregate to "broadband" measures which means integrating over the relevant frequency bands to arrive at one number representing a vessel's SL. As well, the Decibel is a relative measure of the pressure created by a sound wave, and therefore any dB measure is relative to a standard reference pressure and distance from the source. In water, the standard reference is a pressure of 1 (millionth) μ Pascals measured 1m from the source. All of the SL measures we employ use this standard reference.

the area of disturbance around a ship because they ignore the physics of sound dissipation.

To address these issues we model the externality-generating process by developing a sound exposure model. It allows us to weigh vessel km traveled by the relative size of the disturbance bubble created under every ship, and the time this ship takes to complete its voyage. We think the payoff to our small bit of formalism is large. For example, we identify the conditions under which our naive measure using annual km can be interpreted as a measure of noise disturbance to whales, and when these conditions fail, the model generates more sophisticated measures that we can use in estimation. Our construction of a noise dispersion model to aid empirical work is very similar in spirit to related work that employs air pollution dispersion models to generate exposure estimates.[41]

In Table 8 below we investigate how these new measures of disturbance shocks affect KW fertility. Disturbance shocks are again given by one-period changes in our disturbance measure. Since, in theory, all vessel km are now weighed correctly to create vessel disturbance, there is no longer any need to examine vessel class-specific disturbances. Instead, we vary our timing assumptions, aggregation across SRKW pods, and choice of noise disturbance measure. In the first three columns of the table, we use noise disturbance measures from SL estimates derived from a regression specification using wide vessel categories. They are referred to as Noise disturbance 1 regressions. The following three columns use Noise disturbance 2 which is constructed using estimates from our narrow vessel categories shown in Table 3.

Several observations are in order. In all columns, and across both noise disturbance measures, the basic demographic determinants of KW fertility remain important. The terms capturing salmon abundance and within and across competition for prey remain virtually unchanged. The age profile estimated for fecundity also retains its hump shape with maximum fertility near the age of 20.

Focusing on the first three columns we again find a significant negative impact of noise disturbance shocks on KW fertility. The impact on the SRKW is clearly negative; the impact on the NRKW is always estimated to be far less and very close to zero.

[41] See for example the model used in Schlenker and Walker (2016).

Table 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.

In column I we include only lagged disturbance shocks, but in column II we include contemporaneous and lagged shocks. It appears that both contemporaneous and lagged shocks are now important, although the coefficients on contemporaneous shocks are uniformly smaller and estimated less precisely. This is somewhat different from our previous results where only lagged shocks mattered. In column III we allow the disturbance shocks to have different impacts by pod. Here we find some heterogeneity across the SRKW pods with the K pod in particular being the least affected. The impact on the NRKW is now measured by the main effect which is small and indistinguishable from zero. These results are also slightly different and perhaps an improvement over our Unitised

km alone-based measures. For example, the negative impact on K pod is clear here but less clear in say Table

Overall, the results are highly consistent with our earlier results using the simpler km measures for disturbance shocks. The results are in many cases more precisely estimated, and in one case the new disturbance shock suggests a negative contemporaneous impact on fertility.

In moving to columns IV, V, and VI we find very similar results. The basic demographic determinants are very similar to those in the first three columns and of course similar to all earlier results. We again find evidence that contemporaneous disturbance shocks may matter to fertility, and confirm again the smaller or even zero impact on the NRKW. Disaggregating across pods again seems to strengthen the above results.

We can now calculate the magnitude of these shocks for a wide variety of vessel classes, and compare them to our previous results for Unitised vessels. Previously we reported that the average yearly change in vessel km in the critical habitat was approximately 23,000 km with a standard deviation of 76,000 km. We also reported that a one std. deviation increase in Unitised km would lower the odds of birth by 22%. To compare our results with those earlier requires two steps. First, we note that in either set of regressions (I-III) or (IV-VI), we have chosen a numeraire vessel and therefore the coefficient estimates reflect this choice.

Consider the last three columns which use small Bulk vessels less than 200 meters in length as their numeraire. To find the impact of a ΔX change in the vessel km traveled by these small Bulk vessels we simply multiply ΔX by the coefficient estimate of -.4 in column IV to find the resulting change in the log odds of an SRKW birth. For a one std. deviation increase this impact is relatively small at only 3%. In contrast for other vessel classes it is much higher. To find the impact of a ΔX change in the km traveled by any other vessel type we multiply ΔX by the Relative Disturbance drawn from Table 8 and then by the coefficient estimate of -.4. A quick way to see if our results here are of a similar magnitude is to multiply -.4 by the 7.55 for large container ships to find the appropriate coefficient on a disturbance shock coming from very large container ships is

approximately - 3.02! Therefore a one std. deviation increase in noise coming from container ships lowers births by 26%.

We now complete our discussion by examining the impact of noise disturbance shocks on deaths. We follow the same logic as above and consider our two different measures for noise

Table 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.

disturbance shocks. Consider first the basic demographic determinants of death in Table 9. It is clear that the role of salmon abundance and competition for prey retain their sign and significance throughout the table. Salmon abundance lowers mortality; competition for prey raises it.

Columns I and IV show that lagged disturbance shocks necessarily raise SRKW mortality, with the change in NRKW much lower but not as precisely estimated. When we include both contem-

poraneous and lagged disturbance shocks in columns II or V, the size of the impact grows as does the significance of the coefficients. The estimates suggest that a one-time shock working through its current and lagged impact would raise SRKW mortality by the sum (.35 + .24 =.59) and for the NRKW (.59 - (.25+.46) = -.1) using column II estimates. Again we could then directly compute the implied change in the log odds of mortality from say a ΔX change in the km traveled by small Bulk vessels. Or we could multiply these by 7.55 to find the impact for large container vessels.

In columns III and VI we allow the disturbance shock to differ across pods. Again the main effects capturing the impact on the NRKW are small and negative, but not distinguishable from zero. Again similar to what we found in the previous columns. The impacts on the pods vary, as before, with J pod being the most affected, followed by L pod, and then with K pod perhaps unaffected. In total, these results present very similar evidence. Again, if we multiply the disturbance shock coefficients by 7.55, we find coefficient estimates similar to those found earlier.

VI Can Environmental Policy Save the Whales?

We have found consistent evidence that noise disturbance shocks reduce birth rates and increase death rates, which, in the long run, must lower the SRKW population. Despite these findings, if the implied reduction in KW numbers was small, it may not be worthwhile to develop a new policy to internalize noise pollution; in contrast, if the reduction is large, then controlling noise pollution may be necessary to avoid their extinction. Therefore, we need to have at least a rough idea of the magnitude of the impact. To do so, we can use our theory and empirical estimates to solve for the long-run impact of the noise pollution increases on KW numbers. Then we can ask how much salmon restoration would be needed to offset this impact.

To see how return to our simple theory linking the growth rate of a (homogenous) whale population to carrying capacity per whale. The population birth rate is equal to the expected number of births, divided by the entire population. This is just the estimated probability of birth for fe-

male whales, p^b, evaluated at average population characteristics, multiplied by the sex ratio; that is, $p^b[F/N]$, where F is the number of female whales in the population of N. Similarly, the death rate amongst all whales in the population is equal to the expected number of deaths divided by the total population; that is, $[p^d N/N]$. Therefore, population growth can be written as:

$$g = p^b[\frac{F}{N}] - p^d \tag{3}$$

We have estimated p^b and p^d as functions of the determinants of the carrying capacity K (salmon abundance, vessel disturbance, competition for prey), the size of the population N, and whale-specific age and gender characteristics. Our empirical work provides estimates of these probabilities and we evaluate them at sample average values for our regressors yielding:

$$p^d = \frac{e^{X'\beta}}{1 + e^{X'\beta}} \equiv h(X'\beta) \tag{4}$$

$$p^b = \frac{e^{\tilde{X}'\tilde{\beta}}}{1 + e^{X'\tilde{\beta}}} \equiv h(\tilde{X}'\tilde{\beta}) \tag{5}$$

where βX and $\tilde{\beta}\tilde{X}$ are understood to be the estimated parameter and sample average vectors from the death and birth regressions respectively. Using these estimates, population growth becomes:

$$g = h(\tilde{X}'\tilde{\beta})(\frac{F}{N}) - h(X'\beta) \tag{6}$$

We showed earlier that starting from an initial steady state, where $g = 0$, an increase in disturbance D drives the birth rate down and the death rate up. This sets in motion a process of adjustment in the population size to bring us back to a steady state with zero population growth. In this new steady state, N has adjusted to the change in D.

We want to know what our empirical results imply for this long-run impact - dN/dD. To do so, note that in steady state, $g = 0$, and the sex ratio is fixed at some fraction $1 > \gamma > 0$ independent of population size. For example, the stable sex ratio identified by the life Olesiuk, Bigg and Ellis

(1990) using life tables has 56% of the population being female. Therefore, for a given K, the number of whales, N, must solve:

$$h(\tilde{X}'\tilde{\beta})\gamma = h(X'\beta) \tag{7}$$

Totally differentiate to obtain:

$$h'(\tilde{X}'\tilde{\beta})\gamma[\tilde{\beta}_0 dN + \tilde{\beta}_1 dD] = h'(\tilde{X}'\beta)[\beta_0 dN + \beta_1 dD] \tag{8}$$

If we divide by the steady state condition, we obtain:

$$\frac{\tilde{h}'}{\tilde{h}}[\tilde{\beta}_0 dN + \tilde{\beta}_1 dD] = \frac{h'}{h}[\beta_0 dN + \beta_1 dD] \tag{9}$$

It is relatively easy to show that $\frac{h'}{h} = 1/[1+e^{X'\beta}] = 1-p^d$, similarly for $\frac{\tilde{h}'}{\tilde{h}}$ we have $1-p^b$. As well, zero population growth implies $p^b\gamma = p^d$. Making these substitutions and rearranging we find:

$$\frac{dN}{dD} = \left[\frac{[1-p^b][\beta_1 - \tilde{\beta}_1] + p^b[1-\gamma]\beta_1}{[1-p^b][\tilde{\beta}_0 - \beta_0] - p^b[1-\gamma]\beta_0}\right] \tag{10}$$

Since the sex ratio is a fraction (recall .56), and the average probability of birth is small (Supplementary Table A.2 reports it is .09 for SRKW females) we know that $[1-\gamma]p^b$ is of second-order. If we set these second-order terms to zero in the numerator and denominator, we find the long-run elasticity between population levels and a permanent disturbance shock is quite simple:

$$\frac{dN}{dD}\frac{D}{N} \cong \left[\frac{\beta_1 - \tilde{\beta}_1}{\tilde{\beta}_0 - \beta_0}\right]\frac{D}{N} \tag{11}$$

How big is this? If we take estimates from the noise disturbance regressions in Tables 8 and 9, and then make use of the fact that the average disturbance shock over the entire sample period, D is .1227 and the average SRKW whale population, N is 86, the elasticity estimates range from approx-

imately .2 to .35.[42] This implies that if there was a permanent 100% increase in the disturbance, the SRKW would fall by perhaps 30%.

Another way to interpret this is to recall that births and deaths are only functions of K/N. This means that noise disturbance lowers the quality of their existing acoustic environment – as measured by carrying capacity K – with an elasticity of perhaps -.3.

How much did the level of disturbance rise over our sample? If we compare averages of either noise disturbance measure over the first and then the last, five years of the sample, we find the level of noise disturbance has approximately doubled – implying an approximate 100% change over the period.[43] Using 100% as our long-run change in disturbance, our back-of-the-envelope calculation tells us that the SRKW population is approximately 30% lower than it would have been in the absence of the permanent increase in vessel traffic. Given the population profile shown in Figure 5, this is a provocative result.

VI.I A First-Best Solution to Saving the Whales

Returning the acoustic environment in the Salish Sea to its condition in the early 1980s is impossible without a drastic change in vessel traffic. However, such a change in vessel traffic is not likely to be optimal because any least-cost solution should rely on a combination of noise abatement and salmon restoration to raise population numbers.

To see how this policy would work assume noise from vessels is a well-mixed pollutant. This implies a unit of noise emitted at any one point of a voyage is equally damaging to the same amount emitted at a later point; similarly, damages from vessel A do not negate, amplify, or modify damage from vessel B. Although clearly fictional, these are the same assumptions we use to justify a

[42] For example using column II estimates from Tables 8 and 9 and our full formula from (29), we find: $\tilde{\beta}_0 = -.003$, $\beta_0 = .003$, $\tilde{\beta}_0 - \beta_0 = -.006$. $\tilde{\beta}_1 = -.49 - .37 = -.86$, $\beta_1 = .35 + .24 = .59$, $\beta_1 - \tilde{\beta}_1 = 1.45$. Take $p^b = .09$ and $\gamma = .5$. To calculate the elasticity, we plug in D and N and find $(\frac{.91\times1.45+.09\times.5\times.59}{.91\times(-.006)-.09\times.5\times.003})\frac{.1227}{86} = -.34$. The simpler formula (30) leads to $(\frac{1.45}{-.006})\frac{.1227}{86} = -.35$.

[43] In contrast, our measure of salmon abundance is slightly higher in the last five-year period than it was in the first five-year period.

common tax on gasoline that internalizes local pollution.

If a pollutant is well mixed, efficiency requires all pollution sources (vessels) have equal marginal abatement costs. Equality of marginal abatement costs is achieved when all sources pay the same price for emissions because they either pay a common tax on noise pollution or must acquire a permit to pollute from a tradeable permit system. In either case, heterogenous sources, at the margin, have equal marginal costs for noise abatement.

In addition efficiency will require that we also undertake salmon restoration. Since salmon availability raises KW numbers and noise disturbance lowers them, noise abatement, A, and salmon restoration, S, are substitutes in conservation. Either or both can raise an environment's carrying capacity, K, and in the long run, KW numbers rise to meet K as shown in Figure 7. Suppressing other determinants, we can write $K = K(A, S)$. Level sets of K represent the physical trade-off between our conservation measures. Our empirical work gave us a local measure of this trade-off which we encapsulate in Table 10 below.

Table 10: Relative Productivity of Restoration versus Noise Abatement

One σ Δ in Vessel km	Requires a Δ σ increase in Salmon Abundance
Bulk carrier 200-	0.47
Bulk carrier 250+	1.77
Cargo 150+	0.96
Container ship 250-	0.88
Container ship 250-320	2.11
Container ship 320+	3.55
Tanker 165+	1.03
Vehicle carrier	0.85

Notes: Calculations use the estimated coefficients from Column II of Table 8 and Table 7.

The table relates one std deviation changes in vessel km for different vessel classes to the increase in salmon abundance necessary to leave the long run population unaffected. If we think of reducing vessel km as a crude method of abatement, then the table reflects the trade-off between noise abatement and salmon restoration along a level set of $K(A, S)$. As shown, offsetting a one

std. deviation increase in traffic from a small Bulk carrier is relatively easy; but offsetting a one std. deviation increase in traffic from a large container ship requires a change in salmon abundance that is truly incredible.

With this machinery in place, the policy problem is, in theory, simple to solve. First, the planner chooses the optimal mix of conservation measures to minimize the cost of sustaining any target population. By solving this problem we can construct a minimum cost function for conservation. This is the (long run) supply function for KW: it tells us the marginal conservation costs of sustaining any level of KW carrying capacity; i.e. KW numbers. Combining the schedule of marginal conservation costs with a schedule of marginal valuation of KW, allows us to solve for the first best level of conservation, the first best whale population, and the implied activity levels of each conservation measures (via Shepherd's Lemma).

These two steps are shown in the figure below. In the left-hand panel, the planner minimizes the total cost of maintaining any given whale population by adjusting conservationist measures to achieve a given carrying capacity. The planner faces σ unit costs of salmon restoration of ρ, and noise abatement σ unit costs of τ. The figure is drawn such that the origin of the left panel represents the current noise disturbance level of $\overline{N}$ with zero abatement and zero salmon restoration. We associate the isoquant through the origin with an extinction level of whales, and therefore $K(0,0) < MSP$.[44] In the figure, we have also assumed isoquants are strictly convex and the overall map exhibits decreasing returns. Decreasing returns follows because the fixed size of the Salish Sea will always limit the beneficial effects of salmon restoration and noise abatement.

A typical cost-minimizing solution is at point M. Using this solution we solve for the minimum cost function or $TC = C(\rho, \tau, K)$. It represents the total cost of conserving K whales given unit

[44] The SRKW population is on an extinction path. The reason is simply that the net reproduction rate – or replacement rate – for female KW born into cohorts reaching their peak reproductive years after 2000 is below 2.1 whales per female whale. In contrast, cohorts of female whales who reached their peak fertility prior to 2000 had lifetime fertility above replacement. Details upon request. These changes in the replacement rate over our sample period should put to bed any notion that our temporary noise shocks are just harvesting whale deaths and delaying whale births in noisy years only to be made up in quiet years. Current replacement rates imply eventual extinction, and this fact anchors our status quo level set.

costs of noise abatement and salmon restoration. This cost function is strictly convex in K given decreasing returns to the variable inputs.

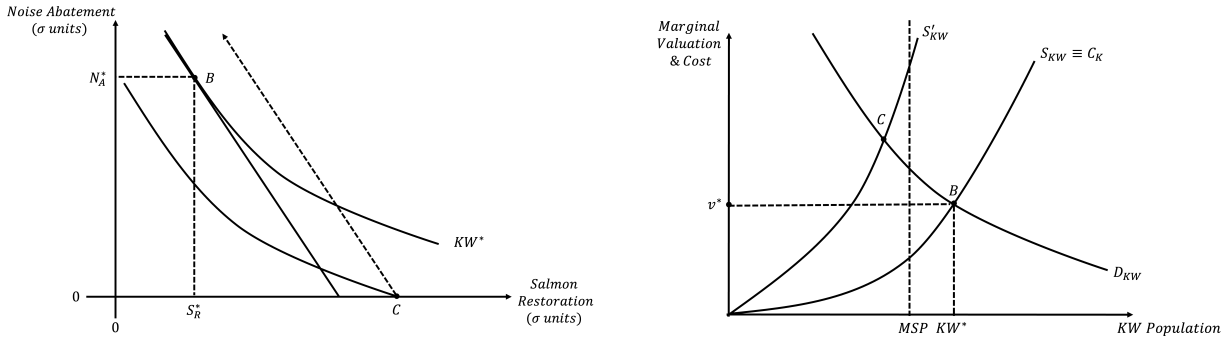
In the right panel, we combine the marginal cost of conservation, which can be thought of as a supply curve of whales, $\partial TC/\partial K = C_K$ or S_{KW}, with the public's demand for conservation, D_{KW} (ignore for the moment the supply curve S'_{KW}). The demand for conservation is the marginal valuation the public attaches to KW, and we have assumed it is declining in population size . The public's demand for any KW population is the sum of their non-consumptive use value to tourism and whale watching in the Pacific Northwest, plus the non-use value of KW to those individuals elsewhere in the U.S and Canada who may never see one in the wild. These non-use values come from some combination of bequest motives, option values, and perhaps the intrinsic value of conserving this very charismatic mega-fauna.

Combining the marginal cost of conservation with the public's demand for conservation generates candidate optima. One possibility is shown by point B where KW^* whales exist in perpetuity. An alternative solution occurs at point C where the implied population would be lower and importantly below the minimum sustainable population level, MSP, leading to extinction.[45] In this case, the costs of restoring salmon or reducing vessel noise are just too high, and we chose to let the SRKW population dwindle.

Finding a point like B or C, means we have to estimate the marginal cost of enhancing carrying capacity via noise abatement and salmon restoration. This estimate does not currently exist, although the costs of salmon restoration are fairly well known.

Greater hatchery releases can effect small and temporary changes in salmon abundance; larger and permanent changes can be made by stream restoration projects or even the complete restoration of river systems through dam busting, etc. Both the Canadian and the US government have undertaken several of these measures with the express purpose of helping the SRKW's survival. On

[45] We assume the cost function exists for levels of K below MSP and then deduce extinction from the interior solutions of marginal costs and demand. We could alternatively treat the cost function as defined over only a restricted range, and then show an interior equilibrium doesn't exist in all cases. We think our method is a bit cleaner.



(a) Noise abatement (b) Marginal Valuation/Cost and KW Population

Figure 9: Can Economics Save the Whales?

the Canadian side the Oceans Protections Plan has specific SRKW-related measures. Its Coastal Restoration Fund awarded $26.5 million dollars to various projects in British Columbia over the 2017-2022 period aiming to improve salmon outcomes. The Whales Initiative of the Canadian government ($167.4 million) also contains several measures to restrict salmon fishing to preserve prey for the SRKW in key areas. A further $61.5 million was set aside in 2018 to enact several protective measures for the SRKW over the next five years.[46] These Canadian measures also include the release of 1 million juvenile Chinook from the Chilliwack River Chinook Hatchery each year between 2019 and 2023, which reach the SRKW critical habitat through the Fraser River.

On the US side the SEAK Chinook Salmon Fishery Mitigation Program is part of the Pacific Salmon Treaty since its renewal in 2009 which aims to compensate for the reduction in salmon fishing imposed by the treaty on the US (15% in 2009, and another 7.5% in 2019). Under this program $3.35 million were spent on salmon enhancement projects in Alaska between 2010 and 2015 and more recently $5.01 million in 2020-2021. The financed measures also include the annual release of 2.5 million yearlings from seven hatcheries. In comparison the US promised to pay Canada $30 million to mitigate the effect of the 30% reduction in WCVI salmon fishing imposed by the treaty

[46] These include the improvement and expansion of noise reduction measures with more involvement of the marine industry, identifying new key habitat areas of the SRKW that could benefit from enhanced protection, developing better tools to reduce vessel-whale encounters, introducing new protective measures for Chinook stocks important for the SRKW, and expanding regulatory control over pollutants affecting the whales.

in 2009. Additionally, in the US NOAA manages the Pacific Coastal Salmon Recovery Fund that provides grants to states and tribes for restoration purposes. This fund has awarded approximately $1.7 billion up over the 2000 to 2022 period and received a further $ 2.1 billion outside contribution over the same period of time. It has financed several projects in West Coast states which aimed to restore salmon spawning grounds. While these expenditures alone tell us very little about the marginal cost of conservation, if we add up all of these commitments on both sides of the border, we can calculate the annual average cost of salmon restoration, and they total a few hundred million dollars per year.

In contrast, noise abatement efforts have thus far been voluntary and/or temporary. As a result, there is only very limited information on the costs of noise abatement.[47] To the extent that these estimates do exist, they focus on individual ship level adjustments in speed, equipment, and hull and propeller design. Our own empirical work, connecting source level noise to vessel characteristics, shows vessel speed, its age, dwt, and length all determine its noise profile. Many of these characteristics can be adjusted to lower noise, although the salutary effects of slowdowns are small.[48]

While these vessel specific determinants are surely important, we are interested in the shipping industry's marginal noise abatement costs, and at the industry level, there are many other additional channels through which abatement could occur.[49] For example, a shift towards smaller or larger container vessels may be part of a cost-minimizing adjustment, just as a shift towards newer and

[47] See Merchant (2019) for a review of current practices for reducing noise pollution from ships. In short, the vast majority of noise from ships comes from propeller movement, which creates shock waves. These waves are also destructive to the propeller itself, and therefore, ongoing efforts to extend propellor life also tend to quiet ships.

[48] Slower speeds means more time in the water and a longer duration of noise disturbance. Combining these two elements gives us an elasticity of noise disturbance to vessel speed of .2. Details upon request. This estimate implies solving the noise problem by speed reductions alone is not a credible solution. Using our elasticity of .2 would imply a 300% reduction in speed is required to undo the approximate 50% increase in noise disturbance in the Salish since 1998. Therefore, altering speed would be an incredibly costly stand-alone policy. One way to see how costly is to calculate the costs of the implied time delay following the work of Hummels and Schaur (2013). Routine calculations will show the costs are astronomical.

[49] If there are many channels for abatement it means that τ is itself the unit cost of noise abatement across the industry. This complicates the analysis somewhat but doesn't alter the basic policy prescription.

quieter vessels in the fleet.

On the benefits side, it is, of course, difficult to value KW populations.[50] Fortunately, there are recent estimates of willingness to pay for the recovery and status improvement of the Southern Residents from their current endangered position. Wallmo and Lew (2016) develops estimates of both national and regional willingness to pay for marine species conservation using data drawn from a nationwide survey of over 5000 US households for eight threatened or endangered marine species. Using choice experiment methods, they estimate on average, nationwide, US households are willing to pay approximately $110/year (2023 dollars) for ten years to help the SRKW to full recovery. A smaller figure of approximately $60/year (2023 dollars) for ten years was estimated for the smaller conservation goal of moving the SRKW from endangered to merely threatened.

The results represent respondents' willingness to pay for ten years of conservation efforts, but our long run steady state analysis needs a measure of permanent commitments to noise abatement and salmon restoration. We can convert these ten-year commitments into a financially equivalent permanent commitment to conservation, but since there are approximately 130 million households in the US and 15 million in Canada, any measures of annual aggregate willingness to pay will be in the billions of dollars per year. For example, if we use standard exponential discounting at 10%/year, the annual willingness to pay for the recovery of the SRKW is approximately 9.1 billion US dollars per year in perpetuity! If we ignore the promise to pay in future years and take the $110 as a one-time payment, the equivalent annual willingness to pay is still 1.6 billion per year.[51]

These figures seem large at first blush, but less surprising when we consider the popularity of Sea World, Shamu, and the associated Killer Whale "shows" which have run from the mid 1960s

[50]For an introduction to valuation in contexts where non-use values are paramount, see Lew (2015). In the U.S., non-consumptive values may be used in designating critical habitat for species listed under the Endangered Species Act (ESA) and in evaluating species recovery actions; in Canada non-consumptive values can be used in determining whether to list a species under the Species At Risk Act (SARA).

[51]The PDV of 110$/year for ten years is $632.00. This amount would buy a perpetuity payment of 63.20 per year given a discount rate of 10%. Multiplying by 145 million people gives 9.164 billion per year. A lump sum of $110, generates a perpetuity of $11 per year or $1.595 billion. In theory, these estimates reflect the change in surplus under D_{KW} from today's current position at a point to the left of MSP to somewhere along the demand to a point above MSP like B. Integrating over this range gives the willingness to pay for the improvement in KW numbers.

to today. KW awareness has also been primed by the very popular Warner Brothers major motion picture about freeing one such captive whale (Free Willy made 320 million dollars in 2023 dollars, and had three sequels). This interest has if anything grown over time as evidenced by the Southern Resident's Facebook page, a very active Orca Network of volunteers, press stories about large sums of money spent on very public efforts to free two (remaining) captive whales (Keiko and Lolita) to return them to their natural habitat, or the 2018 worldwide coverage of the female KW (Tahlequah or J-35) who kept her dead calf afloat for over 17 days while she *grieved her loss*. For better or worse, the SRKW are probably the most visible and highly valued whale population on the planet.

While many uncertainties remain as to the costs and benefits of conservation policy, it is unlikely zero abatement of noise pollution can be optimal. Current policies have placed far too much burden on fishery restrictions and salmon restoration. One way to understand the implications of this impact for conservation is to return to the conservation cost minimization in figure 9. In panel a) it is obvious that if we constrain the cost minimization solution to lie on the horizontal axis (with zero noise abatement), then the costs of achieving any level of conservation are higher. Turning to panel b) it implies that we can now interpret the difference between our two marginal cost conservation schedules as reflecting the difference between the marginal costs of conservation with noise abatement constrained to be zero (which generates S'_{KW}) and the marginal costs of conservation when the choice of noise abatement is determined optimally (which generates S_{KW}). Clearly, at least in this example, the implications for the conservation of whales is huge (point C implies extinction, point B does not). Moreover, it is entirely possible that the total costs of conservation with noise abated could well be lower as well: good policy can save more than just the whales.[52]

The way forward is obvious. Current efforts measured by the costs of conservation are in the order of hundreds of millions of dollar per year while the public's *annual* willingness to pay for their full recovery is on the order of several billion dollars. An efficient policy must first lower the costs of conservation by regulating vessel noise via a flexible market-based system of taxes or

[52] The area under S'_{KW} to C may well be more than the area under S_{KW} to B.

permits. Putting a price on noise pollution will allow firms to choose their own, cost-minimizing method to lower noise pollution. With conservation costs minimized, policy should then move, via incremental steps, towards what our first-best solution via a gradual tightening of policy.

VII Conclusion

The purpose of this paper was to investigate the slow-motion extinction of the Southern Resident Killer Whales in the hopes of designing a least-cost solution that saves these whales. To aid in this effort we employed several tools from economics - from the mundane (national income accounting, lessons from Malthus) - to the more sophisticated (exploiting a natural experiment using Rubin's potential outcomes framework) - to come to a somewhat provocative conclusion. Noise pollution from commercial shipping, tied to growing international trade flows, has degraded the quality of the SRKW critical habitat. This degradation lowered KW birth rates and raised their death rates considerably. If noise pollution had remained at its level in the early 1980s, then fertility would have been higher, mortality lower, and the long-run population of the SRKW would be approximately 30% larger. These changes would largely undo their precipitous population decline. Salmon restoration, while helpful, is not a credible solution unless combined with measures to reduce vessel noise.

While noise pollution has long been known to negatively affect marine mammals, this study is unique in providing the first direct link between noise pollution and population-level events - births and deaths. Absent this link, policymakers have been reluctant to regulate or constrain in any way international commercial shipping, despite a legislative requirement to do so if their critical habitat is degraded by economic activity.

This paper's major contribution is to demonstrate how Economics writ large can be a very powerful tool for studying biodiversity losses at the ecosystem level. Economics has, of course, made huge advances in the last thirty years in our ability to credible identify and quantify causal relationships using observational data. This makes our tools ideally suited to explore many pressing

biodiversity issues not amenable to lab or field experiments.

And these tools are desperately needed. Thirty different Cetacean populations in the U.S. alone are listed as either threatened or endangered under the Endangered Species Act or depleted under the Marine Mammal Protection Act.[53] And this number grows to well over 100 populations worldwide. Many of these species are reliant on the health of rich coastal ecosystems where interference by the noise of commercial shipping is relevant. To what extent the findings we present here carry over to these other populations is unclear; but at the very least our evidence on the SRKW constitutes prima facie evidence for the potential importance of noise pollution to the health of marine mammals.

Other marine activities, complementary to containing climate change such as underwater mining and offshore wind installation, also contribute to the soundscape whales face. To what extent these activities affect whale health is as yet unknown, but both activities are forecast to increase, making the methods and tools developed here all the more valuable to policymakers in the future.

[53] For example, the North Atlantic right whale, Southern Resident Killer Whales, several populations of Humpback whales, etc. An up-to-date list can be found here https://www.mmc.gov/priority-topics/species-of-concern/status-of-marine-mammal-species-and-populations/

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A Supplementary Materials Online

A.I Habitats

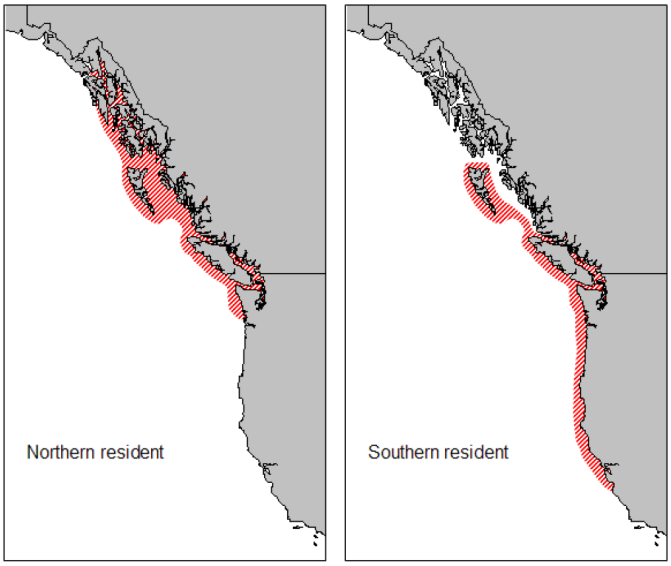


Figure A.1: Northern and Southern Overlapping Habitats
Known geographical ranges of northern (left) and southern (right) resident killer whales. Extent of movement offshore is unknown. Source: Figure 1. in Ford (2006)

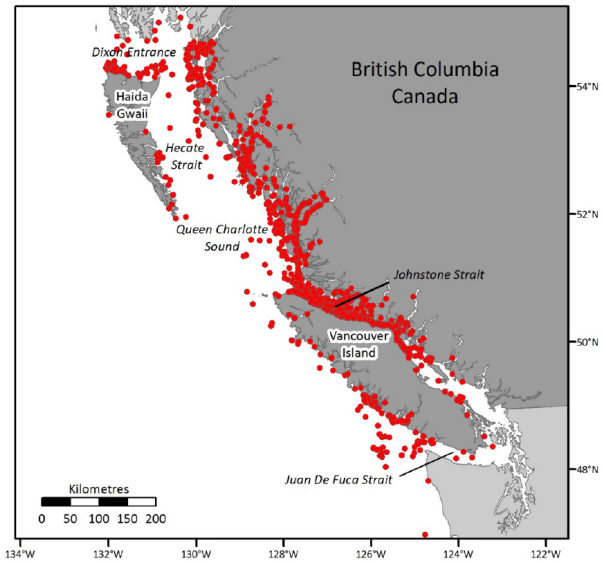


Figure A.2: Locations of sightings and encounters with Northern Resident Killer Whales, 1973–2014. Source: Figure 1. in Ford et al. (2017)

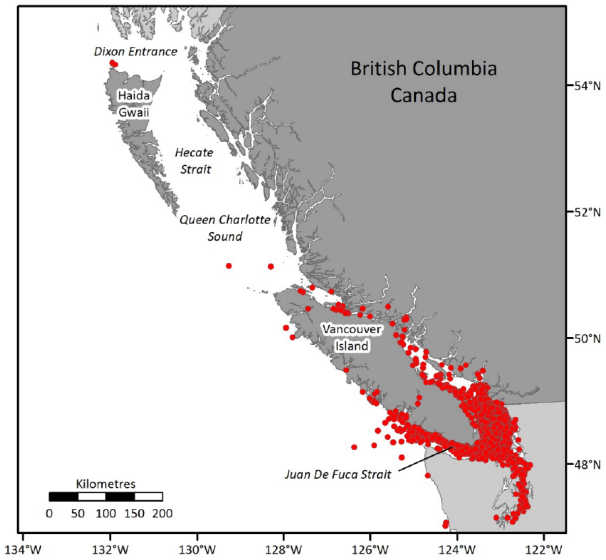


Figure A.3: Distribution of sightings and encounters with Southern Resident Killer Whales. Source: Figure 2. in Ford et al. (2017)

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

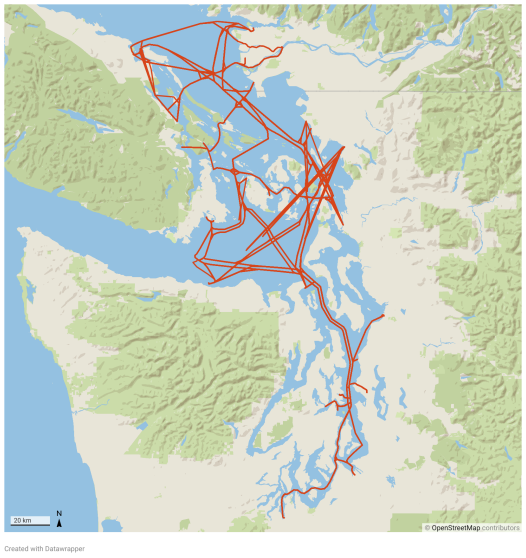


Figure A.5: Routes within the critical habitat

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.[54]. 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.[55] Information from these

[54]These are available here: https://indigo-ukulele-jm29.squarespace.com/sightings-report-archive
[55]These encounter reports are available here: https://whaleresearch.wixsite.com/archives

sources helped to determine missing dates of births and deaths. They also helped to augment missing information for the NRKW.

A.V The Mechanics of Identification

We compare whales more or less exposed to noise pollution shocks. The implicit control group for a treated whale is an identically situated (age, gender, etc.) whale, subject to a smaller or zero noise pollution shock. Treatment varies over time because changes in the scale and composition of vessel traffic create significant over-time variation in noise pollution. We allow treatment effects to vary across our two whale populations (NRKW and SRKW) because their use of the Salish is very different. Apriori we expect the impact of vessel noise on the NRKW to be close to zero; the reader might think of our inclusion of the NRKW as an informal Placebo test; i.e. the NRKW should not respond to noise because they are not subject to it.

To match our theory, the fitness of any given whale is related to K/N (carrying capacity per whale), and assume this underlying fitness determines life outcomes. Specifically, we assume the fitness of an individual whale i at time t, denoted Y_{it}, is determined by a linear function of several control variables plus a term measuring the noise disturbance this whale receives from vessels. Fitness determines significant life events (births or deaths a' la Malthus), with the right-hand side variables in (A.1) affecting the likelihood of this event.[56] We write this dependence as follows:

$$Y_{it} = X'_{it}\beta + \rho_i D_{it} + \epsilon_{it} \tag{A.1}$$

where X_{it} represents controls for whale i at t, D_{it} is the dose of noise exposure experienced by whale i at t and ρ_i is its dose-response to noise. ϵ_{it} is a stochastic error term. Both the dose-response and the scale of noise disturbance experienced, are whale specific.

Whales are very social animals and their populations can be grouped into smaller units that share

[56] In our empirical implementation we treat fitness as a latent variable determining binary outcomes.

common characteristics. Any individual whale i is a member of a matriline j, and several matrilines comprise a pod k. A population, denoted by either $North$ or $South$, consists of many pods. Each whale belongs to a unique matriline, unique pod, and unique population. These associations are life-long.

Whales live and move in close proximity to others in their matrilines, and matrilines differ in terms of their behavior and travel patterns. Killer whales within a matriline share common genetic traits, and less obviously, they often share food. Since these attributes affect fitness, are largely unobservable, and are arguably constant over time (genetics, a culture of food sharing, common travel patterns), we introduce matriline fixed effects in our estimation.

Matrilines travel with other matrilines in their pods, but this movement is far less structured and can ebb and flow (a matriline can be a day behind the rest of its pod). Our limited data on pod locations tells us that some pods are resident in the Salish more months of the year than others. Since these and other pod-level differences may affect hunting success and fitness, we introduce a time-varying pod-level component to our error.[57]

Finally, individual whales are of course unique in many ways, and hence we introduce a whale-specific component to our error as well. Putting these assumptions together we write the error term for whale i in matriline j and pod k at time t as:

$$\epsilon_{ijkt} = f_j + \alpha_{kt} + \mu_{it} \tag{A.2}$$

where f_j is the matriline fixed effect, α_{kt} and μ_{it} are the pod and individual-level errors.[58]

[57] J pod is almost always resident in the Salish, while K and L are not. See Table B.1 in the appendix for month/year residence figures.

[58] To anticipate slightly, errors are clustered at the pod level. There are 19 pods in our dataset.

A.V.1 Vessel Disturbance and Dose-Response

We assume whale activities may be disturbed by underwater noise coming from vessels. The Salish Sea is a very large area and the exposure of any individual whale will depend on its travel pattern, and perhaps avoidance behavior. We assume the exposure of whale i to noise comes from two sources: background ocean noise and noise created by vessels. Exposure to either source could be matriline or even whale-specific, but only vessel noise varies over time. We write the noise exposure of whale i at t, NX_{it}, as:

$$NX_{it} = \pi_B + \pi_i NP_t + \eta_{it} \tag{A.3}$$

$$\eta_{it} = \gamma_i + v_{it} \tag{A.4}$$

where π_B is background ocean noise, NP_t is the vessel noise produced in the Salish at time t, and π_i is a measure of exposure of whale i to a unit of this noise. η_{it} a random error in turn composed of an individual fixed effect, γ_i, plus an idiosyncratic error v_{it}.

Given their travel behavior, it is likely that whales within a matriline have similar or identical (π_i, γ_i); and parameter values across matrilines but within a pod are probably quite similar as well. While this is somewhat helpful, whales move constantly, are underwater for extended periods, and cannot be tracked in real time. These plus a myriad of other reasons mean exposure is unobserved and probably unobservable which raises two issues.

Do whales sort across geographic space to alter their exposure, just like humans do when they face a polluted environment? Sorting means exposure to treatment is endogenous to whale characteristics, some of which may also determine fitness. Although Fact 8 suggests there is little sorting, we address this challenge by relying on shocks to vessel noise.[59]

[59]Similar issues arise in the human health context where agents sort across locations that differ in their pollution levels. If agents sort on the basis of a characteristic X, and the level of X matters to an agent's response to pollution, then this failure of random geographic assignment has consequences. The relevant covariate X will not be balanced across treatment and control. Researchers meet this challenge by employing a combination of individual-level controls such as income and education (if X is observable) and geographic fixed effects (if X is unobservable), to lessen the risk

Shocks play two roles. First, all whales independent of their individual specific travel pattern experience a change in noise exposure proportional to the shock in vessel noise. Since our shocks are constructed from year-over-year changes in vessel activity, this implies constant level differences across whales in exposure $\gamma_i \neq \gamma_{i'}$ are eliminated. Second, if the change in exposure is rapid - truly a shock - then it is less likely whales undertake significant avoidance measures. The implicit assumption is that the avoidance behavior whales may have undertaken over a longer time span is not possible during the shock period length, and therefore noise pollution shocks provide as good as randomly assigned exposure to treatment.

To be more precise, define the disturbance shock experienced by whale i at t, as:

$$DS_{it} = [NX_{it} - NX_{it-1}] = \pi_i[\Delta NP_t] + [v_{it} - v_{it-1}] \tag{A.5}$$

The term, $\pi_i \Delta NP_t$ is whale i's *dose* of the "disturbance shock" created by the change in vessel traffic; that is,

$$DS_{it} = D_{it} + [v_{it} - v_{it-1}]. \tag{A.6}$$

The dose D_{it} is individual-specific and could be close to zero for some whales. Finally, substituting (A.5) in (A.1) we obtain:

$$Y_{it} = X'_{it}\beta + \rho_i D_{it} + \rho_i[v_{it} - v_{it-1}] + \epsilon_{it} \tag{A.7}$$

If we view the disturbance shock as the treatment, then whales are subject to different treatments by virtue of experiencing different doses; as well, whales may respond heterogeneously to any given dose by virtue of their potential whale specific *dose-response* ρ_i.

Our goal is to estimate the impact of vessel noise disturbance on an average whale. Average

that omitted variables are tainting the *otherwise identical* assumption implicit in their control/treatment comparison. To see how fixed effects can help address this problem see the example in Table 2 of Graff Zivin and Neidell (2013).

here means two things: a whale experiencing an average dose of noise, who also has an average dose response to this noise. These averages are always conditional on whales being in either the Northern or Southern populations and in some cases represent averages within one of the three Southern whale pods.

A.V.2 Potential Outcomes

To understand the assumptions needed to identify this average impact, it is useful to work through these conditions when the set of treatments is finite.[60] To do so, divide time periods into those with a shock present and those without a shock; i.e. ΔNP_t = {no shock = 0, shock =1}. Since there are a finite number of whales, whose exposure to the shock can differ because $\pi_i \neq \pi_j$, the set of possible treatments is also finite. Therefore, $D_i \in \{0, \text{D}\}$ with $D_i = 0$ when there is zero treatment; $D > 0$ when any non-zero treatments is present.

We will estimate the difference in conditional means $E[Y_{it}|D_i = D]$ across treatments:

$$E[Y_{it}|D_i = D] - E[Y_{it}|D_i = 0] \tag{A.8}$$

to identify the impact of noise pollution on health outcomes. Using (A.7), the average treatment effect we would like to identify is:

$$ATE = E[\rho_i D_i|D_i = D] - E[\rho_i D_i|D_i = 0]. \tag{A.9}$$

It is easy to show that the gap between the difference in conditional means in (A.8), which we will estimate, and our ATE in (A.9), which we would like to identify, can be written as the sum of three conceptually distinct terms. We label these A, B, and C and discuss them in turn.

[60] The interested reader can carry forward the logic to find parallel but less transparent conditions in the case where D_{it} is continuous.

$$E[Y_{it}|D_i = D] - E[Y_{it}|D_i = 0] = ATE + A + B + C \tag{A.10}$$

A is related to covariate balance; B to avoidance behavior; and C to selection based on fitness. If our identification assumptions hold, then these terms are zero in expectation. Before discussing these assumptions, the construction of the ATE in (A.9), requires further discussion.

A.V.3 Dose-response and Dosage

We cannot separately identify the impact of a larger dose of noise on outcomes, from that of a heightened sensitivity of whales to noise; as a result, we have relied on our double-barrelled average whale interpretation of (A.9). However, to do so, we need to make an assumption on the joint distribution of ρ_i and D_i. To see why, reconsider the ATE defined above:

$$ATE = E[\rho_i D_i|D_i = D] - E[\rho_i D_i|D_i = 0] \tag{A.11}$$

Note these expectations are over both the intensity of treatment and the dose-response of whales. If ρ_i and D_i are independently distributed throughout the population, then the expectation of their product is equal to the product of their expectations. In this case, we find our average treatment effect is given by:

$$\begin{aligned} ATE &= E[\rho_i]E[D_i] - E[\rho_i]E[0] \\ &= E[\rho_i]E[D_i] \end{aligned} \tag{A.12}$$

And our estimated treatment effect captures the impact on a whale with an average dose-response, exposed to an average amount of disturbance. Two special cases merit attention: if all whales were equally sensitive to noise pollution, but had different exposure, the ATE simplifies to $\overline{\rho}E[D]$; if the exposure was the same across whales, but its effects were different for different whales, the ATE

simplifies to $E[\rho_i]\overline{D}$.

Are ρ_i and D_i likely to be independent? The size of the dose response for any whale depends on its personal health attributes - whether it's old, young, female, male, weak, strong, etc. It is an individual-specific attribute reflecting its sensitivity to noise pollution. In contrast, D_i measures exposure to the shock. It reflects where the whale travels in the Salish Sea, and how long it lingers there. These are not determined by the individual whale, but by matriline and pod behaviors in conjunction with contemporaneous responses to the vagueries of salmon runs and weather. D_i is of course driven by shocks to vessel noise. All of these considerations support our assumption of independence.

With this clarification in hand, return to our three terms A, B, and C.

A.V.4 A: Covariate balance

One of the components of the difference we created using (A.9) and (A.8) is captured in A which we write as:

$$A = E[X'_{it}\beta|D_i = D] - E[X'_{it}\beta|D_i = 0] \tag{A.13}$$

A= 0 requires covariate balance across those whales shocked and those whales not shocked. There are two different comparison groups in the data. There are two whale populations and these differ greatly in their residence in the Salish Sea. A priori we expect Northern whales to be far less affected than Southern given their differences in habitat; consequently we introduce dummy variables in (A.7) to estimate average whale effects within each population. This leaves us with the overtime variation. There are years t with a shock present and years t' where it is absent. Since we have a panel, where individual whales enter and exit, we are in effect comparing outcomes across whales, within a given population, in shock versus non-shock years. If whales in shock years were older, sicker, or facing more competition, than those in no-shock years, then covariate balance would fail.

The natural and straightforward way to evaluate covariate balance in this context is to identify shock years, and then compare observable controls for those years versus years with no shocks.

Table A.2: Covariate balance

	SRKW					NRKW			
	Mean age of		Mean		Mean aggregate salmon abundance	Mean age of		Mean	
	females	males	population	sex ratio		females	males	population	sex ratio
Negative shock	28.20	14.08	85.75	1.76	3.04	21.58	15.41	196.00	1.40
Control	28.58	14.99	87.13	1.56	3.54	22.21	15.81	226.69	1.41
Positive shock	28.06	14.46	86.00	1.49	3.26	23.37	16.33	238.80	1.44
Negative vs control	-0.38	-0.91	-1.38	0.20	-0.50	-0.64	-0.40	-30.69	-0.01
Control vs positive	0.51	0.52	1.13	0.07	0.28	-1.16	-0.52	-12.11	-0.03
Negative vs positive	0.13	-0.38	-0.25	0.27	-0.22	-1.79*	-0.92	-42.80	-0.04

Control years: noise disturbance shocks (calculated as in Figure 8) are within one standard deviation of their mean. Positive (negative) shocks: noise disturbance shocks are more than one standard deviation above (below) their mean.
Negative shock years: 1979, 1981, 2001, 2010. Positive shock years: 1980, 1998, 2003, 2012, 2018.
***: significant at 1% level, ** significant at 5% level, *: significant at 10% level.
Sex ratio calculated by dividing number of females by number of males.
Aggregate salmon abundance is the sum of the three salmon indices shown on Figure 4.

Given the construction of our shock variable, we can go slightly further by distinguishing between positive (noisy) shock years (more than 1 st dev above the avg.), and negative (quiet) shock years (more than 1 st dev below the avg.). The control years have small shocks of less than 1 std deviation from the average. Table A.2 shows that for the Southern residents, the incidence of positive or negative shocks is unrelated to the average age of whales by gender, the existing sex ratio within their population, their prey availability as measured by salmon abundance or by the competitive pressures they face from members of their own population or others. The same is true for the Northern residents with one exception.

For example, in the first column, we see that the average age of female Southern residents is 28.20 in quiet years, 28.06 in loud years, and 28.58 otherwise. These very small differences are not significantly different from zero. Column three shows us the SRKW population is quite similar across these years: 85.75 in quiet years and 86 in noisy years. Their sex ratio is also similar across years, and in column five we find that coast-wise salmon abundance is very similar across loud and quiet years. In the remaining columns, we see that the Northern residents are younger, and their population larger, but again only one of the differences – in the mean age of Northern resident

females – across quiet or noisy years reaches a marginal level of significance.

The key, and comforting, takeaway from the table is that only noise shocks themselves differ across these periods. This conclusion may come as something of a surprise. After all, the Southern resident population is now much smaller and perhaps less healthy than in earlier periods, and salmon availability is thought to have declined over time. While both are true to some extent, positive and negative noise shock years arrive both early and late in the sample period. Consequently, they hit whale populations with very similar attributes.

A.V.5 B: Noise Shocks cannot be Avoided

The second element B, captures a key reason why researchers use shocks to help with identification. Formally we write B as:

$$B = E[\rho_i[v_{it} - v_{it-1}]|D_i = D] - E[\rho_i[v_{it} - v_{it-1}]|D_i = 0] \tag{A.14}$$

Recall that ρ_i is the whale-specific dose-response parameter. $v_{it} - v_{it-1}$ is the difference between two different period error terms in the noise exposure equation (A.4). $v_{it} > 0$ means the whale deviated from its usual travel patterns that period and was exposed to a bit more noise than would be expected. Since these errors reflect potential deviations in travel patterns, it is natural to think they may be persistent. For example, if these deviations were only slowly changing, we might write $v_{it} = bv_{it-1} + \phi_{it}$ where $b < 1$ and ϕ_{it} i.i.d. Under this assumption, define $K_{it} \equiv v_{it} - v_{it-1} = b[v_{it-1} - v_{it-2}] + \phi_{it} - \phi_{it-1}$. Now using K_{it} in B, we find it now equals:

$$B = E[\rho_i K_{it}|D_i = D] - E[\rho_i K_{it}|D_i = 0] \tag{A.15}$$

All the elements of K_{it} except ϕ_{it} are determined prior to the disturbance shock, DS_{it}, at t. We have already argued that the dose a whale receives is independent of its dose response because

individual whales do not dictate travel patterns; those arguments also apply here, and by extending our independence assumption slightly to the disturbance shock a given whale receives, then we can simplify B to:

$$B = E[\rho_i]E[K_{it}|D_i = D] - E[\rho_i]E[K_{it}|D_i = 0] \tag{A.16}$$

$$B = E[\rho_i]\Big[E[\phi_{it}|D_i = D] - E[\phi_{it}|D_i = 0]\Big] \tag{A.17}$$

Assuming B = 0 amounts to assuming whales cannot adjust to contemporaneous noise pollution. Contemporaneous avoidance behavior by whales would tend to make $\phi_{it} < 0$ when $D_i = D$ since this lowers the whale's exposure. If this cannot happen over the space of one season, then B should be zero.

In theory, whales could adjust on two margins: they could spend less time in the Salish Sea, or they could spend less time in noisy locations. To investigate the first we obtained long-term presence absence data on the three SRKW pods residence in the Salish. This data (available on request) shows there has been very little if any change in the presence of the SRKW in the Salish over the sample period. Therefore, avoidance at the level of presence in the Salish has not been observed.

With regard to locations, it is most important to remember that the SRKW are largely hunting Chinook salmon returning to the mouth of the Fraser River from either the north via the inside passage or west via Juan de Fuca Strait. Adjusting hunting locations is severely constrained by the specificities of their diet and the vagueries of salmon returns -neither of which is related to vessel traffic. The intensity of occurrence maps we overlaid with vessel tracks to develop Fact Eight tells us the SRKW are often present in areas of very high vessel traffic. Why? Because the very same deep ocean trenches needed for large commercial vessel passage are also favored by Chinook salmon. As the authors of this research note: "It is of interest to note that the majority of high-intensity occurrence polygons are located in close proximity to areas of high vessel traffic (both

commercial vessel traffic along the shipping lanes and recreational vessel transits from adjacent ports and marinas). While SRKW is known to be affected by physical and acoustic disturbance ... The enduring presence of SRKW in areas of elevated vessel traffic should not necessarily be taken as evidence of tolerance of, or acclimation to disturbance, but instead as a measure of the vital importance of these locations to the needs of the population" (Thornton et al., 2022, p.15). Avoidance comes at a steep cost, and this why conflict is inevitable.

A.V.6 C: Fitness Based Selection is Absent

Finally, consider our last term C which is related to our model's determinants of fitness. We can write C as follows:

$$C = E[\epsilon_{it}|D_i = D] - E[\epsilon_{it}|D_i = 0] \tag{A.18}$$

$$C = E[\alpha_{kt} + \mu_{it}|D_i = D] - E[\alpha_{kt} + \mu_{it}|D_i = 0] \tag{A.19}$$

where the second equality follows because matriline fixed effects cannot vary over treatments, and therefore cancel out.

We have already argued that observable determinants of fitness (salmon availability, age, gender, etc.) in shock vs. no shock years are very similar, but of course, this says nothing about unobservables. And C asks us whether there is selection into treatment for individual whales or entire pods based on unobservable determinants of fitness.

It is always possible to construct a threat to validity by positing an unobservable factor perfectly correlated with treatment, and hence identification arguments will always rely on judgment. In our case, we are comforted by our inclusion of matriline fixed effects which sweep away many of the most common threats. Since we have the population of all whales adding up our matriline fixed effects gets us very close pod and population-level effects as well.[61] Time-invariant unobservables

[61] There is a subtle issue here. Matrilines occasionally die out and new ones appear. Consequently, the matriline

at either of these two levels is almost surely rendered moot. This implies that α_{kt} reflects only pod level over-time variation in fitness unrelated to the underlying health of its constituent matrilines; while μ_{it} reflects over-time variation in unmeasured fitness again not captured by the underlying health of its constituent matriline.

Because noise pollution shocks come from changes in trade flows driven by variations in the economic activity of the U.S., Canada, and their set of Asia Pacific trade partners thousands of miles away, and this variation is amplified by ongoing, and worldwide, technological progress in shipping that has altered the composition of vessel fleets, it seems to us very unlikely that the implied variation in noise disturbance shocks is related to any other, remaining, and time-varying, unobserved, determinant of KW health (fitness based selection is absent).

A.VI 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.[62] 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.VI 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.

composition of pods fluctuates over time, and so does their sum, which therefore is slightly different from having pod-level fixed effects.

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

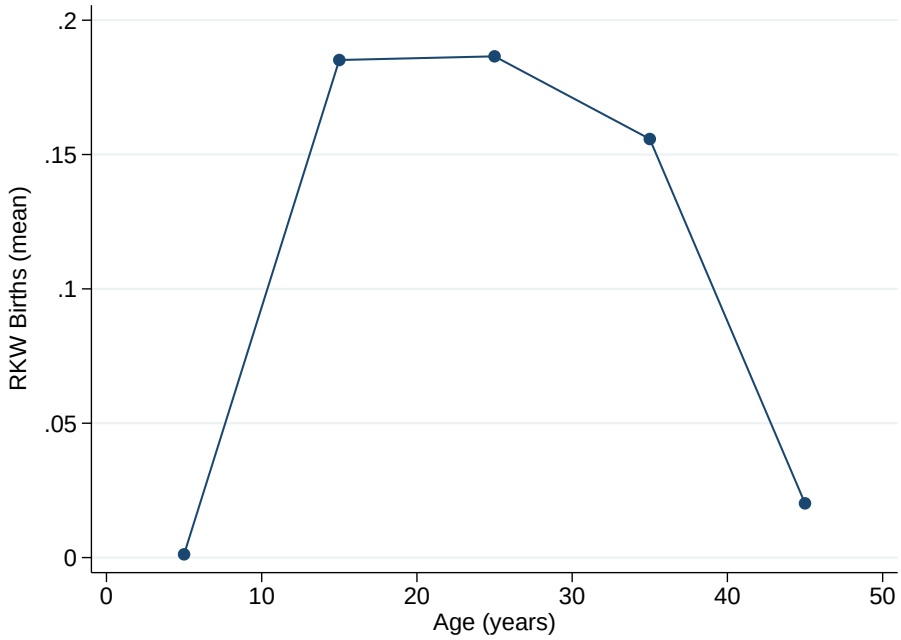


Figure A.6: Percentage of females with births by age in the pooled RKW populations, 1979-2019

Table A.3: 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.4 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.

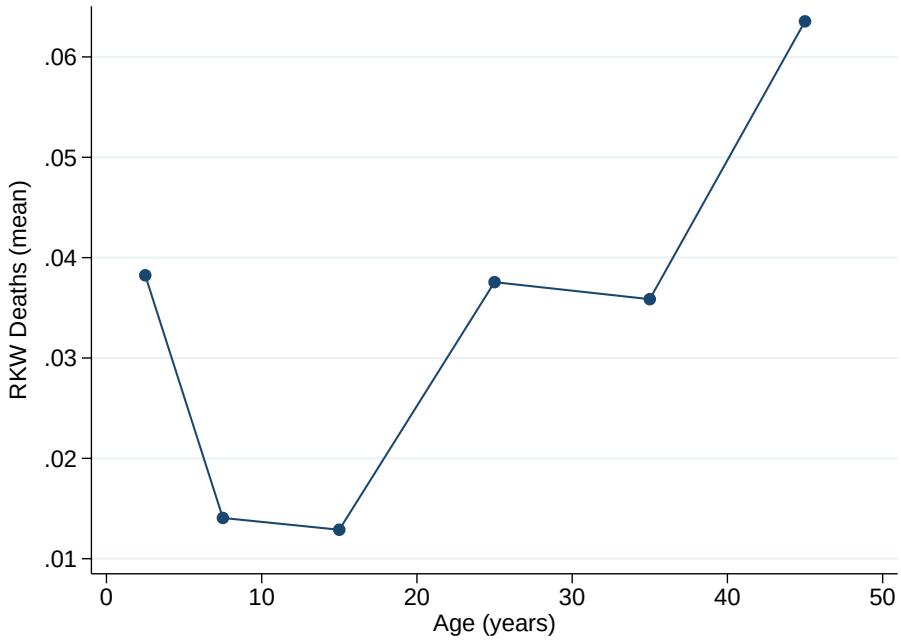


Figure A.7: Percentage of deaths by age in the pooled RKW populations, 1979-2019

Table A.4: Deaths in the pooled RKW populations by age, 1979-2019

		Death		
Age group	*n*	No	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.VII Fertility, Mortality Plots

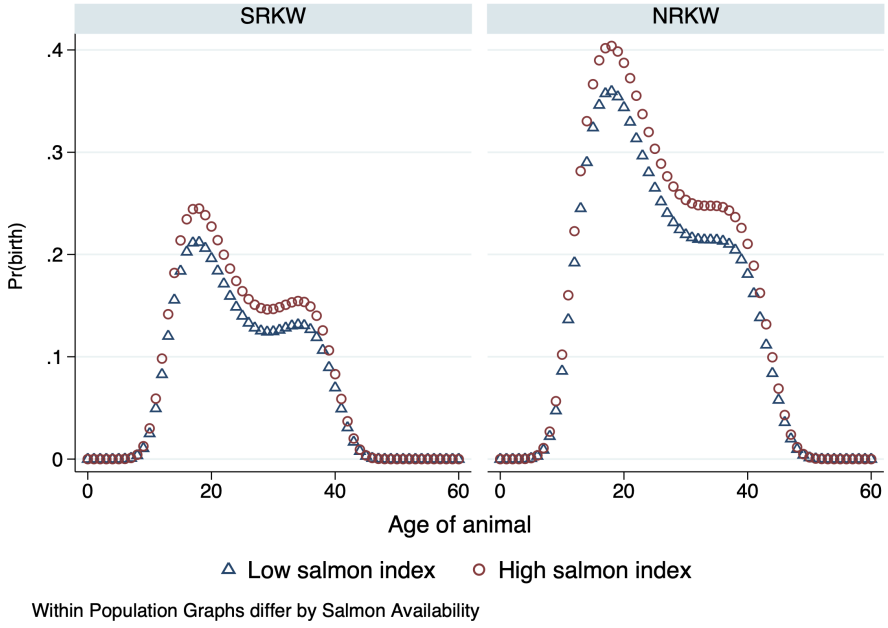


Figure A.8: Fertility Profiles

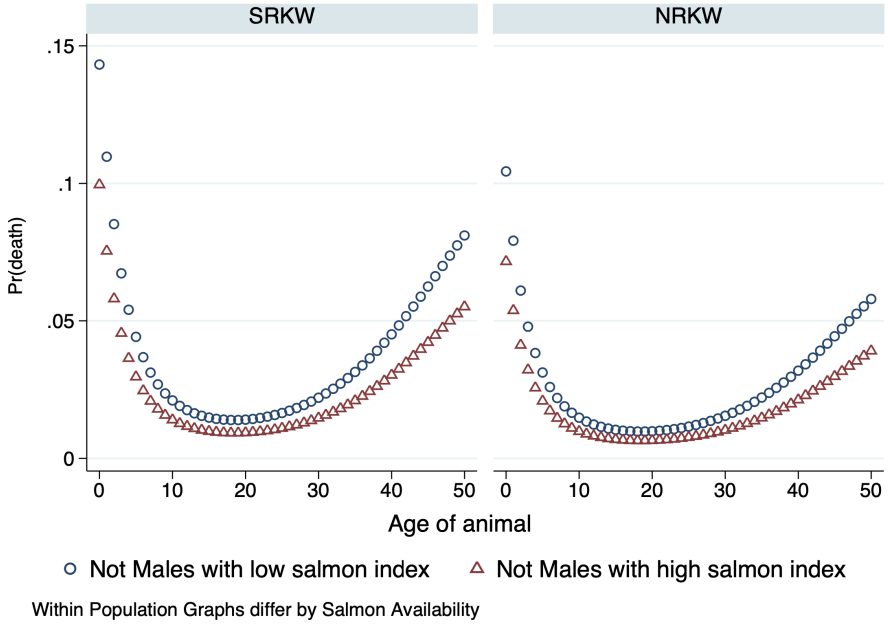


Figure A.9: Mortality Profiles

A.VIII Matriline FE regressions: Pod level Clustering

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

Table A.5: Baseline Demographic Determinants of Fertility

	I.	II.	III.	IV.	V.
Constant	−0.04	−0.07	−0.05	0.09	0.07
	0.000	0.000	0.000	0.002	0.020
Age	0.03	0.03	0.03	0.03	0.03
	0.000	0.000	0.000	0.000	0.000
Age^2	−0.001	−0.001	−0.001	−0.001	−0.001
	0.000	0.000	0.000	0.000	0.000
Age^3	1.18E-05	1.21E-05	1.23E-05	1.19E-05	1.10E-05
	0.000	0.000	0.000	0.000	0.000
Age^4	-4.16E-08	-4.39E-08	-4.47E-08	-4.13E-08	-4.25E-08
	0.003	0.002	0.001	0.002	0.000
NRKW	0.04	0.04	0.06	−0.03	−0.01
	0.006	0.005	0.000	0.210	0.721
L1.Salmon abundance		0.03	0.03	0.03	0.03
		0.019	0.025	0.041	0.036
L1.Within competition			−0.0002	−0.0003	−0.0003
			0.012	0.005	0.001
L1.Across competition				−0.0005	−0.0004
				0.000	0.003
Matriline FE	Yes	Yes	Yes	Yes	Yes
NRKW × Age	No	No	No	No	Yes
N	5821	5707	5707	5707	5707
Log likelihood	-774.12	-753.46	-751.25	-745.41	-734.52
R^2	0.10	0.09	0.10	0.10	0.10

Standard errors are clustered at the pod level. P-values appear under the coefficient.

N records the number of viable female-whale-years which excludes the year preceding a birth when pregnant and the year post birth nursing.

Table A.6: Baseline Demographic Determinants of Mortality

	I.	II.	III.	IV.	V.
Constant	0.06	0.08	0.08	0.02	0.02
	0.001	0.001	0.001	0.580	0.660
Age	−0.01	−0.01	−0.01	−0.01	−0.02
	0.006	0.006	0.006	0.006	0.000
Age^2	0.0003	0.0003	0.0003	0.0003	0.0006
	0.026	0.027	0.027	0.029	0.000
Age^3	-3.26E-06	-3.23E-06	-3.24E-06	-3.08E-06	-8.17E-06
	0.102	0.108	0.108	0.119	0.000
Age^4	1.32E-08	1.29E-08	1.29E-08	1.18E-08	3.78E-08
	0.204	0.220	0.220	0.248	0.000
NRKW	−0.01	−0.001	−0.003	0.04	0.03
	0.680	0.956	0.859	0.132	0.261
L1.Salmon abundance		−0.02	−0.02	−0.02	−0.02
		0.029	0.031	0.043	0.047
L1.Within competition			0.00004	0.00005	0.00001
			0.404	0.325	0.801
L1.Across competition				0.0002	0.0003
				0.010	0.001
Matriline FE	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes
NRKW × Age	No	No	No	No	Yes
N	12793	12571	12571	12571	12571
Log likelihood	5140.01	4996.31	4996.78	5000.70	5020.22
R^2	0.05	0.05	0.05	0.05	0.06

Standard errors are clustered at the pod level. P-values appear under the coefficient.

N records the number of viable female-whale-years which excludes the year preceding a birth when pregnant and the year post birth nursing.

Table A.7: First difference Impacts on Births

	I.	II.	III.	IV.	V.
Constant	0.06	0.06	0.06	0.05	0.05
	0.057	0.062	0.052	0.062	0.070
Age	0.03	0.03	0.03	0.03	0.03
	0.000	0.000	0.000	0.000	0.000
Age^2	−0.001	−0.001	−0.001	−0.001	−0.001
	0.000	0.000	0.000	0.000	0.000
Age^3	1.10E-05	1.11E-05	1.11E-05	1.11E-05	1.10E-05
	0.000	0.000	0.000	0.000	0.000
Age^4	-4.25E-08	-4.30E-08	-4.28E-08	-4.28E-08	-4.24E-08
	0.000	0.000	0.000	0.000	0.000
NRKW	0.001	0.006	0.003	0.004	0.006
	0.957	0.846	0.909	0.875	0.814
L1.Salmon abundance	0.03	0.03	0.03	0.03	0.03
	0.035	0.038	0.046	0.032	0.046
L1.Within competition	−0.0004 − 0.0004	−0.0003	−0.0003	−0.0003	
	0.001	0.001	0.001	0.001	0.001
L1.Across competition	−0.0003 − 0.0004	−0.0004	−0.0004	−0.0004	
	0.008	0.008	0.004	0.004	0.004
L1.Δ Total Vessel km	−0.04				
	0.000				
L1.Δ Total Vessel km $\times$ NRKW	0.06				
	0.003				
L1.Δ Other km		0.04			
		0.310			
L1.Δ Other km $\times$ NRKW		0.01			
		0.887			
L1.Δ Unitised km		−0.21	−0.18	−0.18	0.01
		0.012	0.001	0.001	0.922
L1.Δ Unitised km $\times$ NRKW		0.18	0.19	0.19	
		0.110	0.015	0.012	
Δ Unitised km				−0.08	
				0.164	
Δ Unitised km $\times$ NRKW				0.01	
				0.932	
L1.Δ Unitised km $\times$ J pod					−0.16
					0.007
L1.Δ Unitised km $\times$ K pod					−0.07
					0.204
L1.Δ Unitised km $\times$ L pod					−0.25
					0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes
NRKW $\times$ Age	Yes	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707	5707
Log likelihood	-733.45	-731.30	-732.29	-731.12	-731.91
R^2	0.10	0.10	0.10	0.10	0.10

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.

Table A.8: First difference Impacts on Deaths

	I.	II.	III.	IV.	V.
Constant	0.02	0.02	0.01	0.01	0.01
	0.640	0.650	0.680	0.720	0.734
Age	−0.02	−0.02	−0.02	−0.02	−0.01
	0.000	0.000	0.000	0.000	0.000
Age^2	0.001	0.001	0.001	0.001	0.001
	0.000	0.000	0.000	0.000	0.000
Age^3	-8.21E-06	-8.21E-06	-8.20E-06	-8.19E-06	-8.13E-06
	0.000	0.000	0.000	0.000	0.000
Age^4	3.80E-08	3.80E-08	3.80E-08	3.79E-08	3.76E-08
	0.000	0.000	0.000	0.000	0.000
NRKW	0.03	0.03	0.03	0.03	0.03
	0.256	0.251	0.248	0.208	0.195
L1.Salmon abundance	−0.02	−0.02	−0.02	−0.02	−0.02
	0.053	0.055	0.047	0.051	0.051
L1.Within competition	9.30E-06	8.21E-06	1.14E-05	1.23E-05	1.27E-05
	0.845	0.862	0.809	0.796	0.788
L1.Across competition	0.0002	0.0002	0.0003	0.0002	0.0003
	0.001	0.001	0.001	0.001	0.001
L1.Δ Total Vessel km	0.02				
	0.026				
L1.Δ Total Vessel km × NRKW	−0.02				
	0.179				
L1.Δ Other km		0.02			
		0.140			
L1.Δ Other km × NRKW		−0.02			
		0.403			
L1.Δ Unitised km		0.03	0.05	0.05	
		0.033	0.005	0.004	
L1.Δ Unitised km × NRKW		−0.03	−0.04	−0.05	
		0.242	0.121	0.104	
Δ Unitised km				0.06	−0.01
				0.053	0.676
Δ Unitised km × NRKW				−0.07	
				0.052	
Δ Unitised km × J pod					0.10
					0.000
Δ Unitised km × K pod					−0.04
					0.034
Δ Unitised km × L pod					0.09
					0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571	12571
Log likelihood	5021.67	5021.69	5021.09	5022.51	5022.70
R^2	0.06	0.06	0.06	0.06	0.06

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.

Table A.9: Noise-weighted distance fertility regressions

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Constant	0.05	0.05	0.05	0.05	0.05	0.05
	0.064	0.075	0.073	0.063	0.075	0.073
Age	0.03	0.03	0.03	0.03	0.03	0.03
	0.000	0.000	0.000	0.000	0.000	0.000
Age^2	−0.001	−0.001	−0.001	−0.001	−0.001	−0.001
	0.000	0.000	0.000	0.000	0.000	0.000
Age^3	1.11E-05	1.11E-05	1.10E-05	1.11E-05	1.11E-05	1.10E-05
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	-4.26E-08	-4.26E-08	-4.25E-08	-4.26E-08	-4.26E-08	-4.25E-08
	0.000	0.000	0.000	0.000	0.000	0.000
NRKW	0.003	0.004	0.005	0.003	0.004	0.005
	0.895	0.891	0.848	0.895	0.892	0.850
L1.Salmon abundance	0.03	0.03	0.03	0.03	0.03	0.03
	0.039	0.028	0.039	0.039	0.028	0.040
L1.Within competition	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003
	0.001	0.001	0.001	0.001	0.001	0.001
L1.Across competition	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003
	0.006	0.006	0.006	0.006	0.006	0.006
L1.Δ Distance weighted by noise	−0.03	−0.03	0.01	−0.02	−0.02	0.01
	0.000	0.000	0.419	0.000	0.000	0.435
L1.Δ Distance weighted by noise × NRKW	0.03	0.03		0.03	0.03	
	0.002	0.002		0.002	0.002	
Δ Distance weighted by noise		−0.02			−0.02	
		0.005			0.008	
Δ Distance weighted by noise × NRKW		0.01			0.01	
		0.352			0.374	
L1.Δ Distance weighted by noise × J pod			−0.03			−0.03
			0.001			0.001
L1.Δ Distance weighted by noise × K pod			−0.02			−0.02
			0.015			0.012
L1.Δ Distance weighted by noise × L pod			−0.04			−0.03
			0.000			0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707	5707	5707
Log likelihood	-732.90	-731.56	-732.79	-732.88	-731.56	-732.78

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.

A.IX 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

Table A.10: Noise-weighted distance effects on mortality

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Constant	0.02	0.01	0.01	0.02	0.01	0.01
	0.662	0.692	0.704	0.660	0.691	0.704
Age	−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^2	0.001	0.001	0.001	0.001	0.001	0.001
	0.000	0.000	0.000	0.000	0.000	0.000
Age^3	-8.22E-06	-8.22E-06	-8.17E-06	-8.21E-06	-8.22E-06	-8.16E-06
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	3.80E-08	3.81E-08	3.78E-08	3.80E-08	3.80E-08	3.77E-08
	0.000	0.000	0.000	0.000	0.000	0.000
NRKW	0.031	0.032	0.032	(omitted)	0.032	0.032
	0.248	0.228	0.224		0.229	0.223
L1.Salmon abundance	−0.02	−0.01	−0.02	−0.02	−0.01	−0.02
	0.050	0.058	0.054	0.050	0.057	0.053
L1.Within competition	0.00001	0.00001	0.00002	0.00001	0.00001	0.00002
	0.848	0.771	0.724	0.840	0.763	0.722
L1.Across competition	0.0002	0.0002	0.0003	0.0002	0.0002	0.0003
	0.001	0.001	0.001	0.001	0.001	0.001
L1.Δ Distance weighted by noise	0.01	0.01		0.01	0.01	
	0.004	0.004		0.006	0.005	
L1.Δ Distance weighted by noise × NRKW	−0.01	−0.01		−0.01	−0.01	
	0.129	0.132		0.129	0.137	
Δ Distance weighted by noise		0.01	−0.005		0.01	−0.004
		0.017	0.247		0.017	0.247
Δ Distance weighted by noise × NRKW		−0.01			−0.01	
		0.015			0.014	
Δ Distance weighted by noise × J pod			0.02			0.02
			0.000			0.000
Δ Distance weighted by noise × K pod			0.001			0.001
			0.823			0.843
Δ Distance weighted by noise × L pod			0.02			0.01
			0.001			0.001
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571	12571	12571
Log likelihood	5021.88	5023.35	5022.11	5021.75	5023.25	5022.20

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.

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 (2021) 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.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.[63] 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.

[63] 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]	

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 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. Col-

umn 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 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.

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.

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 some-

what 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.[64] 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.[65] 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:

$$D_{it} = [\text{Fraction of V disturbed}] \cdot [\text{Fraction of time V disturbed}] \leq 1 \tag{A.20}$$

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.[66] In our empirical work

[64] 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.

[65] 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.

[66] In theoretical work this assumption is almost always unstated because it is so common. In the empirical health

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. 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.[67]

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

$$SL + TL(d) = B \tag{A.21}$$

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:

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.

[67] 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.

$$TL = 10\log_{10}[d_1/d_2]^2 = 10\log_{10}[1/d_2]^2 \tag{A.22}$$

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.21) and (A.22) the distance at which this excess – disturbance – becomes indistinguishable from background ocean noise is simply:

$$d_2 = 10^{X/20} \tag{A.23}$$

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:

$$V_D = \frac{2}{3}\pi r^3 = \frac{2}{3}\pi[d_2]^3 \tag{A.24}$$

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:

$$D_{it} = \left[\frac{V_D}{V}\right] \cdot \left[\frac{t^*}{T}\right] \tag{A.25}$$

where V_D is solved using by (A.21) to (A.24). Since the choice of V and the units of T are arbitrary, we substitute for t^*, and rearrange to find:

$$D_{it} = \Omega V_D \left[\frac{x}{s}\right] \tag{A.26}$$

where Ω is a positive constant reflecting the geography of V and the time frame selected. Therefore, (A.26) 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:

$$D_{it} = \Omega \sum_{j \in N} \left[\frac{V_{Djt} x_j}{s_j}\right] \tag{A.27}$$

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.27) simplifies further to:

$$D_{it} = \Omega' \sum_{j \in N} x_j \tag{A.28}$$

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.27) 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.27) 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. Details upon request.

B Available on Request

B.I Presence/Absence and Intensity of Use

In Table B.1 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 B.1: 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

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

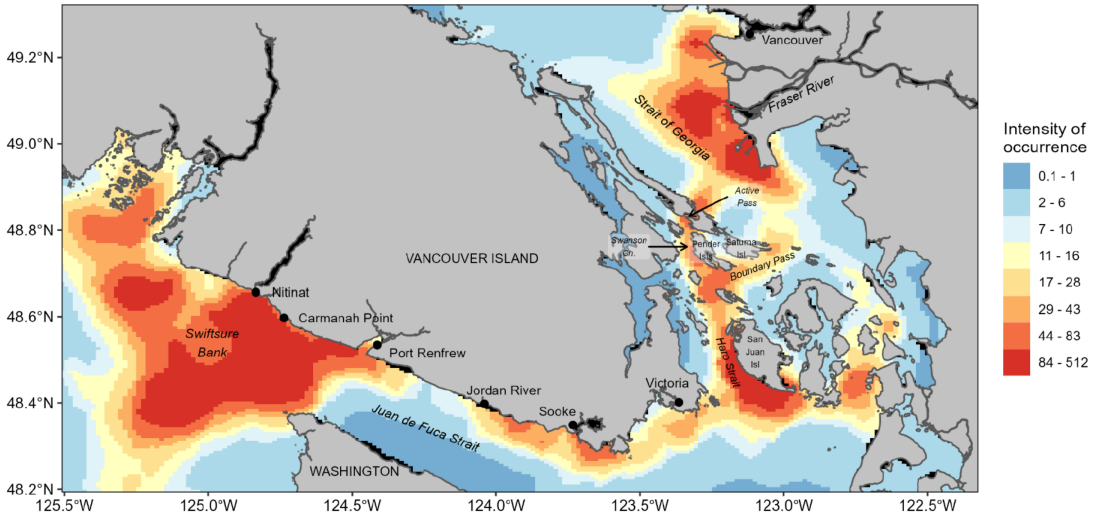


Figure 11. Annual SRKW intensity of occurrence as estimated by the SRKW occurrence model using combined WW and DFO data for May to October, 2009—2020.

Figure B.1: Intensity of Use, DFO and Whale Watch Data

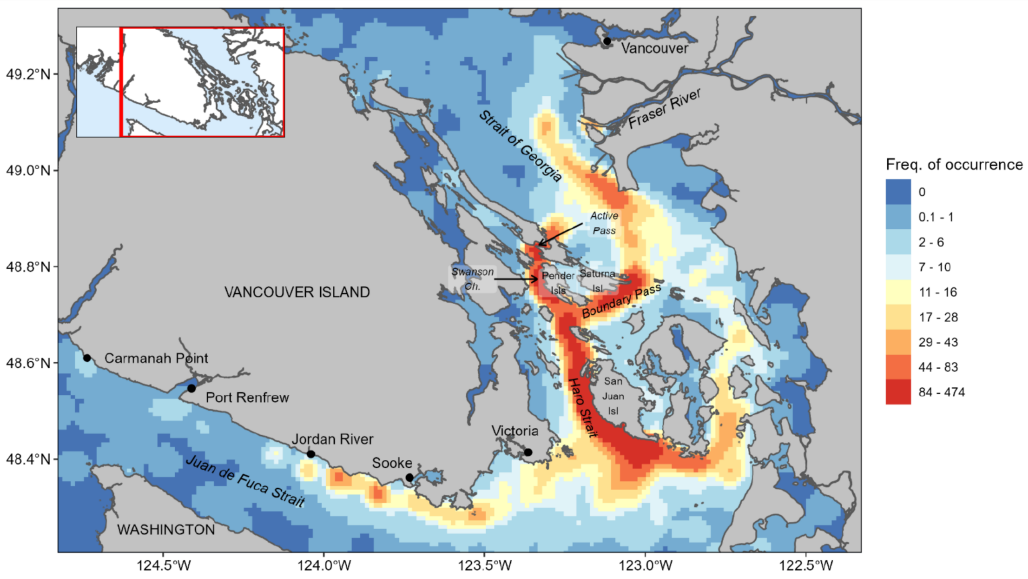


Figure 9. Annual frequency of SRKW occurrence from May to October as predicted by the 2009-2018 platform of opportunity (BC Cetacean Sightings Network/OrcaMaster) sightings fit to a Kernel Density model.

Figure B.2: Intensity of Use, Platforms of Opportunity Data

B.II How important is Vessel Speed?

To see this, take (A.26) and plug in (A.24) for V_D then (A.23) for d_2 in the resulting equation to express $D_i t$ 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:

$$\frac{dD_{it}}{\ln(10) D_{it}} = \frac{3dX}{20} - \frac{ds}{\ln(10)s} \tag{B.1}$$

To get to dX, plug in X for $TL(d)$ into (A.21), 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 (B.1) 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:

$$\frac{dD_{it}}{ds} \frac{s}{D_{it}} = \frac{3 \ln(10)}{20} SL'(s) \cdot s - 1. \tag{B.2}$$

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 (B.2) 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.

Table B.2: Instrumenting for noise-weighted distance in fertility regressions, second stage

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Constant	0.05	0.05	0.05	0.05	0.05	0.05
	0.054	0.064	0.074	0.053	0.062	0.072
Age	0.03	0.03	0.03	0.03	0.03	0.03
	0.000	0.000	0.000	0.000	0.000	0.000
Age^2	−0.001	−0.001	−0.001	−0.001	−0.001	−0.001
	0.000	0.000	0.000	0.000	0.000	0.000
Age^3	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	-4.26E-08	-4.26E-08	-4.24E-08	-4.26E-08	-4.26E-08	-4.24E-08
	0.000	0.000	0.000	0.000	0.000	0.000
NRKW	−0.12	−0.12	−0.11	−0.12	−0.12	−0.11
	0.008	0.009	0.010	0.008	0.008	0.010
L1.Salmon abundance	0.03	0.03	0.03	0.03	0.03	0.03
	0.024	0.015	0.024	0.024	0.015	0.025
L1.Within competition	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Across competition	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003	−0.0003
	0.001	0.001	0.001	0.001	0.001	0.001
L1.Δ Distance	−0.04	−0.04	0.001	−0.03	−0.03	0.001
weighted by noise	0.000	0.000	0.916	0.000	0.000	0.916
L1.Δ Distance	0.04	0.04		0.03	0.03	
weighted by noise × NRKW	0.005	0.004		0.005	0.004	
Δ Distance		−0.02			−0.02	
weighted by noise		0.128			0.132	
Δ Distance		0.001			0.001	
weighted by noise × NRKW		0.927			0.936	
L1.Δ Distance weighted			−0.03			−0.03
by noise × J pod			0.002			0.002
L1.Δ Distance weighted			−0.01			−0.01
by noise × K pod			0.172			0.173
L1.Δ Distance weighted			−0.05			−0.04
by noise × L pod			0.000			0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707	5707	5707
Endogeneity test	F(2,18)	F(4,18)	F(4,18)	F(2,18)	F(4,18)	F(4,18)
F statistics	2.91	2.25	8316.08	2.59	2.05	6522.85
	0.080	0.104	0.000	0.102	0.130	0.000

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.

Table B.3: Instrumenting for noise-weighted distance in fertility regressions, first stage

	First stage of column I of Table B.2		First stage of column II of Table B.2			
Outcome variable	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × NRKW	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × NRKW	Δ Distance weighted by noise	Δ Distance weighted by noise × NRKW
Constant	−0.11	0.06	−0.11	0.06	0.08	0.03
	0.170	0.445	0.178	0.430	0.003	0.371
Age	0.003	0.002	0.003	0.002	0.003	0.001
	0.060	0.097	0.061	0.097	0.001	0.107
Age^2	−0.00002	−0.00003	−0.00002	−0.00003	−0.00006	−0.00001
	0.772	0.147	0.772	0.151	0.117	0.130
Age^3	-7.59E-07	-1.95E-07	-7.60E-07	-1.97E-07	3.77E-07	-6.65E-08
	0.470	0.544	0.468	0.542	0.608	0.578
Age^4	7.56E-09	3.18E-09	7.56E-09	3.20E-09	1.65E-10	1.17E-09
	0.216	0.250	0.214	0.251	0.968	0.275
NRKW	−0.07	−0.18	−0.07	−0.18	−0.11	−0.07
	0.160	0.000	0.164	0.000	0.000	0.002
L1.Salmon abundance	0.002	−0.006	0.001	−0.007	−0.004	0.001
	0.744	0.160	0.870	0.120	0.509	0.861
L1.Within competition	0.001	0.001	0.0006	0.0007	0.0001	0.0002
	0.000	0.000	0.000	0.000	0.012	0.000
L1.Across competition	0.0002	−0.0004	0.0002	−0.0004	−0.0001	−0.0002
	0.603	0.097	0.600	0.097	0.281	0.108
L1.Δ Unitised km	5.00	0.01	5.00	0.01	0.17	0.005
	0.000	0.287	0.000	0.298	0.000	0.165
L1.Δ Unitised km × NRKW	−0.10	4.89	−0.09	4.89	0.06	0.22
	0.008	0.000	0.008	0.000	0.041	0.000
Δ Unitised km			−0.03	0.01	4.93	0.004
			0.327	0.218	0.000	0.223
Δ Unitised km × NRKW			0.10	0.06	−0.08	4.84
			0.004	0.003	0.038	0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707	5707	5707
F-test	F(38,5601)	F(38,5601)	F(39,5599)	F(39,5599)	F(39,5599)	F(39,5599)
F statistics	22885.8	10735.34	17396.52	10592.38	15882.97	23034.01
	0.000	0.000	0.000	0.000	0.000	0.000
R^2	0.86	0.86	0.86	0.86	0.86	0.86

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.

Table B.4: Instrumenting for noise-weighted distance in fertility regressions, first stage

	First stage of column III of Table B.2			
Outcome variable	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × J pod	L1.Δ Distance weighted by noise × K pod	L1.Δ Distance weighted by noise × L pod
Constant	−0.10	−0.04	−0.03	−0.08
	0.182	0.277	0.291	0.120
Age	0.003	0.001	−0.001	0.001
	0.055	0.392	0.280	0.282
Age^2	−0.00002	−0.00001	0.00005	−0.00003
	0.745	0.643	0.277	0.233
Age^3	-7.23E-07	-6.41E-08	-9.51E-07	4.89E-07
	0.488	0.846	0.274	0.108
Age^4	7.34E-09	1.47E-09	5.37E-09	-2.69E-09
	0.227	0.348	0.278	0.026
NRKW	−0.08	0.03	0.02	0.06
	0.152	0.277	0.286	0.131
L1.Salmon abundance	0.002	0.002	0.001	0.005
	0.740	0.243	0.287	0.220
L1.Within competition	0.0007	−0.00002	−0.00002	−0.00004
	0.000	0.343	0.338	0.350
L1.Across competition	0.0002	0.0002	0.0001	0.0003
	0.602	0.275	0.288	0.107
L1.Δ Unitised km	4.91	0.001	0.001	0.002
	0.000	0.324	0.347	0.333
L1.Δ Unitised km × J pod	0.05	4.95	−0.004	−0.010
	0.061	0.000	0.287	0.107
L1.Δ Unitised km × K pod	0.05	−0.01	4.97	−0.01
	0.033	0.299	0.000	0.132
L1.Δ Unitised km × L pod	0.14	−0.01	−0.005	5.051
	0.000	0.242	0.262	0.000
Matriline FE	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707
F-test	F(38,5599)	F(38,5599)	F(38,5599)	F(38,5599)
F statistics	7493.05	206.19	16.95	2583595.69
	0.000	0.000	0.000	0.000
R^2	0.86	0.87	0.86	0.86

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.

Table B.5: Instrumenting for noise-weighted distance in fertility regressions, first stage

	First stage of column IV of Table B.2		First stage of column V of Table B.2			
Outcome variable	L1.Δ Distance weighted by noise 2	L1.Δ Distance weighted by noise 2 × NRKW	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × NRKW	Δ Distance weighted by noise	Δ Distance weighted by noise × NRKW
Constant	−0.12	0.06	−0.12	0.06	0.08	0.03
	0.145	0.466	0.158	0.446	0.003	0.371
Age	0.003	0.002	0.003	0.002	0.003	0.001
	0.065	0.095	0.065	0.097	0.001	0.107
Age^2	−0.00001	−0.00003	−0.00001	−0.00003	−0.00006	−0.00001
	0.830	0.150	0.832	0.156	0.117	0.130
Age^3	-9.30E-07	-2.18E-07	-9.33E-07	-2.22E-07	3.77E-07	-6.65E-08
	0.400	0.539	0.399	0.537	0.608	0.578
Age^4	8.82E-09	3.53E-09	8.84E-09	3.55E-09	1.65E-10	1.17E-09
	0.169	0.247	0.169	0.248	0.968	0.275
NRKW	−0.09	−0.21	−0.09	−0.21	−0.11	−0.07
	0.134	0.000	0.135	0.000	0.000	0.002
L1.Salmon abundance	0.000	−0.009	−0.001	−0.010	−0.004	0.001
	0.978	0.092	0.859	0.063	0.509	0.861
L1.Within competition	0.001	0.001	0.001	0.001	0.000	0.000
	0.000	0.000	0.000	0.000	0.012	0.000
L1.Across competition	0.0002	−0.0005	0.0002	−0.0005	−0.0001	−0.0002
	0.514	0.096	0.516	0.096	0.281	0.108
L1.Δ Unitised km	5.90	0.01	5.90	0.01	0.16	0.00
	0.000	0.323	0.000	0.339	0.000	0.165
L1.Δ Unitised km × NRKW	−0.11	5.78	−0.11	5.78	0.06	0.22
	0.011	0.000	0.010	0.000	0.041	0.000
Δ Unitised km			−0.01	0.01	4.93	0.00
			0.738	0.222	0.000	0.223
Δ Unitised km × NRKW			0.12	0.09	−0.08	4.84
			0.004	0.000	0.038	0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707	5707	5707
F-test	F(38,5601)	F(38,5601)	F(39,5599)	F(39,5599)	F(39,5599)	F(39,5599)
F statistics	22619.75	8518.56	82913.55	43644.48	15882.97	23034.01
	0.000	0.000	0.000	0.000	0.000	0.000
R^2	0.87	0.88	0.87	0.88	0.86	0.86

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.

Table B.6: Instrumenting for noise-weighted distance in fertility regressions, first stage

	First stage of column VI of Table B.2			
Outcome variable	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × J pod	L1.Δ Distance weighted by noise × K pod	L1.Δ Distance weighted by noise × L pod
Constant	−0.12	−0.05	−0.04	−0.09
	0.158	0.277	0.291	0.145
Age	0.003	0.001	−0.001	0.001
	0.059	0.415	0.275	0.290
Age^2	−0.00002	−0.00001	0.00005	−0.00003
	0.801	0.741	0.272	0.229
Age^3	-8.89E-07	-1.62E-07	-1.05E-06	5.41E-07
	0.419	0.629	0.268	0.094
Age^4	8.57E-09	2.15E-09	5.89E-09	-3.01E-09
	0.180	0.203	0.271	0.017
NRKW	−0.09	0.03	0.03	0.06
	0.126	0.278	0.286	0.174
L1.Salmon abundance	0.000	0.002	0.001	0.006
	0.973	0.241	0.287	0.216
L1.Within competition	0.0008	−0.00003	−0.00002	−0.00005
	0.000	0.344	0.339	0.351
L1.Across competition	0.0002	0.0002	0.0002	0.0004
	0.513	0.275	0.288	0.107
L1.Δ Unitised km	5.79	0.001	0.001	0.002
	0.000	0.327	0.356	0.340
L1.Δ Unitised km × J pod	0.05	5.84	−0.005	−0.01
	0.104	0.000	0.284	0.106
L1.Δ Unitised km × K pod	0.06	−0.01	5.86	−0.02
	0.025	0.300	0.000	0.131
L1.Δ Unitised km × L pod	0.16	−0.01	−0.01	5.96
	0.000	0.242	0.261	0.000
Matriline FE	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707
F-test	F(38,5599)	F(38,5599)	F(38,5599)	F(38,5599)
F statistics	8318.13	58.97	15.79	2188239.27
	0.000	0.000	0.000	0.000
R^2	0.87	0.88	0.87	0.87

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.

Table B.7: Instrumenting for noise-weighted distance in mortality regressions, second stage

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Constant	0.02	0.01	0.01	0.02	0.01	0.01
	0.640	0.674	0.717	0.641	0.673	0.716
Age	−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^2	0.001	0.001	0.001	0.001	0.001	0.001
	0.000	0.000	0.000	0.000	0.000	0.000
Age^3	-8.21E-06	-8.21E-06	-8.16E-06	-8.21E-06	-8.21E-06	-8.16E-06
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	3.80E-08	3.80E-08	3.77E-08	3.80E-08	3.80E-08	3.77E-08
	0.000	0.000	0.000	0.000	0.000	0.000
NRKW	0.03	0.03	0.03	0.03	0.03	0.03
	0.223	0.188	0.168	0.223	0.189	0.168
L1.Salmon abundance	−0.02	−0.02	−0.02	−0.02	−0.02	−0.02
	0.027	0.029	0.030	0.027	0.029	0.030
L1.Within competition	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
	0.803	0.777	0.763	0.804	0.777	0.763
L1.Across competition	0.0003	0.0002	0.0003	0.0003	0.0002	0.0003
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Δ Distance	0.01	0.01		0.01	0.01	
weighted by noise	0.001	0.001		0.001	0.001	
L1.Δ Distance	−0.01	−0.01		−0.01	−0.01	
weighted by noise × NRKW	0.101	0.104		0.101	0.106	
Δ Distance		0.01	−0.002		0.01	−0.001
weighted by noise		0.032	0.658		0.032	0.658
Δ Distance		−0.01			−0.01	
weighted by noise × NRKW		0.031			0.031	
Δ Distance weighted			0.02			0.02
by noise × J pod			0.000			0.000
Δ Distance weighted			−0.008			−0.01
by noise × K pod			0.021			0.021
Δ Distance weighted			0.02			0.02
by noise × L pod			0.000			0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571	12571	12571
Endogeneity test	F(2,18)	F(4,18)	F(4,18)	F(2,18)	F(4,18)	F(4,18)
F statistics	1.89	129.28	1202.52	1.41	122.95	975.06
	0.179	0.000	0.000	0.270	0.000	0.000

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.

Table B.8: Instrumenting for noise-weighted distance in mortality regressions, first stage

	First stage of column I of Table B.7		First stage of column II of Table B.7			
Outcome variable	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × NRKW	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × NRKW	Δ Distance weighted by noise	Δ Distance weighted by noise × NRKW
Constant	0.002	0.120	0.01	0.12	0.04	0.06
	0.984	0.290	0.963	0.280	0.319	0.190
Age	0.005	0.003	0.005	0.003	0.004	0.001
	0.020	0.091	0.020	0.088	0.000	0.181
Age^2	−0.0001	−0.0001	−0.0001	−0.0001	−0.0001	−0.00002
	0.043	0.122	0.043	0.119	0.015	0.479
Age^3	9.04E-07	4.87E-07	9.12E-07	4.97E-07	1.06E-06	-6.25E-09
	0.244	0.389	0.240	0.382	0.156	0.987
Age^4	-9.68E-10	-2.46E-10	-9.91E-10	-2.77E-10	-2.95E-09	1.08E-09
	0.812	0.938	0.808	0.931	0.450	0.614
NRKW	−0.11	−0.19	−0.11	−0.19	−0.04	−0.07
	0.166	0.011	0.160	0.011	0.118	0.006
L1.Salmon abundance	−0.02	−0.02	−0.02	−0.02	−0.02	−0.02
	0.063	0.003	0.050	0.003	0.000	0.000
L1.Within competition	0.001	0.001	0.001	0.001	0.0002	0.0002
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Across competition	0.00002	−0.00056	0.00002	−0.00056	−0.00013	−0.00022
	0.959	0.122	0.962	0.121	0.357	0.112
L1.Δ Unitised km	4.92	0.01	4.92	0.01	0.21	0.004
	0.000	0.285	0.000	0.291	0.000	0.381
L1.Δ Unitised km × NRKW	−0.12	4.79	−0.12	4.79	0.07	0.27
	0.000	0.000	0.000	0.000	0.038	0.000
Δ Unitised km			0.01	0.02	4.89	0.01
			0.862	0.146	0.000	0.106
Δ Unitised km × NRKW			0.10	0.08	−0.10	4.77
			0.008	0.000	0.001	0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571	12571	12571
F-test	F(15,12420)	F(15, 12420)	F(16,12418)	F(16,12418)	F(16,12418)	F(16,12418)
F statistics	1430915.09	415760.88	64738.89	150716.71	1124711.57	165138.16
	0.000	0.000	0.000	0.000	0.000	0.000
R^2	0.85	0.86	0.85	0.86	0.85	0.85

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.

Table B.9: Instrumenting for noise-weighted distance in mortality regressions, first stage

	First stage of column I of Table B.7			
Outcome variable	Δ Distance weighted by noise	Δ Distance weighted by noise × J pod	Δ Distance weighted by noise × K pod	Δ Distance weighted by noise × L pod
Constant	0.04	−0.01	−0.01	−0.003
	0.272	0.335	0.290	0.709
Age	0.004	0.001	0.0002	0.0021
	0.000	0.303	0.574	0.076
Age^2	−0.0001	−0.00003	0.00001	−0.00008
	0.007	0.281	0.427	0.065
Age^3	1.19E-06	4.24E-07	-2.33E-07	9.95E-07
	0.085	0.253	0.212	0.050
Age^4	-3.79E-09	-2.19E-09	1.61E-09	-4.17E-09
	0.288	0.217	0.213	0.032
NRKW	−0.05	0.01	0.01	0.01
	0.090	0.266	0.274	0.564
L1.Salmon abundance	−0.02	−0.002	−0.0003	−0.0012
	0.000	0.327	0.364	0.317
L1.Within competition	0.0002	−0.00001	−0.00001	−0.00003
	0.000	0.373	0.381	0.352
L1.Across competition	−0.0001	0.00003	0.00003	0.00005
	0.443	0.277	0.271	0.104
Δ Unitised km	4.78	0.001	0.0004	0.0015
	0.000	0.328	0.345	0.315
Δ Unitised km × J pod	0.04	4.81	−0.001	0.0004
	0.029	0.000	0.246	0.567
Δ Unitised km × K pod	0.07	−0.002	4.85	−0.01
	0.000	0.262	0.000	0.124
Δ Unitised km × L pod	0.14	−0.001	−0.001	4.913
	0.000	0.304	0.270	0.000
Matriline FE	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571
F-test	F(15,12418)	F(15,12418)	F(15,12418)	F(15,12418)
F statistics	984.02	6.30E+07	69.02	122031.06
	0.000	0.000	0.000	0.000
R^2	0.85	0.87	0.87	0.86

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.

Table B.10: Instrumenting for noise-weighted distance in mortality regressions, first stage

	First stage of column IV of Table B.7		First stage of column V of Table B.7			
Outcome variable	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × NRKW	L1.Δ Distance weighted by noise	L1.Δ Distance weighted by noise × NRKW	Δ Distance weighted by noise	Δ Distance weighted by noise × NRKW
Constant	−0.008	0.129	−0.004	0.13	0.03	0.06
	0.953	0.300	0.975	0.287	0.463	0.206
Age	0.005	0.003	0.005	0.003	0.004	0.001
	0.023	0.093	0.023	0.090	0.001	0.181
Age^2	−0.0001	−0.0001	−0.0001	−0.0001	−0.0001	0.0000
	0.051	0.128	0.049	0.123	0.017	0.486
Age^3	9.13E-07	5.22E-07	9.28E-07	5.35E-07	1.09E-06	-2.17E-08
	0.268	0.404	0.262	0.395	0.176	0.960
Age^4	-6.46E-10	-2.06E-10	-6.90E-10	-2.45E-10	-2.77E-09	1.30E-09
	0.878	0.953	0.871	0.945	0.505	0.582
NRKW	−0.13	−0.21	−0.12	−0.21	−0.05	−0.09
	0.159	0.009	0.159	0.009	0.114	0.003
L1.Salmon abundance	−0.02	−0.02	−0.02	−0.03	−0.02	−0.02
	0.042	0.003	0.031	0.002	0.000	0.000
L1.Within competition	0.001	0.001	0.001	0.001	0.0003	0.0003
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Across competition	0.00007	−0.00062	0.00006	−0.00062	−0.00010	−0.00024
	0.877	0.121	0.885	0.121	0.509	0.110
L1.Δ Unitised km	5.81	0.01	5.81	0.01	0.27	0.004
	0.000	0.296	0.000	0.305	0.000	0.425
L1.Δ Unitised km × NRKW	−0.14	5.65	−0.14	5.65	0.08	0.34
	0.000	0.000	0.000	0.000	0.043	0.000
Δ Unitised km			0.03	0.02	5.77	0.01
			0.463	0.145	0.000	0.108
Δ Unitised km × NRKW			0.11	0.12	−0.12	5.64
			0.006	0.000	0.001	0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571	12571	12571
F-test	F(15,12420)	F(15,12420)	F(16,12418)	F(16,12418)	F(16,12418)	F(16,12418)
F statistics	1666860.98	453557.12	2213792.35	353242.5	1182310.39	162694.21
	0.000	0.000	0.000	0.000	0.000	0.000
R^2	0.87	0.87	0.87	0.87	0.87	0.87

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.

Table B.11: Instrumenting for noise-weighted distance in mortality regressions, first stage

	First stage of column VI of Table B.7			
Outcome variable	Δ Distance weighted by noise	Δ Distance weighted by noise × J pod	Δ Distance weighted by noise × K pod	Δ Distance weighted by noise × L pod
Constant	0.04	−0.01	−0.01	−0.01
	0.396	0.310	0.296	0.667
Age	0.004	0.001	0.0002	0.002
	0.000	0.308	0.582	0.073
Age^2	−0.0001	−0.00003	0.00001	−0.0001
	0.007	0.293	0.431	0.059
Age^3	1.26E-06	4.41E-07	-2.60E-07	1.08E-06
	0.088	0.271	0.196	0.040
Age^4	-3.84E-09	-2.24E-09	1.76E-09	-4.53E-09
	0.303	0.239	0.195	0.020
NRKW	−0.05	0.01	0.01	0.01
	0.082	0.272	0.281	0.629
L1.Salmon abundance	−0.03	−0.002	0.000	−0.002
	0.000	0.330	0.362	0.323
L1.Within competition	0.0003	−0.00001	−0.00001	−0.00003
	0.000	0.381	0.385	0.355
L1.Across competition	−0.0001	0.00005	0.00005	0.0001
	0.634	0.283	0.280	0.099
Δ Unitised km	5.65	0.001	0.0005	0.002
	0.000	0.326	0.340	0.311
Δ Unitised km × J pod	0.05	5.68	−0.002	−0.0002
	0.030	0.000	0.257	0.853
Δ Unitised km × K pod	0.08	−0.003	5.72	−0.01
	0.000	0.272	0.000	0.117
Δ Unitised km × L pod	0.16	−0.002	−0.002	5.80
	0.000	0.300	0.274	0.000
Matriline FE	Yes	Yes	Yes	Yes
NRKW × Age	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571
F-test	F(15,12418)	F(15,12418)	F(15,12418)	F(15,12418)
F statistics	9684.77	3.38E+07	149.540	107886.44
	0.000	0.000	0.000	0.000
R^2	0.86	0.88	0.88	0.88

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.

C Evidence for a Slow-Motion Extinction

There is of course an entire literature examining the conditions for extinction in both biology and economics. Most of this work examines the likelihood of extinction based on biological characteristics, market fundamentals, and various forms of uncertainty.[68] My approach here is to use a simple application of economic demography informed by specific biological features of killer whales. To do so, I shift my focus away from individual whale fecundity and mortality to focus on cohorts of whales; specifically cohorts of female whales. For many marine mammals, and KW in particular, the ratio of mature males to females in the population is of negligible importance to reproduction. KW exhibit sexual dimorphism (the sexes are very unequal in sizes), which leads to only a few large males breeding. This allows me to ignore the evolution of the male population entirely, and focus my attention on the total fertility rate (TFR) of female whales in a cohort. A key observation is that, for a given sex ratio at birth of 50-50, if female whale total fertility rate falls below 2 - and remains there - then extinction is inevitable.[69] This extinction is likely to be a slow-motion march to oblivion given killer whales' very long time to maturation and then senescence.

A second key observation is that a cohort's total fertility rate neatly sums up all of the separate impacts of changing salmon availability, increased vessel noise, and perhaps even reduced genetic variability, on *both* births and deaths. For example, a shock lowering the fertility of individual whales lowers the TFR of all females in a given cohort directly; similarly, a shock raising individual whale mortality reduces the number of reproductive females remaining in a cohort, again lowering cohort TFR (because either female whales do not reach sexual maturity or they die before the end of their reproductive lifespan).

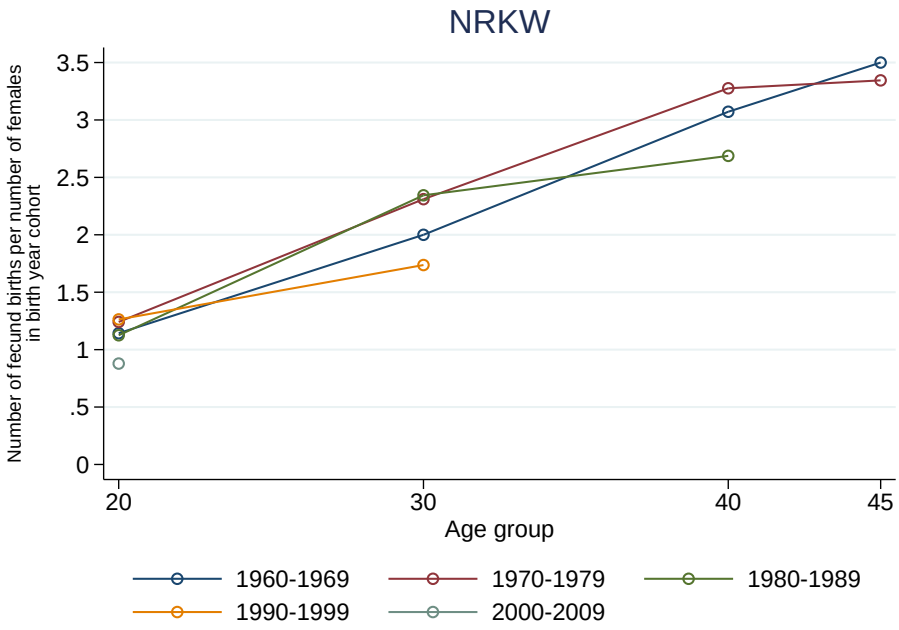
It proves useful to consider a healthy population to fix ideas; therefore, in Figure C.1 below I plot the cumulative number of surviving-to-one-year births (fecund births) per female whale in five

[68] See for example Purvis et al. (2000) in biology and the classic work in economics by Vernon Smith (1975).

[69] Recent work on the SRKW population has found that only two existing males are responsible for over 50% of recent offspring. There is also some evidence from SRKW births in the last 20 years, that the sex ratio at birth has been skewed towards males making extinction even more likely.

NRKW cohorts. The whales are grouped into ten year birth cohorts from 1960 to 2009. Members of the 1980 cohort have just reached an age of 40; the 1990 cohort only 30 and so on. As shown, the 1960 and 1970 cohorts' total lifetime fertility, or their TFR, is close to 3.5 whales. This is of course well above replacement fertility of 2.0 and indicates a healthy and growing population. These two early cohorts also seem quite similar, while the remaining three appear somewhat different.

Figure C.1: Female NRKW Cohorts



In relation to the first two cohorts, the 1980 cohort has reduced fertility over the last ten years of their reproductive life. This is also true for the 1990 cohort and for the 2000 cohort. This suggests the pattern of reduced total fertility is not a pure cohort effect. To understand why, suppose that over time the increased leaching of PCBs and other organic chemicals into the Salish Sea were driving births down and deaths up. In this case, we would expect cumulative fertility at all ages to be lower with each cohort now being exposed to an increasingly polluted sea. A similar result would hold if there was a long run reduction in salmon availability.

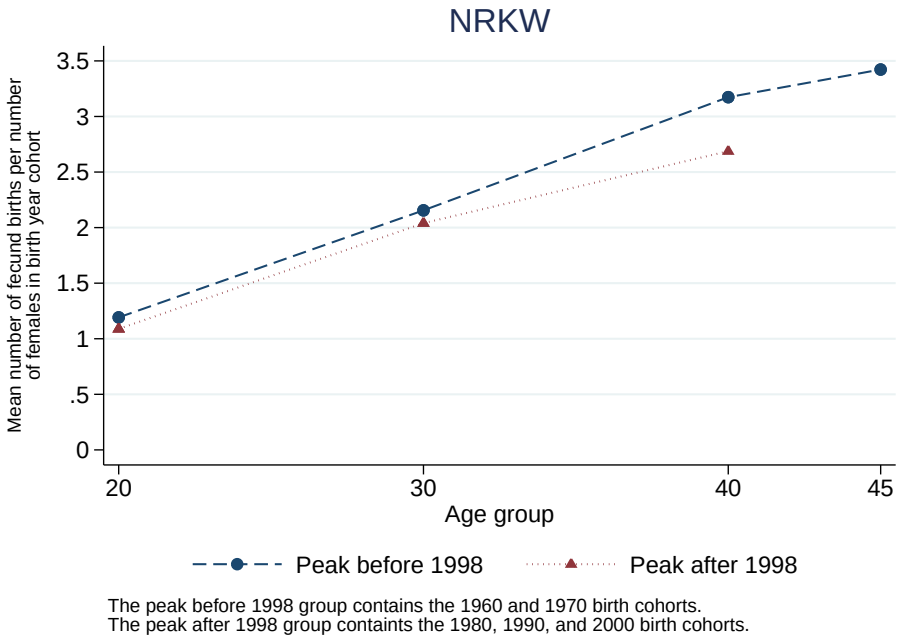
Instead what the figure shows is that the lowered fertility periods are all post 1998, and this

suggests a cohort x period explanation: those whales who reached their peak fertility years, ages 20-30, prior to the large change in vessel disturbance have an unaltered fertility profile; those that reached their peak after, suffer its long term effects. For example, the 2000 cohort has spent all of its (reproductive) lifetime with greater vessel traffic; the 1990 cohort only 2/3; and the 1980 cohort only 1/2. Each has reduced fertility, but interestingly only the fertility of the 1990 and 2000 cohort fertility are significantly different from earlier cohorts.

With these results in mind, consider an alternative grouping of whales to highlight the cohort $\times$ period explanation. In Figure C.2 I divide the whales into two groups: those that reached their peak fertility age of 20 before 1998, and those that reached peak fertility after 1998. The red line now gives the total fertility per whale for a whale reaching age 20 and beyond regardless of their specific birth age cohort. As shown, the two cohorts now differ only slightly but regularly, with the post-1998 cohort having slightly lower fertility at all ages. Importantly, by age 40 even the post-1998 group exhibits total fertility well above replacement. Therefore, it appears the sum total of changing salmon availability and increased vessel disturbance has had only a relatively small effect on NRKW fertility, and has had no effect on their long term viability.[70] This is of course entirely consistent with the estimates I provided earlier on the strong conjecture.

[70] In fact, there is no statistically significant difference between the cumulative fertility across the two groups at any age in the figure.

Figure C.2: Female NRKW Synthetic Cohorts



In Figure C.3 below I now redo this analysis using the same age cohorts for the SRKW population.

Figure C.3: Female SRKW Cohorts



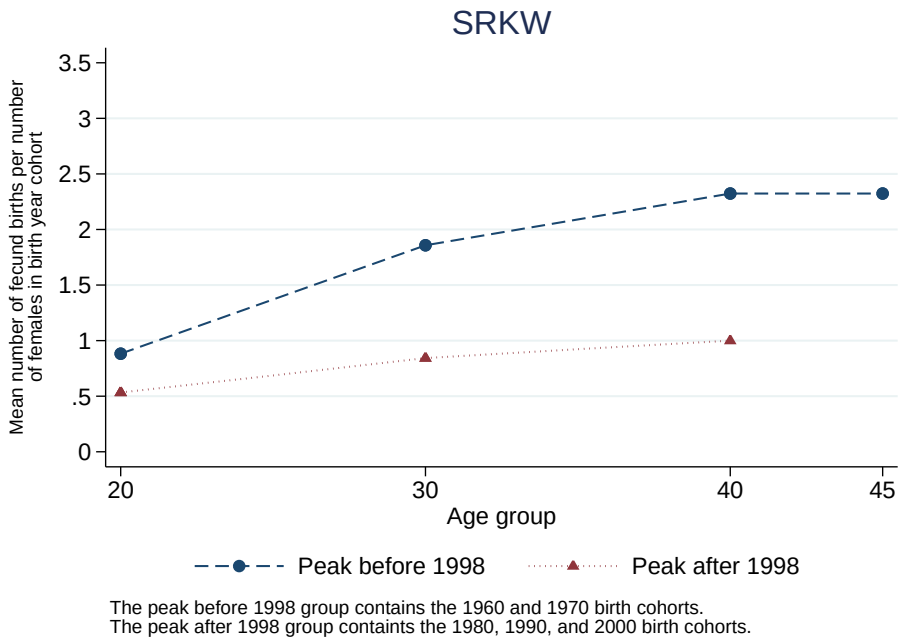
The two earliest cohorts now exhibit somewhat different profiles. The 1970 cohort exhibits higher fecundity at later ages in contrast to the 1960 cohort. It is very tempting to attribute the reduced fertility of the 1960s cohort to the live capture industry. The 1960 cohort would have been subject to the capture industry and associated harassment for the first 20 years of life; whereas the 1970s cohort less so.[71]. Whatever the reason, there are broad similarities and in fact these two cohorts are statistically indistinguishable from one another at all ages. Both cohorts show rising fertility with age and reproduction rates at or exceeding replacement levels. But now consider the remain three cohorts. The 1980s cohort shows no reduction in fertility at age 20, but a severely reduced continuing fertility at all later ages (and these differences are statistically significant). The 1990s cohort has low age 20 fertility and continuing low fertility at 30. The latest 2000 cohort seems, if anything, in worse shape than its recent predecessors. Its age 20 fertility is significantly

[71]The very first whale "Moby Doll" was captured in 1964; and the last in 1977; in total, 68 whales were taken primarily from the SRKW. Several, or perhaps many others, died in the capture process. For an excellent, even handed, and very interesting account of the personalities behind the capture industry and its evolution see Colby (2018)

different from all but the reduced fertility of the 1990 cohort.

Again the figure suggests an alternative grouping based on pre and post 1998 observations, and hence I now provide the same calculations for the two synthetic pre and post SRKW cohorts. This is shown in Figure C.4 below.

Figure C.4: Female SRKW Synthetic Cohorts

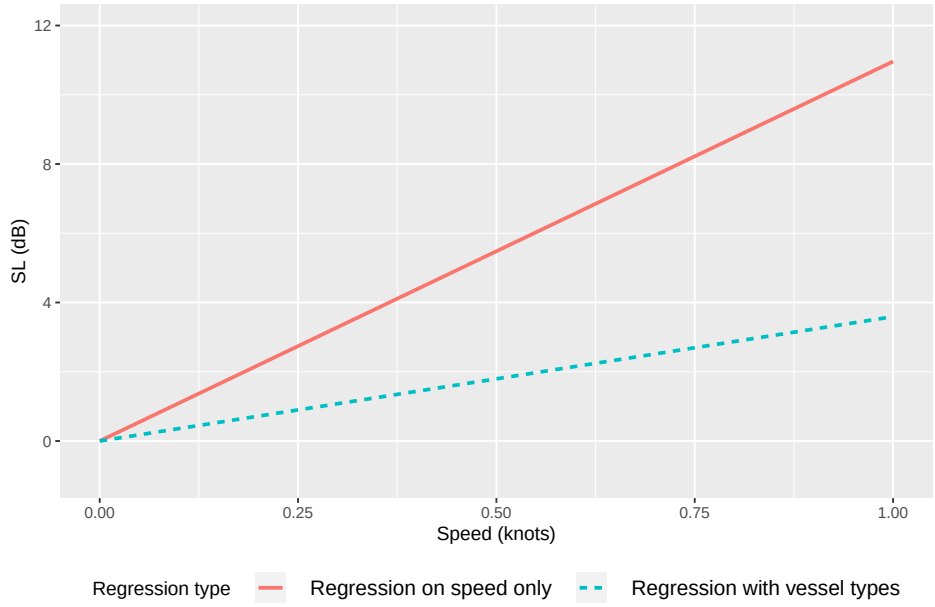


In the pre-1998 period, total fertility is above replacement near 2.5 whales per female by the end their reproductive lives. In contrast, the post-1998 synthetic cohort exhibits very low fertility. By age 40 this cohort is producing only one whale per member which is, of course, well below replacement. The differences at age 30 and 40 are significantly different from the pre-98 cohort. The conclusion is now painfully obvious: the total fertility profile for SRKW cohorts reaching peak fertility before 1998 has shifted downwards post 1998; the post 1998 cohort exhibits a total fertility rate well below the minimum replacement of 2; and the SRKW population is on a slow-motion path to extinction.

To understand why this result is novel, in Figure C.5 below we have plotted our data's speed and

SL noise relationship in two different circumstances. One simply estimates a bivariate relationship with no controls for vessel class; the other uses our estimates from Table A.12 to generate the slope of the relationship.[72] It is clear that not accounting for vessel class leads to a severe over-estimate of the speed noise relationship. The coefficient on $\log_{10}(\text{speed})$ is 25.24 in the bivariate regression, which implies the 20% reduction in speed considered above, would now be predicted to lower SL by (25.24/2.3)·.2 = 2.19 or a little over 2 dB! The reason is simple OVB. The noisiest vessel, independent of speed is container ships, but they are also the fastest. Not accounting for this correlation can lead to the incorrect conclusion that vessel speed has a stronger relationship to SL noise than otherwise.

Figure C.5: Omitted Variable Bias



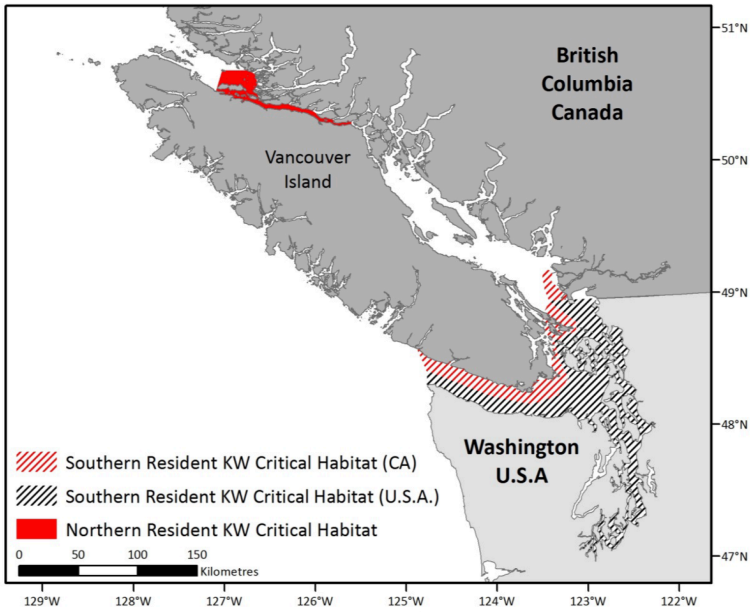
C.I Disturbance to the NRKW Critical Habitat

Figure C.6 below is a map of the area originally designated as critical habitat for the NRKW. A discussed earlier a subsequent expansion occurred late in 2018, but here I focus on the original

[72] In the resulting regression the constant is 144.61 and the slope on $\log_{10}(\text{speed})$ is 25.24.

designation highlighted in solid red. The area shown is part of the inside passage and starts soon after the end of Discovery Passage (at Blind Channel to be precise), which connects the Strait of Georgia with Johnstone Strait. The NRKW critical habitat is contained wholely in Johnstone Strait and ends just north of Malcolm Island. The entire length of the CH is approximately 110 km with its only port, Port McNeil, being 10 km from the northern boundary.

Figure C.6: NRKW in Context



I ignored this component of KW habitat thus far because there is very little large-sized commercial traffic traversing this part of the inside passage. There is only one port in the habitat itself - Port McNeil, and only one port nearby - Port Hardy. Both are small port towns primarily servicing the tourism and fishing industries. Port Hardy is however the terminus for a government operated ferry that runs north to Prince Rupert and Bella Coola, but the ferry route does not traverse critical habitat. More importantly, Port McNeill contains a large commercial gravel pit operation engaged in international trade. Their combined population is less than 8,000, and this of course stands in

stark contrast to the over 7 million individuals living on the edge of the Salish Sea.

Information obtained from Sea routes, indicates that large commercial vessels do not travel up the inside passage to Port McNeil. Some cruise ship companies do offer cruises through this portion of the inside passage to Alaska, but this is not the most common route. Most cruises travel on the Pacific side of Vancouver Island, simultaneously avoiding Seymour Narrows and the necessity of using Canadian pilots onboard. Nevertheless, there is some commercial Bulk vessels going into Port McNeil over the sample period. By combining data from Lloyd's and from pilotage records from the Pacific Pilotage Authority from 2008 onwards, I have developed a measure of total km traversed by these vessels for every year. Accordingly, in Table X below I present an augmented Table 5 which includes the NRKW km in all specifications. Several observations are in order.

Table C.1: The Impact of Salmon Abundance on Fertility

	I.	II.	III.	IV.	V.	VI.
Constant	-24.27^{***}	-24.39^{***}	-24.76^{***}	-24.58^{***}	-24.47^{***}	-24.35^{***}
	(3.31)	(3.31)	(3.27)	(3.29)	(3.33)	(3.35)
Age	3.95^{***}	3.95^{***}	4.00^{***}	3.97^{***}	3.96^{***}	3.94^{***}
	(0.66)	(0.66)	(0.65)	(0.65)	(0.66)	(0.67)
Age^2	-0.24^{***}	-0.24^{***}	-0.24^{***}	-0.24^{***}	-0.24^{***}	-0.24^{***}
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.05)
Age^3	0.01^{***}	0.01^{***}	0.01^{***}	0.01^{***}	0.01^{***}	0.01^{***}
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Age^4	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}	-0.0001^{***}
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
L1.Depletion	-0.005^{**}	-0.004^{**}	-0.004^{**}	-0.004^{**}	-0.004^{**}	-0.004^{**}
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
L1.Total Unitised km	-0.84^{***}	-0.82^{***}	-0.73^{***}	-0.77^{***}	-0.80^{***}	0.54^{**}
	(0.06)	(0.06)	(0.09)	(0.12)	(0.07)	(0.24)
L1.Total Unitised km × NRKW	1.39^{***}	1.36^{***}	1.24^{***}	1.30^{***}	1.34^{***}	
	(0.25)	(0.25)	(0.30)	(0.32)	(0.25)	
L1.SEAK Abundance	0.22^{**}			-0.01		
	(0.09)			(0.81)		
L1.NBC Abundance		0.29^{***}		0.20		
		(0.11)		(1.17)		
L1.WCVI Abundance			0.41^{*}	0.19		
			(0.22)	(0.49)		
L1.Salmon Abundance					0.34^{***}	0.32^{***}
					(0.11)	(0.12)
L1.Salmon Abundance × NRKW					-0.02	
					(0.19)	
L1.Total Unitised km × J pod						-1.27^{***}
						(0.25)
L1.Total Unitised km × K pod						-1.40^{***}
						(0.27)
L1.Total Unitised km × L pod						-1.39^{***}
						(0.27)
NRKW & NRKW × Age		Yes	Yes	Yes	Yes	Yes
N	5,707	5,707	5,707	5,707	5,707	5,707
Log likelihood	-1404.5411	-1404.3142	-1404.4071	-1404.1991	-1404.2712	-1404.1563

Standard errors are clustered at the pod level and appear in parentheses. $^{***}: p < 0.01$, $^{**}: p < 0.05$, $^{*}: p < 0.1$

Distances are measured in million km. N records the number of female-whale-years

C.II Evaluation of the Vessel In-Vessel Out assumption

The accuracy of this measurement of missing outgoing foreign trips depends on two assumptions. First, the vessel in/vessel out assumption is a budget constraint on ship movements, and like any

other empirically measured budget constraint, it is unlikely to hold perfectly over short time periods. If one vessel lands late in year t and exits in year $t+1$ to a domestic port, then foreign exits in year t will be overestimated because we require landings to match exits year by year. In year $t+1$, foreign exits will be underestimated by one because there is an exit to a domestic port with no accompanying landing in that year. Similarly, if one vessel lands late in year t and exits in year $t+1$ to a foreign port, then foreign exits in year t will be overestimated by one and underestimated by one in year $t+1$. In both cases, the errors to either foreign or domestic outgoing will cancel if we aggregate over t and $t+1$. Since the frequency of the data is monthly, this seems like a small concern.

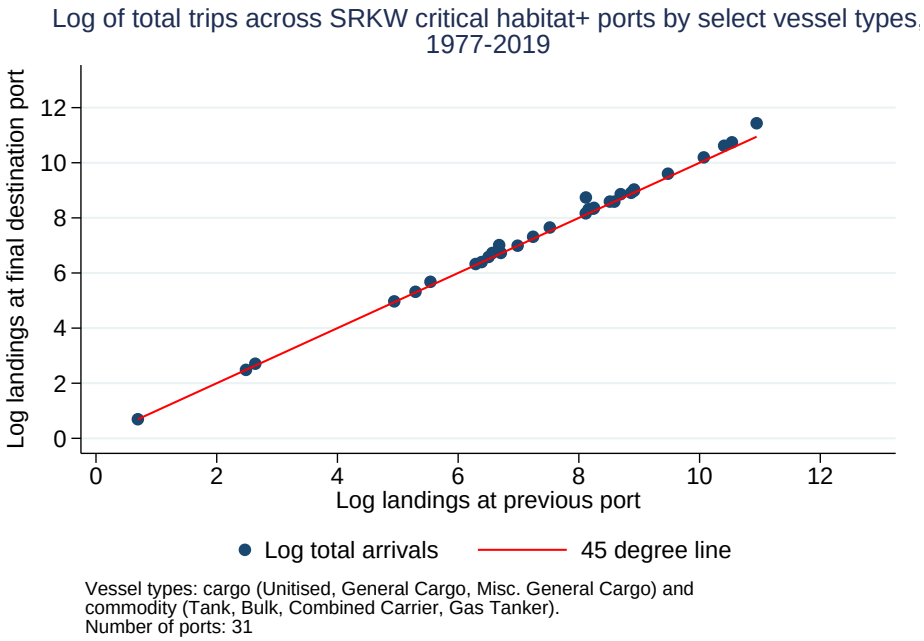
Second, the construction relied on an accurate measurement of vessels entering and leaving the CH. The data contains some landing entries where the previous port is not recorded, and these entries can create errors in my measure of incoming, within, and outgoing trips. These missing entries are however relatively small, and it is easy to examine both their size and distribution across both ports and time to allay any concerns that their absence may be pivotal. Similarly, vessels could enter or leave undetected, but since my focus is on larger vessel categories such as Bulk, Unitised, etc. and not the much smaller tugs, fishing boats, passenger, etc., this also seems a minor concern.

As a check on the method, we can add up all landings to any specific set of ports over t, and compare these to exits over t. A landing is captured by the current port designation in the data (VL_t); exits from ports are captured by the previous port designation OD_t. A positive difference between current port and previous port designations imply the existence of positive OF_t in (**??**). A negative value would indicate a problem of missing or mis-measured trips and/or a failure of the vessel in/vessel out assumption.

In Figure C.7 and C.8 below, current vs. previous port landings are compared for the set of 31 CH ports. Figure C.7 plots on a log scale the trip pair (VL_t, OD_t) made by all large commercial vessels. The trips are aggregated over 1977-2019 to minimize carry over errors. The red 45° line identifies any port where current landings exactly equal previous port landings. The log scale is useful here is showing the strong positive relationship, consistent with the vessel in/vessel out

assumption, holds for ports of all sizes.

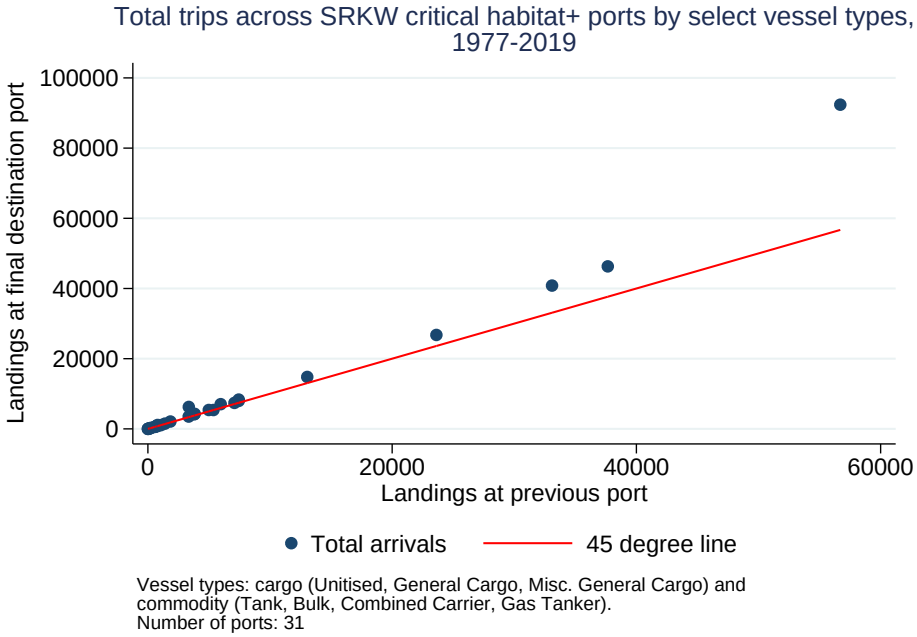
Figure C.7:



The log scale, however, also hides other interesting features and Figure C.8 presents the same data without the log scale. It is now easy to see that all deviations from the 45° line are weakly positive. These positive deviations are positively correlated with port activity implying foreign outgoing vessel traffic is far more important at larger ports. This is not surprising because there are a limited number of deep draft ports that can handle large foreign ships. Finally, its apparent that port sizes differ dramatically. There is a highly skewed distribution of traffic. The top four ports shown in the figure are Vancouver (CAN), Seattle, Tacoma, and the Fraser River port.[73] Since larger ports are likely to have their ship movements recorded more accurately (by terrestrial or AIS systems), this suggests measurement error may be less of a problem.

[73]The distributions of landings across all ports in the data looks similar to graphical depictions of the distribution of firm sizes or city sizes, and may well be approximately Pareto. A fuller investigation is left to future work.

Figure C.8: Evaluating the Vessel In and Out Assumption



C.III Variation in Vessel Types over Time

Overall the table suggests that not only has the vessel traffic on the West Coast grown tremendously over the period; its composition has shifted dramatically to foreign ocean-going vessel traffic.

Table C.2: Landings at all ports by commercial vessels, aggregated over two periods

	(1)	*(2)*	*(3)*	*(4)*
	1977-1997		1998-2019	
Vessel type	Landings	Share in total	Landings	Share in total
Bulk	95,590	29.4%	110,343	20.5%
Combined Carrier	811	0.2%	172	0.0%
Gas Tanker	1,088	0.3%	1,696	0.3%
General Cargo	52,050	16.0%	38,660	7.2%
Misc. General Cargo	24,934	7.7%	90,428	16.8%
Tank	69,782	21.5%	93,659	17.4%
Unitised	80,558	24.8%	203,699	37.8%
Total commercial	**324,813**	**100.0%**	**538,657**	**100.0%**

Table C.2 provides additional information on these landings by looking the variation in vessel types. Bulk vessels have fallen in importance over the two periods, as has tanker and tank traffic. In contrast, Unitised cargo in particular has grown from 25% to 38% with an increase in number of over 120,000 landings.

The new areas of critical habitat are on the southwest of Vancouver Island and the western Dixon entrance. These new zones came into effect December 19th, 2018. The southwest of Vancouver Island is used throughout the year by both NRKW and SRKW. The SRKW use this area during the summer when they make excursions into this area from their usual habitat, and in winter when the whales are mostly outside of their critical habitat. The NRKW frequent this area during the spring when they are out of their current critical habitat along Johnstone Strait. Acoustic measurements indicate RKW at Swiftsure banks one out of every three days at least. During May to September

the SRKW were found 43% of the time at Swiftsure, and previous work has found them in their typical habitat 80% of the time in the same May to September window, so when they aren't around Saturna or San Juan, they are out here on the banks. From November to May - the winter period, K and L pod range downt the coast to northern california and are found again in swiftsure banks. Where J pod goes, I don't know. NRKW were detected at swiftsure bank in ALL months of the year but especially in March and April. In their critical habitat on the inside passage they are found almost every day in the summer months, but less than 10% of the time in March and April. This seems to be most important for G Clan, but all pods have been found on swiftsure. So clearly they are eating the same fricking fish!!!

80% of the Chinook the RKW eat off of southwestern Vancouver island come from the Fraser River system. And 88% of the salmon they eat in this region is Chinook. The new habitat starts at the old one, goes west tracing out our exclusive economic zone until it hits 200 m depth and runs north to a point. It includes the area where 90% of the sightings/recordings were made for the SRKW, and a majority for the NRKW.