Trade, Competitive Exclusion, and the Slow-Motion Extinction of the Southern Resident Killer Whales

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July 1, 2021

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 whales (SRKW) have declined by more than 25 percent, and this population appears on a slow-motion path towards extinction. This paper combines elements from biology and economics to put forward a new methodology for investigating their collapse and presents empirical work supporting its novel explanation - the Orca Conjecture. The key mechanism is ecological - Gause's law of competitive exclusion - combined with a shock coming from booming trade with Asia. Using three different empirical methods drawn from economics, I find the attendant noise disturbance from increased ship traffic post 1998 has lowered births and raised deaths significantly, placing the SRKW on a slow-motion path towards extinction.

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 region. In the past two decades the Southern Resident Killer whales (SRKW) have declined by more than 25 percent, and now appear on a slow motion path towards 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 current discussion, but it is unclear which of these is the most significant driver of the decline. Surprisingly, other Orca populations have not fared as poorly. For example, the Northern Resident Killer whales (NRKW), whose range overlaps with that of the South, has grown over this same period.

This paper combines elements of biology and economics to put forward a new method for investigating, and a new rationale for explaining, the severe decline in the SRKW. The paper makes three contributions.

First, I show how to construct from widely available information on commercial vessel landings in ports, a measure of the km travelled in the critical habitat of killer whales. Such a calculation could be made from satellite data that keeps track of transmissions from vessels using their automated identification system (AIS), but this data is only available after 2009; my method allows researchers to construct commercial vessel km travelled within a habitat from the late 1970s onward. The post-2009 period is, after all, just far too short to be useful to researchers studying population dynamics of long lived marine mammals.[1] In particular, the trouble with the SRKW started in the 1990s and has continued since. Therefore, a retrospective study using this longer, over 40 year, time period is likely to be critical to identifying cause and effect.[2]

The method I employ is not complicated and is in fact transparent. To determine both the scale of transport within the habitat and the composition of these km across foreign

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[1]Cetaceans, like killer whales, have gestation periods measured in terms of years; they live incredibly long periods of time before sexual maturity and after; and have considerable fat stores that can smooth out short run variations in foraging success. Ten years is not long in the lifetime of any one whale, let alone a population.

[2]A very small number of studies have exploited AIS data to look at vessel traffic in the Salish Sea. For example, McWhinnie et al. (2021) exploits vessel traffic data for only 24 months spread over the period 2012-2016. The author's goal is to understand traffic hot spots, vessel speeds, and the distribution of vessel types. Perhaps not surprisingly, they do not link their vessel traffic measures to KW health or population processes as I do.

and domestic destined vessels, I need only a relatively straightforward application of two principles drawn from economics: value-added accounting from National Income Accounting; and Walras' law from general equilibrium theory. With these two simple tools I am able to reconstruct potential measures of vessel disturbances by month, year, location, and vessel type. This new method may prove very useful in the study of marine mammal interference more generally, since there is a growing interest in marine pollution and the impact of noise pollution on whales in particular.

The second contribution is to provide a rationale for the divergent histories of the SRKW and NRKW that is based in theory and provides two testable hypotheses. The key mechanism linking the two populations is familiar to economists - competition for scarce resources - although ecological speaking, it goes by Gause's Law of Competitive Exclusion and is embedded in the Lotkka-Volterra model of competing species I employ.[3]

The intuition of the model and its results are decidedly simple. A positive shock to vessel traffic in the critical habitat of the SRKW lowers their hunting productivity and directly weakens their ability to compete for the prey they share with the NRKW. This shock falls primarily on the South, but also potentially weakens the North. The logic of competitive exclusion means the unequal sharing of the shock is then magnified by across-population competition and becomes, in principle, many times more potent. If the shock is large and asymmetric, it will lead to extinction of the SRKW.

The hypothesis linking an asymmetric shock all the way through to probable extinction, is what I refer to as The Orca Conjecture. It proves useful to refine this hypothesis further, by dividing it into a weak and strong version. The strong version remains just as described above; the weak version assumes there is no across-population competition between the NRKW and the SRKW, and hence no magnification of the shock driving extinction. The two populations may still move in sympathy but only if they face similar shocks.

With new data in hand and two hypotheses in play, the last contribution must be empirical. I first provide evidence for the *weak* and *strong conjecture*, and then employ an analysis of whale cohorts to examine the likelihood of extinction. Across three different empirical approaches, I find consistent evidence for a vessel shock driving the SRKW population downwards. Using the change in average vessel traffic pre and post 1998 as my metric, I find the odds of a SRKW birth fall by about 30%, while the odds of death rise by more than 40%. These are large and significant effects. To put them in context, I also find a strong and

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[3]See Begon, Harper and Townsend (1996) for a textbook treatment of the model, and Gause (1932) for the original work giving rise to the law.

consistently positive impact of salmon availability on KW fecundity and mortality. Using these results, I find that only a permanent, three standard deviation, increase in salmon availability above its historic mean, could offset the negative impacts of vessel disturbance. These results constitute the very first evidence we have connecting noise disturbance from commercial vessels to lower births and higher deaths of a marine mammal.

The empirical evidence also favors the strong vs. the weak conjecture. Not only do I find strong evidence for across-population competition when I evaluate the strong conjecture, there is also suggestive evidence in the evaluation of the weak conjecture of omitted variables. This finding may be unwelcome news to the many researchers who have treated the two populations as if they evolve independently. To study extinction, I exploit a feature of KW biology to argue that an analysis of female whale cohorts is sufficient to settle the question. The cohort analysis - which neatly encapsulates the grand sum of salmon and vessel noise impacts - shows SRKW fertility is now well below replacement. Given the evidence on the weak and strong conjecture, the forces driving this result are permanent: the obvious conclusion is that the SRKW are on a slow-motion path to extinction.

This paper uses tools drawn from several fields of economics to provide, what I hope, is a convincing solution to an important biological puzzle - what is responsible for the precipitous decline of the Southern resident killer whales? Since an effective policy response can only come from a good scientific understanding of the issue, the findings may also provide guidance for policy design. Current policy options range from the dramatic breaching of important dams, a moratorium on sport and some commercial fishing, an elimination of whale watching, and the redirection of vessel shipping lanes. While I provide no explicit policy recommendations, the analysis I provide and its conclusions could very well inform such decisions. This study also provides important evidence of the complicated and sometimes subtle links between economic activity and conservation outcomes.

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; and it also owes its existence to lucky happenstance.

The data comes from three sources. First, I 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. Data before the late 1970s is a growing sample and not a complete census until the last pod was identified and catalogued, but since 1979 it represents a complete accounting of all killer whale births and deaths for either population, for every year. This data is quite extensive, and is the work of a large scientific community

spanning professional government scientists, whale enthusiasts, and a large community driven whale spotting network.

Second, I have obtained a series of salmon abundance measures for key salmon stocks from the Pacific Salmon Commission. Some of these stocks have been used previously, but were less complete in geographic coverage or in terms of the time period considered. These stocks are aggregated by the commission into three different abundance measures for geographically distinct stocks. The movement of these indices is however, highly correlated, and I aggregate further to obtain one measure of salmon abundance.

Finally, since the shock under consideration is trade related, I need trade related data. While trade per se is likely to track vessel movements reasonably well over very short periods, there has of course been both major technological (the movement to container shipping) and policy (the accession of China to the WTO) changes during the study period which makes using trade flows problematic. As well, measures of noise disturbance from the scientific community show a strong relationship across vessel type, size and speed necessitating a more detailed look at the externality generating process. Fortunately, data on ship movements from Lloyds of London has been collected for over a hundred years, and I exploit their records from 1977 to 2019.

The critical summer habitat for the SRKW is in and around several small islands and deep straits in the Salish Sea. And these same waters contain several very busy shipping lanes leading to Canadian and US ports (33 ports in fact). To understand the time series and geographic variation in this potential disturbance, I obtained a (complete) list of all trading vessels landing at over 120 ports across the coast of North America from the Baja peninsula to the Alaskan panhandle. This data documents, the month of arrival in port, vessel size, type, and last two ports of call. It captures approximately 5 million vessel movements over the period. This level of detail and coverage was important to obtain as I exploit it in the empirical work.

At bottom, this study is an attempt to determine, using quasi-experimental methods, the cause of a rapid population change for a subject that ranges over several thousand miles, across two countries, while mostly underwater. Moving this exercise from the realm of science fiction to that of social science requires a bit of luck. And as luck would have it, the SRKW happen to be the world's most intensively studied population of whales; their critical habitat happens to coincide with several of the world's busiest ports; and these ports happened to have experienced a rapid change in the composition and scale of their vessel traffic over the precise period the KW started to fail. It is, for these reasons, that I am able to provide a

tentative answer to what ails the SRKW.

There is of course an existing, and large, literature examining killer whales in general, and the more recent poor performance of the Southern residents, in particular.[4] A recent, and authoritative study undertaken by the National Oceanographic and Atmospheric Association (NOAA Fisheries (2014)) summarized the findings over ten years of federally funded research studying killer whales. It provides an excellent introduction to the main conservation issues, research, and remaining unknowns. A similarly targeted, but more recent summary is provided in Lacy et al. (2017). Similar work focusing on Canadian issues is Ford et al. (2017) and Ford (2006).

While there are literally hundreds of articles discussing the conservation, reproduction and protection of killer whales, there has been relatively few studies examining population events empirically. One early approach to studying the populations was through the construction and use of life tables. (Olesiuk, Bigg and Ellis (1990),Olesiuk, Ellis and Ford (2005a),Olesiuk, Ellis and Ford (2005b)). Life tables have been a staple of demographers for many years, and they have been used extensively to reconstruct population histories in economic history. Life tables are of course very useful devices for predicting the likelihood of future events, when populations are stable or in steady state. The life histories of the NRKW and SRKW have, however, been anything but stable - starting with a period of early harassment and wanton killing, to interference by the capture industry, to increasing vessel traffic, and more recently variable salmon returns. These facts, make any analysis based on life tables suspect.

Alternatively, a handful of researchers have tried to explain 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 behavioural changes arising from vessel traffic and associated noise (e.g. (Williams et al. (2014))).

I follow the tradition in biology by modelling the probability of KW birth and deaths using a logistic, but depart from this earlier work in several significant ways. I construct measures of commercial vessel km travelled in the critical habitat of KW that simply did not

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[4]See for example Wiles (2004) and the most recent action plan and report for the Washington state government.

exist before. These data allow me to evaluate, much more rigorously, the impacts of vessel disturbance. I also introduce two hypotheses drawn directly from theory and evaluate them empirically; in contrast, the existing literature is largely devoid of theory. And I conduct this investigation by using the many tools of economics - from the mundane to the reasonably sophisticated.

This work is also a contribution to the large and growing literature examining the environmental consequences of international trade (See Copeland, Shapiro and Taylor (2021) forthcoming for a review). 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 unintended consequences of commercial shipping. Vessel noise is now thought to be a major form of underwater pollution which can affect all types of marine life, especially marine mammals. This paper also bears a family resemblance to earlier work I have conducted using the tools of economics to solve other *mysteries* in the social sciences, be they anthropological (Brander and Taylor (1998)) or historical (Taylor (2011)).

The rest of the paper proceeds as follows. Section II presents the relevant history and necessary biology with a focus on the NRKW and SRKW. In section III, I use the competing species model to show how a large negative shock to one of the whales' habitat affects KW populations, and may lead to extinction. These theoretical results define the weak and strong form of The Conjecture. Section IV establishes that a negative shock to the SRKW critical habitat did occur by employing data on vessel landings and my new methods for constructing vessel miles travelled. With the existence of a negative shock established, section V turns to empirical evaluation of the weak and strong conjecture, while section VI discusses extinction and alternative hypotheses. A short conclusion ends the paper. An online appendix, at https://www.mstaylor1.org/, contains supplementary tables, figures, and background material that may be of interest to the reader.

II   Killer Whale (Orcinus Orca) Background

II.I   History

The history of Orcinus Orca and human interaction is somewhat tortured. In the period before the early 1960s, very little was known about the species. During this time, KW were

viewed as a pest and dangerous to humans. 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 destroy's saddle-rock oysters.

Not surprisingly, KW were often shot by fishermen, boaters and sometimes by the US airforce.[5] 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 started with the Vancouver Aquarium taking a leading role. The industry is still in existence today.

In response to the demand for display specimens, and the lack of regulation on capture, both US and Canadian authorities started to fund research into killer whales. Initially this research was to calculate what might be a "sustainable" harvest of killer whales for the display industry, but eventually branched out to become an important area of research on marine mammals. Almost all of our current scientific knowledge was discovered from the early 1970s onwards.

This knowledge includes an understanding of the different eco-types (offshore, transient, and resident); the structure of their society (its a matriarchy); and detailed knowledge of their communicative, reproductive, and foraging behaviors. Importantly, a Canadian fisheries scientist - Michael Biggs - developed a method of identification relying on each KW's unique saddle patch and fin notches. Using these methods, researchers could now count and identify individual whales. This facilitated a whale census starting in the early 1970s that provided researchers (including this one) with invaluable data on killer whale (KW) numbers. This census 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. Subsequent work has identified each pod and each matriline within populations, as well as establishing our understanding of their interactions. A map of the habitats for US and Canadian whales is below, together with a graph of the SRKW population history.

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

Figure 2: A Tumultuous History
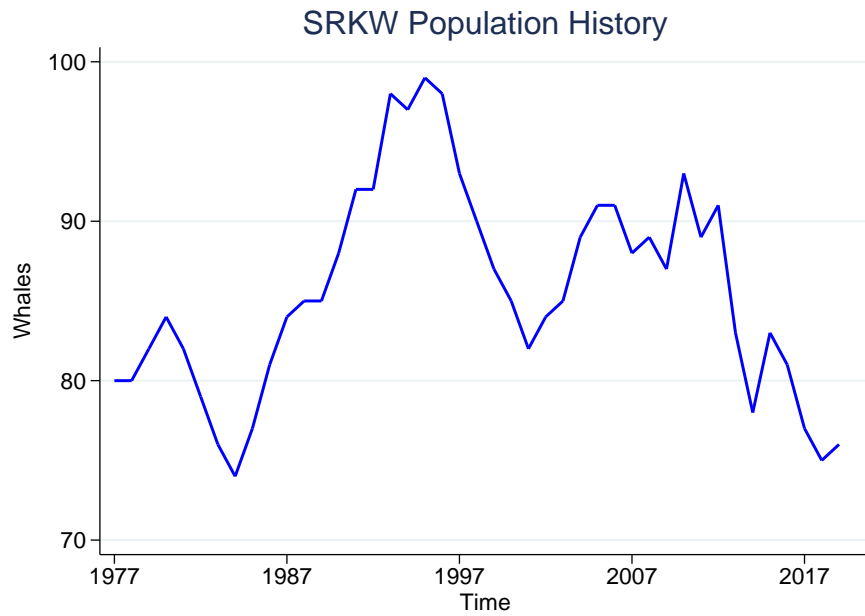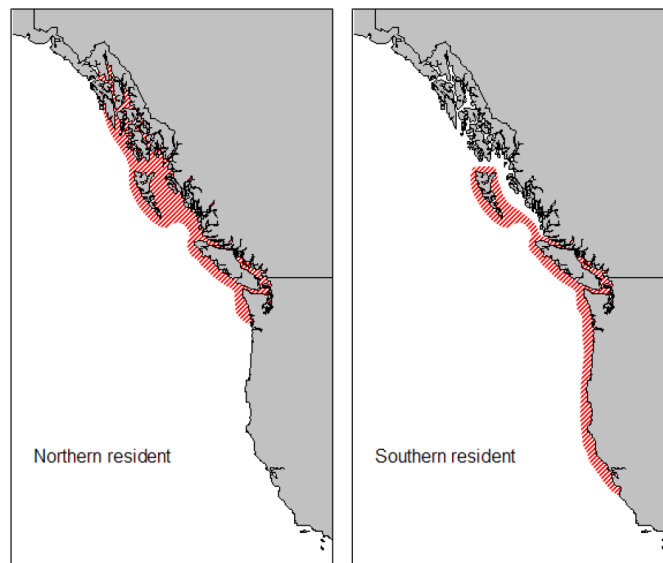

Figure 1: Northern and Southern Overlapping Habitats

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

Killer whales (KW) were protected under the Canadian Fisheries Act since 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 with the population peaking in the late 1990s before falling more or less continuously as shown by the figure.

In response to the precipitous decline shown, 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 were 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. A recovery strategy document was completed in 2011, the primary purpose of which is to identify critical habitat for KW.

In the last five or so years, increased national and international attention on the plight of the SRKW has followed from the release of an extensive ten year review of research by NOAA scientists, the recommendations of the Orca Task force put together by Washington Govenor J. Inslee, but perhaps most salient to outside observers was the international media attention given to the one SRKW female who pushed and kept afloat her stillborn calf for 17 days before abandoning it. Emotions aside, the SRKW population has continued its slide downward while the age and sex composition of the population only worsens. After what appeared to be a swift recovery from the end of the live capture industry in the 1970s, and given protection as an endangered species in the early 2000s, why have the Southern Residents failed to recover?

II.II   Biology

Killer whales are within the toothed whale family, Odontoceti, whose closest relatives are the oceanic dolphins (spinner, bottlenose, common).[6] 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.

There are several features of their biology relevant to the argument I will present. The first is that killer whales exhibit sexual dimorphism with the males considerably larger than

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[6]The other major group of whales is the Mysticeti or baleen whales. This group includes for example gray, humpback, right, blue, and fin.

females. For example, fully grown male Orcas can reach 7 or 8 meters in length and weigh up to 6,000 kg. In contrast, females are significantly smaller at 5-6 meters, and only 3,000 kg. It is typical, but not a rule, that sexually dimorphic species rely on only a few mature males for reproduction. This feature is important to questions of extinction, and to my empirical methods for examining the likelihood of extinction.

Second, there are three different types of killer whales defined by their ecological niche. While these three eco-types differ in their social structure, their size and body structure, and their movement and communication patterns, 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, although all three eco-types have been spotted in both Canadian and US waters. Residency means that, almost every year, every living whale in the resident populations are spotted, counted, and recorded in my data. No whale has ever switched matrilines; and only one orphaned whale changed pods. This means 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.

Third, the NRKW do not reproduce with the SRKW population. The societal structure of a family grouping or pod, consists of a series of matrilines, which in turn are composed of a senior female and all living offspring (both males and females). Reproductive maturity for females occurs at about year ten and continues until their early forties. Calves tend to be born in autumn and winter months, and gestation is 16 to 18 months. This places conception in the important spring and summer months of the preceding year when the whales are often resident in the Salish Sea. The length of gestation suggests I adjust for the fact this year's conditions may largely determine next year's fecundity.

Fourth, killer whales are very specialized predators. The two resident populations not only specialize in eating almost exclusively members of the salmon family, they are 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.

While the habitats of the NRKW and SRKW overlap, it is unclear to what extent they compete with each other for prey. However, recent acoustic and photo identification studies suggest the NRKW and SRKW share the very important Chinook feeding grounds off the southwestern tip of Vancouver Island. This new emerging evidence strengthens the cases

for the competing species interpretation. In fact, there appears to be mutual indifference. Pods from each population ignore each other; there is no fighting, no interbreeding, and no communication either. Language or calls are specific to pods and differ significantly across members of the NRKW and SRKW. Therefore, the only point of contact between these populations is over prey, and the non-interference and non-reproduction features are necessary assumptions of the competing species model. Whether and to what extent they compete for salmon and habitat is for the data to decide.

Finally, although it may seem obvious that the continuous presence of large and very noisy vessels in a critical habitat would interfere with hunting, mating, and other social behaviors, recent work has made several important connections that complete the line of logic from vessel activity to potential disturbance. For example, it is now well documented that commercial vessels create significant noise in frequencies used by KW for both communication (lower frequencies) and echolocation (higher frequencies).[7] This suggests large vessels interfere with foraging, socializing, and may raise stress hormone levels. As well, observational studies have now provided dose-response estimates of how behaviour changes when large boats are near, implying an energetic cost to KW.[8] Moreover, different vessel types radiate sound at different amplitudes and frequencies therefore it may be important to distinguish across vessel types and over time.[9] Any noise disturbance shock could come from either a change in the overall scale of vessel traffic, a change in its composition, or both.

III   Theory

III.I   The NRKW and SRKW as Competing Species

I assume the NRKW and SRKW are, at least potentially, competing species. While they do not appear to compete for habitat and do not interbreed, they both prey very heavily on Chinook salmon. Chinook returning to spawning grounds in the Salish Sea (primarily the Fraser river), and along West Coast of Vancouver Island are prey of both NRKW and

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[7]Early work by Hall and Johnson (1972) established an initial range of KW hearing from 500 Hz to 32 kHz using a captive whale at Sea World San Diego.

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

[9]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.

SRKW. In particular, salmon returning via the inside passage between Vancouver Island and the continent must run through the critical habitat of the NRKW in Johnstone Strait before returning to spawn further south.[10] It is of course possible that sharing prey has little effect on population growth given the relative magnitudes of salmon runs, commercial fishing, and natural mortality. Modelling them as competing species may be a distinction that makes little difference empirically.[11] As such, in the empirical section I will distinguish between a strong and weak version of The Conjecture. The strong version assumes that competition across the populations is empirically relevant; the weak version assumes the populations evolve independently but may be affected by correlated shocks.

III.II   Within and Across Population Competition

I focus on the dynamics of the NRKW and SRKW populations and ignore that of their common prey, which in the case of Orcinus Orca, is largely Chinook salmon. A reduction in foraging efficiency created by increased vessel disturbance or reduced Chinook availability is modelled as a fall in the maximum population either could obtain (its carrying capacity).[12] The benefit of adopting this simple specification is that it provides us with a very clean (state space) method of analysis.

Denote the size of the Northern Resident population by N, and that of the Southern by S. I treat both as real numbers, and ignore the age and sex composition of the populations although these will be accounted for in the empirics. The evolution of population sizes, from given initial conditions, is driven by two non-linear differential equations:

$$\frac{dN}{dt} = rN[1 - \frac{N}{K_N} - \frac{\alpha S}{K_N}] \tag{1}$$

$$\frac{dS}{dt} = rS[1 - \frac{S}{K_S} - \frac{\beta N}{K_S}] \tag{2}$$

where $r, \alpha, \beta, K_N, K_S$ are strictly positive given parameters of the system (defined below).

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[10]For example, 80% of the Chinook taken by KW off southwestern Vancouver island and in the Strait of Juan de Fuca are destined for the Fraser River, and 88% of all observed predation events involve Chinook Salmon. Fisheries and Oceans Canada: Canadian Science Advisory Secretariat (2017)

[11]Estimates of KW daily fish take suggest otherwise. Estimates of their dietary requirements range widely (from 100 to 400 kg/day) and are based on a mix of information gleaned from the capture industry and theoretical models of their energetic requirements in the wild. If we take the 100-400 kg/day at face value, then the 300 plus NRKW alone would consume tens of thousands of kg of salmon daily and this is not inconsequential. Therefore, it would be unwise to reject the competing species model out of hand.

[12]A less transparent three species model can deliver qualitatively similar results.

Initial populations are assumed to be non-negative ($N(0) \geq 0$, $S(0) \geq 0$).

Consider equation (1). It says that per capita growth in N is a linearly declining function of both population levels. This implies that growth is *density dependent*. Absent density dependence effects, the NRKW would grow exponentially at rate r which is sometimes referred to as their intrinsic rate of growth. A similar interpretation holds for the SRKW in (2). Exponential growth at r is not possible because competition for prey limits growth. Competition for prey comes from members within the same population – within-competition – and from members of the opposing population – across-population competition. If we ignore across-population competition by setting $\alpha = \beta = 0$, the equations tell us that increases in own population size lowers growth from its theoretical maximum of r down to zero when each population approaches its carrying capacity population of K_S or K_N. With no across-population competition, it is simple to show that starting from any positive biomass, populations grow monotonically towards their steady state values. Shocks can of course disturb these paths and alter eventual steady states, but extinction is never an outcome.

When there is competition across populations, extinction is now a possibility, but so too is mutual co-existence. Which case is relevant depends on the relative magnitudes of two sets of parameters. The first set is determined by the relative strength of across versus within competition. A one unit increase in, say S, lowers potential per capita growth of S by $1/K_S$ – this is the magnitude of within-population competition; whereas, a one unit change in N lowers per capita growth in S by α/K_S. Therefore for the system as a whole, the (relative to one) magnitude of the *competition terms* α and β determines the strength of across vs within, competition. The natural, and common, assumption is that within-competition is more potent than across-population competition. Since the NRKW and SRKW habitat overlap to a limited extent (both geographically and temporally) and yet the populations are physiologically identical with identical foraging behavior and nutritional requirements, I assume both competition terms are weakly positive but less than one in magnitude.

III.III   The Existence and Stability of Steady States

The Salish Sea has seen tremendous increases in vessel traffic over the last thirty years, and since this interferes with the whales ability to forage it represents an effective reduction in the environment's carrying capacity. Similarly, changes in the availability of Chinook salmon or increased PCB pollution could also be shocks to the system. Exploring the implications of these shocks requires a comparative steady state analysis.

While understanding how shocks affect steady states is important, it cannot be everything. The data on NRKW and SRKW population numbers are very unlikely to reflect repeated observations at the steady state of this natural system. One simple reason is that prior to the early 1970s, KW were largely considered a nuisance to fishermen and a potential threat to humans. Large scale destruction, incidental shooting and slaughter were common. Public sentiment started to change with the advent of the live capture and display industry, but this of course created other problems. My data starts in the mid 1970s, when both populations were still subject to a sometimes very destructive live capture hunt and runs until 2019. Over this more than forty year period, many important conditions (such as salmon availability, habitat protection, etc.) have changed dramatically. Killer whales, like most marine mammals, are a very long-lived species and this means shocks may take literally decades to play out. To cover the breadth of these processes, I first employ empirical methods based on approximations to contemporaneous birth and death processes consistent with (1) and (2); and then employ a cohort analysis identifying long run trends reflective of transition paths when discussing the likelihood of extinction.

To understand both the short and the long run response to shocks, I present in Figure 2 below the two isoclines ($\dot{N} = 0$ and $\dot{S} = 0$ loci) from the system (1) and (2), under an assumption on parameters that ensures both populations survive in steady state. The
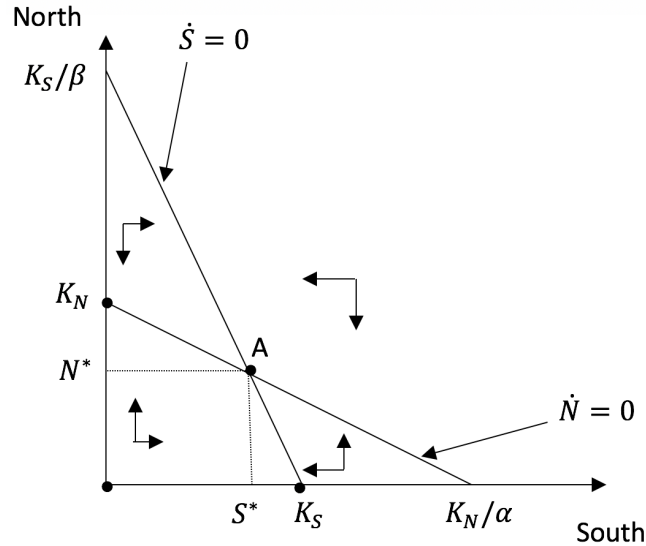

Figure 3:

isoclines are indeed linear as shown because Northern growth is zero whenever: $N + \alpha S = K_N$.

Similarly, Southern growth is zero whenever: $S + \beta N = K_S$. The interior steady state, when it exists, is shown at a point like A. In drawing the figure I have assumed both $\alpha < 1$, and $\beta < 1$. This ensures the relative slopes of the isoclines are as shown.

While A is the interior steady state, it is relatively easy to see that there are in fact four possible states as indicated by the bolded dots. The steady states along the North or South axis represent possible steady states, as does the steady state at the origin. None of these steady states can be reached from any interior starting point.[13] Therefore, A is the only interesting option. It is also apparent from the arrows of motion that A is globally stable. It is less clear that there are a number of possible paths to A, depending on initial conditions. And less clear still that a limit cycle cannot arise, but this is a very well studied system with known results. Limit cycles do not exist and starting from any interior point the system converges to point A.

The figure is drawn for a given degree of within vs across competition that sets relative slopes, but if the carrying capacities differ too greatly, point A would move towards one or the other axis eliminating the interior steady state. At this point the system with mutual co-existence turns into one of competitive exclusion. Therefore, the second (relative) requirement needed for mutual co-existence is a restriction on relative carrying capacities. Although Figure 3 depicts a roughly symmetric situation there is no requirement for K_N to equal K_S nor for α and β to be the same or similar. The resulting steady state could be highly asymmetric with one population much larger than the other as long as the condition in (3) is met.

$$\frac{1}{\beta} > \frac{K_N}{K_S} > \alpha \tag{3}$$

Given our assumptions on within vs. across competition, this is a restriction on the relative size of carrying capacities. In biological terms, the Southern population can only survive, if there is, in some sense, "excess carrying capacity" that its members can exploit even when the Northern population becomes very large. To see why rearrange the leftmost inequality in (3) to find it requires $K_S - \beta K_N > 0$. This is a measure of available carrying capacity excess to the needs of its Northern competitor when its Northern competitor is at its theoretical maximum. Rearranging the rightmost inequality, the Northern population survives when $K_N - \alpha K_S > 0$. Again, a measure of excess capacity is positive. These inequalities are of course important because large shocks to the steady state at A, could easily run afoul of

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[13]For example the steady state at $N = K_N$ and $S = 0$ can only be reached if the arrows of motion for S are made irrelevant by setting $S = 0$ to start with. This initial condition then allows an approach along the vertical axis; a similar argument applies to the steady state at $S = K_S$ and $N = 0$.

the restriction for mutual co-existence. This intuition is reinforced by the solutions for the steady states at A which are:

$$N^* = \frac{K_N - \alpha K_S}{[1 - \alpha\beta]} > 0, \quad \text{and} \quad S^* = \frac{K_S - \beta K_N}{[1 - \alpha\beta]} > 0. \tag{4}$$

A key suspect for the violation of (3) is of course increased vessel disturbance.

III.IV   The Impact of Vessel Disturbance

To understand how a shock lowering one KW carrying capacity more than the other can lead to extinction, I start with a shock altering both carrying capacities equiproportionately. I refer to this as a *common shock*. The figure below makes things transparent. Starting from A, the shock shifts both isoclines out or in, and the new steady states would lie along a ray from the origin thru A as both populations respond. One such possibility is a move to D created by a equiproportionate reduction in both NRKW and SRKW carrying capacities. Another would be a positive shock (a permanent positive change in salmon availability will be one such shock), moving the steady state upwards from A.
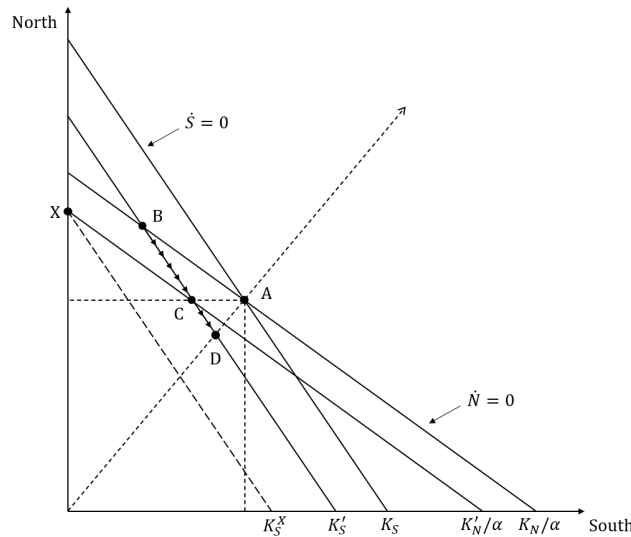

Figure 4:

Things are however quite different if the shocks are not common. Suppose the South suffers a reduction in the carrying capacity from K_S to K_S' while K_N remains constant. This is what I refer to as an *asymmetric shock*. The resulting steady state moves from A to

B. A key and surprising feature of this movement is the beneficial change in the Northern population from the negative shock to the South's habitat – despite the fact that Northern whales share some of the Southern habitat. The logic is simple. The direct impact of the shock is to lower the carrying capacity of the South's primary habitat and this shock lowers the Southern population directly (as it would in the absence of any across population). But as a consequence of the Southern population shrinking, the North experiences less competition for its own resources, and grows. This feature is of course why the model is called " the competing species " model, as competition for scarce resources is at its core.

Next, consider a situation where both North and South suffer a shock to their carrying capacity, but the Northern shock is relatively smaller. This is the case of *correlated shocks*. From the geometry of the set up its easy to see that keeping the shock to the South in play, a simultaneous fall in the carrying capacity of the Northern population to K_N' could lead to a new steady state at C or in fact at any point along the ray with arrows BD. Point C with its associated reduction is the North's carrying capacity, represent an important special case. For Northern shocks smaller than the reduction to K_N', the North's population rises with the correlated shock despite the reduction in its own carrying capacity. This is because the beneficial reduction in across-population competition swamps the direct negative effect of the fall in its carrying capacity. For Northern shocks larger than the one represented by K_N', both the Northern and Southern populations fall.

One final possibility is an *extinguishing shock*. Without doing too much violence to the figure, consider the case with a large shock that falls primarily on the South's carrying capacity. This shock lowers the South's carrying capacity to K_S^X, and the North's to K_N'. The shock is highly asymmetric and correlated. The new dashed $\dot{S} = 0$ isocline intersects the new $\dot{N} = 0$ isocline at X along the vertical axis. In this case, the only remaining steady state features extinction of the Southern population. And in this case, the existence of the Northern population facilitates and indeed speeds the path to extinction.[14]

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[14]None of these results should be a surprise to any student of the two-sector Neoclassical model underlying much of general equilibrium trade theory. When both populations co-exist, the two isoclines are isomorphic to full employment constraints for northern and southern carrying capacities. Northern whales are intensive in their use of the Northern habitat; Southern whales intensive in the use of theirs. The surprising result coming from an asymmetric shock would be, to a biologist, the workings of Gause's Law of Competitive Exclusion, we would associate it with the Rybczynski Theorem. The extinction result at X, is nothing more than a movement to specialization in one good (or one whale population). And yes, the condition in (3) is the sometimes dreaded cone of diversification.

III.V   The Weak and Strong Conjecture

With the classification of shocks in hand, it is now possible to distinguish between two important cases underlying The Conjecture. The previous section made it very clear that a large asymmetric shock to the South's carrying capacity, or one that is largely asymmetric but correlated, could move the system from one of mutual co-existence to one with competitive exclusion and extinction. In the next section, I develop measures of vessel disturbance that arguably, represent exactly these large and asymmetric shocks. In support of the empirical strategy I employ, a further refinement of asymmetric shocks is needed.

Consider the impact of a marginal negative shock on the South's carrying capacity (parallel results holds for a Northern shock). The impact of this shock on the South's population can be written as:

$$\Delta S = [1 + \frac{\alpha\beta}{[1 - \alpha\beta]}]\Delta K_S \tag{5}$$

Written this way its clear that there are two different forces driving the South towards extinction. First, is the direct and proportional change in the South's population from the shock to its carrying capacity ΔK_S. This is identical to what would have occurred in an isolated environment with no across-population competition. The hypothesis that vessel disturbance is in fact the cause of this negative change in carrying capacity, and there is no across-population competition, is the hypothesis I refer to as the *weak conjecture*. Under the weak conjecture, shocks to either or both carrying capacities drive their relevant populations downward but these processes are only linked if the shocks come from a common source; i.e. they are correlated.

But when the two populations are engaged in across-population competition, the second term in (5) comes into play and the original shock is magnified. This is Gause's Law of Competitive Exclusion at work.[15] If the shock is large enough only the North survives while the South is, to some extent, the victim of the North's success. I refer to this hypothesis as the *strong conjecture*. The second term in (5) is, in fact, exactly the change in N created by this same shock multiplied by the relevant competition coefficient. Therefore, when across-population competition is present, separately identifying the direct and indirect impacts of any vessel disturbance shock is likely to be challenging and may require different empirical methods than those examining the weak conjecture.

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[15]To a trade theorist its Jones' Magnification effect.

IV The Data

There are many ways to degrade the carrying capacity of the Southern Residents. Three prime suspects mentioned in the literature, and press, are: (1) a reduction in the availability of prey species caused by over-fishing, dam construction, or increased predation by seals; (2), an increase in vessel traffic interfering with hunting, socializing, and mating behaviors; (3) reduced fecundity caused by exposure to PCBs that continue to leach into the waters of the critical habitat. These alternative explanations are not mutually exclusive. In fact, they may well be reinforcing; however, thus far, no research has been able to quantify the impact of any one (or combination) of channels given the extreme difficulty of observing and then measuring the potential causal effects on a population which ranges over thousands of square miles of habitat and is, for the majority of the time, below the surface.[16]

To investigate I have collected data from six major sources, and three minor sources. Data on vessel landings and vessel characteristics obtained from Lloyd's of London; data on travel distances between ports and other important locations obtained from the vessel tracking service *Sea Routes*; data on the location of critical habitat zones taken from US and Canadian government websites; information on the potential magnitude of noise disturbances by vessel class (drawn from Veirs, Veirs and D. (2016)); data on the availability of salmon made available by the Pacific Salmon Commission et al. (2017); and data on the populations of the Northern and Southern Residents was obtained from various whale census documents.

In addition, I have also collected data, primarily used for cross-checking from three other sources. These are vessel pilotage assignments from the Pacific Pilotage Association from 1973-2020; vessel movement data from the State of Washington for various years; and international trade data from both US and CDN government sources. Of all of these data sources, the Lloyd's data is by far the most important given its geographic and temporal coverage.

IV.I Vessels: The Lloyd's List Data

Lloyd's list has been providing data on international shipping since 1778, and is the premier data provider of shipping data worldwide. Important to my study, is that unlike the many newer data providers, Lloyd's has vessel traffic data prior to the introduction of Automated

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[16]One commonly mentioned, and seemingly plausible, chain of causation is that reduced salmon availability (for whatever reason) lowers fat stores in the whales which then releases the previously trapped (in fat) PCBs into their system lowering their fecundity. Some populations of killer whales have extremely high levels of PCBs stored in fat tissues; and concentrations at these levels have been linked to lower fecundity in other marine mammals.

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. While this change in measurement methods poses some challenges, the use of a long time series of data is absolutely necessary if we are to identify changes in the fecundity of a long-lived marine mammal such as killer whales.[17]

The data obtained from Lloyd's list is contained in two related subsets. One subset of data contains, 'previous movements'. The 'previous movements' data contains information on the current port of arrival and the last two ports visited, for vessels making a landing at one of 121 ports on the west coast of North America from 1977 to 2019.[18] I refer to this set of ports as the Ports of Interest (PoI). Each entry includes the port landing, the count of vessels landing, their vessel class, and the month/year of the landing. Vessel classes include fishing vessels, research vessels, dredging vessels, tugs, passenger, and military vessels but most importantly, it contains a set of vessels commonly employed in international trade: these are, two types of tankers, two types of bulk carriers, and three classes of cargo vessels. In total, the data contains approximately 1.8 million current landings, which combined with information on their past two landings, yields information on over 5 million vessel movements.

The remaining subset is the 'vessel characteristics' set. It contains average vessel characteristics for the same vessel landings by ports/vessel type/month/year. The characteristics recorded include dead-weight tonnage, vessel length, year of build, and several measures of container capacity (when relevant). These data provide a little over 100,000 additional, but related, observations by month/year/port/vessel type.[19] The two subsets of data report information on the same set of trips, and therefore provides an internal consistency check on the data itself. Every individual vessel landing recorded in the previous movements data, must also be present in the counts recorded in the vessel characteristics data.

The data is incredibly rich with detail, and after cleaning, checking and organizing, it

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[17]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, finding AIS data prior to 2009 has proven very difficult. 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.

[18]See the Online appendix at mstaylor1.org for a list of ports and map of their location.

[19]In theory, the purpose of obtaining this information is to ensure I am comparing apples to apples in terms of vessel type and potential for vessel disturbance. The length, breadth and weight of vessels has changed dramatically over time and it also varies with the port of landing within a given vessel class. This data allows me to 'normalize' vessel trips much as we would normalize or deflate nominal variables for inflation. This work is ongoing and future versions of this paper will compare these normalized measures to the raw data I use here.

allows me to make statements like the following: 8 tankers arrived in Vancouver harbour in December of 1983, they had an average length of 121 meters, average dead-weight tonnage of 316 tonnes, and were on average 13.4 years old. Of the 8 tankers, 5 came directly from the Cherry point refinery in Washington State, 2 of the tankers stopped at ports in Oregon before arriving in Vancouver, and one tanker came directly from outside North America. The purpose of the data is, of course, to determine the magnitude of vessel movements within the critical habitat of killer whales. Before introducing my methods for doing just that, I need to define the critical habitat under study.

IV.I.1   Defining the Critical Habitat

Both the US and Canadian government have identified critical habitat 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.[20] In this paper, I will employ these original designations of CH. Critical habitat should "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.)

If all vessel trips were simple one stop voyages arriving at a port in the critical habitat from outside and exiting similarly, then the landing data could be easily matched with route distances to calculate distance travelled in the critical habitat. The world however is not that simple: many vessels make several stops in the critical habitat before exiting; some vessels stay within the critical habitat and never leave; some vessels traverse the critical habitat without every landing at any port within; and others leave the critical habitat and then re-enter before turning towards the Pacific. Therefore, the number of port landings is at best a very gross measure of vessel traffic. In the next section, I describe a method to transform the landing data into km travelled in the critical habitat for all of these trip types. Since the method is tailored to the relevant geography, it is necessary to discuss this first. Figure 6 presents a map of an area of the west coast near Vancouver, Seattle, and Puget sound, commonly referred to as the 'Salish Sea'.

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[20]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. The Online Appendix contains a map of this new area (Fisheries and Oceans Canada: Canadian Science Advisory Secretariat, 2017).
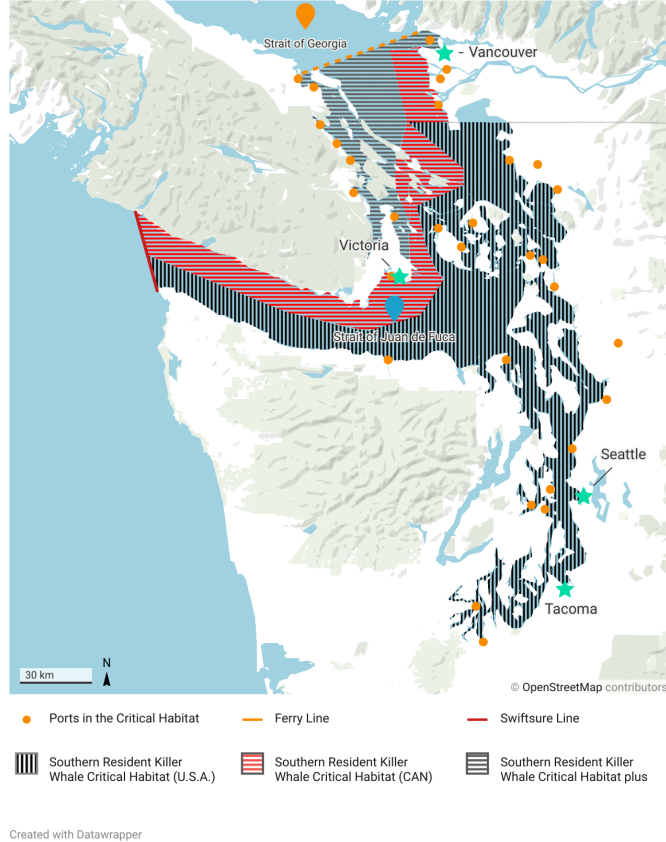
Figure 5: Designated critical habitats for Southern Resident Killer Whales

The map shows three shaded areas, and ports of interest shown with a dot. I have drawn in two bolded lines to demarcate entrances and exits from what I refer to as the critical habitat plus. The critical habitat plus (henceforth CH) is sum of the three shaded areas. Any vessel enters 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. Travel up Georgia Strait and exiting to the Pacific via the Queen Charlotte Strait is difficult, somewhat treacherous, and time consuming. Small cargo vessels, tugs, some cruise ships, and fishing vessels are the primary users of the inside passage.[21] As

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[21]In particular any vessel must travel through Discovery Passage and Seymour Narrows to Johnstone Strait before reaching Queen Charlotte strait. Seymour narrows, where the Pacific Ocean and inside water currents meet, remains a difficult passage. Historically, hundreds of ships have wrecked on the Narrows' Ripple rock and no one less than Captain George Vancouver referred to it as one of the vilest stretches of water in the

a consequence of this geography, vessel trips can be classified into a limited number of types.

The western entrance lines is drawn at Swiftsure banks off the western tip of Vancouver island. This line captures the movement of a vessel when it enters (or exits) national waters off either the US or Canada. I refer to this as the Swiftsure line or just Swiftsure. The second line is drawn from Horsehoe Bay on the mainland coast just north of Vancouver, to Naniamo on Vancouver Island, and I refer to this as the Ferry line. In this way, I close off the critical habitat in Salish sea to the north by the Ferry line, and to the west by the Swiftsure line.

The remaining 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 over estimate of the actual area since there are small areas which are not included such as bays, some ports etc. In all cases of significance, getting to these ports requires a vessel traverse the official critical habitat, and hence I believe my critical habitat plus assumption is innocuous. For example the Port of Vancouver is not within the official critical habitat but entry from the Juan de Fuca requires passage through the zone, and I will count km to the Port itself rather than the entrance to Burrard inlet. The same is true for several other ports. This will inflate the km travelled within the zone slightly, but consistently over time. It is also true that vessels do not necessarily follow their proscribed minimum km routes to ports as given by *Sea Routes*[22] The purpose of this simplification is solely to allow me to calculate distances to a port rather than pick an arbitrarily chosen exit point along the edge of the official habitat.

IV.II   Vessel Arithmetic

With the critical habitat defined, I now divide vessel trips into one of five, mutually exclusive and exhaustive, trip categories: incoming, within, outgoing, pass through, and irrelevant. Since I would like to identify the role of international trade, it proves useful to divide outgoing trips into those outgoing to domestic ports (somewhere else in North America) and those outgoing to foreign ports. To do so I exploit, what is in effect, a vessel-version of Walras's Law.

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world. In 1958, the Canadian government used underwater explosives to lower Ripple Rock and make passage easier. Nevertheless, even today large ships can only pass during slack tide.

[22]For example, many vessels lay up in the sheltered coast of Vancouver Island near Valdes, Thetis, and Penelakut island before proceeding to Vancouver or other major ports.

IV.II.1 Vessel Trip Types

A trip is identified by its origin (previous port) denoted by o, and its destination (landing port) denoted by d. Although the data contains detail on vessel types and month of landing, this level of detail is not required to define trip types and is ignored here. Let X_{odt} be the number of trips from origin o to destination d at time t. The "length" of t can be as short as one month, but for the most part it is useful to think of time in calendar years.

Incoming trips are vessel trips originating outside the CH but landing in the CH. Let u_c be the set of ports (33 elements) within the CH, then incoming trips during t, or I_t, are:

$$I_t = \sum_{i \notin u_c} \sum_{j \in u_c} X_{ijt} \tag{6}$$

where $i \notin u_c$ is the set of all ports (domestic and foreign) not in the CH.

Trips with origin and destination ports within the CH are defined as *Within trips*. These are given by W_t where:

$$W_t = \sum_{i \in u_c} \sum_{j \in u_c} X_{ijt} \tag{7}$$

Outgoing trips are trips originating within the CH, but having destinations outside the CH. In obvious notation, these are trips satisfying:

$$O_t = \sum_{i \in u_c} \sum_{j \notin u_c} X_{ijt} \tag{8}$$

Pass Through trips are trips originating and ending outside the CH, but whose voyage traverses the CH. Denote by u_p the set of Pass through ports outside the critical habitat but connected by a voyage traversing the critical habitat. In obvious notation, these are trips satisfying:

$$P_t = \sum_{i \in u_p} \sum_{j \in u_p} X_{ijt} \tag{9}$$

If we let U be the universe of all ports in the world, then *Irrelevant trips* are trips with origins and destinations in U but not in any of the four categories defined above.

An example of the routes reflected in Incoming and Outgoing trips together with their destinations/origins is presented in the figure below.

Figure 6: Incoming and Outgoing Trip Types

IV.II.2   Walras' Law

Because pass through trips by definition - pass through the habitat - total vessel landings in the CH over period t, VL_t, are simply the sum of incoming and within trip landings:

$$VL_t = I_t + W_t \tag{10}$$

All vessels landings lead to subsequent port exits. Exits from a port in the CH must also, be recorded as either outgoing trips or exits arising from within trips. Putting this together, implies:

$$
\begin{aligned}
VL_t &= VE_t \\
VE_t &= O_t + W_t
\end{aligned}
\tag{11}
$$

The equations in (11) reflect a vessel in / vessel out assumption. The data itself is described by Lloyd's as representing both a landing and its exit, so the only assumption involved is that both occur in the same period t. Therefore, all landing vessels in t exit in t; as a result,

$VL_t = VE_t$. This is effectively budget balance applied to vessel trips in aggregate over the period of t. Another application of the assumption is reflected in the division of exits given in the second line. Every within trip creates both a landing and an exit within the CH; therefore total exits equal within trip exits and outgoing trips.

My data only contains landings at North American ports. This implies that any vessel exiting from a CH port to a foreign port is not observed in the data. However, if the vessel in / vessel out assumption holds, we can, however, measure these foreign destined trips as well.

To see how, first note using (10) and (11) we have

$$I_t = O_t \tag{12}$$

Because incoming trips are measured, and outgoing trips consist of both outgoing trips to domestic ports (measured), and outgoing trips to foreign ports (unmeasured), it follows that:

$$I_t = \sum_{\substack{i \in u_c}} \sum_{\substack{j \notin u_c \\ j \in \underline{u}}} X_{ijt} + \sum_{\substack{i \in u_c}} \sum_{\substack{j \notin u_c \\ j \in \bar{u}}} X_{ijt} \tag{13}$$

where $\underline{u}$ is the set of ports in North America (PoI) and $\bar{u}$ is the set of ports outside of North America (PoI). In obvious notation, the first term in (13) is outgoing domestic trips, OD_t, and the second is, outgoing foreign trips, OF_t. Using this notation, and rearranging shows

$$OF_t = I_t - OD_t \tag{14}$$

Outgoing foreign vessel trips can be found by use of landing data relevant to the CH, and outgoing trips to domestic ports.[23]

IV.II.3 Result 1: Walras Law

In Table 1, I leverage the Vessel Arithmetic developed above to provide trip figures for vessels departing the CH over two time periods. The time periods divide the sample years into two

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[23]This is indeed Walras' Law. The vessel in/out assumption is budget balance and it implies that demand for landings (across all trip types) must be met with supply of exits (across all trip types); i.e, the sum of excess demands by trip type must sum to zero. Every within trip creates its own demand and its own supply which then necessarily balance. Incoming trips create a demand for landings that must be met with a supply of exits coming from either domestic destined exits (measured) or foreign destined exits (unmeasured).

roughly equal time periods, and differ greatly in the extent of vessel traffic.[24] I 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. Although the table is rather busy, several features stand out.

First, summing the two period totals from the All Departures column shows there were approximately 300,000 trips by large commercial vessels recorded as departures from CH ports over the entire time period. 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. The increase in 55,000 represents a 46% increase in trips. Therefore in some sense traffic in the Salish Sea has increased significantly.

Columns (2), (3), and (4) tell us where these departures are destined to land. For example, the Domestic departures column represents those departures from US (CDN) ports within the CH that were destined for other ports in the US (Canada). These trips are not directly involved in international trade, and their share of total departures fell from 51% of total departures to 42%. Their absolute number grew however by approximately 12,000 trips. Therefore, it seems safe to assume that 12,0000 of the increase in 55,000 trips are not associated with growing international trade.

The last two columns record departures 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. Surprisingly, these within North America trips fell over the period, not only in percentage terms but in absolute numbers from 53,987 to 40,106. Therefore, 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 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 4600 in the earlier period to 61,061 over the latter. One conclusion is inescapable: commercial vessel traffic in the Salish Sea has growth 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 trips to international markets outside of North America.

A second, and somewhat speculative, conclusion is that when we substitute, a (shorter) within US/Canada trip with a (longer) US/Canada to third foreign market trips, total vessel

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[24]A similar table can be constructed directly from the data on arrivals, and can be found in the Online Appendix at mstaylor1.org.

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, unitised.
**: 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

km travelled within the CH would rise even absent a change in overall trip numbers. Therefore, dividing trip data by trip types is bound to be important: the composition of trips matters.

Finally, the table provides a warning. Departures did rise by 55,000 over a twenty year period. This amounts to an annual increase of perhaps 2750 departures spread out over potentially many ports. Since departures must be matched by arrivals, this could represent 5500 in and out trips. If each trip was to a large port (Seattle, Tacoma, Vancouver) far from Swiftsure Banks, the km travelled would be about 300 km each way, implying that Annual vessel km travelled in the habitat grew by 1.65 million km over the time period - which is a very large number! As it turns out, this figure is almost double of what actually occurred, and the method of its calculation flawed because of serious double counting. This is exactly why we need the Vessel Arithmetic outlined previously. Traffic and total trip numbers alone are almost useless.

IV.II.4   Result 2: Distances in the Critical Habitat

To find the km travelled within the critical habitat, I transform the information on trip types into measures of the net distance added by each vessel trip within the critical habitat.

It is useful to fix ideas by considering an artificial vessel trip made by a cargo ship originating in the port of Los Angeles. After leaving port and heading north past the coast of Washington State it enters the Salish Sea via the strait of Juan de Fuca. Its first stop is Tacoma WA where it unloads containers before leaving for the port of Point Roberts BC where it unloads more containers and takes on bulk cargo. It then turns north moving through Georgia Strait leaving the CH at the ferry line, and eventually landing in Campbell River BC. It again offloads cargo and adds frozen salmon to its hold. It leaves Campbell River, turns south and re-enters the CH, traverses Boundary pass and then exits to the Pacific Ocean via the Juan de Fuca strait. There it turns west for an ocean voyage landing in Asia in 50 days time.

This one voyage would appear as four current landings in the data: Los Angeles, Tacoma, Point Roberts and Campbell River, but only two of these are in the critical habitat. The eventual landing in Asia does not appear in the data. Each landing will appear as one of perhaps many cargo vessels arriving in these busy ports during the relevant month/year combination. There is little hope of tracing the vessel's exact path through data, and less still in identifying its characteristics. There are of course millions of trips like these in the Lloyd's data.

For each landing observed in the data, I count only the net contribution in terms of km traveled from its previous port to its current landing port. In essence, I am calculating something akin to value-added (km in the CH) from transactions data (all possible landings) by only counting the value of final sales net of intermediate purchases (the distance from the current landing from previous port). The distance this same vessel travelled in the zone to get to the previous port is ignored, since, in theory, it will be captured elsewhere when it appears as this vessel landing at that specific port (just as intermediate goods producers will record final sales they made to producers). Using this method, I do not need to track individuals vessels to count up their movements within the critical habitat – just as we do not need to access firm level data to calculate GDP: industry - read vessel/port - aggregates will do just fine.

To see the method in action, reconsider the artificial voyage. The first trip to Tacoma would add km in the critical habitat equal to the distance from Swiftsure Banks to the port of Tacoma. It would be identified in the data by using the fact that its current port is Tacoma,

its previous port Los Angeles was outside the critical habitat, and this previous port is not located anywhere north of the ferry line along the inside passage. Therefore, this vessel must have entered via international shipping lanes from Swiftsure to the Port of Tacoma. The km of this travel is collected from the voyage planning company, *Sea Routes*, and entered as an incoming trip distance for that vessel type in a given month/year.[25] Aggregating across all incoming trips of this type, gives us the km travelled by incoming trips in period t, which I denote by K_{It}. It is simply:

$$K_{It} = \sum_{i \notin u_c} \sum_{j \in u_c} X_{ijt} k_{sj} \qquad (15)$$

where k_{sj} is the km distance travelled from Swiftsure banks, s, to port j in the CH. The trip from Tacoma to the Fraser River would be identified by its current port being the Fraser River while its previous port was Tacoma. Since both are within the critical habitat this trip would contribute to the within distances travelled in the critical habitat. I aggregate across all trips of this type to find the total within distances during t, are given by K_{Wt}. This is simply:

$$K_{Wt} = \sum_{i \in u_c} \sum_{j \in u_c} X_{ijt} k_{ij} \qquad (16)$$

where k_{ij} is the km travelled from port i to j both in the CH.

The next leg of the vessel's journey to Campbell River on Vancouver Island would be identified by its current port Campbell river, which is outside the critical habitat, but with its previous port, the Fraser River port, being within. Since Campbell River is north of the ferry line in Georgia Strait, this landing would be allocated a distance from the Fraser River port to the ferry line. Again this distance is obtained from *Sea Routes* and would add to the distance for outgoing trips for this vessel type/month/year.

Using now similar notation, the sum total of these trips is given by:

$$K_{Ot} = \sum_{i \in u_c} \sum_{j \notin u_c} X_{ijt} k_{ig} \qquad (17)$$

where the outgoing distance k_{ig} is either to Swiftsure k_{is} or the Ferry line, k_{if}.

The next part of the journey is a Pass through trip. It is identified by three criteria: one,

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

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its current port is outside the critical habitat; two, its previous port was within Georgia Strait north of the ferry line; and three, its current port is not further north along inside passage. There are a relatively small number of ports along the inside passage, in Georgia Strait and below Seymour narrows. For trips involving these ports, I assume vessels turn south and retrace their step down Georgia Strait to Juan de Fuca, and then exit to the Pacific. The km given to this trip are from the ferry line in Georgia Strait down through the Salish Sea and out to the Pacific passing the line at Swiftsure. This distance is obtained from *Sea Routes* and would add to the distance for pass through trips for this vessel type/month/year.

In obvious notation, these trip distances are given by:

$$K_{Pt} = \sum_{i \in u_p} \sum_{j \in u_p} X_{ijt} k_{fs} \tag{18}$$

The sum total of incoming, within, outgoing and pass through trips in any given year is the kilometer total denoted by KT_t.[26] Since the vessel landing data has both vessel type and month variation, this total can be made vessel type specific (Unitised or Bulk for example), can weigh vessel km of different vessel by impact factors tied to vintage, dwt or length, and can limit the time dimension to any portion of the years thought to be especially important for foraging or reproduction (such as the very important summer months). Therefore, if vessel disturbance is sensitive to vessel type or more important for some months of the year than others, it is possible to alter the relevant sum of vessel miles in the habitat to investigate these possibilities. The method appears to be a very powerful tool for examining the likelihood of vessel disturbance on marine mammals.

Below I plot the calculated vessel km in the CH, for various vessel types, over the entire time period.

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[26]Outgoing trips to foreign ports from a port X in the CH are allocated the average distance of incoming trips to that port in the relevant vessel type/month/year cell.

Figure 7: Vessel Km in Critical Habitat
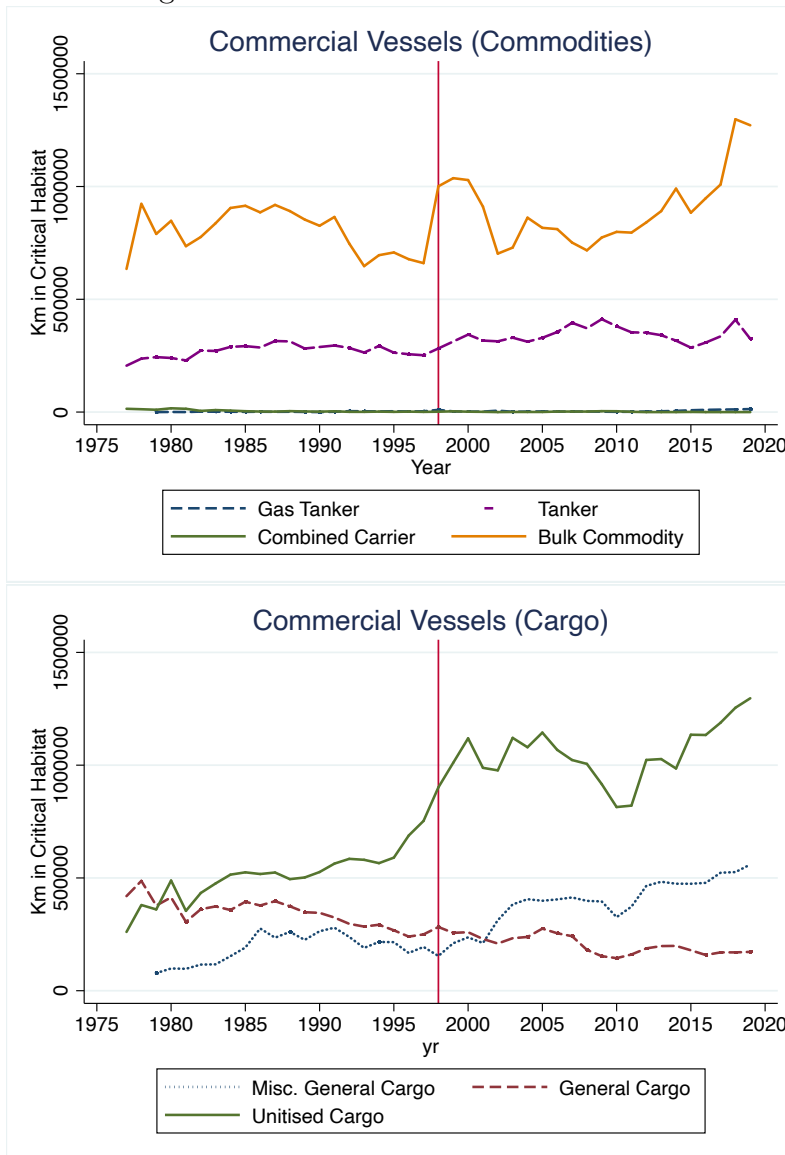
Figure 8:

Four features stand out. First, the vast majority of km in the critical habitat come from Bulk carriers and Unitised (container) Cargo ships. Tankers and Combined Carriers make up an infinitesimal contribution, followed by that of Gas 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

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total vessel km grew tremendously over this period more than doubling from a little over 1.5 million km in 1977 to over 3.5 million in 2019. In annual average terms, over the pre-and-post 1998 periods indicated by the vertical line, vessel km in the CH rose from 2.1 million to 2.9 million. This represents an annual average increase of 800,000 km or 36%. This difference in means is also highly significant. Note that this 800,000 figure is about half of the 1.65 million km of my earlier naive calculation. Fourth, and finally, it is obvious that what is driving most of the increase is the change in km travelled by Unitised (container) shipping. Moreover this increase first takes off in the late 1990s remains very high for almost ten years only to fall during the credit crisis years to then recover and continue its growth entering 2019. [27]

V   Empirics

I have presented only summary statistics and simple graphs to suggest a causal link between changing whale populations and increased vessel disturbance in the Salish Sea. To investigate further, I proceed in two steps following the division of the *Orca conjecture* into its two subsidiary hypotheses.

The *weak conjecture* maintains that increased vessel disturbance linked to international trade has lowered the quality of the SRKW critical habitat, and as a consequence the steady state population of both the NRKW and SRKW. Under the weak conjecture, $\alpha = \beta = 0$, and in terms of Figure 3, the North's (now) horizontal isocline and the South's (now) vertical isocline intersect at a point like A. Point A is, again, the only interior stable steady state. Negative shocks to their habitats would lower their individual carrying capacities, moving any new steady state to a point Southeast of A.

The *strong conjecture* maintains that the vessel disturbance shock to the SRKW critical habitat has been magnified by the existence of the competition from the NRKW, and, via the principle of competitive exclusion, is driving the SRKW to extinction. Under the strong conjecture, the NRKW and SRKW populations are linked by the competing species model because $\alpha \neq 0$ and $\beta \neq 0$. While the negative shock may partially fall on the NRKW, the

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[27]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 travelled. While there is a strong seasonal component to whale watching, fishing and cruise ship activity none of these are in my commercial vessel categories which show very little seasonal influence.

impact of the vessel disturbance shock is large enough to ensure extinction of the SRKW; that is, it is exactly as discussed and shown in Figure 4.

I evaluate the weak conjecture first, and then turn to examine the more nuanced, and more difficult to evaluate, strong conjecture. To do so, I adopt methods commonly employed by economists studying Malthusian population dynamics. Since Malthus was the inspiration for Darwin survival of the fittest, and Darwin the inspiration for Gause's Law of Competitive Exclusion, we have now run full circle by adopting an economic approach to solve a biological puzzle.

V.I   Back to Malthus

Population growth is by definition the difference between births and deaths. Assuming the stock (or biomass) of a population is proportionate to its numbers, the population growth of $SRKW$ whales can be rewritten using (2) as:

$$\frac{dS}{dt} = S[B_S - D_S] \tag{19}$$

where in obvious notation, $B_S - D_S$ is the rate of births minus deaths, which in turn is a function of underlying parameters driving (2). Under the weak conjecture, the SRKW population density setting (19) to zero is K_S. A similar equation and implication holds for the NRKW. In Malthusian (biological) terms, these population levels are those sustainable given their implication for per capita income (carrying capacity).

Births and deaths are discrete and uncertain events recorded only annually in my data. Let $dt = \Delta t$ equal one year and model births and deaths as Bernoulli random variables where, in obvious notation, this implies:

$$b_N = \begin{cases} 1 & \textit{if a birth occurs} \\ 0 & \textit{otherwise} \end{cases} \tag{20}$$

$$d_N = \begin{cases} 1 & \textit{if a death occurs} \\ 0 & \textit{otherwise} \end{cases} \tag{21}$$

Since births and deaths are not uniformly distributed across an undifferentiated biomass of the competing species model, S, I now divide the killer whale populations into k mutually exclusive groups. Whales within a given group i share relevant attributes (age, sex, pod affiliation, population, etc.) and each group has n_i members. The number of whales at any

moment is just n_i summed over the k groups.

If the probability of a population event for any one member in group i, is independent of other realizations in that group, then it is very well known that the distribution of births (or deaths) is binomial with each whale in group i having the probability π_i of the relevant population event (birth/death).[28] The expected birth rate (death rate) for the entire population as a whole is a n_i weighted average of the relevant π_i across the k groups.

For simplicity, and to aid comparison to existing work in biology on KW, I model the log odds of population events as a linear function of the factors determining k group membership; that is:

$$\log(\pi_i/(1 - \pi_i)) = x_i'\beta \tag{22}$$

where x_i is a vector of attributes determining membership in the i group, and β_i the regression coefficients to be estimated.[29] For the most part, I will follow the Malthusian tradition of assuming the determinants of births and deaths to be the same, albeit with some minor differences introduced by the 15-18 month gestational lag of killer whales. Prime candidates for inclusion in x_i are environmental determinants of carrying capacity (salmon abundance and vessel disturbance) and a measure of competition for the scarce carrying capacity (both within and across populations). Important demographic determinants of life events are age, sex and possibly population affiliation.

When researchers estimate an equation like (22) on human populations, the key econometric issue is the endogeneity of income, which researchers address by finding exogenous shocks to productivities which then drive exogenous variation in incomes.[30] In our context, matters are simpler. Unlike national income which increases with population or labor force growth, the environment's carrying capacity is not endogenous to whale numbers. And shocks that create exogenous variation in the per capita availability of habitat, such as the abundance of prey, the (noise) quality of the habitat, and overall population numbers are arguably exogenous to any k group outcome.[31]

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[28]The independence assumption across whales within a group rules out some silly possibilities such as whales dying from grief when another k group member's calf dies during birth; but also some more realistic dependence that might arise from the sharing of food and joint hunting strategies both of which have been observed for KW.

[29]The logit specification is commonly used by physical scientists in biology and ecology; moreover it has been used in influential work on KW in particular. See Ward, Holmes and Balcomb (2009)

[30]See for example Ashraf and Galor (2011) and Lagerlöf (2015).

[31]Vessel km are clearly exogenous; variation in salmon availability, as shown later in Figure 18, is driven largely by ocean wide events not KW predation; and overall KW population numbers can at best respond

V.II   The Weak Conjecture

Under the weak conjecture, NRKW and SRKW population events are independent although they may be driven by similar, and sometimes common, factors. I divide these factors into those that are species specific - such as demographic determinants of fertility by age - and those that may be population specific - measures of vessel disturbance and whale population density. Any fertility determinant that is (potentially) population specific calls for a main effect and a population specific interaction term.

Unobserved commonalities within the populations suggests errors should be clustered, although it is unclear at what level. One option is to cluster at the matriline. Matrilines are the most stable family unit since membership is lifelong. And whales rarely travel far from other matrilineal members which suggests they may experience common (unobserved) shocks. Matrilines are however quite small and as a result several matrilines die out over the sample period, which would render the number of clusters variable and potentially endogenous. In contrast, pods (which consist of many matrilines) are also very stable social structures. Whales in the same pod typically travel together, suggesting common exposure to vessel noise and prey availability, and the number of pods has been stable throughout the sample period. Moreover, I will at times allow exposure to treatment (vessel disturbance) to vary with pods. The acoustic grouping, clans, and the geographic grouping, populations, are much larger aggregates, but also very heterogeneous in terms of the location and travel of their pod members which argues against clustering to reflect common unobserved effects. Perhaps more importantly, the number of clans and populations is also incredibly small (two for populations). In light of these choices, I adopt the pod as the unit for clustering errors. There are 19 pods across the sample of two populations.

V.II.1   Births

It is well known that female whales reach sexual maturity by their mid teens and remain potentially reproductive into their early forties.[32] 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. This feature of their reproduction is shown graphically below and, then more concretely, in table form. The fecundity of KW is maximized near an age of

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only minutely to current population events.

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

20 when almost twenty percent of females in this age category will succeed in giving birth. Fecundity falls off dramatically after the age of 40 with a lengthy period of senescence starting in their late 20s.

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

Figure 9: Percentage of females with births by age in the pooled RKW populations, 1979-2019
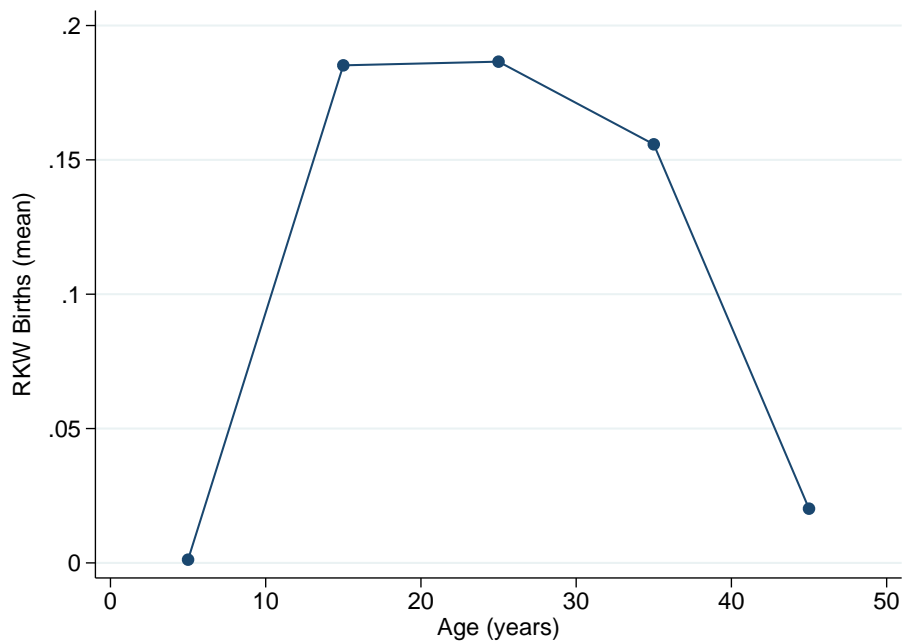
Table 2: Births in the pooled RKW populations by age, 1979-2019

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

In Table 3 below I investigate the basic demographic and environmental determinants of KW births. The most parsimonious and restrictive models appear in the first column, with more general versions following as we move rightwards. Several features are noteworthy. First, the coefficient estimates governing the polynomial in age are stable across all specifications with only small differences in magnitudes as we move from column I to IV. 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 unclear and best left to Figure 10 which I soon discuss.

Second, in columns II -IV, the indicator variable for a whale belonging to the NRKW is positive and significant. The coefficient estimates on NRKW differ somewhat across columns with the mode of about .5. There are a variety of ways to interpret this .5 coefficient. One way is to note it implies the odds of a birth for a NRKW is 65% higher than for a SRKW - which is considerable.[33] More concretely, recall that average fecundity at 20 was almost .2. If we adopt this as the baseline fecundity of a SRKW 20 year old, then the estimated NRKW coefficient implies the probability of birth of a similarly situated 20 year old NRKW is almost .3. It therefore implies a large difference in the probability of successfully calving. Why this would be true is unclear.

Third, in columns III onward there is evidence that prey availability matters to fertility. I follow the literature in using one year lags for any shock to fertility given gestation is 15 to 18 months for KW. High salmon years appear to raise subsequent fecundity, while low salmon years reduce births considerably. The mean and standard deviation of the salmon

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[33]Because exp[.5]=1.648

index, over the entire period, are 1.15 and .28 respectively. Therefore a one std. deviation good salmon year raises the odds of a birth by a little over 11%; a great, two std. deviation salmon year raises them 23%. These are significant but not extremely large effects.

Table 3: Baseline Demographic Determinants of Fertility

	I.	II.	III.	IV	V.
Constant	−18.05***	−18.37***	−18.94***	−18.82***	−25.24***
	(1.51)	(1.47)	(1.52)	(1.5)	(3.4)
Age	2.77***	2.74***	2.78***	2.78***	3.96***
	(0.29)	(0.29)	(0.29)	(0.29)	(0.68)
Age^2	−0.16***	−0.16***	−0.16***	−0.16***	−0.24***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.05)
Age^3	0.0039***	0.0039***	0.0039***	0.0039***	0.006***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Age^4	−0.00004***	−0.00003***	−0.00004***	−0.00004***	−0.00006***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
NRKW		0.54***	0.54***	0.83***	7.95**
		(0.1)	(0.09)	(0.22)	(3.67)
L1.Salmon Abundance			0.37***	0.34***	0.34***
			(0.13)	(0.12)	(0.12)
L1.Within-Competition				−0.002	−0.002
				(0.0013)	(0.0013)
Age × NRKW interactions	No	No	No	No	Yes
N^a	5,821	5,821	5,707	5,707	5,707
Log likelihood	-1452.72	-1440.33	-1411.76	-1410.27	-1407.6

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

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

Fourth, in columns IV and V, I find what may be evidence for within-population competition. In theory it arises from competition for prey, and hence its coefficient is also lagged one period. The coefficient estimate implies that adding 100 whales to the population, would reduce the odds of a birth by 20%, although this estimate is not significant at standard levels. Given the difference already found for the NRKW main effect, I allow for a full set of NRKW x Age interactions in column V. There are small changes to the existing coefficient estimates and a small change in the log-likelihood, but the implications for any NRKW vs. SRKW fertility comparison are now far less clear.

To complete our discussion of these baseline determinants, and clarify the NRKW vs SRKW fertility differences, I plot the predicted probability of birth at various ages in Figure 10 using the regression estimates from column V. The panels differ in terms of the population

considered, and the two lines in each panel correspond to the state of a low salmon index (evaluated at one std deviation below its mean) and high salmon index (evaluated at one std. deviation above).[34] The figure shows very well the rapid rise in fecundity with age, the slower decline post its maximum near age 20, the period of senescence with the eventual steep drop off after 40. The large differences across panels reflect the impact of the NRKW interactions, while the smaller differences within panels reflect salmon availability. Overall, Table 3 and Figure 10 provide a strong foundation for examining the potential impact of vessel disturbance.

Figure 10: Fecundity by Age, Population, and Salmon Availability
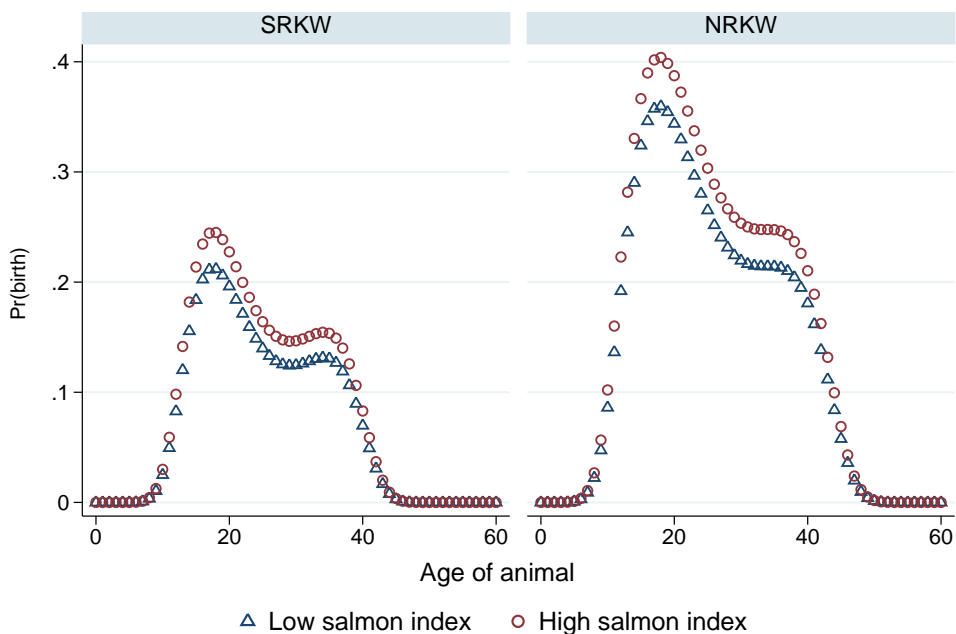
I now extend the demographic and environmental model to include potential effects from vessel disturbance. One difficulty in doing so is deciding on a metric for *disturbance*. Guidance from the relevant physical sciences literature is limited given the difficulty of observing KW in the wild in suitable experimental conditions.[35] In general, vessel noise can affect

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[34] I set the within-competition coefficient to zero in the figures.

[35] For example, a recent Fisheries and Oceans Canada report states "Similarly, the types and levels of underwater sound that cause short-term and long-term effects on Resident Killer Whales are poorly known. There has been considerable recent research on the noise levels in Resident Killer Whale habitats and responses of the animals to such noise, but thresholds that might result in critical habitat destruction are still unclear" Fisheries and Oceans Canada: Canadian Science Advisory Secretariat (2017), p10.

communication, foraging, reproduction, navigation and in some cases, predator avoidance.

Despite the difficulties involved in evaluating the hearing of marine mammals in the wild, novel work by ecologists and biologists has established that: commercial vessels emit sounds at frequencies KW use for both communication and echolocation (Hall and Johnson, 1972); measured noise disturbances from marine vessels *in situ* are significant and long lasting (McKenna et al., 2012); Unitised vessels (i.e. container ships) are the loudest of all commercial vessels with vessel speed increasing disturbance (Veirs, Veirs and D., 2016); whale behaviour changes when vessels are near with changes to diving, socializing and foraging creating an energetic cost to whales (Williams, Trites and Bain, 2002), (Williams et al., 2014); and finally, constant, high amplitude background noise can drive KW from an area (Morton and Symonds, 2002).

Since underwater noise pollution is both new and unfamiliar concern for researchers in economics, it might be useful to put these findings in more human terms. 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).[36] Sounds 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, its important to recognize that large commercial vessels are surprisingly noisy with decibel levels at the source of up to 180 db; to put this in perspective, humans suffer permanent hearing loss if exposed to 100 db for 5 minutes, while 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. Of the commercial vessels I study, the group of bulk carriers and most cargo ships and tankers have a similar noise impact, whereas container ships (Unitised cargo) have a significantly different noise signature.[37]

Despite these major accomplishments by the biology community in detailing the probable

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

[37]For variation across vessel types see McKenna et al. (2012) and Veirs, Veirs and D. (2016). And while most studies focus on exposure relatively near the source ($\leq$3km for example), it is disconcerting that McKenna et al. (2012) finds vessels even 20km away (cargo ships) generate noise signatures discernible from the background. Many studies, including the two mentioned above, provide evidence linking noise output (measured in decibels) and a vessel's speed. A good introduction to the issue of vessel noise that contains a literature review is Southall et al. (2017).

chain of causation, researchers have, as of yet, failed to link increasing ocean noise pollution to a population level event - like births or deaths of a marine mammal. In the face of this abyss, I proceed cautiously, conservatively and hopefully transparently.

I start by first aggregating across all vessel types to examine the impact of total vessel km in the CH. In column I of Table 4, I simply add total vessel km (measured in millions of km per year) to the already established model for births. Total vessel km includes all the commercial categories shown in the two panels of Figure 7. Because whales from the NRKW spend far less time in this CH, in column II I introduce an interaction term to differentiate between the impacts on the NRKW and SRKW populations. Taken at face value, the coefficient estimates and significance levels in column II indicate a strong negative relationship between fecundity and vessel disturbance for the SRKW. To put this in perspective, the average km travelled per year in the CH by commercial vessels over the 1977-1997 period was to 2.1 million; in the post 1998 period it rose to 2.9 million. Using this .8 million km change as our metric, the estimates from column I imply a fall in the odds of a SRKW giving birth of 32%. Adding the relevant coefficients, the estimated impact on the NRKW is smaller but is positive.

Because Unitised vessels are considerably noisier and faster than other vessel classes, I divide total vessel km into those of Unitised vessels and the sum of all other vessels in columns II onwards. In Column II I again allow the impacts to differ by populations and this again appears to be very important with the SRKW impact being strongly negative, while that on the North is smaller and positive. These coefficients again imply very large negative impacts on the SRKW and smaller, but still positive impacts on the NRKW. For logical completeness, I evaluate the impact of all other commercial vessel km in Column III. Perhaps not surprisingly, the measures of disturbance are now much smaller and insignificant. Finally, in column IV I include both measures of vessel disturbance. The results are similar to those reported in Column II. and III. The km travelled by Unitised vessels is clearly important; other vessel km may have no effect at all. Since column IV nests column II and III, it is possible to evaluate using standard model selection criteria; given the changes in the log-likelihood, the more parsimonious column II is preferred.

Table 4: The Impact of Vessel Disturbance on Fertility

	I.	II.	III.	IV.
Constant	−24.00***	−24.45***	−24.24***	−24.33***
	(3.42)	(3.30)	(3.71)	(3.65)
Age	3.98***	3.96***	3.99***	3.97***
	(0.66)	(0.66)	(0.67)	(0.66)
Age^2	−0.24***	−0.24***	−0.24***	−0.24***
	(0.04)	(0.04)	(0.05)	(0.04)
Age^3	0.01***	0.01***	0.01***	0.01***
	(0.001)	(0.001)	(0.001)	(0.001)
Age^4	−0.0001***	−0.0001***	−0.0001***	−0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
L1.Salmon Abundance	0.33***	0.32***	0.35***	0.32***
	(0.13)	(0.12)	(0.12)	(0.12)
L1.Within-Competition	−0.004**	−0.004**	−0.002	−0.004**
	(0.002)	(0.002)	(0.002)	(0.002)
Total Vessel km	−0.49***			
	(0.14)			
Total Vessel km × NRKW	0.73***			
	(0.19)			
Total Unitised km		−0.81***		−0.76**
		(0.06)		(0.37)
Total Unitised km × NRKW		1.34***		1.30***
		(0.26)		(0.48)
Total Other km			-0.65	-0.11
			0.58	0.87
Total Other km × NRKW			0.74	0.11
			0.68	0.95
NRKW & NRKW × Age	Yes	Yes	Yes	Yes
N	5,707	5,707	5,707	5,707
Log likelihood	-1404.9851	-1404.273	-1406.7047	-1404.2572

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

Distances are measured in million km.

[a]: "Total Other km" is the vessel total less the distance traveled by unitised vessels.

[b]: N records the number of female-whale-years

Despite the sometimes changing magnitudes across these columns there is much similarity. Across all columns the basic demographic determinants of fertility remain in all cases. The size, sign and significance of salmon abundance remains and the estimated precision of Within-Competition improves markedly.

One puzzling feature of the results is the small positive effects on the NRKW. Under the weak conjecture, we would expect that a negative shock to the SRKW would have no effect on the SRKW or perhaps a small negative effect since they shared part of the Salish Sea CH. The finding of slightly positive effects is therefore slightly concerning, although it

may be reflective of across-population competition which is ruled out here by assumption. In contrast, the vessel disturbance impacts on SRKW births are always found to be large, negative, and significant. Vessel km are found to be important when they come from the noisiest class of vessels, which we know have also increased the most over the sample period.

V.II.2 Deaths

The demographic and environmental determinants of death are very standard and similar to those for births: age, access to prey and gender. Before proceeding to a regression analysis, in Figure 11, I present the mean death rate at various ages. Since deaths early in life are very common the 0-9 year window has been divided above and below the age of 4. As shown there is significant neonatal fatality which declines quite quickly so that by a whale's mid-teens mortality is at its lowest. Thereafter mortality rises with age with an especially steep increase post 40. Although there are some very old whales in my sample, the age axis is cut off at age 50 for presentation. This same information is presented in tabular form in Table 5 where it is easier to see that mortality does not rise to the neonatal level until whales are past 40 years of age. The figure and table again suggest a specification for deaths with a higher order polynomial in age.

Figure 11: Percentage of deaths by age in the pooled RKW populations, 1979-2019
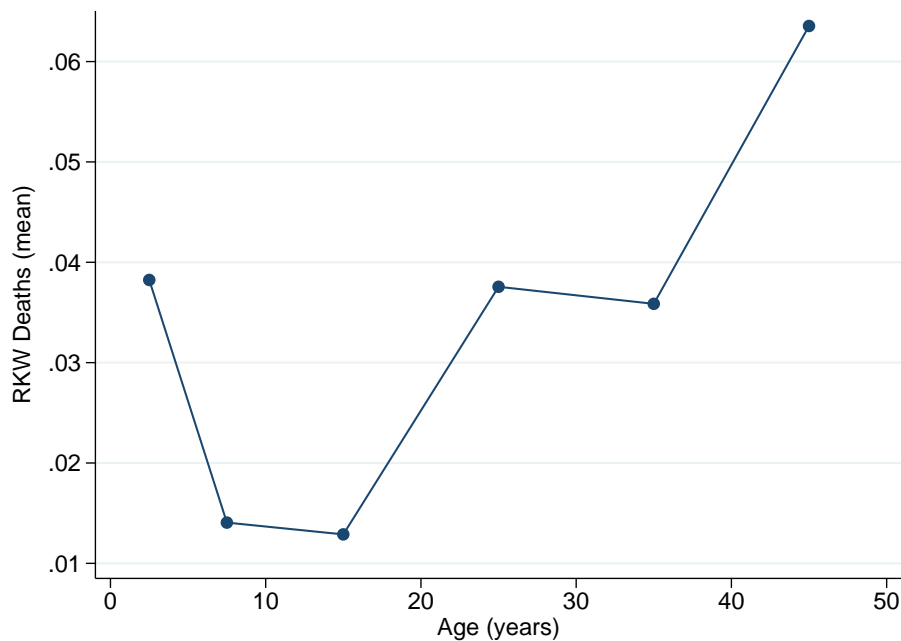
Table 5: Deaths in the pooled RKW populations by age, 1979-2019

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

In Table 6 below I investigate the basic demographic and environmental determinants of KW deaths. As before, less restrictive models are estimated 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 as we move from column I to V. Differences, when they do arise, occur when I introduce a full set of Male x Age interactions in Column III, and then a full set of NRKW x Age interactions in Column IV forwards. Mortality falls steeply at first, and eventually rises although the exact shape is best left to Figure 10 which I will soon present.

Second, in Columns I-II there is a singular indicator variable for a whale being male. These coefficient estimates are clustered around .34 and are highly significant, indicating the odds of death are significantly higher for males. In columns IV and V, I add interactions of Age with Male and then also Age with NRKW. Judging from the change in the log likelihood, the Age interactions with Male appear to be the most important. This is not surprising since many female KW live past 60 whereas this is unheard of for males.

In columns II onward there is consistent evidence that prey availability matters to mortality. Interestingly, the impact of a bad salmon year are more than twice as large as they were for births.[38] Unlike the case of births, it is unclear whether this year's or last year's

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

prey availability matters, so in Column V I include both. It appears lagged abundance is the more relevant of the two. Finally, there is little evidence that within-competition affects deaths. The coefficient signs vary across columns and are never precisely estimated.
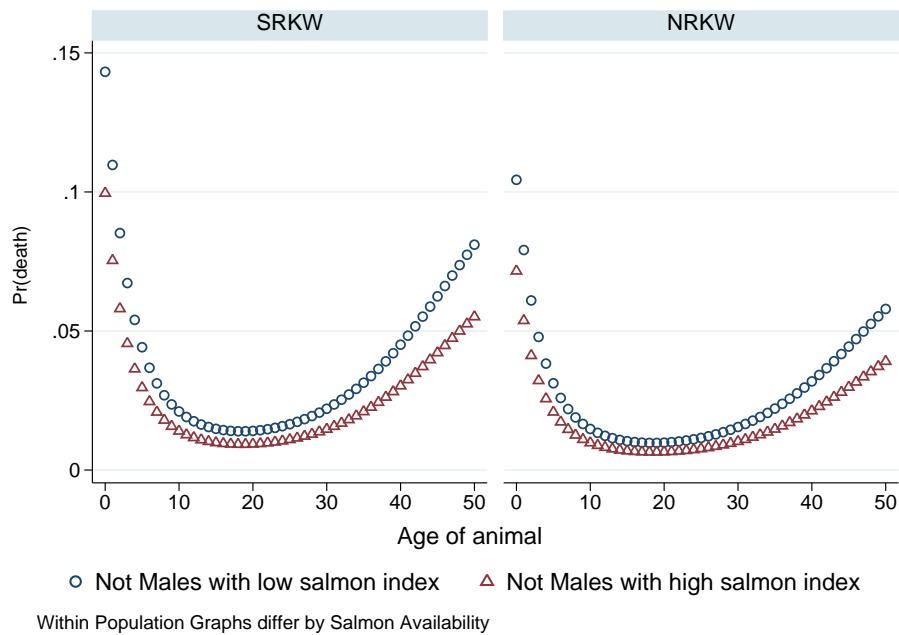
Table 6: Baseline Demographic Determinants of Mortality

	I.	II.	III.	IV.	V.
Constant	-2.97^{***}	-2.09^{***}	-1.14^{***}	-0.54	-0.71
	(0.25)	(0.45)	(0.54)	(0.46)	(0.52)
Age	-0.22^{***}	-0.22^{***}	-0.32^{***}	-0.41^{***}	-0.41^{***}
	(0.03)	(0.03)	(0.06)	(0.04)	(0.04)
Age^2	0.01^{***}	0.01^{***}	0.01^{***}	0.02^{***}	0.02^{***}
	(0.001)	(0.001)	(0.003)	(0.002)	(0.002)
Age^3	-0.0002^{***}	-0.0002^{***}	-0.0002^{***}	-0.0002^{***}	-0.0002^{***}
	(0.00002)	(0.00002)	(0.00004)	(0.00003)	(0.00003)
Age^4	0.000001^{***}	0.000001^{***}	0.000001^{***}	0.000001^{***}	0.000001^{***}
	(0.000000)	(0.000000)	(0.000000)	(0.000000)	(0.000000)
NRKW	-0.36	-0.28	-0.36	-1.17^{***}	-1.20^{***}
	(0.31)	(0.30)	(0.29)	(0.39)	(0.39)
Male	0.34^{***}	0.34^{***}	-2.53^{***}	-2.72^{***}	-2.71^{***}
	(0.10)	(0.10)	(0.61)	(0.64)	(0.64)
L1.Within-Competition	0.001	0.0002	-0.0004	-0.0004	-0.0002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
L1.Salmon Abundance		-0.72^{***}	-0.74^{***}	-0.74^{***}	-1.15^{***}
		(0.27)	(0.28)	(0.28)	(0.30)
Salmon Abundance					0.18
					(0.14)
Age $\times$ NRKW	No	No	No	Yes	Yes
Age $\times$ Male	No	No	Yes	Yes	Yes
N	12,571	12,571	12,571	12,571	12,571
Log likelihood	-1575.1001	-1568.5674	-1496.0125	-1488.3142	-1486.7264

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

^{a}: N records the number of female-whale-years

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Figure 12: Mortality by Age, Salmon Availability, and Gender

○ Not Males with low salmon index   △ Not Males with high salmon index

Within Population Graphs differ by Salmon Availability

To complete our discussion of these baseline determinants, I plot the predicted probability of death at various ages in Figure 12 using the regression estimates in column IV from Table 6. The panels differ in terms of the population considered, and the lines in each panel correspond to the state of a low (one std. deviation below average) salmon index or not. One complication arises in the case of mortality because whales die before their gender is revealed which is often at the age of 10 or more. Therefore, not Male implies being either classified as female or yet to be classified which includes almost all low-aged deaths. The figure shows very well the rapid fall in mortality in the first few years of life, but rapid rise after the age of 30. As well, comparing the panels it appears that on all dimensions the NRKW suffer lower mortality than do the SRKW although these differences are not large.

Overall, Table 6 and Figure 12 provide a strong foundation for examining the potential impact of vessel disturbance. Accordingly, in Table 7 I augment the basic demographic determinants with measures of vessel disturbance. Again, I proceed cautiously.

Table 7: The Impact of Vessel Disturbance on Mortality

	I.	II.	III.	IV.	V.
Constant	-0.89	-0.60	-0.42	-0.32	-0.36
	(0.65)	(0.81)	(0.54)	(0.52)	(0.54)
Age	-0.42^{***}	-0.41^{***}	-0.42^{***}	-0.42^{***}	-0.42^{***}
	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
Age^2	0.02^{***}	0.02^{***}	0.02^{***}	0.02^{***}	0.02^{***}
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Age^3	-0.0002^{***}	-0.0002^{***}	-0.0002^{***}	-0.0002^{***}	-0.0002^{***}
	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00003)
Age^4	0.000001^{***}	0.000001^{***}	0.000001^{***}	0.000001^{***}	0.000001^{***}
	(0.000000)	(0.000000)	(0.000000)	(0.000000)	(0.000000)
NRKW	-1.06	-0.87	-0.97^{**}	-1.09^{***}	-1.01^{**}
	(0.76)	(0.92)	(0.42)	(0.39)	(0.42)
Male	-2.73^{***}	-2.72^{***}	-2.74^{***}	-2.74^{***}	-2.73^{***}
	(0.65)	(0.64)	(0.65)	(0.64)	(0.64)
L1.Salmon Abundance	-0.76^{***}	-0.72^{***}	-0.73^{***}	-0.71^{***}	-0.73^{***}
	(0.27)	(0.28)	(0.25)	(0.26)	(0.26)
L1.Within-Competition	-0.003	0.001	-0.008^{*}	-0.008^{**}	-0.009^{**}
	(0.0030)	(0.0016)	(0.0043)	(0.0039)	(0.0043)
Total Vessel km	0.24^{**}				
	(0.12)				
Total Vessel km × NRKW	0.08				
	(0.37)				
Total Other km		-0.03			
		(0.28)			
Total Otherl km × NRKW		-0.24			
		(0.52)			
Total Unitised km			0.74^{***}		2.27^{***}
			(0.17)		(0.65)
Total Unitised km × NRKW			0.97		-1.51
			(0.77)		(1.08)
L1.Total Unitised km				0.58^{**}	-1.61^{*}
				(0.24)	(0.85)
L1.Total Unitised km × NRKW				1.14^{*}	2.71^{***}
				(0.67)	(0.99)
Age × NRKW	Yes	Yes	Yes	Yes	Yes
Age × Male	Yes	Yes	Yes	Yes	Yes
N	12,571	12,571	12,571	12,571	12,571
Log likelihood	-1486.8069	-1488.0229	-1479.931	-1480.3884	-1478.2748

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

Distances are measured in million km.

[a]: "Total Other km" is the vessel total less the distance traveled by unitised vessels.

[b]: N records the number of female-whale-years

Column I investigates the impact of total vessel km in the CH again allowing for a NRKW interaction. The estimated coefficient on the main effect in column I is positive and precisely

estimated implying disturbance raises mortality; the interaction is close to zero. In column II forward, I divide total km travelled into those of all other vessels and those travelled by Unitised vessels. Other vessel km in Column II appear to have little impact on mortality; whereas Unitised km in Column III drive up mortality significantly. In both cases, the NRKW interaction terms are insignificant. Since Unitised vessel km appear to be the most important, in Column IV I investigate whether lagged vessel km are relevant, and then in Column V try to ascertain whether contemporaneous or lagged are key to mortality. The evidence is similar across columns. Consider just the last column. Adding the contemporaneous and lagged effects suggests vessel disturbance from Unitised vessels raises mortality for the SRKW. Since vessel km are measured in millions of km, and Unitised vessel km in the CH rose by about .5 million across the two pre and post time periods, the coefficient estimates imply this change raises the odds of a SRKW death by almost 40%. Doing the same for the interaction terms suggests a very similar conclusion - mortality also rises for the NRKW. Therefore, unlike births, the mortality impacts of vessel disturbance appear to be very similar for both the NRKW and SRKW.

V.II.3 Assessing the Weak Conjecture

Combining evidence for and against the weak conjecture, three conclusions stand out.

First, the Malthusian methods work very well in capturing the basic demographic and environmental determinants of population events. Salmon availability is always, and within-competition is often, found to be important to births and deaths. The age profiles for fertility and mortality make sense, and match, to the extent possible similar work.

Second, the impact of vessel disturbance on the SRKW is clear; on the NRKW less so. The SRKW population is always negatively impacted by km travelled by vessels in the habitat - whether this be by falling birth rates or rising death rates. The evidence for impacts on the NRKW are mixed: on births, it appears vessel km spur higher births; but on deaths it appears to spur higher deaths. In theory, these effects could net to a zero impact on NRKW population growth - but this is a tortured explanation. A better one is simply that the weak conjecture is just a poor representation of reality for the NRKW: that the positive impact of vessel km on NRKW births is indicative of model misspecification; and that by the usual omitted variable logic, the prime candidate for such an omission is a variable highly correlated with vessel km in the critical habitat. Third, vessel disturbance impacts for Unitised vessels is consistently important to both births and deaths, always large in magnitude, and almost always statistically significant. With this assessment in mind, I now turn to examine the

strong conjecture.

V.III   The Strong Conjecture

Any empirical evaluation of the strong conjecture must be incomplete - it requires evidence from an event that has yet to occur - the extinction of the SRKW population. Nevertheless, I will marshall relevant evidence for and against. To do so, I present evidence showing the SRKW do in fact compete for scarce resources with the NRKW, and show how vessel disturbance shocks have impacted the SRKW greatly while leaving the NRKW relatively unscathed. This evidence supports my treatment of the NRKW and SRKW as competing species with one population subject to a much larger vessel disturbance shock. To complete my argument, I then present evidence showing that the SRKW have indeed shifted to a population trajectory consistent with their slow-motion extinction, and argue this shift was created by the change in vessel disturbance over the sample period.

V.III.1   Within and Across-Population Competition

Thus far, I have assumed the two populations evolve independently, although both were affected by increases in vessel disturbance and changes in Chinook salmon availability. Under this assumption, the estimated impacts of competition from other whales reflected only within-population competition for scarce resources (habitat and its accompanying prey). It meant that the probability of a population event for either the NRKW and SRKW was independent of the population size of the others' population; as a result, differences in their fertility or mortality could be captured by population specific dummies and relevant interactions.

I now relax this assumption, and allow for the possibility that competition is both within and across-populations; i.e., $\alpha \neq 0$ and $\beta \neq 0$. Therefore, the size of the Northern population may directly affect Southern population events and vice versa. The relevant *Across-Competition* variable now enters as potential determinant of population events, replacing, at least partially, the role played earlier by the time invariant population specific dummies and their interactions. The importance of this substitution depends on the time-series properties of the two populations. Since the SRKW population has ebbed and flowed over the sample period and ended very close to where it started in the mid 1970s, excluding this variation in the SRKW population may have had little consequence. In contrast, the NRKW population has grown tremendously, and almost continuously, over the period more than doubling since

the late 1970s.[39] If the competing species model is correct, this is variation we would be foolish to ignore.

The competing species model tells us this growth in the NRKW population comes from two conceptually distinct sources. The NRKW population should grow towards its own biological carrying capacity even absent the SRKW; and arguably its population size in the early 1970s was likely below this carrying capacity given the ongoing negative impacts of the live capture industry, and commonplace harassment of KW. Therefore, some NRKW growth over the sample period is to be expected.[40] But in addition to this transitional growth, there is also growth created by any vessel disturbance that falls primarily on the SRKW. This growth is created by across-population competition and can be examined using phase plane analysis. Suppose we start at a point like A in Figure 3 where all transitional growth has been completed. From this starting point, small negative shocks to K_S, coming from vessel disturbance, would shift the $\dot{S} = 0$ locus inwards. This immediately places the the previous steady state at A in the new IV quadrant of the phase plane. The dynamics necessitate an increasing Northern population and a falling Southern population. If these negative shocks continued they would drive K_S downwards over time moving the system towards a new steady state at B. They could of course lead to extinction. Therefore, a key implication of the competing species model is that the time series of vessel disturbance and the NRKW population should be positively correlated.

To investigate this implication, in Figure 13 below I plot the NRKW population level and millions of km by Unitised Vessels in the SRKW critical habitat over the entire time period. Since they differ in units, I have graphed them on separate vertical axes.

Its obvious from the figure that the two time series are strongly correlated, and in fact the simple correlation between the two is .87.[41] Two observations follow. The first is that separately identifying the impact of vessel disturbance on SRKW population events vs. the impact of NRKW population growth is likely to be very difficult if not impossible. This is fundamentally a data problem. The second is that the figure presents evidence consistent with, but not necessarily for, the competing species model underlying the strong conjecture. The result shown could be nothing more than happenstance: the NRKW grew and so did the activity of major ports in the Salish Sea. Both observations suggest we find other sources

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[39]The SRKW went from 83 in 1979 to 77 in 2019; the NRKW started at 139 and ended at 335.

[40]This is exactly the growth that we would see in the phase plane of Figure 3. in the movement to point A, when the isoclines meet at 90 degrees and the NRKW population is initially below its steady state.

[41]A similarly large correlation exists with total vessel km at .85 which is not too far from the correlation between Unitised and All Vessel Km which is .92!

of variation in the data to separate these effects to resolve the correlation vs. causation question.

Figure 13: Correlation or Causation?
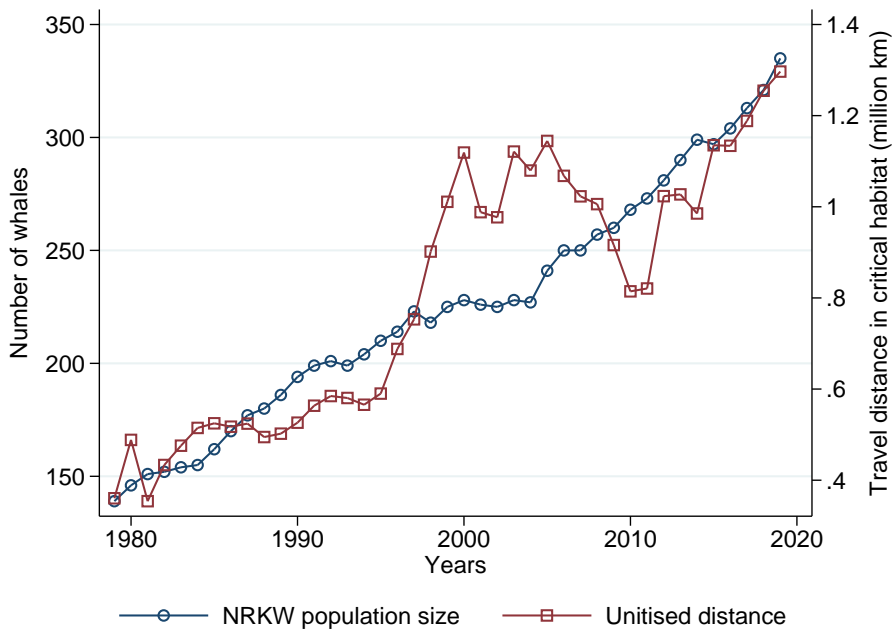
Two features specific to the KW context provide the necessary help. First, it is well known that wildlife in general, including marine mammals, often habituate to human disturbances and develop avoidance strategies to minimize their impact.[42] This suggests that while increasing vessel disturbance in the Salish may continuously degrade the habitat, large and rapid changes in disturbance may be especially harmful since they are new and unexpected. Moreover, relating changes in vessel disturbance to changes in population size (via both births and deaths) allows us to sidestep the obvious correlation problem in levels. Second, marine mammals like the SRKW are most vulnerable during key feeding and breeding seasons. This is, in the SRKW context, the summer months starting in May and ending in September when they are primarily resident in the Salish Sea. Putting these together, suggests an analysis of changes (in population) on changes (in vessel disturbance). The results of this analysis are presented in Table 8 below.

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[42]See for example Wortzok et al. (2003).

Table 8: First difference Impacts on Births and Deaths

	Births			Deaths		
	I.	II.	III.	IV.	V.	VI.
Constant	−17.58***	−17.59***	−17.58***	−1.80***	−1.79***	−1.80***
	(1.46)	(1.42)	(1.46)	(0.64)	(0.63)	(0.64)
Age	2.80***	2.79***	2.80***	−0.32***	−0.32***	−0.32***
	(0.29)	(0.28)	(0.29)	(0.06)	(0.06)	(0.06)
Age^2	−0.16***	−0.16***	−0.16***	0.01***	0.01***	0.01***
	(0.02)	(0.02)	(0.02)	(0.00)	(0.00)	(0.00)
Age^3	0.004***	0.004***	0.004***	−0.0002***	−0.0002***	−0.0002***
	(0.001)	(0.001)	(0.001)	(0.0000)	(0.0000)	(0.0000)
Age^4	−0.00004***	−0.00003***	−0.00004***	0.00000***	0.00000***	0.00000***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Male				−2.54***	−2.53***	−2.54***
				(0.61)	(0.61)	(0.61)
L1.Within-Competition	−0.002*	−0.002*	−0.002*	-0.0003	-0.0002	-0.0003
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
L1.Across-Competition	−0.01***	−0.01***	−0.01***	0.003**	0.002**	0.003**
	(0.00)	(0.00)	(0.00)	(0.001)	(0.001)	(0.001)
L1.Salmon Abundance	0.29**	0.32***	0.29**	−0.69**	−0.69**	−0.69**
	(0.12)	(0.11)	(0.12)	(0.27)	(0.28)	(0.27)
L1.Δ Total Unitised km	−3.24***	−3.29***	0.02	1.47***	1.43**	0.18
	(0.71)	(0.67)	(0.67)	(0.53)	(0.59)	(0.87)
L1.ΔTotal Unitised km × NRKW	3.25***	3.30***		-1.29	-1.23	
	(0.98)	(0.95)		(1.00)	(1.03)	
L1.ΔTotal Unitised km × J pod			−3.78***			1.84*
			(0.71)			(1.02)
L1.ΔTotal Unitised km × K pod			-1.03			0.39
			(0.70)			(1.00)
L1.ΔTotal Unitised km × L pod			−3.97***			1.34
			(0.66)			(0.96)
ΔTotal Unitised km		-1.23			1.86**	
		0.90			(0.77)	
ΔTotal Unitised km × NRKW		0.21			−2.15**	
		1.09			(0.97)	
Age × Male	No	No	No	Yes	Yes	Yes
N	5,707	5,707	5,707	12,571	12,571	12,571
Log likelihood	-1403.76	-1402.39	-1403.35	-1494.25	-1492.99	-1494.1502

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

Distances are measured in million km.

[a]: Δ denotes first differences.

[b]: N records the number of female-whale-years for births; all whale years for deaths.

The first three columns examine births, the remaining three examine deaths. The base specifications for both births and deaths are very similar to those presented earlier; I then account for vessel disturbance shocks in slightly different ways across columns. As well, the population specific main and interaction effects are now replaced by the across-competition

variable. This variable measures, at each whale-year observation, the population size of the competing population; just as the within-competition variable measures the population size of its own population. For consistency with earlier results I retained the one year lag on all demographic and environmental determinants.

With these facts in mind, consider the first three columns examining births. Consistent with earlier results, salmon abundance has a strong positive effect on births, while the negative coefficient for within-competition indicates there is competition for habitat and prey. All of these coefficients are precisely estimated, as is the polynomial in age whose structure is also stable across columns. Surprisingly, the across-competition variable is also negatively signed and precisely estimated. Moreover, the coefficient estimate is large. Taken at face value, this is strong evidence for very robust competition between the NRKW and SRKW populations for prey.

Turning now to vessel disturbance, in the first column I introduce the (lagged one period) first difference in km travelled by Unitised vessels in the critical habitat. Since this impact should or could differ across populations, it is also interacted with NRKW. The coefficient on the change in Total Unitised is negative, large, and precisely estimated. Since km are measured in units of millions, the estimate implies a 100,000 change in Unitised km travelled in the CH would lower the odds of a SRKW birth the next year 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 contrast, the size and positive sign of the NRKW interaction on this term completely removes any direct impact of these shocks on NRKW births. Therefore, the vessel shocks in the SRKW habitat only affect the SRKW. In column II, I include both the contemporaneous shock to vessel km along with its one period lag, again with the appropriate NRKW interactions. The estimates from column I remain virtually unchanged suggesting that it is important that the shock occur during the important breeding period one year prior to births. In column III, I divide the impacts across the three SRKW pods, J, K and L. The impact on the NRKW is now captured by the main effect in Total Unitised, which is close to zero - consistent with the earlier column results. The pod specific interactions suggest a strong negative effect of vessel km shocks on births, although the impact on the K pod is not precisely estimated. This may be due to K pod's small size (mean of 20). The other coefficient estimates are slightly different, but retain their sign and remain important. Overall, the results on births are surprisingly good and very supportive of a competing species interpretation of population interaction.

Now consider the last three columns examining deaths. Again, I estimate what is very

close to the earlier demographic model with environmental controls. The coefficients on within-competition are small and insignificant, similar to those estimated in in Table 6. In contrast, the across- competition coefficients are positive and significant, although relatively small in terms of magnitude. A 50 whale increase in the other whale population raises the odds of death by 16%. Salmon abundance again drives deaths downward and is precisely estimated.

Starting in Column IV, I introduce the one period lag change in Unitised km, and in Column V add to this the contemporaneous shock to vessel km. These columns are consistent in finding a strong positive effect of vessel km shocks on mortality, although it is unclear whether contemporaneous or last year's shocks are the most salient. The implied impact on the NRKW, from the interactions, is always far less. The magnitude of the impacts is perhaps one half of those on births. This is consistent with the known importance of the Salish for breeding activity. Unlike the case of births, in column V, I cannot rule out a small increase in NRKW mortality from the changes in vessel km. In the final column I again divide the impact across the three SKRW pods. In this case, the main impact on the NRKW may well be zero. The impact on the SRKW varies across pods, is always positively signed, but only significant in one of the three cases. The coefficient estimates are however, again approximately one half of those on births.

Overall the results are very encouraging. In all cases, the basic demographic and environmental variables hold up very well in terms of sign, significance and magnitude. Most importantly, the across-competition variable appears with the appropriate sign and is highly significant across all specifications. Moreover, the vessel km shocks appear to do just that - provide an unwelcome shock to the KW during their sensitive breeding period in the Salish Sea; the direct impact on the NRKW births is precisely estimated at zero. The evidence on deaths is less convincing, but still consistent with the results on births. The vessel km shocks appear to be less salient for deaths, and the timing of their effect is unclear. 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. If we compare and contrast the results in Columns II and V we see the same basic story - except now the same gestational logic applies to killer whales.

Combining the results of this section with those earlier provides, in total, overwhelming evidence that vessel shocks have a large negative impact on the SRKW. Although the weak and strong conjecture cannot both be correct, the dissonance this may cause the reader cannot negate the obvious implications of the empirics. The pattern of vessel traffic I documented

earlier shows a rapid acceleration to a much higher level post 1998, and Table 8 exploits those rapid changes to both confirm the negative impacts of vessel disturbance on the SRKW population, and provide evidence for a supporting role played by the NRKW. The estimated impacts on births and death are, almost uniformly, large - so large that only a several std. deviation increase in salmon abundance could keep them at bay. The only remaining question is how have these competing impacts played out for the two populations.

VI Slow-Motion Extinction

There is of course an entire literature examining the conditions for extinction in both biology and economics. Most of this work examines the likelihood of extinction based on biological characteristics, market fundamentals, and various forms of uncertainty.[43] My approach here is to use a simple application of economic demography informed by specific biological features of killer whales. To do so, I shift my focus away from individual whale fecundity and mortality to focus on cohorts of whales; specifically cohorts of female whales. For many marine mammals, and KW in particular, the ratio of mature males to females in the population is of negligible importance to reproduction. KW exhibit sexual dimorphism (the sexes are very unequal in sizes), which leads to only a few large males breeding. This allows me to ignore the evolution of the male population entirely, and focus my attention on the total fertility rate (TFR) of female whales in a cohort. A key observation is that, for a given sex ratio at birth of 50-50, if female whale total fertility rate falls below 2 - and remains there - then extinction is inevitable.[44] This extinction is likely to be a slow-motion march to oblivion given killer whales' very long time to maturation and then senescence.

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

It proves useful to consider a healthy population to fix ideas; therefore, in Figure 14 below

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

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

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

Figure 14: Female NRKW Cohorts
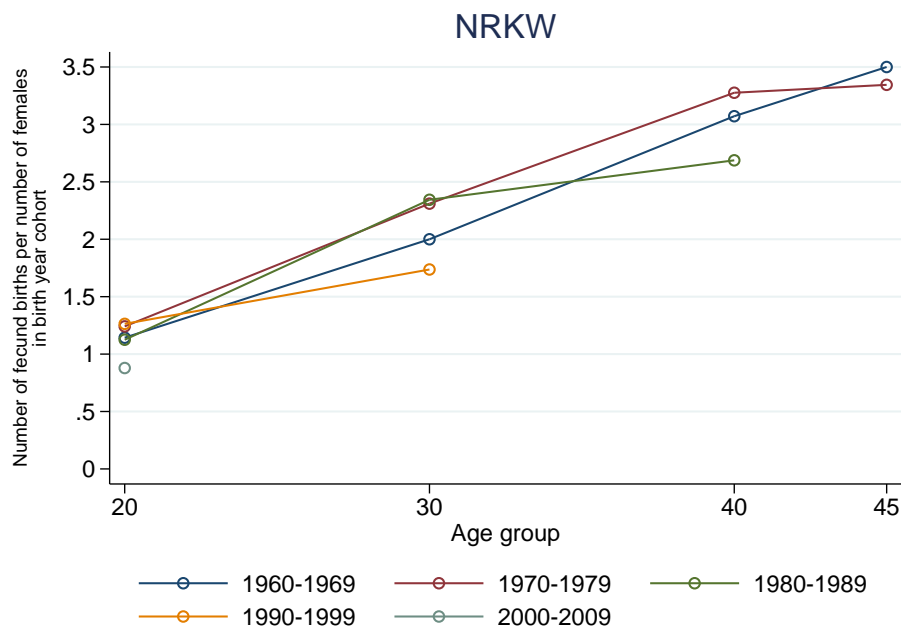
In relation to the first two cohorts, the 1980 cohort has reduced fertility over the last ten years of their reproductive life. This is also true for the 1990 cohort and for the 2000 cohort. This suggests the pattern of reduced total fertility is not a pure cohort effect. To understand why, suppose that over time the increased leaching of PCBs and other organic chemicals into the Salish Sea were driving births down and deaths up. In this case, we would expect cumulative fertility at all ages to be lower with each cohort now being exposed to an increasingly polluted sea. A similar result would hold if there was a long run reduction in salmon availability.

Instead what the figure shows is that the lowered fertility periods are all post 1998, and this suggests a cohort x period explanation: those whales who reached their peak fertility

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

With these results in mind, consider an alternative grouping of whales to highlight the cohort x period explanation. In Figure 15 I divide the whales into two groups: those that reached their peak fertility age of 20 before 1998, and those that reached peak fertility after 1998. The red line now gives the total fertility per whale for a whale reaching age 20 and beyond regardless of their specific birth age cohort. As shown, the two cohorts now differ only slightly but regularly, with the post-1998 cohort having slightly lower fertility at all ages. Importantly, by age 40 even the post-1998 group exhibits total fertility well above replacement. Therefore, it appears the sum total of changing salmon availability and increased vessel disturbance has had only a relatively small effect on NRKW fertility, and has had no effect on their long term viability.[45] This is of course entirely consistent with the estimates I provided earlier on the strong conjecture.

Figure 15: Female NRKW Synthetic Cohorts
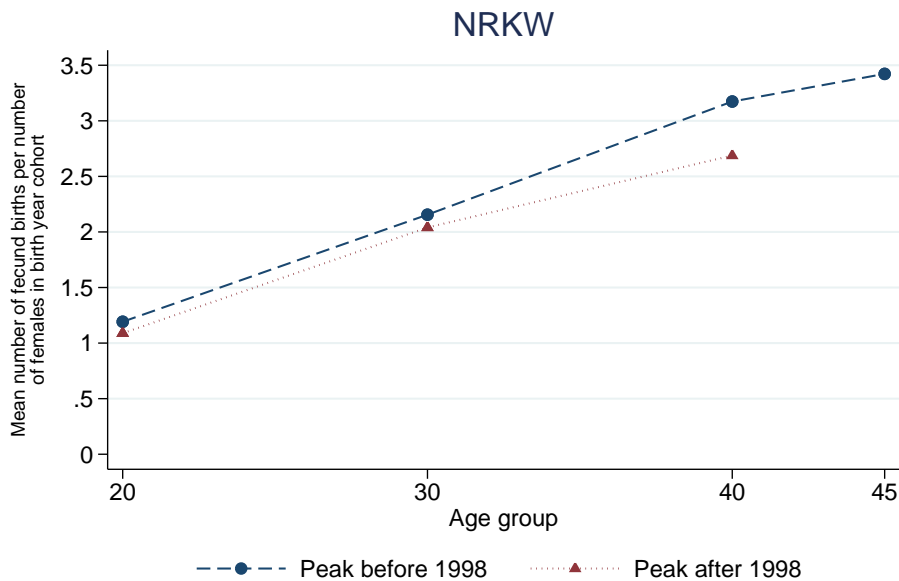
The peak before 1998 group contains the 1960 and 1970 birth cohorts.
The peak after 1998 group containts the 1980, 1990, and 2000 birth cohorts.

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

In Figure 16 below I now redo this analysis using the same age cohorts for the SRKW population.
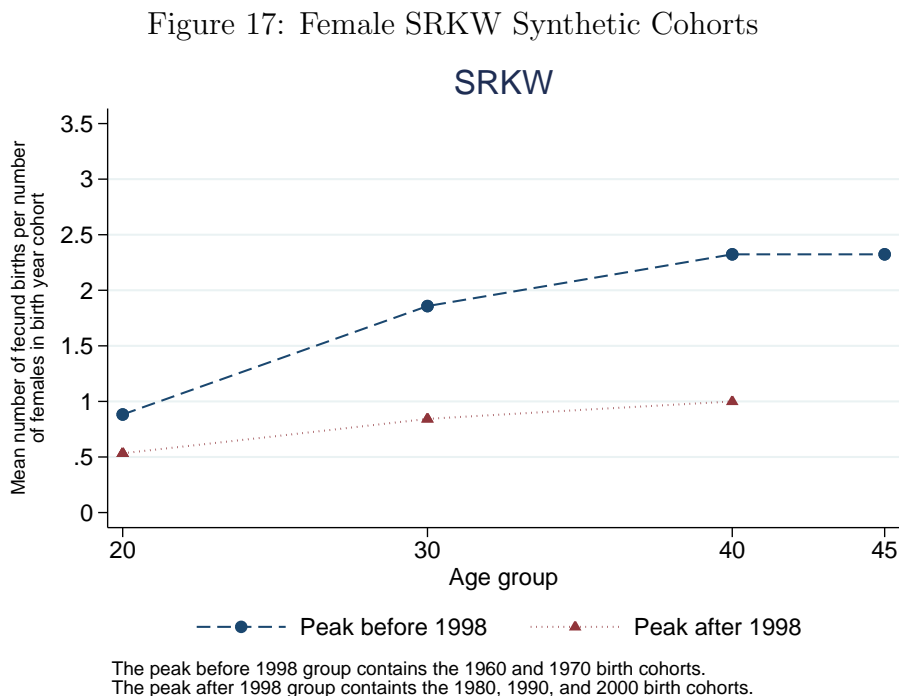
Figure 16: Female SRKW Cohorts
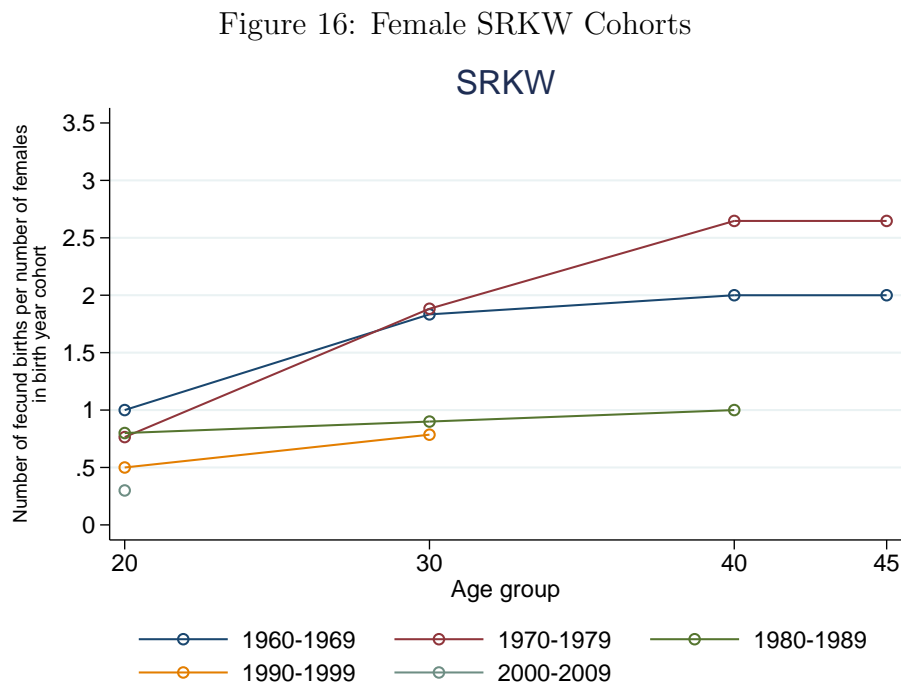
The two earliest cohorts now exhibit somewhat different profiles. The 1970 cohort exhibits higher fecundity at later ages in contrast to the 1960 cohort. It is very tempting to attribute the reduced fertility of the 1960s cohort to the live capture industry. The 1960 cohort would have been subject to the capture industry and associated harassment for the first 20 years of life; whereas the 1970s cohort less so.[46]. Whatever the reason, there are broad similarities and in fact these two cohorts are statistically indistinguishable from one another at all ages. Both cohorts show rising fertility with age and reproduction rates at or exceeding replacement levels. But now consider the remain three cohorts. The 1980s cohort shows no reduction in fertility at age 20, but a severely reduced continuing fertility at all later ages (and these differences are statistically significant). The 1990s cohort has low age 20 fertility and continuing low fertility at 30. The latest 2000 cohort seems, if anything, in worse shape than its recent predecessors. Its age 20 fertility is significantly different from all but the

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

reduced fertility of the 1990 cohort.

Again the figure suggests an alternative grouping based on pre and post 1998 observations, and hence I now provide the same calculations for the two synthetic pre and post SRKW cohorts. This is shown in Figure 17 below.

Figure 17: Female SRKW Synthetic Cohorts

The peak before 1998 group contains the 1960 and 1970 birth cohorts.
The peak after 1998 group containts the 1980, 1990, and 2000 birth cohorts.

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

VI.I   Alternative Hypotheses

Thus far I have kept to a tight script and entertained few alternatives. I did so primarily for transparency and directness in presenting what is a quite unusual set of arguments. There

are however at least two alternative hypotheses that merit discussion. The first is that the SRKW have been struggling because of a long term reduction in their available prey - Chinook salmon. The second is that the long term consequences of PCBs leaching into the Salish Sea has lowered SRKW reproductive potential.

It is certainly true, and widely recognized, that salmon returns on the West coast of B.C, Washington and Oregon have declined from earlier levels. Whether, and to what extent, this is due to climate change, the construction of dams blocking spawning streams, over fishing, or other marine mammal predation of young Chinook is less clear.[47] Salmon, as a suspect, has attracted most of the attention because policies to effect salmon stocks are well understood. For example, this could be through increased hatchery programs, stream restoration and/or further fishing restrictions. Alternatively, and more dramatically it could involve large changes to a set of Columbia river dams in the hope of altering the abundance of Columbia river Chinook dramatically.[48]

An important input to any evaluation would be the expected resulting impact on SRKW populations. On this front, several estimates in the paper could be useful. For example, the results on births in both Tables 3 and 4 and have salmon abundance coefficients between .32 and .37. Similarly, Tables 6 and 7 show an impact almost twice that large on deaths. Taking .35 as a point estimate for births and -.73 as that for deaths, implies a permanent two-standard deviation rise in the value of the Aggregate Salmon Index above its mean would raise the odds of a birth by 22% and lower the odds of death by 34%. These are very large changes, albeit for a two-standard deviation increase in the abundance index.[49] To see whether these estimated effects are large enough and whether salmon availability fell enough over the sample period to offer a credible alternative, I present in Figure 18 below the values of the three Chinook salmon indices making up my Aggregate Salmon index. To facilitate discussion about magnitudes I present them as z-scores.

Three observations follow. First, the three indices are highly correlated which is, of course, why I created the Aggregate Salmon index as their simple average. Second, all of the

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[47]For example, recently Welch, Porter and Rechisky (2021) finds that smolt to adult returns (the ratio of young adults leaving the stream to the ocean to those returning) are no different on the dammed rivers than others in the Pacific Northwest; that returrns have fallen from 1960 levels; and that ocean wide processes rather than local ones are likely responsible.

[48]For example, Washington State has recently proposed a $1.1-billion Orca recovery budget which includes $750,000 to study the removal of the dams which are run by the federal government.

[49]In fact, only a 3 std. deviation increase in the overall index could undo the effects of the increase in Unitised vessel traffic on the SRKW. A three std. deviation increase would raise births by 34% and lower deaths by 46%; but a 500,000 km increase in Unitised vessel km lowers births by 32%, and raises deaths by 45%.

Figure 18: Z-scores of major salmon indices over time
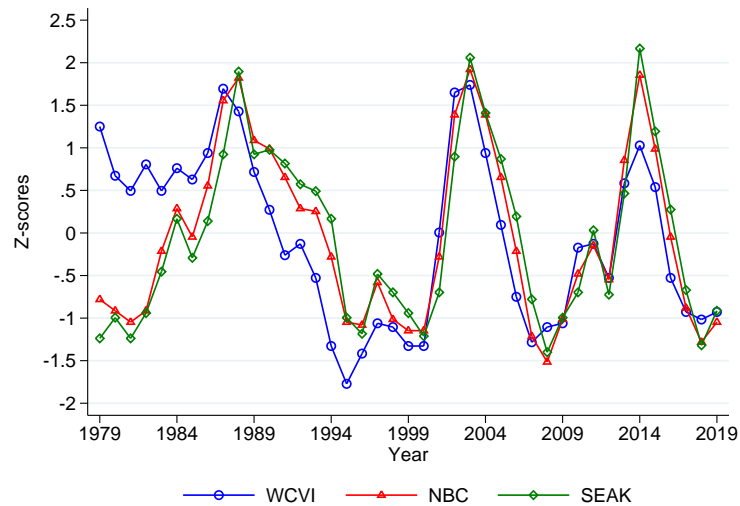
indices are highly variable but only one index ever exceeds the two std. deviation threshold used above. And lastly, it is easy to identify the extremely bad salmon years in the late 1990s which drove the populations downward and were the proximate cause of their listing as endangered species; of course, the issue is why then did they not recover during the two extremely positive periods that followed. Therefore, despite my findings that salmon availability can have a significant impact on both births and deaths - there is little evidence that changes in salmon availability post 1998 are key to the SRKW decline.[50]

An alternative long run decline hypothesis is that PCB pollution in the marine environment is impairing the reproductive ability of killer whales. Although PCBs production/import/sale was banned by both US and Canadian governments in the late 1970s, release to the environment and storage were not regulated until the mid 1980s. Nor were PCB laden materials stripped from existing machinery. Since PCBs and other related organic pollutants are extremely long lived in the environment, they have clearly impacted sea life in general, and killer whales in particular. Previous work has for example found the levels of PCBs in Salish sea fish has remained virtually unchanged over the last twenty years despite remediation efforts; more to the point, several studies have shown that PCB concentrations

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[50]One feature of the data is missing from this figure. The indices were constructed so the average stock abundance over the 1979-1982 period was equal to one. Since then the WCVI index has fallen slowly and has a sample period mean of .8; conversely, NBC and SEAK have risen to 1.25 and 1.4. Therefore there are some level differences across the indices relative to the initial period benchmarking. However as the figure suggests replacing my aggregate index with any of the components has no little empirical effect, and nothing significant hinges on the choice of salmon index. See the Online Appendix for details.

in the fat tissues of killer whales is quite high by marine mammal standards. Higher, for example, than similar levels known to cause reproductive impairment in other marine mammals (like seals). What is missing from the PCB explanation is any variation over time or geography consistent with the decline of the SRKW and continued growth of other KW populations. For example, the cohort analysis I conducted previously appears to be at odds with any explanation suggesting a long run uniform reduction in fertility arising from whales spending more of their life in an increasingly polluted Salish Sea. More damaging still is the observation that Transient killer whales frequenting these same waters have seen steady population increases, despite having the very highest levels of PCB concentrations.

Physical scientists, and social scientists alike, are - rightly so - suspect of mono-causal explanations for complex phenomena. The impact of vessel disturbance I have highlighted here, while significant, is unlikely to be the only cause of the SRKW decline. Vessel disturbance may have instead magnified the SRKW's existing vulnerabilities coming from variable and sometimes poor salmon returns and increasingly high PCB levels. Nevertheless, the time pattern of SRKW rapid recovery from the capture industry, and then subsequent decline, are first-order properties of their history that are difficult, if not impossible, to reconcile with the alternative hypotheses without a large role given to vessel disturbance.

VII   Conclusion

This paper set out a potential economic explanation for the slow-motion extinction of the Southern Resident Killer Whales. It did so by developing a competing species model of competitive exclusion where the Southern Residents faced competition from their Northern relatives which share part of their habitat. Within this context I showed how shocks that degraded their habitat could be magnified by this competition, lowering the populations of one or both RKW. With this theory as guidance I then developed an empirical strategy linking these potential shocks to fertility and mortality. These links were formalized in two hypotheses I named the weak and strong conjecture. The methods I employed to evaluate them are standard and similar to those of economic historians studying human populations living under Malthusian constraints.

A key input to this investigation was the collection of over 40 years of landings data at over 120 ports on the West Coast of North America. The richness of this data allowed me to calculate the yearly vessel km travelled, by various large vessel types, within the SRKW critical habitat. Transforming the landings data, via my methods, to kilometers of potential

vessel disturbance is completely novel – and potentially applicable to the study of vessel disturbance on other marine mammals worldwide. Somewhat surprisingly, it comes from the simple and judicious application of Walras' law and principles of National Income Accounting to landings data. By doing so I am able to provide information on potential vessel disturbance from ships, decades before the Automated Identification System and satellite tracking made similar calculations possible.

I find that booming trade with Asia, post 1998, created a huge increase in vessel km travelled in the SRKW critical habitat. Annual vessel km, by large commercial vessels within the critical habitat, rose by a little over 2 million km over the sample period. Most of this increase in annual km travelled occurred during the post 1998 period and most comes from large ships carrying Unitised cargo. With this newly constructed data in hand, I then exploited parallel work in ecology and biology linking the noise emanating from these large ships with reduced socializing and foraging by killer whales. This important work let me complete the chain of logic from booming trade to degraded habitats through to energetic costs on KW.

I then conducted three different empirical evaluations of the link between my measure of potential noise disturbance to KW births and deaths. Although the findings from my analysis of the weak and strong conjecture differ somewhat in their details, they are unanimous in finding a large negative impact of vessel disturbance on SRKW births and deaths. These effects are so large that a permanent three standard deviation increase in salmon availability would be needed to undo their impacts. Not surprisingly then, my cohort analysis shows that total fertility in the post 1998 period has fallen well below replacement, setting the SRKW on a slow motion path to extinction.

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