International Trade, Noise Pollution, and Killer Whales

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Abstract

Orcinus Orca is the world's largest predator, and simultaneously a significant tourist asset and cultural icon for much of the Pacific Northwest. In the past two decades, the Southern Resident Killer whale (SRKW) population has declined by more than 25 percent, putting them at risk of extinction. The cause of this decline is hotly debated. This paper employs novel data, an innovative noise pollution model, and quasi-experimental methods borrowed from environmental economics to solve this puzzle. We find consistent evidence that vessel noise pollution from international shipping has lowered fertility and raised the mortality of the SRKW significantly. Had noise pollution remained at its pre-1998 levels, the SRKW population would be 30% larger. Noise pollution is a growing threat to marine mammals worldwide.

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I Introduction

Orcinus Orca is 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 whales (SRKW) have declined by more than 25% and now appear 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 as yet no consensus as to the key driving forces behind their decline. 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.

This paper exploits several tools from economics to provide an answer to what ails the SRKW. We employ novel data, develop an innovative model of noise pollution dispersion, and employ quasi-experimental methods borrowed from environmental economics to provide what we think is a convincing answer. Vessel noise from increased international trade with Asia is the key factor driving the SRKW decline. If noise pollution had remained at its pre-1998 average, rather than grown by over 50% in the intervening years, our estimates suggest the SRKW population would be 30% higher than otherwise. This change would largely undo the last twenty-five years of population decline.

The paper makes several contributions. While noise pollution has long been known to negatively affect marine mammals, this study is the first to document a direct link between exposure to noise pollution and a population-level event - the birth and death rates of the SRKW. We find consistent evidence that noise pollution coming from commercial shipping, tied to growing international trade flows, has degraded their critical habitat, lowered their birth rates, and raised their death rates.

Previous work has found vessels disturb foraging, socializing, and resting behaviors implying an energetic cost to whales. It has however been very difficult for researchers to move from these individual-specific observations to their cumulative population-level impacts. 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.

Our ability to estimate the link between noise pollution and population size comes from a lucky happenstance: 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. Together, they provide us with a setting where killer whales are exposed to quasi-experimental variation in noise pollution.

We exploit this lucky happenstance by collecting over 40 years of very rich demographic data on KW births, deaths, and family history to establish a baseline understanding of what drives births and deaths. We combine this with a large database we constructed of more than 5 million commercial vessel landings across 121 ports along the West coast of North America. Using the methods developed in Taylor (2021*a*) we use this landings data to estimate the km traveled by large commercial ships in the SRKW critical habitat.[1] 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, rose from approximately 1.5 million km in 1977 to over 3.5 million in 2019. Since commercial vessels differ greatly in the noise they radiate, we then match these many vessel trips with their associated noise disturbance.

We then exploit quasi-experimental variation in our noise disturbance measure - driven by changes in economic activity in the U.S., Canada, and its Asian trading partners - to estimate the causal impact of vessel noise pollution on KW births and deaths. In essence, we compare birth and death outcomes for KW in noisy versus quiet years. The key empirical challenge we face is ensuring that our exogenous variation in noise pollution generates as good as random variation in KW exposure to noise pollution.

To do so we exploit methods often used by environmental economists to identify the impact of air pollution on human health outcomes and follow this literature by taking several steps to ensure that assignment to treatment (exposure) is as good as random.

Whales with poor (or very good) fitness may alter travel patterns and sort across locations to avoid the impacts of vessel disturbance making the intensity of exposure endogenous to KW health. To address this risk, we employ shocks to our noise disturbance measure rather than its level. The logic for doing so is simple - if mitigation actions take time to learn, are habit driven, or come about from slow-moving variation in overall fitness, then noise disturbance

[1] The methods described in Taylor (2021*a*) 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.

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.

Even if whales do not sort across locations, they may choose to avoid noise contemporaneously to lessen its impact. Avoidance by itself implies our estimates of causal effects may be underestimated since exposure is lessened by defensive actions. However, if the ability to avoid is tied to fitness, then exposure is again endogenous to health. Features of KW social structure make this threat unlikely. Individual killer whales travel closely with those in their matriline, and matrilines in turn tend to track their specific pod. This means that individual-level variation in fitness is unlikely to affect pod-level travel patterns and hence exposure.

In addition, we present data showing killer whales have very limited ability to avoid vessel noise. This is because the very same deep channels used by international shipping, and the very same river mouths leading to major ports, are also locations favored by their prey returning from the ocean to spawn. Therefore, avoidance or mitigation comes at a very steep cost, and as a result, conflict is inevitable (this is presented as fact #8 in section III).

Our data is an unbalanced panel capturing outcomes from a changing population; and we study whale-specific responses to variation in noise pollution in a given year, with these whales drawn from the then-current population. The characteristics of this population change over time, and therefore it is important to ensure that the distribution of noisy and quiet years is independent of changes in population characteristics that may be tied to fitness. For example, if all the noisy years occurred when the population was already under stress because of a lack of prey (or other reasons), our treatment and control groups are not comparable.

To address this concern we show that the distribution of noise shocks is independent of other important covariates determining fitness. Prey abundance, sex ratios, competitive pressures from other whales, and the population's average age are very similar across noisy vs. quiet years. This comparison suggests we are indeed making like-to-like comparisons in noisy versus quiet years. This comparison is however based on observables.

To ensure that other potentially important - but unobservable - determinants of fitness be they - genetic, environmental, related to specific travel patterns, or foraging success - are also comparable across years, we employ matriline fixed effects. Matrilines are comprised of very closely related whales who share genetics, but they also travel in very close proximity, share successful kills, and have common learned behaviors and language. Some of these features could affect both fitness and exposure; fortunately, most are also fixed and over time. As a result, matriline fixed effects should sweep away their influence.

This paper uses tools drawn from several fields of economics to provide, what we hope, is a convincing solution to an important puzzle - what is responsible for the precipitous decline of the Southern resident killer whales? Our methods are closely related to those exploited by quasi-experimental work in environmental economics linking pollution exposure to health outcomes. Two very useful reviews of this work are Graff Zivin and Neidell (2013) and Greenstone and Gayer (2009). Prominent similar work, such as Chay and Greenstone (2003), Currie et al. (2009), and Hanna and Oliva (2015), all employ a similar pollution shock research design. Schlenker and Walker (2016) also relies on pollution shocks but in addition contains an explicit model of pollution dispersion and exposure, which is similar in spirit and purpose to the sound exposure model we develop. This literature has been very influential and the substantial health costs of pollution are now well documented (Fuller et al., 2022).

The paper also bears a family resemblance to earlier work on Malthusian population dynamics. An increase in vessel noise degrades the acoustic environment making hunting, socializing, and foraging less productive. To an economist, this is technological regress. Not surprisingly it has short to medium-run consequences for births and deaths for any population whose fitness drives reproduction. In this sense, crop failures and weather shocks influenced early modern European populations much like vessel noise shocks influence the population of killer whales today.[2]

While economics can be a powerful lever, this paper owes its existence to the hundreds of researchers, academic and otherwise, who collected and collated the many sources of data needed. The data comes from four sources. First, we acquired a complete inventory of all Southern and Northern resident whales starting from the very first exploratory whale census in the 1970s, through to the latest figures up 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.

Second, we obtained a series of salmon abundance measures from the Pacific Salmon Commission. The Commission's Chinook Technical Committee collects data from thirty indicator stocks, each distinguished by their spawning location and in some cases by the age of fish considered. These stock measures are then aggregated to produce abundance measures that we employ.[3]

[2]Influential work in this vein includes Ashraf and Galor (2011) and Lagerlöf (2015).

[3]See Section A.X in the appendix for details on the abundance measures and our use of them.

Third, we obtained 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*a*)). 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.

Fourth, there are only a 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). Both studies collect ship sounds with the help of a seafloor-mounted hydrophone. They combine these readings with information about the ship's passage from AIS to calculate the noise radiated at the source level, SL, in decibels.[4] 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 cases, vessels were tracked opportunistically, and therefore selection into the samples was randomly determined.

While there are literally hundreds of articles discussing the conservation, reproduction, and protection of killer whales, there have been relatively few studies examining population-level events empirically. 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 to the extent that we condition on salmon abundance and adopt the

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

same discrete choice framework favored by natural scientists. It is unique in every other way - in terms of our research design which focuses on the identification of a causal impact, our construction and use of a new noise disturbance measure, our use of a Malthusian framework to guide estimation and provide counterfactuals, our treatment of within and across population competition for prey, and by the sheer length of our sample period.

Our work is also a contribution to the large and growing literature examining the environmental consequences of international trade (See Copeland, Shapiro and Taylor (2022)). The closest connection is to the small set of studies linking the international transport of goods to carbon emissions. Cristea et al. (2013) was the first to document trade and transport emissions, with valuable subsequent work by Shapiro (2016). This paper is related to these earlier contributions in the sense that vessel noise, just like carbon emissions, are an unintended consequence of commercial shipping. Vessel noise is now thought to be a major form of underwater pollution that can affect all types of marine life, especially marine mammals.

Finally, this paper is related to earlier work by one of us. Taylor (2021*a*) develops the method for calculating km traveled in the critical habitat from landings data. It presents summary statistics and conjectures that vessel disturbance is driving the SRKW to extinction. Parts of Taylor (2021*b*) were cannibalized to produce Taylor (2021*a*); other elements were refined and significantly extended (after input from seminar audiences) to be included here. The research design, sound exposure model, econometric results and Malthusian resource model, etc. are all novel to this paper. In a companion paper in process, we use the estimates developed here to create a market for pricing ocean noise disturbances. We argue this market-based solution is relatively easy to implement given today's satellite tracking of vessels via the Automated Identification System (AIS). As a result, the methods we develop here could be employed to measure and then inform policies to lower noise disturbance elsewhere.[5]

The rest of the paper proceeds as follows. Section II presents a short history and relevant biology of KW with a focus on the SRKW. In section III, we turn to eight facts drawn from our data. These facts allow us to frame our argument while introducing data sources. We develop our research design in section IV. Our empirical implementation then follows. A short conclusion ends the paper. All lengthy calculations, plus considerable detail on our methods and data is contained in our Appendix A which is available online.

[5] In the United States alone, there are 30 marine mammals in the Cetacean (whale and dolphin family) listed under either the Endangered Species Act (ESA) as endangered or threatened, or depleted under the Marine Mammal Protection Act (MMPA). Worldwide this number grows to 124 cetacean populations under threat. See https://iucn-csg.org/status-of-the-worlds-cetaceans/. Noise disturbance is a potential cause in many of these cases.

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 easily 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.[6] Not surprisingly, KW were often shot by fishermen, boaters, and sometimes by the US airforce.[7] 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.[8]

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.

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 Appendix A.I.

Our detailed knowledge of the 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-*

[6] 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."

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

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

types of killer whales defined by their ecological niche. 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 both 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 of very young whales yet to be recorded. 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.[9] 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.[10]

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

[9] 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.

[10] 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.

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 destined 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. Consequently, these paths are either very close to or on top of, international shipping lanes. This means any attempt to avoid 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 dim to very dark deep water ($\geq$10 m depth); 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).[11] 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.[12] Therefore, we allow for vessel-specific noise

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

[12] 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.

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.[13]

III Eight Facts to Frame our Argument

We start by presenting eight facts that frame our argument. They are with one exception descriptive statistics. Together they provide suggestive evidence of a link between noise pollution and the decline of the SRKW population.[14]

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.[15] In this paper, we employ the original designations of CH. By definition, critical habitat should

[13]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).

[14]Three of these facts also appear in Taylor (2021*a*).

[15]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.

"include sufficient quantity and quality of prey species, particularly Chinook Salmon, water of a sufficient level so as not to 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*a*) 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 Appendix A.II). While several of these ports are very small and never host large commercial vessels, the Port of Vancouver is Canada's biggest 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.

III.II The Growth in Vessel Traffic is Huge

We now ask 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

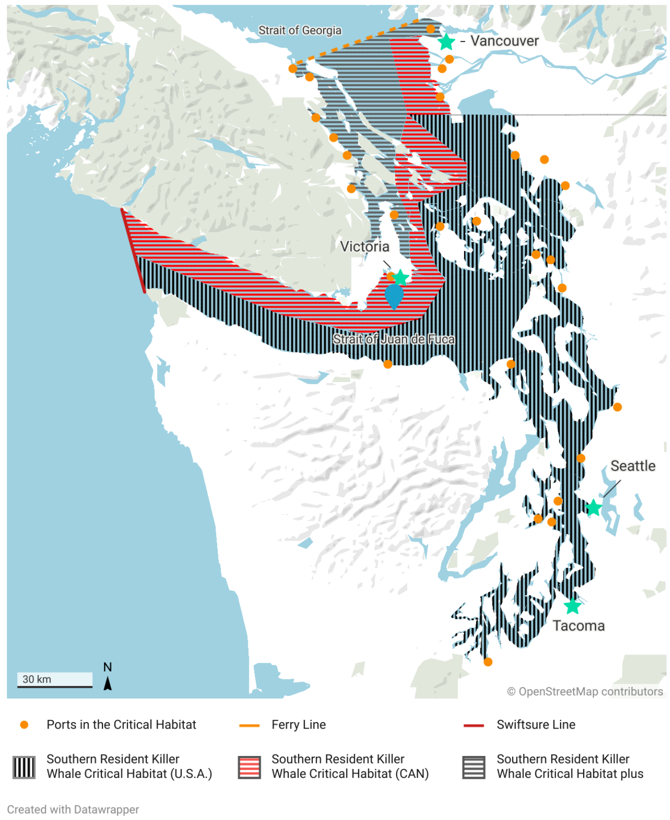

Figure 1: Designated critical habitats for Southern Resident Killer Whales

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.[16]

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

[16]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.

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 then 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 vessel trips to international markets outside of North America.[17]

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.[18]

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%**

[17] 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.

[18] This table also appears as Table 2 in Taylor (2021*a*).

Three things are evident from the table. First, the two most common large vessels are Bulk vessels and Unitised (container ships). Together they account for a little over 60% of all vessel landings in both periods. Second, in absolute terms 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! In percentage terms, 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.

Together facts one and two tell us 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. Since Container ships are the *sine qua non* of international trade, this final observation is not surprising.

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

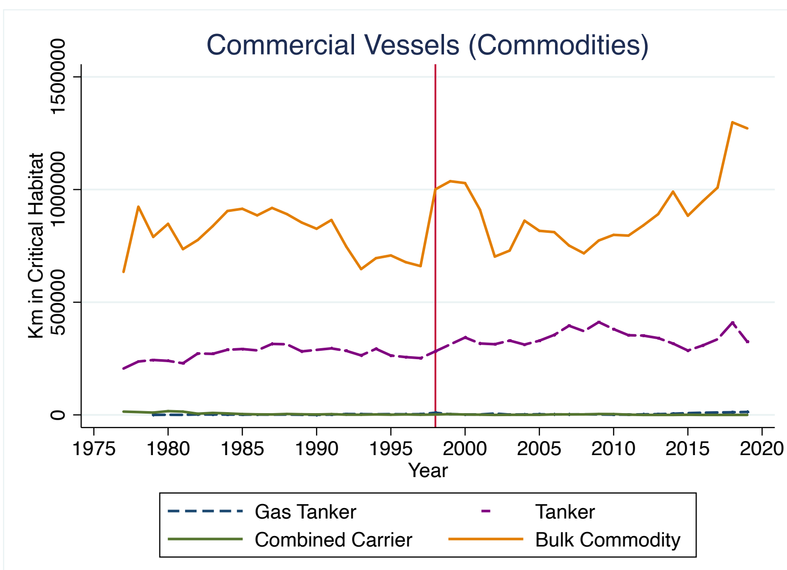

Figure 2: Vessel Km in Critical Habitat by commodities vessels

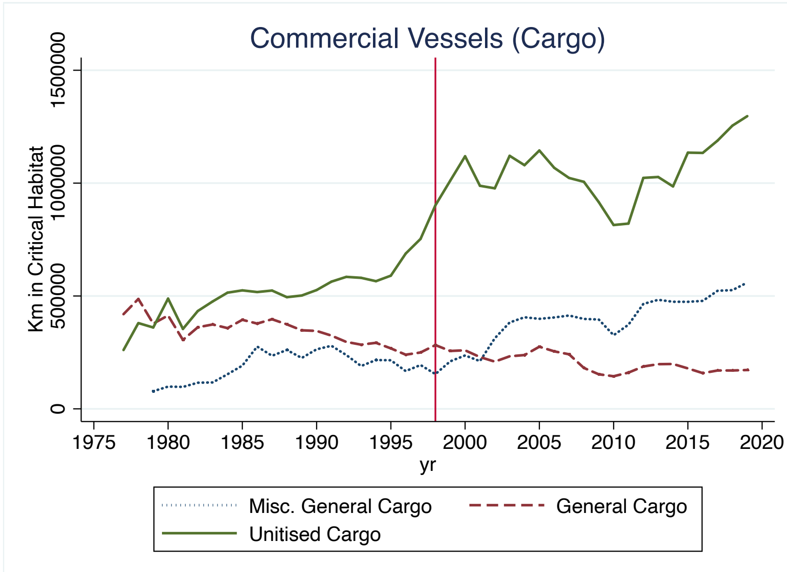

Figure 3: Vessel Km in Critical Habitat by cargo vessels

To generate our third fact we employ the *Vessel Arithmetic* developed in Taylor (2021*a*) 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.[19] 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 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

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

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.[20]

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 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.[21]

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

[20]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.

[21]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.

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 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.[22] 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 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

[22] 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

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

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).[23] Figure 4 plots these indices over the sample period.

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

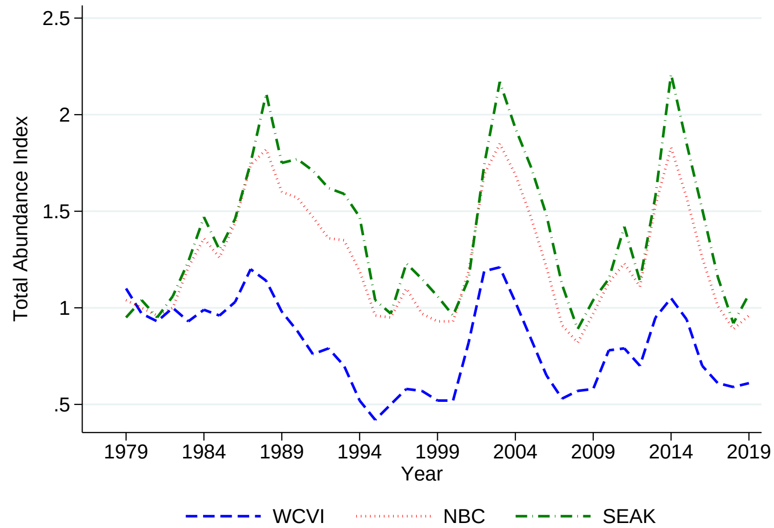

Figure 4: Total abundance indexes of the three AABM fisheries

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.[24]

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.[25] Z-scores calculated from these three indices have very high (> .9) pair-wise correlations. This means, in effect, there is really one salmon abundance index and not three. Consequently, we aggregate these

[24]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.

[25]Although abundance appears to be higher for the two northern fisheries, this may be a feature of setting the base to one in 1979 for all series. Suppose all indices were pretty well the same, but differed by random error. If 1979 was a relatively poor year for SEAK and NBC stocks, but not for WCVI then benchmarking to 1979 can create this pattern.

indices into one overall salmon abundance measure for our empirical work.

To us, the key feature of the figure is not one of trend decline or growth - it 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.[26] 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 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 appendix).

[26] A credible 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 start of the very first census in the early 1970s.

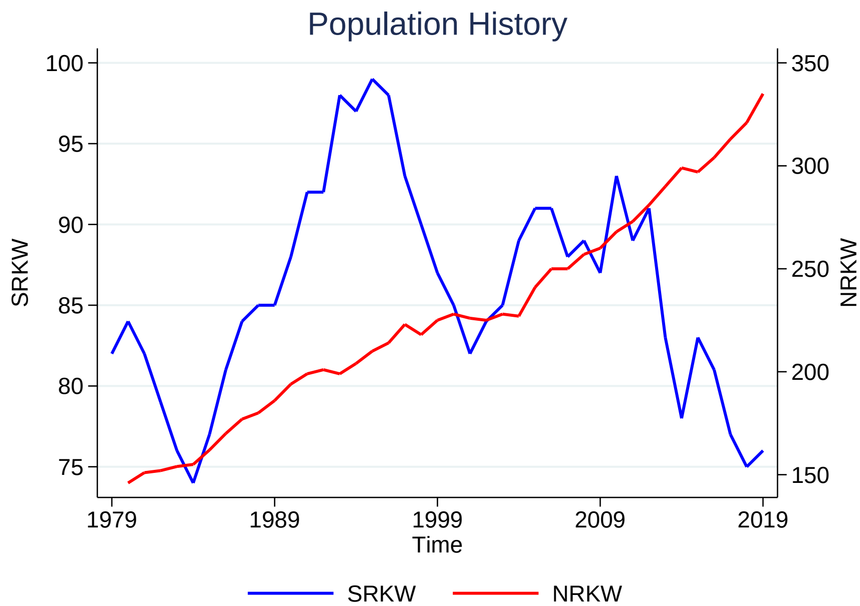

Figure 5: A Tumultuous History

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.[27] Consequently, our seventh fact is that the SRKW population decline is unique amongst KW populations on the West Coast.

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

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.[28] As shown there are several KW hotspots. First, the area of Swiftsure Banks at the entrance to the Juan de Fuca Strait; second 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 initial 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 is there evidence that vessel noise has the means to harm killer

[28] 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 as well. We reproduce both graphs in the supplementary materials.

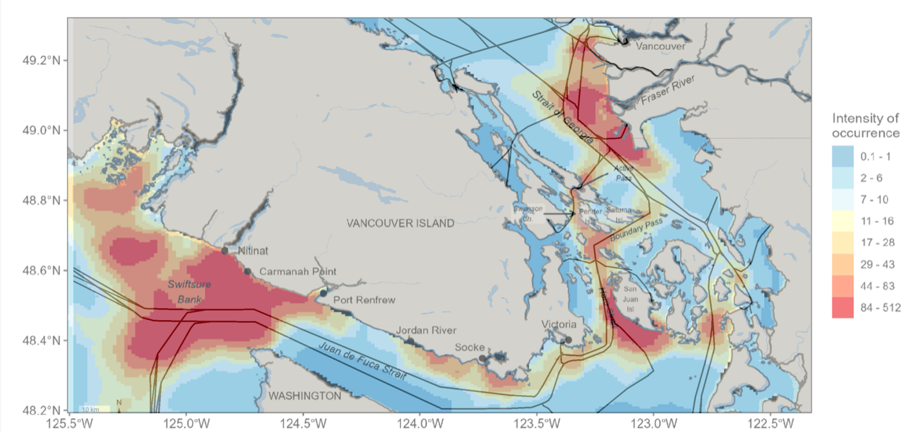

Figure 11. Annual SRKW intensity of occurrence as estimated by the SRKW occurrence model using combined WW and DFO data for May to October, 2009—2020.

Figure 6: Conflict is Inevitable

whales? If so, how might largely unobservable noise disturbance 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.[29] 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

[29] There are many observational studies showing avoidance behavior by KW from nearby surface vessels, but fewer studies 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).

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 maximum at the carrying capacity K in the very long run.

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.

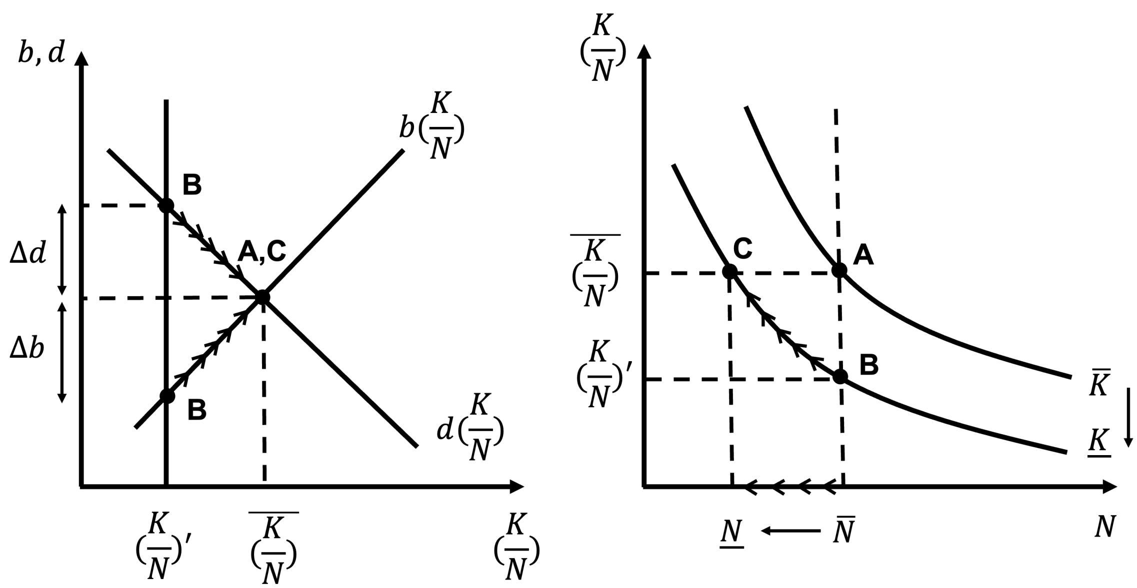

Figure 7: Births, Deaths, and Noise

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 the birth rate rises with K/N while the death rate falls with K/N. Naturally, the whale population is stationary when the birth and death rates are equal; and this equality occurs at what we might call the Malthusian subsistence level denoted by $K/N = \overline{K/N}$ (as shown). In the figure's 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. It does so by masking prey and potential hazards and by 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. As a consequence, and in the left panel shown by points 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 habitat loss caused by vessel noise.

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, or size, 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 age and gender composition of the population. Less obvious is that it will also allow us to estimate the long-run relationship between noise disturbance and population in levels.[30]

IV.II The Quasi-Experiment

Our research design is related to existing methods in environmental economics that link quasi-experimental variation in pollution exposure to human health outcomes. While whales are surely not human, many of the same challenges for inference arise. The key challenge, in both cases, is to find variation in the exposure to pollution that is as good as randomly assigned across units (individuals or whales) to investigate their health impacts.[31] The existing health and environment literature has focused on three specific threats to identifying these impacts: sorting, avoidance behavior, and measuring exposure accurately. We explain our methods in this context.

Our first step is to find variation in noise pollution that is unrelated to any characteristics of the KW population. To do so we rely on the annual variation in vessel traffic. This variation 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

[30] The details are provided in our penultimate section How Important is Vessel Noise?

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

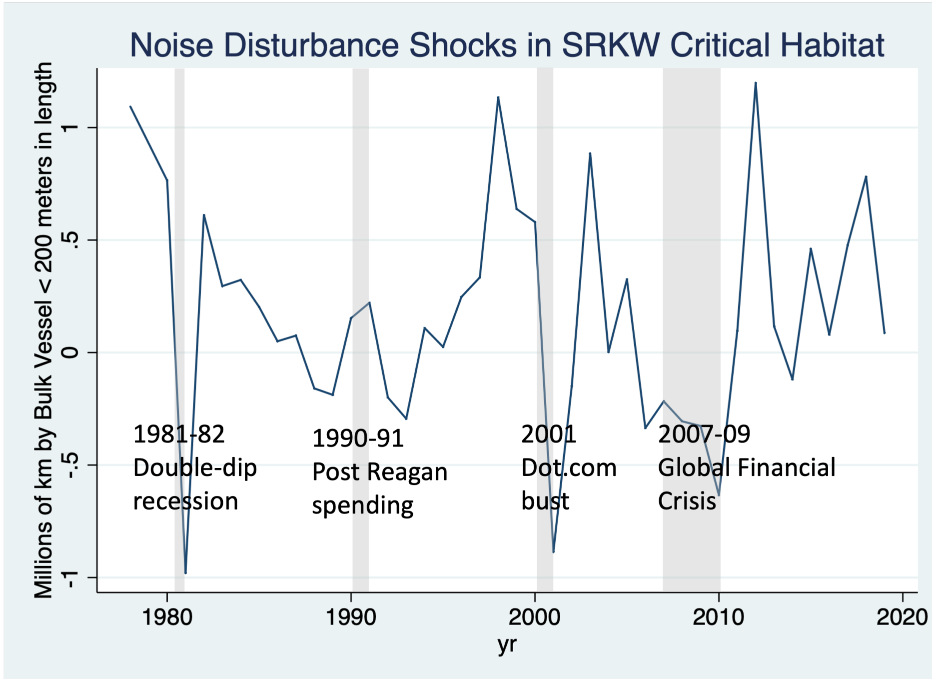

Figure 8: Noise Disturbance & Recessions

shocks are denominated in a common numeraire but represent an aggregation across vessel types taking into account their relative noise disturbance.[32] Three things are apparent from the figure. First, both positive and negative shocks are distributed over the sample period. Second, the size of shocks is fairly 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.

While the timing and scale of these noise disturbance shocks are clearly exogenous to KW characteristics, KW exposure to these shocks is not. And this is the real challenge we face. Under what circumstances does the variation in exogenously propagated noise pollution shocks shown in Figure 8, imply as good as randomly assigned variation in KW exposure to noise pollution? To answer this question precisely, we employ a simplified potential outcomes framework tailored to our setting.

[32]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 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 because their use of the Salish is so very different.

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 (2) affecting the likelihood of this event.[33] We write this dependence as follows:

$$Y_{it} = X'_{it}\beta + \rho_i D_{it} + \epsilon_{it} \tag{2}$$

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 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 and extremely stable.

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. This means we identify treatment effects by exploiting over-time variation in noise exposure, within matrilines, to outcomes.

Matrilines do of course travel with other matrilines in their pods, but this movement is

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

far less structured and can ebb and flow over time and geographic space (a matriline can be a day behind the bulk 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 as well.[34]

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

$$\epsilon_{ijkt} = f_j + \alpha_{kt} + \mu_{it} \tag{3}$$

where f_j is the matriline fixed effect, α_{kt} and μ_{it} are the pod and individual-level errors.[35]

IV.III.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 adopt the least restrictive of these by writing the noise exposure of whale i at t, NX_{it}, as:

$$NX_{it} = \pi_B + \pi_i NP_t + \eta_{it} \tag{4}$$

$$\eta_{it} = \gamma_i + v_{it} \tag{5}$$

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}.

Whale i's exposure to background ocean noise is captured by $(\pi_B+\gamma_i)$, and its exposure to changes in vessel noise is reflected in (π_i). 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

[34] J pod is almost always resident in the Salish, while K and L are not. See Table A.10 in the appendix for month/year residence figures.

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

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.[36]

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. This is the key reason researchers exploit pollution shocks. By definition, shocks are short-run unforeseen changes in pollution levels. 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 may provide as good as randomly assigned exposure to treatment.[37]

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

$$DS_{it} = [NX_{it} - NX_{it-1}] = \pi_i[\Delta NP_t] + [v_{it} - v_{it-1}] \tag{6}$$

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,

$$DS_{it} = D_{it} + [v_{it} - v_{it-1}]. \tag{7}$$

[36] 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 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).

[37] In the human context these shocks could arise from plant shutdowns (Hanna and Oliva, 2015), geographic variability in business cycle slowdowns (Chay and Greenstone, 2003), changes in traffic patterns (Currie et al., 2009), network congestion (Schlenker and Walker, 2016), variation in boat traffic (Moretti and Neidell, 2011) etc. In many of these cases, there are additional issues to address because plant shutdowns (for example) also carry with them income shocks that may also negatively affect health.

The dose D_{it} is individual-specific and could be close to zero for some whales. Finally, substituting (6) in (2) we obtain:

$$Y_{it} = X_{it}'\beta + \rho_i D_{it} + \rho_i[v_{it} - v_{it-1}] + \epsilon_{it} \tag{8}$$

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 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.

IV.III.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.[38] 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, D} with $D_i = 0$ when there is zero treatment; $D > 0$ when any of other non-zero treatments is present.

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

$$E[Y_{it}|D_i = D] - E[Y_{it}|D_i = 0] \tag{9}$$

to identify the impact of noise pollution on health outcomes. Using (8), the average treatment effect we would like to identify is:

$$ATE = E[\rho_i D_i|D_i = D] - E[\rho_i D_i|D_i = 0]. \tag{10}$$

It is easy to show that the gap between the difference in conditional means in (9), which we will estimate, and our ATE in (10), which we would like to identify, can be written as the

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

sum of three conceptually distinct terms. We label these A, B, and C and discuss them in turn.

$$E[Y_{it}|D_i = D] - E[Y_{it}|D_i = 0] = ATE + A + B + C \tag{11}$$

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 (10), requires further discussion.

IV.III.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 (10). 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:

$$ATE = E[\rho_i D_i|D_i = D] - E[\rho_i D_i|D_i = 0] \tag{12}$$

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:

$$\begin{aligned} ATE &= E[\rho_i]E[D_i] - E[\rho_i]E[0] \\ &= E[\rho_i]E[D_i] \end{aligned} \tag{13}$$

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.

IV.III.4 A: Covariate balance

One of the components of the difference we created using (10) and (9) is captured in A which we write as:

$$A = E[X'_{it}\beta|D_i = D] - E[X'_{it}\beta|D_i = 0] \tag{14}$$

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 (8) 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.

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 4 shows that for both the Southern and Northern 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.

For example, in the first column, we see that the average age of female Southern residents is 28.20 in quiet years, 28.25 in loud years, and 28.57 otherwise. These very small differences

Table 4: Covariate balance

	SRKW				Mean aggregate salmon abundance	NRKW			
	Mean age of females	Mean age of males	Mean population	Mean sex ratio		Mean age of females	Mean age of males	Mean population	Mean sex ratio
Negative shock	28.2	14.08	85.75	1.76	3.04	21.58	15.41	196	1.40
Control	28.57	14.98	87.33	1.54	3.59	22.27	15.83	229.23	1.41
Positive shock	28.25	14.65	85.43	1.61	3.12	22.8	16.14	224.43	1.44
Negative vs control	-0.38	-0.89	-1.58	0.22	-0.55	-0.7	-0.41	-33.23	-0.01
Control vs positive	0.33	0.33	1.91	-0.07	0.46	-0.53	-0.31	4.81	-0.02
Negative vs positive	-0.05	-0.57	0.32	0.16	-0.08	-1.23	-0.72	-28.43	-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, 1982, 1998, 1999, 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.

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 85.43 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 none of the differences across quiet or noisy years reaches the 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.

IV.III.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:

$$B = E[\rho_i[v_{it} - v_{it-1}]|D_i = D] - E[\rho_i[v_{it} - v_{it-1}]|D_i = 0] \tag{15}$$

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 (5). $v_{it} > 0$ 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:

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

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:

$$B = E[\rho_i]E[K_{it}|D_i = D] - E[\rho_i]E[K_{it}|D_i = 0] \tag{17}$$

$$B = E[\rho_i]\Big[E[\phi_{it}|D_i = D] - E[\phi_{it}|D_i = 0]\Big] \tag{18}$$

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 Salis. This data (see online appendix Table A.10) 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.[39] Why? Because the very same deep ocean trenches needed for large commercial vessel

[39] See Appendix A.IX for this data, analysis and relevant maps.

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). This is why we believe conflict is inevitable.

Surely some avoidance does occur - whales divert from vessel paths - but this does not insulate them from their sound waves. And when some avoidance does occur what is its impact? Estimated treatment effects reflect both the true biological impact of pollution exposure plus the success of the whale's efforts in lessening this exposure.[40] It is smaller.

IV.III.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:

$$C = E[\epsilon_{it}|D_i = D] - E[\epsilon_{it}|D_i = 0] \tag{19}$$

$$C = E[\alpha_{kt} + \mu_{it}|D_i = D] - E[\alpha_{kt} + \mu_{it}|D_i = 0] \tag{20}$$

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

[40] See the discussion of this issue in Graff Zivin and Neidell (2013) where they differentiate between the biological effect and the reduced form effect which measures the net impact inclusive of avoidance.

well.[41] Time-invariant unobservables 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).[42]

IV.IV The Mode of Inference

Our decisions regarding inference are determined by the features of our data, identification strategy, and planned use of estimates. In a nutshell, we employ conditional logit estimation and cluster errors at the pod level.

We adopt the conditional logit for several reasons. First, it provides estimated probabilities, within (0,1), that we use to solve for the estimated long-run effect of noise disturbance on whale numbers. 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, using the predicted probability of death. A similar logic holds for the birth rate. Using these estimates we parameterize our model and calculate the steady-state impacts of noise disturbance on whale populations in our penultimate section.

Second, logit estimation is the standard tool used by marine scientists and biologists in past, influential, work on KW.[43] Biologists are also taken aback by features of the linear probability model and we have no interest in offending the sensibilities of this community. These features are well known to economists: probabilities lying outside of (0,1); heteroscedastic

[41] There is a subtle issue here. Matrilines occasionally die out and new ones appear. Consequently, the matriline composition of pods fluctuates over time, and so does their sum, which therefore is slightly different from having pod-level fixed effects.

[42] In this sense, we are following the strategy of Schlenker and Walker (2016) who rely on variation created by bad weather thousands of miles away from California airports to isolate exogenous variation in pollution exposure.

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

and non-normal errors; and constant marginal effects which in our case are inconsistent with the natural growth function adopted in our theory. By adopting a logit specification we sidestep these issues and can connect our work to past KW research.

Third, an important feature of our identification strategy is the inclusion of matriline fixed effects and this means we (sometimes) employ conditional logit for estimation. One drawback to conditional logit is that observations with no over-time variation in outcomes (or our treatment variable) are dropped from the estimation; this however affects less than 5% of our observations and arises from a handful of observations with no variation in outcomes.

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.[44] 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.[45] We choose to cluster at the pod level because it matches our variation in treatment most closely. Two-way clustering over time is ruled out (pod x 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.[46]

A second lesson from this literature is that the usual cluster robust variance estimator is too large in our setting. As discussed earlier, we strongly suspect that treatment effects are heterogeneous across whales because their distinct travel patterns imply varied exposure, or perhaps because they differ in sensitivity to noise disturbance. As well, our sample is the entire population. In just these cases, the conventional cluster robust standard errors are too conservative. Since this research is already breaking new ground along several dimensions, our goal is to be deadly dull here. We present the simplest and most transparent of possible estimators in the text (plain vanilla logit estimation with conventionally estimated std errors clustered at the pod level), and place the more complicated (conditional logit), in Appendix A.VII. Fortunately, in almost all cases of interest, the results are very similar across these choices. When they are different, we alert the reader via footnotes. [47]

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

[45] 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.

[46] Clustering at the pod x time level while seemingly attractive, is not possible because our matrilineal fixed effects need to be nested within the clusters.

[47] On the one hand, using conditional logit with matriline fixed effects seems best because it narrows the

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 equivalent to adjusting our earlier formulation to:

$$Y_{it} = 1[X_{it}'\beta + \rho_i D_{it} + \epsilon_{it} > 0] \tag{21}$$

where 1[] is the indicator function, and the CDF of ϵ is logistic. In this context, 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 demographic model a naive measure of vessel disturbance shocks. This is simply the year-over-year change in annual km traveled by all commercial vessels in the Salish Sea. 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. In each step, we investigate several different specifications as robustness checks.

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.[48] 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 5 below we investigate the basic demographic and environmental determinants of KW births.[49] The most parsimonious and restrictive model appears in the first column, with

source of variation used for identification; it allows us to sweep away the impact of matriline attributes which may affect both fitness and exposure. But on the other hand, a fixed-effects estimation can make attenuation bias worse. We surely have some measurement error and fixed effects can magnify this problem. In the end, both the plain vanilla logit and the conditional logit estimations are similar and we are indifferent as to which is considered the base case and which is considered robustness.

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

[49]Table A.4 in the Appendix presents very similar results using matriline fixed effects and a conditional

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 .37 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 11%; a great, two std. deviation salmon year raises them 23%. These are large effects.

Third, in columns I through IV, the indicator variable for a whale belonging to the NRKW is positive and often significant suggesting greater fecundity amongst the NRKW. Given these findings we allow for a full set of NRKW x 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. The implications for any north vs. south fertility comparison are now far less clear, and hence we summarize these differences in Appendix A.V where we plot, for each population, the predicted probability of birth at various ages.

Fourth, in columns III onward, we find evidence that both within and across population competition matters. Within competition for an NRKW (SRKW) observation is measured by the size of the NRKW (SRKW) population, whereas across-population competition is measured by the population size of the SRKW (NRKW). Both elements of competition affect births negatively, but only the across-competition term is significant.

logit estimation.

Table 5: Baseline Demographic Determinants of Fertility

	I.	II.	III.	IV.	V.
Constant	−18.37	−18.94	−18.82	−17.72	−24.63
	0.000	0.000	0.000	0.000	0.000
Age	2.74	2.78	2.78	2.80	4.06
	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	−0.00003	−0.00004	−0.00004	−0.00004	−0.00006
	0.000	0.000	0.000	0.000	0.000
NRKW	0.54	0.54	0.83	0.12	7.90
	0.000	0.000	0.000	0.652	0.013
L1.Salmon abundance		0.37	0.34	0.30	0.30
		0.004	0.005	0.012	0.015
L1.Within competition			−0.002	−0.0021	−0.0020
			0.132	0.107	0.113
L1.Across Competition				−0.005	−0.006
				0.000	0.000
NRKW × Age	No	No	No	No	Yes
N	5821	5707	5707	5707	5707
Log likelihood	-1440.33	-1411.76	-1410.27	-1406.61	-1403.8

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.

V..2 Deaths

The demographic and environmental determinants of death are very standard and similar to those for births: age, access to prey, and gender. Deaths early in life are very common but this 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.[50]

In Table 6 below we investigate the demographic and environmental determinants of KW deaths. The determinants of mortality and births are naturally very similar, with two exceptions. Male KW live far shorter lives than females. This difference is captured by gender and gender by age controls. And deaths, in contrast to births, probably respond most strongly to a current lack of prey rather than a lack of prey one year previous. As before, less restrictive models are estimated as we move rightwards.

Several features of the table are noteworthy. First, the coefficient estimates governing the

[50] A graphical presentation of the KW mortality profile is found in Appendix A.VI.

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

Second, in columns II onward there is consistent evidence that prey availability matters to mortality. Interestingly, the impact of a bad salmon year is more than twice as large as they were for births.[51] Finally, there is little evidence that within-competition affects deaths.[52] The coefficient signs vary across columns and are never precisely estimated.

Table 6: Baseline Demographic Determinants of Mortality

	I.	II.	III.	IV.	V.
Constant	−2.04	−1.19	−1.14	−1.78	−1.23
	0.000	0.022	0.036	0.015	0.050
Age	−0.32	−0.32	−0.32	−0.32	−0.42
	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	−0.0002	−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
	0.001	0.001	0.001	0.001	0.000
NRKW	−0.40	−0.42	−0.36	−0.01	−0.81
	0.021	0.014	0.219	0.980	0.073
L1.Salmon abundance		−0.73	−0.74	−0.71	−0.71
		0.008	0.008	0.011	0.011
L1.Within competition			−0.0004	−0.0003	−0.0003
			0.815	0.853	0.854
L1.Across Competition				0.003	0.003
				0.011	0.001
NRKW × Age	No	No	No	No	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes
N	12793	12571	12571	12571	12571
Log likelihood	-1514.37	-1496.06	-1496.01	-1494.99	-1487.10

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

N records the number of female-whale-years

[51] Ford et al. (2010) using quite different methods find some similar results. For example, a one std. deviation decline in salmon abundance raises the odds of death that year by approximately 20%. 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.

[52] In Table A.5 in the appendix, these within competition terms are positive and marginally significant suggesting competition raises death rates.

Together Tables 5 and 6 provide a strong foundation for examining the impact of vessel disturbance.

V.I A Naive Accounting for Vessel Disturbance Shocks

We present in Table 7 a series of results linking disturbance shocks to KW births. We start with our preferred specification for births from column V of Table 5 and then add various measures of disturbance shocks. 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.

V.I.1 Births

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 absolute 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.

Table 7: First difference Impacts on Births

	I.	II.	III.	IV.	V.
Constant	−24.44	−24.31	−24.24	−24.07	−24.32
	0.000	0.000	0.000	0.000	0.000
Age	4.00	4.01	3.98	3.94	3.99
	0.000	0.000	0.000	0.000	0.000
Age^2	−0.24	−0.24	−0.24	−0.23	−0.24
	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
NRKW	7.69	7.69	7.50	7.28	7.57
	0.014	0.010	0.013	0.009	0.013
L1.Salmon abundance	0.31	0.30	0.29	0.32	0.29
	0.012	0.014	0.019	0.006	0.020
L1.Within competition	−0.002	−0.002	−0.002	−0.002	−0.002
	0.098	0.088	0.117	0.164	0.117
L1.Across Competition	−0.005	−0.006	−0.005	−0.005	−0.005
	0.000	0.000	0.000	0.000	0.000
L1.Δ Total Vessel km	−0.61				
	0.000				
L1.Δ Total Vessel km × NRKW	0.84				
	0.001				
L1.Δ Other km		1.00			
		0.236			
L1.Δ Other km × NRKW		−0.52			
		0.603			
L1.Δ Unitised km		−4.13	−3.22	−3.26	0.009
		0.007	0.000	0.000	0.990
L1.Δ Unitised km × NRKW		3.77	3.23	3.26	
		0.036	0.001	0.001	
Δ Unitised km				−1.14	
				0.183	
Δ Unitised km × NRKW				0.11	
				0.915	
L1.Δ Unitised km × J pod					−3.92
					0.000
L1.Δ Unitised km × K pod					−0.96
					0.160
L1.Δ Unitised km × L pod					−3.91
					0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707	5707
Log likelihood	-1402.90	-1399.73	-1400.98	-1399.65	-1400.55

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.

It is well known that unitized cargo ships are, as a group, 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 not affected at all. The implied magnitude is also important. Since km are measured in units of millions, the coefficient estimate of -3.22 implies a 100,000 change in Unitised km traveled in the CH would lower the odds of a subsequent SRKW birth by 28%. A change of 100,000 km is however very large since the average yearly change is only a little over 23,000 km and the std deviation is 76,000. Nevertheless, 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 constituting the SRKW population. J, K, and L pods 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.

Turning back to our core demographic determinants we see that across all columns, and consistent with our earlier results, salmon abundance retains its strong positive effect on births. Similarly, the negative coefficients on our measures of within and across competition 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. 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 8 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 6 and use more refined measures as we move across columns.

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 disturbance shock from 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. 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 small and insignificant, similar to those estimated in Table 6. In contrast, the across-competition coefficients are positive and significant, although relatively small in terms of magnitude. A very large 50-whale increase in the other whale population raises the odds of death by 16%.[53] 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.) have an immediate impact on deaths, but only impact births next year. The same pattern appears here - except now the population under study is killer whales.

[53] The coefficient estimates on across-competition are much larger in Table A.7, where this same change would generate a 64% increase in deaths.

Table 8: First difference Impacts on Deaths

	I.	II.	III.	IV.	V.
Constant	−1.16	−1.21	−1.24	−1.27	−1.27
	0.053	0.044	0.045	0.038	0.039
Age	−0.42	−0.42	−0.42	−0.42	−0.42
	0	0	0	0	0.000
Age^2	0.02	0.02	0.02	0.02	0.02
	0	0	0	0	0.000
Age^3	−0.0002	−0.0002	−0.0002	−0.0002	0.00
	0	0	0	0	0.000
Age^4	0.000001	0.000001	0.000001	0.000001	0.00
	0	0	0	0	0.000
NRKW	−0.84	−0.8	−0.8	−0.76	−0.75
	0.056	0.067	0.077	0.092	0.097
L1.Salmon abundance	−0.68	−0.68	−0.69	−0.68	−0.70
	0.014	0.014	0.011	0.013	0.012
L1.Within competition	−0.0004	−0.0004	−0.0003	−0.0003	0.00
	0.816	0.791	0.85	0.856	0.858
L1.Across Competition	0.003	0.003	0.003	0.003	0.00
	0.001	0	0.001	0.001	0.001
L1.Δ Total Vessel km	0.6				
	0.055				
L1.Δ Total Vessel km $\times$ NRKW	−0.49				
	0.357				
L1.Δ Other km		0.27			
		0.465			
L1.Δ Other km $\times$ NRKW		−0.13			
		0.843			
L1.Δ Unitised km		1.35	1.59	1.55	
		0.001	0.006	0.014	
L1.Δ Unitised km $\times$ NRKW		−1.31	−1.43	−1.38	
		0.143	0.171	0.201	
Δ Unitised km				1.85	−0.33
				0.01	0.619
Δ Unitised km $\times$ NRKW				−2.2	
				0.02	
Δ Unitised km $\times$ J pod					2.28
					0.007
Δ Unitised km $\times$ K pod					−1.33
					0.061
Δ Unitised km $\times$ L pod					3.46
					0.000
NRKW $\times$ Age	Yes	Yes	Yes	Yes	Yes
Male & Male $\times$ Age	Yes	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571	12571
Log likelihood	-1486.32	-1486.15	-1486.25	-1485.0	-1484.6

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.

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.[54] 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, we do not use them as direct measures of vessel disturbance for two reasons. 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 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 explicitly 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

[54] 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.

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.[55]

In Table 9 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 which match our estimates for relative disturbance shown in Table 3 above.

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 may well be zero. 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 7.

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

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 100,000 km change in Unitised km would lower the odds of birth by 28%. 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 -.39 in column IV to find the resulting change in the log odds of an SRKW birth. 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 9 and then by the coefficient estimate of -.39. A quick way to see if our results here are of a similar magnitude is to multiply -.39 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 - 2.95! Our previous estimates ranged from -4.13 to -3.26, and hence we again find that the disturbance caused by vessels can have a large impact on KW fertility.

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 disturbance shocks. Consider first the basic demographic determinants of death in Table 10. 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,

Table 9: Noise-weighted distance fertility regressions

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Constant	−24.31	−23.96	−24.41	−24.31	−23.98	−24.42
	0.000	0.000	0.000	0.000	0.000	0.000
Age	3.98	3.91	4.00	3.98	3.91	4.00
	0.000	0.000	0.000	0.000	0.000	0.000
Age^2	−0.24	−0.23	−0.24	−0.24	−0.23	−0.24
	0.000	0.000	0.000	0.000	0.000	0.000
Age^3	0.01	0.01	0.01	0.01	0.01	0.01
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	−0.00006	−0.00005	−0.00006	−0.00006	−0.00005	−0.00006
	0.000	0.000	0.000	0.000	0.000	0.000
NRKW	7.54	7.15	7.64	7.54	7.16	7.64
	0.015	0.012	0.013	0.014	0.012	0.013
L1.Salmon abundance	0.30	0.32	0.30	0.30	0.32	0.30
	0.015	0.006	0.015	0.015	0.006	0.015
L1.Within competition	−0.002	−0.002	−0.002	−0.002	−0.002	−0.002
	0.110	0.150	0.110	0.111	0.152	0.110
L1.Across competition	−0.005	−0.005	−0.005	−0.005	−0.005	−0.005
	0.000	0.000	0.000	0.000	0.000	0.000
L1.Δ Distance weighted by noise	−0.44	−0.46	0.07	−0.39	−0.40	0.05
	0.000	0.000	0.504	0.000	0.000	0.521
L1.Δ Distance weighted by noise × NRKW	0.51	0.53		0.44	0.46	
	0.000	0.000		0.000	0.000	
Δ Distance weighted by noise		−0.33			−0.28	
		0.006			0.009	
Δ Distance weighted by noise × NRKW		0.20			0.16	
		0.312			0.334	
L1.Δ Distance weighted by noise × J pod			−0.69			−0.59
			0.000			0.000
L1.Δ Distance weighted by noise × K pod			−0.31			−0.27
			0.004			0.003
L1.Δ Distance weighted by noise × L pod			−0.52			−0.45
			0.000			0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	5707	5707	5707	5707	5707	5707
Log likelihood	-1402.11	-1400.79	-1401.98	-1402.06	-1400.75	-1401.94

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.

with the change in NRKW much lower but not as precisely estimated. When we include both contemporaneous 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 (.27 + .23 =.50) and for the NRKW (.50 - (.19+.40) = -.09) using column V results. 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 K pod appearing to be less or perhaps not affected at all. In total, these results, present very similar evidence. And again if we multiply the disturbance shock coefficients by 7.55, we find coefficient estimates similar to those found earlier.

Table 10: Noise-weighted distance effects on mortality

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
Constant	−1.19	−1.22	−1.27	−1.19	−1.22	−1.27
	0.051	0.047	0.043	0.051	0.046	0.043
Age	−0.42	−0.42	−0.42	−0.42	−0.42	−0.42
	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	0.00	−0.0002	−0.0002	0.00
	0.000	0.000	0.000	0.000	0.000	0.000
Age^4	0.000001	0.000001	0.00	0.000001	0.000001	0.00
	0.000	0.000	0.000	0.000	0.000	0.000
NRKW	−0.82	−0.83	−0.79	−0.82	−0.83	−0.79
	0.065	0.062	0.076	0.065	0.061	0.076
L1.Salmon abundance	−0.68	−0.66	−0.69	−0.68	−0.67	−0.69
	0.013	0.019	0.015	0.013	0.019	0.015
L1.Within competition	−0.00042	−0.00025	0.00	−0.00040	−0.00023	0.00
	0.810	0.888	0.932	0.819	0.897	0.934
L1.Across competition	0.0027	0.0025	0.00	0.0027	0.0025	0.00
	0.001	0.001	0.001	0.001	0.001	0.001
L1.Δ Distance weighted by noise	0.33	0.32		0.27	0.27	
	0.011	0.015		0.013	0.019	
L1.Δ Distance weighted by noise × NRKW	−0.24	−0.22		−0.21	−0.19	
	0.269	0.320		0.258	0.318	
Δ Distance weighted by noise		0.25	−0.20		0.23	−0.17
		0.002	0.183		0.002	0.182
Δ Distance weighted by noise × NRKW		−0.47			−0.40	
		0.006			0.005	
Δ Distance weighted by noise × J pod			0.47			0.42
			0.008			0.005
Δ Distance weighted by noise × K pod			0.02			0.02
			0.882			0.898
Δ Distance weighted by noise × L pod			0.64			0.55
			0.001			0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
Male & Male × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	12571	12571	12571	12571	12571	12571
Log-likelihood	-1485.93	-1484.49	-1485.1	-1486.02	-1484.56	-1485.0

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.

V.III How important is Vessel Noise?

Our findings tell us that noise disturbance shocks reduce birth rates and increase death rates, but how have they affected the SRKW population over our sample period? Since future growth in vessel disturbance is likely, will it drive the SRKW below its minimum viable population size ushering in their extinction? Answering these questions requires further assumptions and considerable work. Here we take a first step by using our simple theory and empirical estimates to provide an initial back-of-the-envelope calculation as a guide to future efforts.[56]

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 female 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:

$$g = p^b[\frac{F}{N}] - p^d \tag{22}$$

We have estimated p^b and p^d as functions of the determinants of 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:

$$p^d = \frac{e^{X'\beta}}{1 + e^{X'\beta}} \equiv h(X'\beta) \tag{23}$$

$$p^b = \frac{e^{\tilde{X}'\tilde{\beta}}}{1 + e^{X'\tilde{\beta}}} \equiv h(\tilde{X}'\tilde{\beta}) \tag{24}$$

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:

$$g = h(\tilde{X}'\tilde{\beta})(\frac{F}{N}) - h(X'\beta) \tag{25}$$

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

[56]Why is it a back-of-the-envelope calculation? We adopt a homogenous whale assumption consistent with our theory, but one that neglects the heterogeneity across whales in fertility and mortality we estimate; we provide no standard errors on our estimate; our calculation follows from a long-run comparative steady state analysis; and we do not identify a minimum population size below which the SRKW would be driven to extinction. Future work could, and perhaps should, relax some of these assumptions.

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:

$$h(\tilde{X}'\tilde{\beta})\gamma = h(X'\beta) \tag{26}$$

Totally differentiate to obtain:

$$h'(\tilde{X}'\tilde{\beta})\gamma[\tilde{\beta}_0 dN + \tilde{\beta}_1 dD] = h'(\tilde{X}'\beta)[\beta_0 dN + \beta_1 dD] \tag{27}$$

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

$$\frac{\tilde{h}'}{\tilde{h}}[\tilde{\beta}_0 dN + \tilde{\beta}_1 dD] = \frac{h'}{h}[\beta_0 dN + \beta_1 dD] \tag{28}$$

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:

$$\frac{dN}{dD}\frac{D}{N} = [\frac{[1-p^b][\beta_1 - \tilde{\beta}_1] + p^b[1-\gamma]\beta_1}{[1-p^b][\tilde{\beta}_0 - \beta_0] - p^b[1-\gamma]\beta_0}][\frac{D}{N}] \tag{29}$$

Since the sex ratio is a fraction (recall .56), and the average probability of birth is small (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:

$$\frac{dN}{dD}\frac{D}{N} \cong [\frac{\beta_1 - \tilde{\beta}_1}{\tilde{\beta}_0 - \beta_0}]\frac{D}{N} \tag{30}$$

How big is this elasticity? We take values from the noise disturbance regressions in Tables 9 and 10 employ sample averages for both disturbance and whale numbers. Using estimates from columns IV in each case, we have: $\tilde{\beta}_0 = -.002$, $\beta_0 = -.00040$, $\tilde{\beta}_0 - \beta_0 = -.0016$.

$\tilde{\beta}_1 = -.39$, $\beta_1 = .27$, $\beta_1 - \tilde{\beta}_1 = .66$. The average disturbance shock over the entire sample period, D is .1227. We take the average whale population, N as 86.

Plugging these numbers in implies:

$$\frac{dN}{dD}\frac{D}{N} = [\frac{.66}{-.0016}][\frac{.1227}{86}] = -.59 \tag{31}$$

This implies whale numbers fall by approximately 60% if there was a permanent 100% increase in the disturbance. 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 the existing habitat - as measured by its carrying capacity K - with an elasticity of -.6.[57]

How much did the level of disturbance actually rise over our sample? One simple way to answer this is to compare the pre and post-1998 periods. Comparing the average disturbance shock over these periods shows the average disturbance shock is 50% higher in the second period. Since the periods are of very similar length, the total noise disturbance also grew by 50%. Using this number as our long-run change in disturbance, our back-of-the-envelope calculation tells us that the level of the SRKW population is approximately 30% lower than it would have been in the absence of the permanent increase in vessel traffic post-1998. Given the population profile shown in Figure 5, this is clearly a provocative result.

VI Conclusion

The purpose of this paper was to investigate the slow-motion extinction of the Southern Resident Killer Whales. While millions of dollars of research and countless hours of effort have been expended by hundreds of researchers studying the SRKW, there remains significant disagreement over what can be done, if anything, to alter their plight. 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 pre-1998

[57] Using the coefficient estimates from the alternate measure of noise disturbance in column I, the elasticity is -.69. If we include lagged effects estimated in columns II or V, the elasticities are even larger near -1.0; however the conditional logit estimates for these same regressions are smaller near -.3. Our point is that the impact of noise disturbance is large.

levels, 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 it is combined with measures to significantly 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. Previous work has found negative repercussions in terms of altered activity, avoidance and damage to sensory perception but it has been very difficult for researchers to move from observed individual-specific responses to their population-level impacts. 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 any 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.[58] 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 worldwide.

[58]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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