Presidential Address: The orca conjecture

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Abstract. In this address, I argue that the Southern Resident Killer Whale (SRKW) population has been negatively affected by commercial vessel traffic, tied to international trade, in the post-1998 period. I present new data showing a dramatic increase in both the volume of kilometres travelled and the composition of vessel traffic in the Salish Sea. By exploiting recent work in biology linking vessel noise to changes in foraging and socializing behaviour, I argue that these changes have degraded their habitat significantly. Moreover, because SRKWs and Northern Resident Killer Whales (NRKWs) share prey, this negative vessel disturbance shock to the SRKW is magnified by the existence of across-population competition. Vessel disturbance magnified by competition for prey has placed the SRKW on a slow-motion path towards extinction.

Résumé. La conjecture de l'orque. Dans cette allocution, je soutiens que, depuis 1998, la population d'orques résidentes du sud subit les conséquences néfastes de la circulation de navires commerciaux, étroitement liée au commerce international. Je présente de nouvelles données qui montrent une augmentation spectaculaire du nombre de kilomètres parcourus et de la circulation de navires dans la mer des Salish. Je me fonde sur de récents travaux en biologie qui établissent un lien entre le bruit causé par les navires et les changements dans les comportements de recherche de nourriture et de socialisation de l'orque pour établir que ces changements ont fortement dégradé son habitat. De plus, le fait que l'orque résidente du sud et l'orque résidente du nord se disputent les mêmes proies ne fait qu'amplifier ces perturbations causées par les navires. Les perturbations causées par les navires, amplifiées par une concurrence entre les populations, font en sorte que l'orque résidente du sud se dirige tranquillement vers l'extinction.

JEL classification: Q2, Q5, F6, F18

1. Introduction

CHOOSING A SUBJECT for your Presidential Address is not easy. There is very little guidance given, except that it may be an opportunity to do something quite different. Looking at past addresses gives you an idea of what is

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expected, but it still remains an almost blank canvas. And while there are many excellent previous addresses, I decided to follow in the footsteps of the most famous Presidential Address I knew of—The Tragedy of the Commons, by Garret Hardin. This very well-known article was his Presidential Address to the American Association for the Advancement of Science in 1968. Economists, specifically environmental and resource economists like myself, have a love–hate relationship with his address. We love that it brought attention to the Commons problem and the potential negative costs of externalities, but we are not happy with how he did it.

Hardin's approach was in fact pretty simple. Hardin, who was a biologist, used a well-established economic model to generate a well-known result; he used little to no data and made several bold predictions. And Hardin's dismal conclusions are forever tied to the catchy title of his Presidential Address. All of this is fantastic for anyone teaching environmental economics, and the paper rightly deserves all of its thousands of citations. The problem economists have with the address is that essentially the same result was published 14 years earlier by Canadian resource economist H. Scott Gordon (1954). Gordon's account is far more difficult to read and understand, and it is focused—perhaps rightly—on the fishing industry context. Hardin, on the other hand, argued that the "tragedy of the commons" was a ubiquitous feature of many human dilemmas from the arms race to the debate over the "population problem."

So I thought Hardin was perfect. I can follow his lead by making a foray into biology and at the same time right a historic wrong by giving economics the due it deserves. H. Scott Gordon is also a past president of the Canadian Economics Association (1977–1978), so perhaps its apt that today another president evens the score.

To do so, I will use a well-established biological model to generate a well-known result; I will, however, use more than 5 million observations on vessel movements and salmon fish stocks to make one bold prediction. And I also have a dismal conclusion and a very catchy title—The Orca Conjecture—for my Presidential Address. However, in contrast to the results of Hardin, none of the results I discuss here today appear anywhere else, although some of them appear in a working paper by M. Scott Taylor—a past president of the Canadian Economics Association (2019–2020).[1]

I start by introducing the conjecture and then give you some background on the history and biology of *Orcinus orca*, or killer whales, and the Southern Resident Killer Whales (SRKW) in particular. This will establish some basic facts about orcas and their population history. Next, I will employ the well-known Lotka–Volterra competing species model to show how negative shocks to the carrying capacities of their habitats affect population outcomes.

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[1] I will on occasion refer to results in Taylor (2021) or additional tables and figures available from the online appendix, available at `www.mstaylor1.org`.

Following this, I provide data on what I think is the negative shock affecting the SRKW and then use a simple simulation of the model to argue that, as a result, their extinction is now inevitable.

Throughout, I use the tools of economics to provide a credible answer to a puzzling question in biology: What ails the Southern Residents? Simple tools like National Income Accounting and Walras's law allow me to create new data that shed light on this question, while other results follow from a comparative steady state analysis that is informed by both the Rybczynski theorem and Jones magnification effect drawn from international trade theory.

1.1. The conjecture

Simply put the conjecture is as follows: growing international trade, circa 2000, created a large increase in commercial vessel traffic on the west coast of Canada and the United States. The increased vessel traffic disturbed (foraging, socializing and reproduction) of Resident Killer Whale populations, lowering the quality of their habitat and hence the (maximum) population of killer whales it could support (the carrying capacity). The vessel disturbance shock was asymmetric, affecting the Southern Resident Killer Whales' habitat more than their Northern counterparts. This asymmetric shock was then magnified by the existence of competition between the two populations and has now placed the Southern Resident Killer Whales on a slow-motion path to extinction.

With this in mind, I now turn to introduce *Orcinus orca.*

2. Killer whale (*Orcinus orca*) background

2.1. History

The history of *Orcinus orca* and human interaction makes for painful reading. In the period before the early 1960s, very little was known about the species. During this time, killer whales were viewed as a pest and dangerous to humans, and they were often shot by fishermen and boaters. Following the initial (and inadvertent) capture of a live killer whale off the BC coast in the early 1960s, the display and live capture industry was born with the Vancouver Aquarium taking a leading role. Unfortunately, the industry is still in existence today.[2]

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[2] The capture was inadvertent because a small killer whale was harpooned for use as a sculpting model for a planned statue outside of the Vancouver Aquarium. The killer whale refused to die and was "towed" back into English Bay and went on display as Moby Doll in the Burrard Dry Dock and then at Jericho Beach. Just to be clear, the current orca sculpture outside of the Vancouver Aquarium today was not inspired by Moby Doll. An excellent and even handed account of the history of the capture industry and its many fascinating characters is contained in Colby (2018).

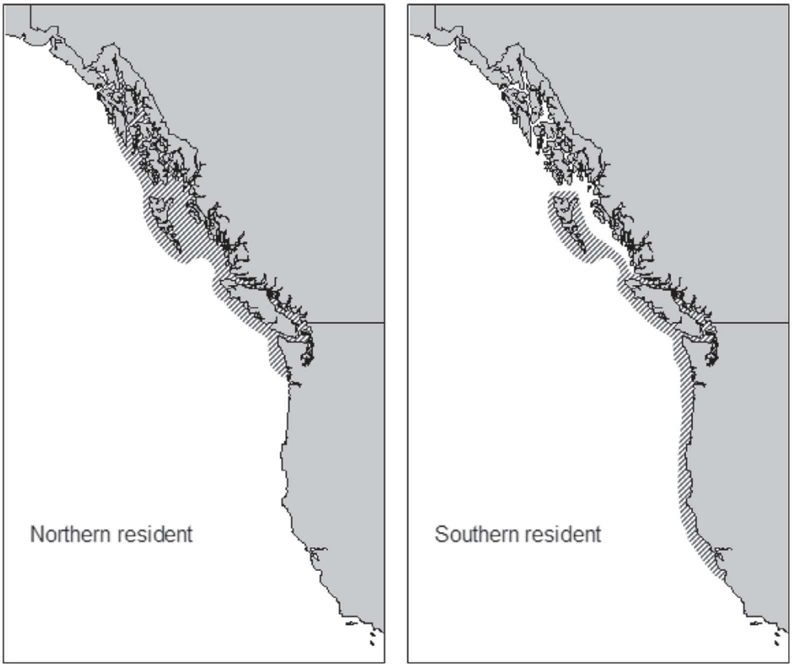

FIGURE 1 Northern and southern ranges
SOURCE: Figure 1 in Ford (2006)

In response to the demand for display specimens, and the lack of regulation on capture, both US and Canadian regulators started to fund research into killer whales. Initially this research was to calculate what might be a "sustainable" harvest of whales for the display industry, but eventually branched out to become an important new area of research on marine mammals.[3] 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 behaviours. Importantly, a Canadian scientist—Michael Bigg—developed a method of identification relying on whales' unique saddle patch and fin markings that allowed for identification. Using these methods, a whale census was begun in the early 1970s that provided researchers (including this one) with invaluable data on killer whale numbers. This census continues to this day and covers both their US and Canadian ranges (see figure 1). Currently, the

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[3] For example, Olesiuk et al. (1990) contains estimates of the sustainable harvests that could be cropped from the Northern and Southern Residents.

SRKW has 74 whales remaining from a peak of 100 in the mid-1990s. The NRKW has over 330 whales and is growing.[4]

Killer whales have been protected under the Canadian Fisheries Act since 1970 and in the USA by the Marine Mammal Protection Act (MMPA) 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 (see figure 4). In 2003, the SRKW were listed as depleted under the MMPA, endangered by Washington State in 2004 and endangered under the US 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 2017). These listings became law under the Species at Risk Act in 2003. A recovery strategy document was completed in 2011, the primary purpose of which is to identify critical habitat for killer whales.

2.2. Biology

Killer whales are within the toothed whale family, Odontoceti, whose closest relatives are the oceanic dolphins (spinner, bottlenose, common).[5] Killer whales are the world's apex 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.

First, there are three different types of killer whales defined by their ecological niche. Although these three eco-types differ in their social structure, body shape and movement and communication patterns, it is simplest to define them by their prey. Resident Killer Whales eat primarily salmon, 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

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[4] For early work describing the census procedures and photo-identification, see Bigg (1982). Subsequently, there has been a huge literature created and supported by the National Oceanic and Atmospheric Administration and Fisheries and Oceans Canada in support of listing the killer whale as endangered and to establish recovery plans, etc. This research is very detailed, very useful and exhaustive. Canadian scientists at Fisheries and Oceans Canada have played a leading role in much of this research.

[5] The other major group of whales is the Mysticeti, or Baleen, whales. This group includes, for example, grey, humpback, right, blue and fin.

are resident killer whales, although all three eco-types have been spotted in both Canadian and US waters.[6]

Because both the NRKW and SRKW are resident in local waters, the annual surveys and photo-identification books have ensured the population figures for this group of whales is extremely accurate. One early discovery from photo-identification was that 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. This initially gave researchers the ability to estimate ages for existing animals, and eventually, as the census period grew, it established the known ages and lineage for most of the population. One surprising finding was that females could live to 80 or more years, although males rarely live to 50.

Despite this lengthy life, their reproductive life is much shorter. Reproductive maturity for females occurs at about age 10 and continues until their early 40s. On average, a female may calve once every 5.3 years, but estimates of neonatal mortality are very high (30% to 40%). 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. For the SRKW in particular, these are the months they are primarily resident in the Salish Sea and, therefore, vessel disturbance may have a critical impact on reproductive success.

Because the NRKW and SRKW habitats overlap, it was initially unclear whether they were reproductively isolated. Again, with the whale identification system in place, it became clear that the two populations do no interact with each other. Later research established that language or calls are specific to pods and differ significantly across members of the NRKW and SRKW. And finally, very recent work has firmly established that the two populations are genetically isolated.

Orcas are large. A fully grown male orca can reach seven or eight metres in length and can weigh over 6,000 kg. In contrast, females are significantly smaller at five to six metres and perhaps only 3,000 kg. Given their large size and constant movement in the water, killer whale researchers estimate that they consume somewhere between 3% to 5% of their body weight in food every day. The two resident populations not only specialize in eating almost exclusively members of the salmon family but also are highly dependent on Chinook salmon. Estimates of this reliance vary across studies, but salmon make up perhaps 70% to 80% of their diet with Chinook salmon being 70% to 80% of this total. This heavy reliance on salmon, and Chinook in particular, is true for both the NRKW and the SRKW populations. Their preference for salmon plus their large size implies that a full grown male orca may consume 300 kg of salmon per day, a female perhaps half this. Multiplying these figures by current population

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[6] The chapter on killer whales in Ford (2017) contains an excellent overview of what we know about killer whales in BC waters. I found the books by Colby (2018), Hoyt (2019) and Morton (2004) all fascinating and useful adjuncts to academic journal articles.

levels and converting to annual requirements indicates that killer whales are large consumers of salmon, even in relation to commercial catches.[7]

Key to my argument is that these two populations compete for prey, despite the fact that the majority of sightings of the NRKW occur in waters not frequented by the SRKW, and vice versa. Figures 2 and 3 report the cumulative number of sightings at locations for each population. The NRKW are most frequently seen above Campbell River on the inside passage and continuing up the coast line. The SRKW sightings are heavily concentrated in the Salish Sea well below Campbell River and throughout the Juan de Fuca and lower stretches of the Georgia Strait. The problem with using these "sightings" as indicative of location frequency is that the vast majority are recorded in summer months from boats or via land and, therefore, reflect variation in effort, weather and the seasonal influence of tourism.

This deficiency is well known, and more recently, researchers deployed acoustic monitoring devices near the mouth of the Strait of Juan de Fuca off Swiftsure Bank. These acoustic devices can, in theory, collect evidence of killer whale activity in all months of the year, in all types of weather and in locations further from shore. This particular location was chosen because the tip of Vancouver Island (near Swiftsure Bank) is a very productive location for Chinook salmon and hence could be potentially important to killer whales. What the researchers found was surprising. The area turned out to be important for BOTH the SRKW and the NRKW.[8]

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[7] A simple back of the envelope calculation would start with a stable population of perhaps 50% juveniles, 30% females and 20% adult males (Olesiuk et al. 1990). If we assume juveniles are 2,000 kg, females 3,000 kg and males 6,000 kg, then an average whale is 3,100 kg. If this average whale consumed 5% of its body weight everyday, it would amount to 155 kg of salmon per day. Current population levels of the NRKW (335) plus SRKW (74) add to 409, implying a daily take in excess of 63,000 kg. An average Chinook salmon is 14 kg, implying that if all killer whale consumption were of Chinook salmon, it would require 1.65 million Chinook salmon yearly. This is a large figure even in relation to several commercial fisheries. For a more formal assessment of killer whale take on the entire west coast of North America, see Chasco et al. (2017), who find that the 2015 killer whale take of 10,900 metric tons of Chinook exceeds that of commercial and sport fishing, at 9,600 metric tons. Since 1975, the largest increase in consumption of salmon has been from the NRKW.

[8] This was somewhat of a surprise given existing location-based data from boat and shore observers. Ford et al. (2017, p. 16) states, "Given the frequent summer occurrence of SRKW pods off southwestern Vancouver Island documented here, it is evident that this area is a primary habitat used by these whales when outside of existing critical habitat during May–September." Similarly, it states (p. 17), "[a]lthough NRKWs were known to occur at least occasionally off the central west coast of Vancouver Island…, the frequent occurrence of this population at Swiftsure Bank reported here was unexpected. NRKWs were detected in all months of the year…."

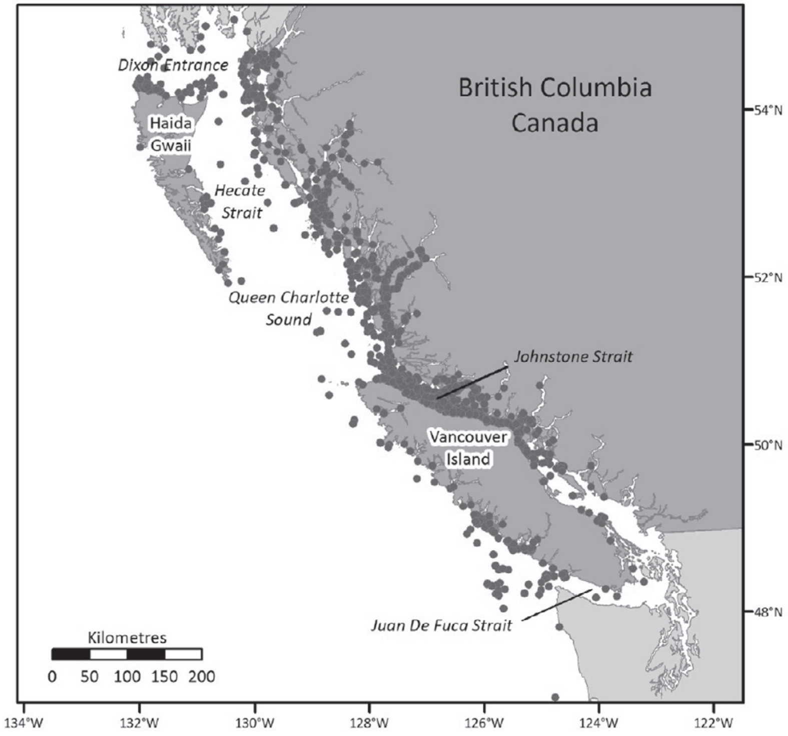

FIGURE 2 Locations of sightings and encounters with NRKW, 1973–2014
SOURCE: Figure 1 in Ford et al. (2017)

Whales from each population were identified using the region in every month of the year. Whales from different populations were located at very similar locations, although separated in time. Moreover, evidence from predation events in this same area clearly showed that both were preying on Chinook destined for the Fraser River.[9] This new evidence tells us the two populations rely on the same prey, destined for the same river, and are hunting it in the same location at the same time.

In addition to this sharing of prey at Swiftsure Bank, the two populations compete more generally for Chinook returning to spawning grounds in the Salish Sea (primarily the Fraser River).[10] For example, salmon returning via

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[9] For example, 80% of the Chinook taken by killer whales 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 2017).

[10] Johnstone Strait, Haro Strait and the Strait of Juan de Fuca are the primary migratory routes for Chinook returning to the Fraser River (Ford et al. 2017, p. 13).

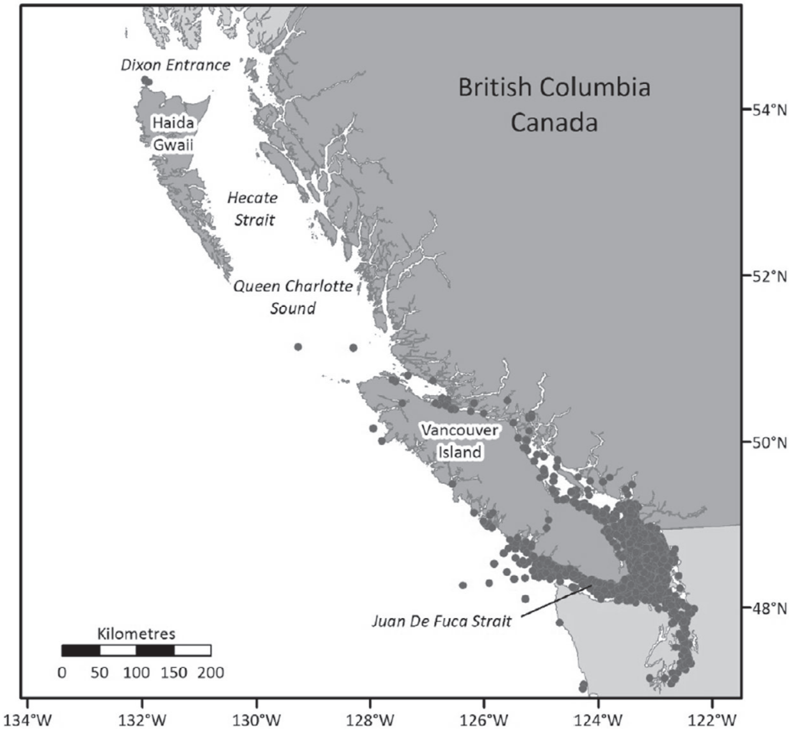

FIGURE 3 Locations of sightings and encounters with SRKW
SOURCE: Figure 2 in Ford et al. (2017)

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.

These features of biology tell us that the only real point of contact between the SRKW and NRKW populations is over prey and that their individual consumption of salmon may be significant enough to affect the other population.

2.3. The problem with the Southern Residents

The Southern Resident population has been on a long downward trend since the mid to late 1990s (see figure 4). The current population size is about where it was in the mid-1970s, when the live capture industry was still active, despite the protections granted them in the early 2000s. In contrast to the Southern Residents, the Northern Residents have experienced almost continuous growth since the late 1970s. One difference between the two is that the Southern Residents were "cropped" far more intensively than were the Northern Residents, but these activities ended long before the decline shown in figure 4.

The vast majority of the research investigating their decline has focused on threats to the carrying capacity of the Southern Residents. Three prime

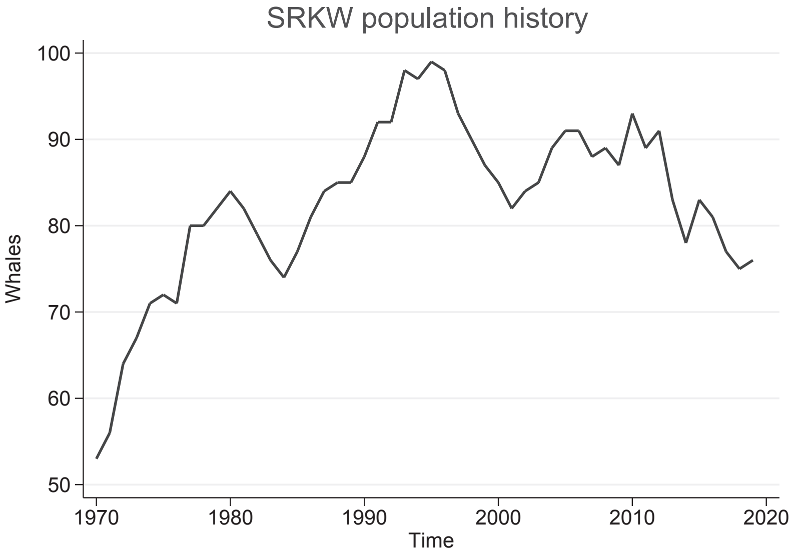

FIGURE 4 History of the SRKW population
SOURCE: Own compilation of population data

suspects mentioned in the literature, and press, are: (i) a reduction in the availability of prey species caused by overfishing, dam construction or increased predation by seals, (ii) an increase in vessel traffic interfering with hunting, socializing and mating behaviours and (iii) reduced fecundity caused by exposure to polychlorinated biphenyls (PCBs) that continue to leach into the waters of their critical habitat. Although the production, import and sale of PCBs were banned by both US and Canadian governments in the late 1970s, the release to the environment and storage were not regulated until the mid-1980s. Nor were PCBs stripped from existing machinery, etc.

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 that ranges over thousands of square miles of habitat and is, for the majority of the time, below the surface.[11] Despite literally tens of millions of dollars of research, the debate over what to do with, or for, the Southern

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[11] 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.

Residents is going nowhere fast. My focus here is on the very plausible, but thus far difficult to quantify, impact of commercial vessel traffic on killer whales.

3. Theory

The purpose of the theory section is to demonstrate how a negative shock to both the SRKW and NRKW carrying capacities can lead to the extinction of the SRKW, if the shock falls primarily on the carrying capacity of the SRKW.

To do so, I model the interactions between the NRKW and SRKW using the Lotka–Volterra competing species model. The model assumes two species, or in our case two populations, that fit a series of assumptions: (i) the populations cannot interbreed, (ii) they cannot interfere with each other and (iii) they need to share some common resource, be it habitat (containing prey) or prey itself. I believe the NRKW and SRKW do satisfy these criteria.

3.1. The model

I denote the Northern Resident population by N and that of the Southern by S. Although the model is strictly about biomass, I will treat both as measures of the population. The interactions between the two populations, from given initial conditions, are described by two differential equations:

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

and

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

where $r,\ \alpha,\ \beta,\ K_N,\ K_S$ are strictly positive given parameters of the system and initial populations are assumed to be non-negative ($N(0) \geq 0,\ S(0) \geq 0$).

This system has several important features. First, inspecting either equation will show that per capita growth of either N or S falls as the populations rise, i.e., it is density-dependent. In fact, per capita growth is a simple linear function of population levels, although this function is also determined by the (constant) carrying capacities K_N and K_S and the competition coefficients α and β. As a result, for very low population levels, the killer whale populations would grow at the exponential rate of r, which is their intrinsic rate of resource growth.

Second, suppose for the moment we set the competition coefficient $\alpha = 0$ in the Northern growth equation. Then starting from any strictly positive value for the initial stock $N(0) > 0$ the Northern population will slowly move towards its steady state of $N = K_N$. A similar result holds for the South if we set $\beta = 0$. A little math will show both populations move to their steady states monotonically, and the steady states are also stable. Therefore, absent any competition between the two whale populations (i.e., if $\alpha = \beta = 0$) both populations survive and approach their individual carrying capacities in the very long run.

Third, when the competition coefficients are not zero, things are very different. To understand how the existence of across-population competition matters, it proves useful to start by solving for their interior steady states by setting (1) and (2) to zero. Assuming $N \neq 0$ and $S \neq 0$, the steady states must satisfy the following two linear equations:

$$K_N = N + \alpha S \tag{3}$$

$$K_S = S + \beta N \tag{4}$$

I like to think of these as full employment conditions. Each carrying capacity has to be fully employed or used up by whales from either the NRKW or the SRKW. Continuing with this interpretation, each Northern whale uses up 1 unit of NRKW carrying capacity, while each Southern whale uses up α units of NRKW carrying capacity. Similarly, each Southern whale uses up 1 unit of SRKW carrying capacity, while each Northern whale uses up β units of SRKW carrying capacity. The natural assumption is that Northern whales are intensive users of Northern carrying capacity and Southern whales are intensive users of Southern carrying capacity. In this case, we have $\alpha < 1$ and $\beta < 1$ and there is both within-population and across-population competition.

Surprisingly, when there is across-population competition, extinction is now a possibility for one population. To examine further, solve for the steady states finding:

$$S^* = \frac{K_S - \beta K_N}{[1 - \alpha\beta]} > 0 \tag{5}$$

$$N^* = \frac{K_N - \alpha K_S}{[1 - \alpha\beta]} > 0 \tag{6}$$

In order for the Southern population to survive in steady state, $S^* > 0$, and it must be true that $K_S - \beta K_N > 0$. This requires that there must be "excess carrying capacity" that its members can exploit even when the Northern population becomes very large and close to K_N. For identical reasons, the Northern population can survive only when $K_N - \alpha K_S > 0$. Again, it requires a measure of excess capacity is positive. Because both of these conditions involve the relative size of the two carrying capacities, it is simple to rearrange to find that a necessary condition for mutual coexistence is

$$\frac{1}{\beta} > \frac{K_N}{K_S} > \alpha. \tag{7}$$

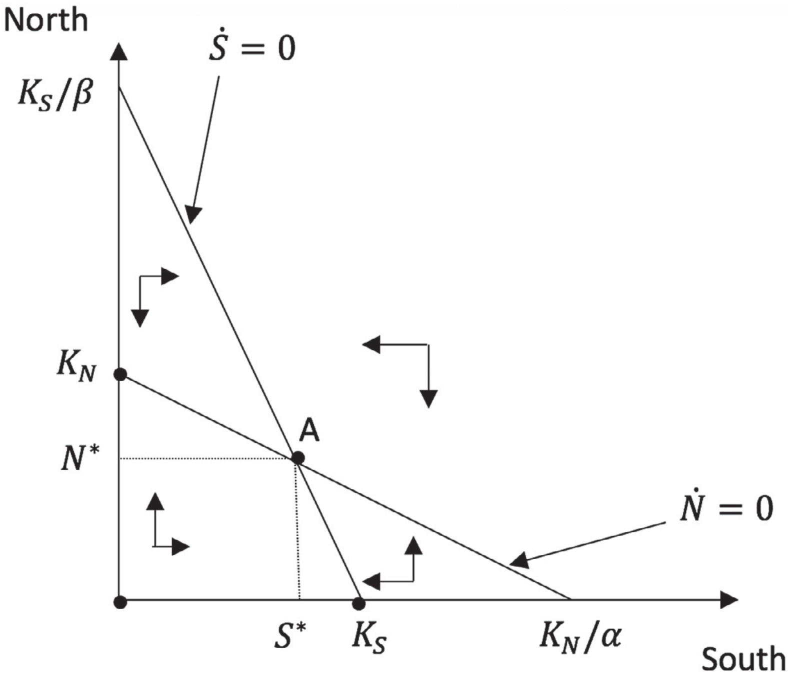

FIGURE 5 Phase plane

If condition (7) is met, and if each population is intensive in the use of its own habitat, then the phase plane corresponding to the dynamic system is shown in figure 5.

The interior steady state, when it exists, is shown at a point like A. In drawing the figure, I have used the assumption that $\alpha < 1$ and $\beta < 1$, which 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 steady 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. In contrast, the steady state at 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.

It is also apparent that if the carrying capacities differ too greatly, then point A would move towards one on the other axis eliminating the interior steady state. At this point, the system with mutual co-existence turns into one of competitive exclusion and condition (7) is violated.

3.2. Rybczynski, Jones and extinction

To understand how a shock that affects carrying capacities can generate extinction it proves useful to exploit the analogy already pursued of full employment conditions. These conditions in the two-sector neoclassical model are key inputs to several well-known results in trade theory that are isomorphic to several of the comparative statics I generate here.

To start, consider figure 6, where I plot the isoclines intersecting at an initial steady state at A. Common shocks lowering (or raising) carrying capacities equiproportionately would move the mutual co-existence steady state at A up or down the dashed line through the origin. Doubling carrying capacities doubles steady state populations. To an economist, this is an implication of constant returns; to a biologist, its the result of each population holding onto its share of carrying capacity as carrying capacity grows.

In contrast, a shock lowering only the Southern carrying capacity to K'_S moves the steady state 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. The logic is simple. The direct impact of the shock is to lower the carrying capacity of the South's habitat, which lowers the Southern population directly, but with the Southern population shrinking, the Northern experiences less competition for its own resources and therefore grows. This

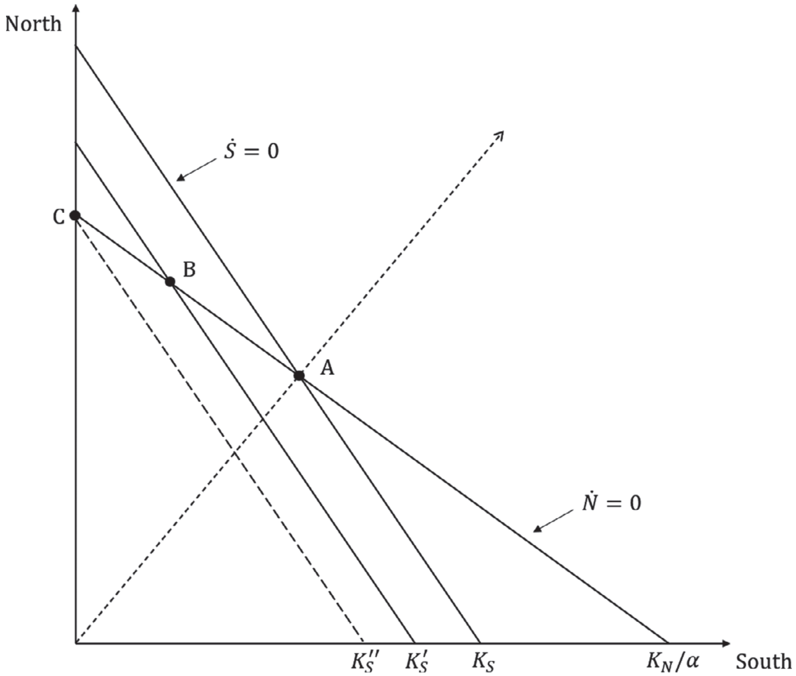

FIGURE 6 Comparative steady states

feature is why the model is called "the competing species" model, as competition for scarce resources is at its core.

To an economist, this result is the Rybczynski theorem (Rybczynski 1955). A reduction in Southern capacity requires a fall in the Southern population because they use its capacity intensively. The Northern population has to grow to keep the Northern carrying capacity fully employed given the South's fall. The composition of output (here whales) changes drastically.

In fact, the fall is so drastic that the Southern population does not just fall, it falls more than proportionately to the shock. To see this, solve for the relevant comparative static using equation (5) and rearrange to find

$$\frac{dS}{S} = \left[1 + \frac{\beta K_N}{K_S - \beta K_N}\right] \frac{dK_S}{K_S}. \tag{8}$$

Written this way, it is clear that there are two different forces driving changes to the South's population. First is the direct and proportional change in the South's population from the shock to its carrying capacity dK_S/K_S. This is identical to what would have occurred in an isolated environment with no across-population competition (that is, set $\alpha = \beta = 0$). 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*.

If, however, the two populations are engaged in across-population competition, the second term in (8) comes into play and the original shock is magnified. This is Gause's law of competitive exclusion at work (Gause 1932). Competition across the populations magnifies shocks. To a trade theorist, this is just the Jones magnification effect (Jones 1965).

Finally, it should be clear that, 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*. This result is captured by the large shock to the Southern carrying capacity lowering it to K_S''. In this case, the steady state moves to C as the South is now driven to extinction. This new steady state is also now globally stable and by the process of competitive exclusion the North drives the South to zero. Again, in terms of trade theory, what is happening is that full employment of both capacities is inconsistent with both populations surviving. This is identical to the case where growth (or reductions) in a factor endowment forces a small open economy to move from diversified production of two goods to specialization in only one.

With these results in hand it is now easy to see how a correlated shock to both carrying capacities could lead to extinction, provided the shock to the Southern Residents is larger. An example fixes ideas. Suppose the Southern carrying capacity falls by 10%, while the Northern falls by 4%. This can be decomposed into a common shock to both of 4%—which moves us along the ray through A—together with a 6% asymmetric shock to only the South that moves us towards a steady state like C. Therefore, a correlated shock that falls primarily on the Southern Residents can generate an extinction outcome even though the Southern and Northern Residents may have mutually co-existed for thousands of years previous.

4. What is the shock?

There are several good candidates for negative shocks primarily affecting the carrying capacity of the SRKW.[12] Here, I focus on two possible shocks: (i) an increase in commercial vessel traffic in the Salish Sea and (ii) a long-run decrease in salmon availability.

To assess the change in vessel traffic, I obtained data from Lloyd's of London, information on all commercial vessel landings at 121 west coast ports in North America over the 1977–2019 period. The data give the number of vessels of certain type X, landing in port Y, during month Z. While it does not identify individual vessels per se, all trips include information about the last two ports for most vessel landings. In total, this data contain information on over 1.8 million landings and over 5 million vessel movements. The data also include information on vessel characteristic by port/month/type, including dead weight ton (dwt), length, age, etc.

To assess the change in salmon availability, I put together an extensive database of salmon stock measures from the Pacific Salmon Commission from 1979 to 2017. These data are contained in three major stock indices for Chinook salmon that reflect conditions at more 30 Chinook indicator stocks.

4.1. The critical habitat plus

The increase in vessel traffic on the west coast of the North America should be relevant only if it disturbs the whales in an important part of their habitat. Fortunately, the US and Canadian governments have identified critical habitat for the SRKW and both are contained in an area of the West Coast, commonly referred to as the "Salish Sea." The Salish Sea contains the Strait of Juan de Fuca, Puget Sound and Georgia Strait. Figure 7 shows three shaded areas, together with a series of ports shown by dots, all contained in the Salish Sea.

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[12] I am ignoring the possibility of vessel shocks affecting the NRKW in their primary habitat and ignoring the potential negative effects on the new critical habitat for both NRKW and SRKW off Swiftsure Bank that came into being in 2018. Vessel traffic on the former is very small and shows little time series variation. Traffic on the latter is highly correlated with the vessel kilometres in the original critical habitat.

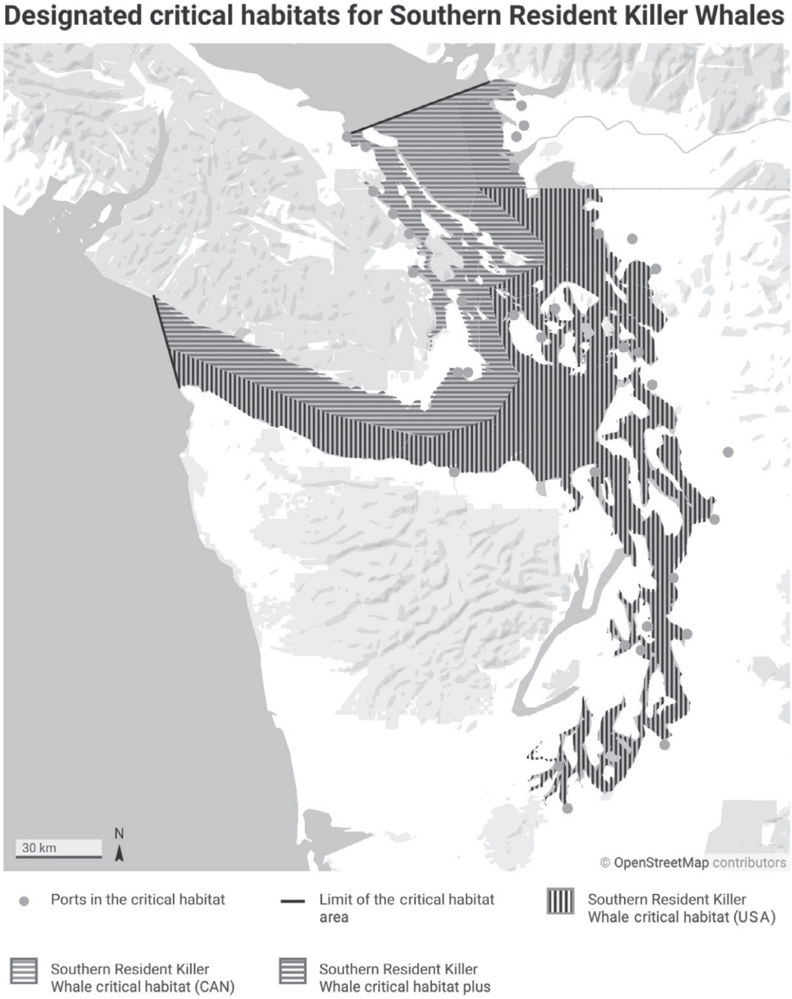

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FIGURE 7 Critical habitat plus

The darker shaded areas are SRKW critical habitat designations that occurred in 2009 and 2006, respectively, although they have recently been subject to review and expansion.[13] A critical habitat designation defines an area

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[13] In December of 2018, the critical habitat for killer whales was expanded to include additional areas off the southwest of Vancouver Island and some areas around Haida Gwaii. This southwest coast is an area of prey abundance, and both the NRKW and SRKW have been identified in this area throughout the year (Fisheries and Oceans Canada 2017).

thought to be crucial to a species survival. Critical habitats 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 2017, p. 2).

Naturally, I take these official designations as part of the relevant area, but also shown on the map are two bolded lines that mark entrances and exits from what I refer to as the critical habitat plus (the three shaded areas combined). Any vessel that enters the critical habitat plus does so in only one of two ways: via the inside passage down the east side of Vancouver Island or 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.

The western entrance to the critical habitat plus is represented by the bolded line at Swiftsure Bank, 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. The second bolded line is drawn from Horseshoe Bay on the mainland coast just north of Vancouver to Nanaimo on Vancouver Island. By use of the critical habitat plus and these two demarcations, I am able to define an enclosed region for traffic calculations. The critical habitat plus is a slight overestimate of the actual area because there are small areas that are not included, such as bays and some ports. 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.

4.2. 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 or irrelevant. Because 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.

4.2.1. 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 contain 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 critical habitat but landing in the critical habitat. Let u_c be the set of ports (33 elements) within the critical habitat, then incoming trips during t, or I_t, are

$$I_t = \sum_{i \notin u_c} \sum_{j \in u_c} X_{ijt}, \tag{9}$$

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

Trips with origin and destination ports within the critical habitat are defined as *within trips*. These are given by W_t, where

$$W_t = \sum_{i \in u_c} \sum_{j \in u_c} X_{ijt}. \tag{10}$$

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

$$O_t = \sum_{i \in u_c} \sum_{j \notin u_c} X_{ijt}. \tag{11}$$

Pass-through trips are trips originating and ending outside the critical habitat but whose voyage traverses the critical habitat. 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

$$P_t = \sum_{i \in u_p} \sum_{j \in u_p} X_{ijt}. \tag{12}$$

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 figure 8.

4.2.2. Walras's law

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

$$VL_t = I_t + W_t \tag{13}$$

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

$$\begin{aligned} VL_t &= VE_t, \\ VE_t &= O_t + W_t. \end{aligned} \tag{14}$$

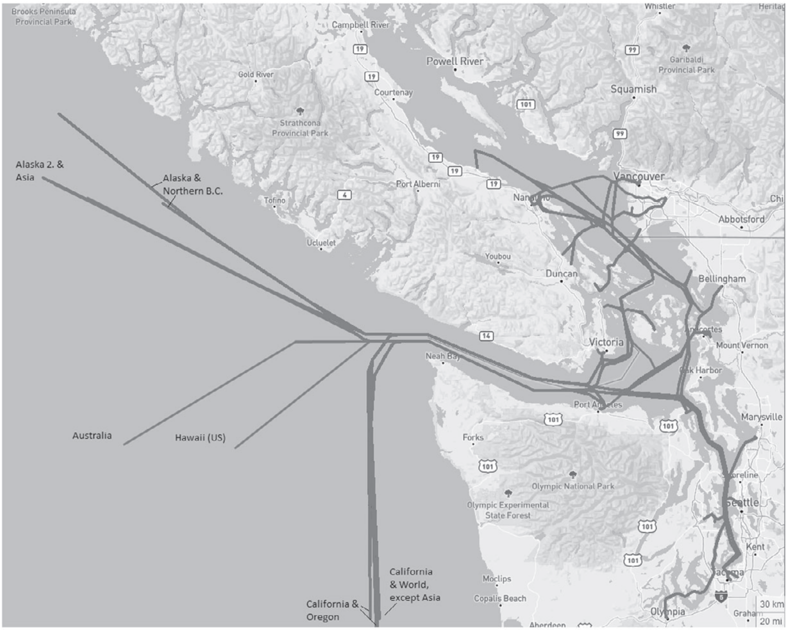

FIGURE 8 Incoming and outgoing trip types

The equations in (14) reflect a vessel in/vessel out assumption. The data themselves are 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 critical habitat; therefore, total exits equal within trip exits and outgoing trips.

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

To see how, first note, using (13) and (14), we have

$$I_t = O_t. \tag{15}$$

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

$$I_t = \sum_{i \in u_c} \sum_{\substack{j \notin u_c \\ j \in \underline{u}}} X_{ijt} + \sum_{i \in u_c} \sum_{\substack{j \notin u_c \\ j \in \bar{u}}} X_{ijt}, \tag{16}$$

where $\underline{u}$ is the set of ports in North America (PoI) and $\bar{u}$ is the set of ports outside of North America. In obvious notation, the first term in (16) is the number of outgoing domestic trips, OD_t, and the second is outgoing foreign trips, OF_t. Using this notation and rearranging shows

$$OF_t = I_t - OD_t. \tag{17}$$

Outgoing foreign vessel trips can be found by use of landing data relevant to the critical habitat and outgoing trips to domestic ports.

4.2.3. Result 1: Walras's law

In table 1, I leverage the vessel arithmetic developed above to provide trip figures for vessels departing the critical habitat over two time periods. The time periods divide the sample years into two roughly equal time periods that differ greatly in the extent of vessel traffic.[14] I have included in this table only departing trips taken by large commercial vessels—bulk carriers, tankers, cargo ships, etc.—because these are well known to be the largest and noisiest ships. Although the table is rather busy, several features stand out.[15]

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 critical habitat 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 in 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 (Canadian) ports within the critical habitat 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, 12,000 of the increase in 55,000 trips are not directly 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 Canadian port within

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[14] A similar table can be constructed directly from the data on arrivals and can be found in the online appendix at `www.mstaylor1.org`.

[15] This is indeed Walras's 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).

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 US or Canada[b]	(4) International departures to third countries[c]
1977–1997				
Canada	58,192	19,418	35,584	3,190
US	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%
US	100%	68%	30%	2%
Total	100%	51%	45%	4%
1998–2019				
Canada	100,276	34,236	25,515	40,525
US	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%
US	100%	53%	20%	28%
Total	100%	42%	23%	35%

NOTES: Commercial vessels: bulk, combined carrier, gas tanker, general cargo, misc. general cargo, tank, unitized. Critical habitat includes Orcas Island (United States) and Vancouver Anchorage (Canada).

[a] Goes from Canada to Canada and from US to US; arrival port may be outside the critical habitat.

[b] Goes from Canada to US and from US to Canada; arrival port may be outside the critical habitat.

[c] Goes from Canada and from US to third country.

the critical habitat but bound for a port in the other. Surprisingly, these within-North America trips fell over the period, not only in percentage terms but also 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 critical habitat bound for foreign ports have skyrocketed. In percentage terms, they rose from 4% of all departures to 35%. In absolute numbers, they jumped from only 4,600 in the earlier period to 61,061 over the latter. One conclusion is inescapable: commercial vessel traffic in the Salish Sea has grown tremendously over these two time periods, not because of rising US–Canada trade (it fell by almost 14,000 trips) or rising traffic within US or Canadian 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 trip, total vessel kilometres travelled within the critical habitat 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 20-year period. This amounts to an annual increase of perhaps 2,750 departures spread out over potentially many ports. Because departures must be matched by arrivals, this could represent 5,500 in and out trips. If each trip was to a large port (Seattle, Tacoma, Vancouver) far from Swiftsure Bank, the kilometres travelled would be about 300 each way, implying that annual vessel kilometres travelled in the habitat grew by 1.65 million over the time period—which is a very large number! As it turns out, this number 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.

4.2.4. Result 2: Distances in the critical habitat

To find the kilometres 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 critical habitat 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 critical habitat, traverses Boundary Pass and then exits to the Pacific Ocean via the Strait of Juan de Fuca. There it turns west for an ocean voyage landing somewhere in Asia in 25 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 the 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 kilometres travelled from its previous port to its current landing port. In essence, I am calculating something akin to value-added (kilometres in the critical habitat) from transactions data (all possible landings) by counting only 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, because, 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 individual 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 kilometres in the critical habitat equal to the distance from Swiftsure Bank 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 Bank to the Port of Tacoma. The kilometres of this travel is collected from the voyage planning company Searoutes and entered as an incoming trip distance for that vessel type in a given month/year.[16] Aggregating across all incoming trips of this type, gives us the kilometres travelled by incoming trips in period t, which I denote by K_{It}. It is simply

$$K_{It} = \sum_{i \notin u_c} \sum_{j \in u_c} X_{ijt} k_{sj}, \tag{18}$$

where k_{sj} is the kilometre distance travelled from Swiftsure Bank, s, to port j in the critical habitat.

The trip from Tacoma to Point Roberts would be identified by its current port being the Point Roberts while its previous port was Tacoma. Because 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, given by K_{Wt}. This is simply

$$K_{Wt} = \sum_{i \in u_c} \sum_{j \in u_c} X_{ijt} k_{ij}, \tag{19}$$

where k_{ij} is the kilometres travelled from port i to j, both in the critical habitat.

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, Point Roberts, being within. Because Campbell River is north of the ferry line in Georgia Strait, this landing would be allocated a distance from Point Roberts to the ferry line. Again, this distance is obtained from Searoutes and would add to the distance for outgoing trips for this vessel type/month/year.

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[16] searoutes.com is a professional tool for route and distance calculation; see `www.searoutes.com`.

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

$$K_{Ot} = \sum_{i \in u_c} \sum_{j \notin u_c} X_{ijt} k_{ig}, \tag{20}$$

where the outgoing distance k_{ig} is to either 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: (i) its current port is outside the critical habitat, (ii) its previous port was within Georgia Strait north of the ferry line and (iii) its current port is not further north along the 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 retrace their step down Georgia Strait to Juan de Fuca and then exit to the Pacific. The kilometres 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 Searoutes 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

$$K_{Pt} = \sum_{i \in u_p} \sum_{j \in u_p} X_{ijt} k_{fs}. \tag{21}$$

The sum total of incoming, within, outgoing and pass-through trips in any given year is the total kilometres denoted by KT_t.[17] Because the vessel landing data have both vessel type and month variation, this total can be made specific to type of vessel (unitized or bulk for example), can weigh vessel kilometres of different vessels 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.

In figures 9 and 10, I plot the calculated vessel kilometres in the critical habitat, for various vessel types, over the entire time period.

Four features stand out. First, the vast majority of kilometres in the critical habitat come from bulk carriers and unitized (container) cargo vessels. Tankers and combined carriers make up an infinitesimal contribution, followed by that of gas tankers. Second, there appears to be some substitution

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

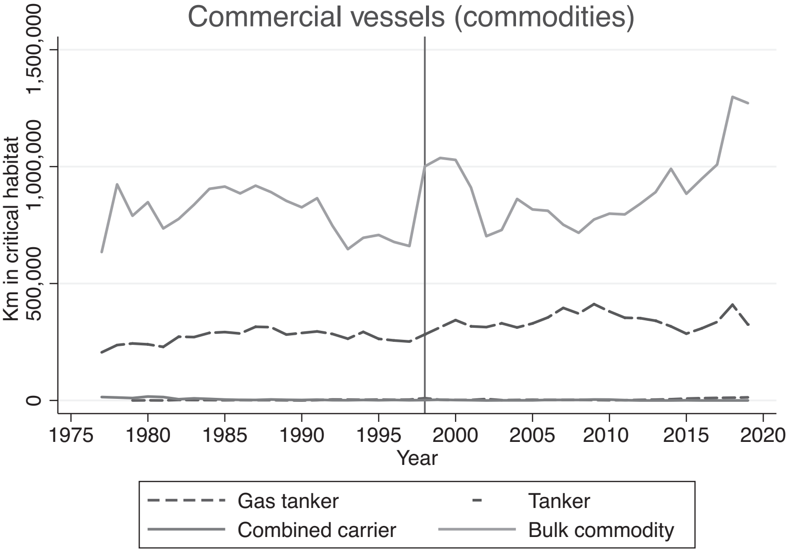

FIGURE 9 Commodities vessel kilometres in critical habitat

across cargo vessel types during the period. General cargo falls throughout being replaced by both miscellaneous general cargo and unitized cargo vessels. Third, the total vessel kilometres grew tremendously over this period more than doubling from a little over 1.5 million kilometres 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 kilometres in the critical habitat rose from 2.1 million to 2.9 million. This represents an annual average increase of 800,000 kilometres, or 36%. This difference in means is also highly significant. Note that this new number is about half of the 1.65 million kilometres of my earlier naive calculation. Fourth, and finally, it is obvious that what is driving most of the increase is the change in kilometres travelled by unitized (container) shipping. Moreover this increase first takes off in the late 1990s remains very high for almost 10 years only to fall during the Credit Crisis years to then recover and continue its growth entering 2019.[18]

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[18] In comparison, McWhinnie et al. (2021) track vessel hours in the critical habitat for two classes of vessels matching our commercial vessel categories. They find vessel hours rise from 6,222 (four-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 kilometres 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.

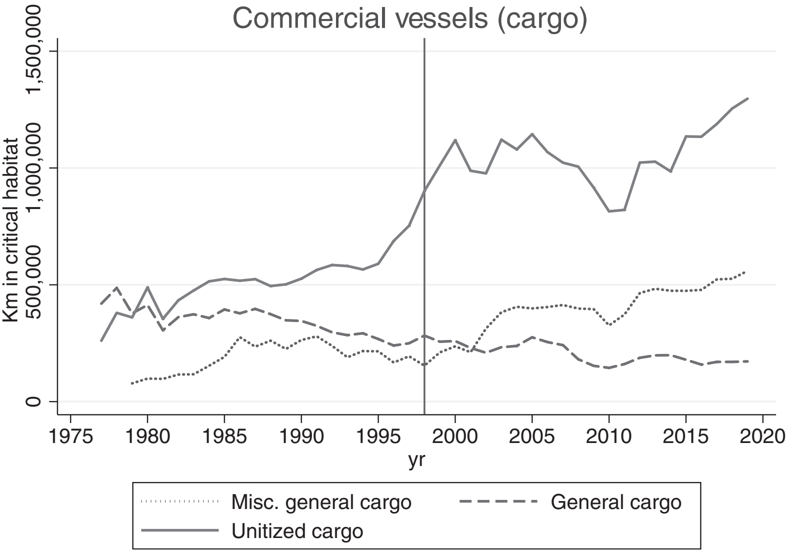

FIGURE 10 Cargo vessel kilometres in critical habitat

TABLE 2

Landings at critical habitat ports by vessel type

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

Finally, as a further check on the importance of changes in unitized vessel traffic, in table 2, I present figures on vessel types. Looking at the table shows results similar to those for vessel kilometres. There is some substitution across cargo ships, but the one very dramatic change is that the share of all arrivals accounted for by large unitized (container) ships grew from 21% of all arrivals to 42% of all arrivals, that is, it doubled! The associated increase in the absolute number of arrivals by unitized cargo ships grew by approximately 47,000 trips. Recall that trips grew in total by only 55,000 over this same period. Because container ships are the sine qua non of international trade, this result may not be all that surprising. It is of course perfectly consistent with the results shown earlier on the change in vessel kilometres.

4.3. An alternative: Changes in salmon abundance

An alternative shock to the Southern Residents' habitat could be a radical change in the availability of Chinook salmon. To investigate, I collected data from the Pacific Salmon Commission on their three measures of Chinook abundance from 1979 to 2019 (the longest period available). The abundance measures are indices constructed from data collected on over 20 individual indicator stocks located up and down the North American coast. Information from individual rivers (primarily escapement figures) are used, by the Chinook technical committee of the PSC, to generate three aggregate salmon abundance indices. Other researchers have used these same data, although my time period is longer and has some new revisions of earlier data. The abundance measures are constructed so that, over the 1979–1982 period, they are unity.

If we just look at the start and the end of the series, there has been some reduction in Chinook salmon abundance. For example, the West Coast Vancouver Island (WCVI) abundance index is 0.61 in 2019 (the latest year figures are available), the Northern British Columbia (NBC) abundance index is at 0.96, but the South East Alaskan (SEAK) abundance index is 1.07. Because the abundance indices are constructed to be unity in the 1979–1982 period, there have been some real reductions especially in the WCVI measure. Its important, however, to understand the variability of the indices over time. We are after all looking for a potential shock that has negatively affected the SRKW from around year 1998 onwards. To that end, in figure 11, I present the three salmon indices in terms of z-scores.

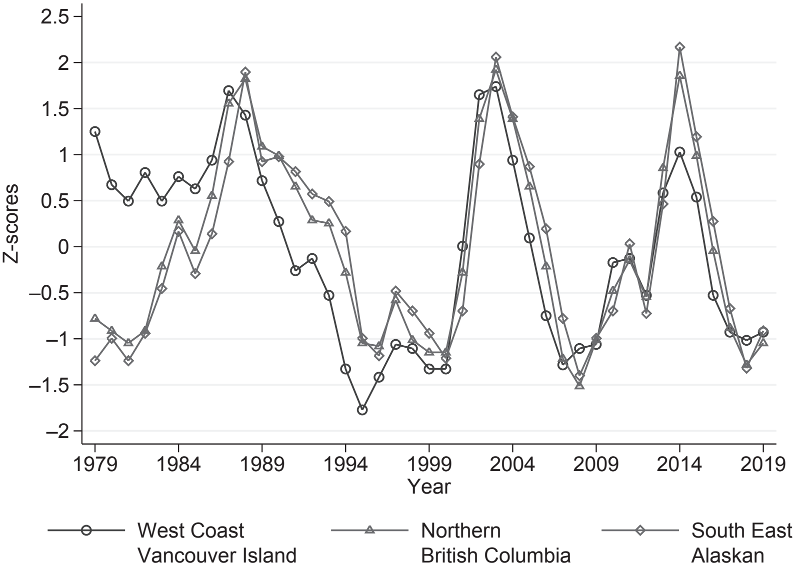

FIGURE 11 Z-scores of major salmon indices over time

As shown, the three indices are highly correlated, showing very poor salmon years in the mid to late 1990s, and subsequently around 2010 and currently. The 1990s decline has often been blamed for the population reductions leading to the listing of the SRKW as an endangered species; however, by the same token, there then remains the real issue as to why they never recovered despite the rising indices post 2000. Because variation in the three indices matches so well, it is very hard to believe that salmon availability has caused a secular decline in the SRKW while the NRKW enjoyed almost continuous growth over the same period. Therefore, while salmon availability is undoubtedly important to their fecundity and mortality (Ward et al. 2009, Ford et al. 2010, Taylor 2021) it is unlikely to be the key element driving the SRKW decline.[19]

5. Do vessels disturb killer whale populations?

The previous section showed that kilometres travelled by commercial vessels within the SRKW critical habitat changed dramatically over the study period. In particular, dividing the period into two halves split at 1998, the change in vessel kilometres was a 36% increase, the change in the number of arrivals was a 46% increase and the share of unitized container vessels doubled. The question remains, however, do vessels traversing a critical habitat interfere with whales and killer whales in particular?

Recently there has been a recognition of the scale and potential importance of underwater noise pollution on marine mammals. There is now a large body of scientific work measuring noise disturbances from vessels and some work studying their effects on killer whales. To my knowledge, there is currently no evidence linking this form of pollution to population impacts on whales of any sort.

Nevertheless, this is a very active area of research for marine scientists, and a small but growing literature on the effects of sound on marine mammals is sufficiently complete that it can be useful here. To start, we know that vessels emit noise at frequencies killer whales use for both communication and echolocation. Hall and Johnson (1972) is the earliest study, but many others have found similar results. We also know from studies in situ—those actually done in the Salish Sea—that measured noise disturbances from commercial vessels are significant and long lasting. While vessels naturally differ in their unique noise signature, McKenna et al. (2012) and others find that unitized vessels are the loudest. Other large vessels are less noisy, but at some frequencies all large vessels appear to be very similar. Moving from a noise disturbance in the right frequency to changes in behaviour is, as you can imagine, not easy, but researchers have found that whale behaviour changes when

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[19] The reader is invited to compare figures 4, 10 and 11 and reach their own conclusions regarding the likely importance of salmon variability and changes in unitized vessel kilometres to the Southern Residents.

vessels are near. For example, diving, socializing and foraging behaviour changes, and as a result, there is an energetic cost (Williams et al. 2002, 2014). Finally, there is some evidence of habituation or avoidance. For example, constant high amplitude background noise can drive killer whales from an area (Morton and Symonds 2002).

What we do not know is whether these disturbances add up to a change in whale populations. Does it lower births, raise deaths? Both? Preliminary evidence from Taylor (2021) suggests the effects are large and significant. Using the measures of vessel disturbance shown here, he documents a large and significant negative impact of vessel kilometres on SRKW births and a large and significant positive impact on deaths. Moreover, these effects are large—so large in fact that it would take an unprecedented beneficial three standard deviation increase in salmon abundance to offset them.

To assess the impact of noise disturbance on the Southern Residents, I take a different tack here and evaluate the strong and weak conjecture using simulations of the competing species model. The simulation will shed light on the magnitude of the shock needed to replicate the data and the mechanisms involved. To do so, I now return to the competing species model developed earlier with the knowledge that a large, permanent shock did occur. My goal is to evaluate whether such a shock within the competing species model can replicate the broad features of SRKW and NRKW population history.

5.1. Evaluating the weak and strong conjecture

It is relatively easy to simulate the dynamics of the Lotka–Volterra model to better understand how shocks to either or both carrying capacities would impact populations. My purpose in doing so is to evaluate which of the two forms of the conjecture are consistent with broad features of the data. I have already shown evidence that salmon availability has varied tremendously over the last 40 years, and while salmon abundance is currently low, changes in its availability cannot explain the long-term decline in the SRKW. Therefore, in the simulations, I focus exclusively on the impact of a permanent shock that reduces carrying capacity.

My method resembles a proof by contradiction. I first assume the weak conjecture is true and choose parameter values for the simulation consistent with what we know about killer whale reproduction and the timing and size of vessel shocks. Depending on the outcome of this exercise, I proceed accordingly.

The model is so simple that there are relatively few parameters to choose in such an exercise. Initial conditions for the NRKW and SRKW populations are pinned down by our existing data on populations in the late 1970s. In particular, I take as initial conditions the 1979 population figures of $N = 139$ and $S = 83$. The first real decision concerns the potential growth rates, or intrinsic growth rates, of the two populations. I take these to be identical because they are the same species and adopt from the existing literature an intrinsic growth rate of 3%.[20]

Under the weak conjecture, there is no across-population competition ($\alpha = \beta = 0$) and the evolution of each population is determined independently of the other. The second decision I make is to assume the NRKW do not experience any vessel shock over the period. In Taylor (2021), I find strong evidence that vessel shocks lower births and raise deaths of the SRKW, but the evidence for impacts on the NRKW are less clear. This population is affected less by the vessel shocks than the SRKW, but whether the net impact is zero is not clear.[21] For clarity, I set the direct impact of vessel shocks on the NRKW to zero.

With these assumptions in hand, I can now choose the Northern carrying capacity so that the simulation generates a 2019 NRKW population near the current value of 335. This requires a NRKW carrying capacity near 850.

To determine the SRKW carrying capacity, I exploit the fact that, over the initial 13 years of observations on population numbers, the two population growth rates did not differ very much at all. Although SRKW growth was far more variable, Olesiuk et al. (1990) find that, from 1974 to 1987, the populations grew at similar rates. Because the populations have the same intrinsic growth rate, this requires that their populations be in the same proportion to their carrying capacities. That is, it requires, $S/K_S = N/K_N$. Using the initial conditions for populations at 1979, and the already determined K_N, this implies the Southern carrying capacity is equal to $K_S = (850)(83/139) = 507$.

At this point, we are very close to seeing the contradiction. The SRKW population peaked in 1995 at 100 whales and fell thereafter. While it is clear that the extremely poor salmon years in the mid to late 1990s were largely responsible for their immediate decline, it has continued, almost interrupted, for the next 25 years despite two very positive periods of salmon availability (recall figure 11).[22] Under the weak conjecture, the only way to generate long-term negative growth is to have the killer whale population consistently above the new, much lower, carrying capacity, that is, it requires the vessel shock to have lowered the carrying capacity from 507 to some level below 100 to start the negative trend; in fact, it requires the new steady state lie below the

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[20] For example, Olesiuk et al. (1990) create life tables for the NRKW and SRKW populations using data from the 1974–1987 period and estimate the intrinsic rate of growth for both populations at 2.92%.

[21] See the section Assessing the Weak Conjecture in Taylor (2021, p. 49).

[22] In Taylor (2021), I find strong evidence that salmon availability affects both births and deaths. For example, in the 1990s, salmon fell by almost two standard deviations below its average over the 1979–2019 period. My estimates tie a 2 standard deviation reduction in salmon availability to a decrease in the odds of a killer whale birth of 22% and an increase in the odds of a death by 34%.

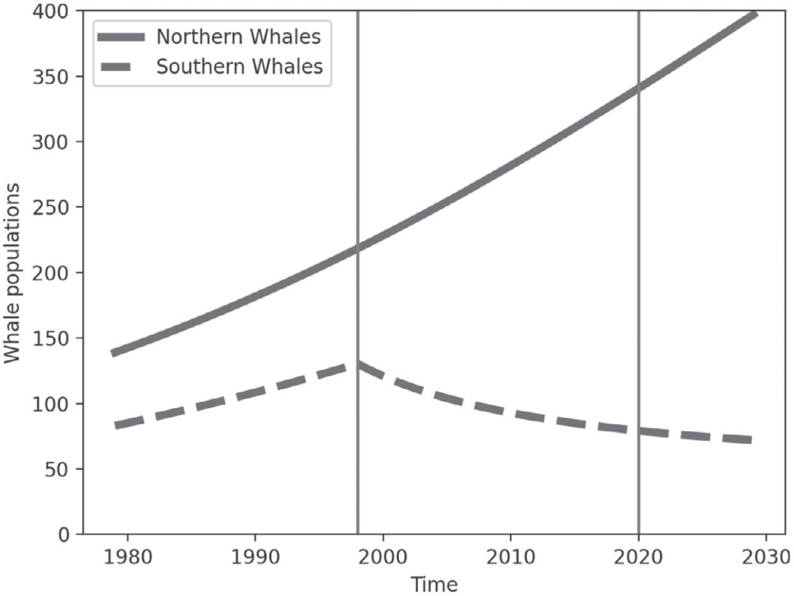

FIGURE 12 The problem with the weak conjecture

current population level of 74 to ensure the downward trajectory for 20 years. Therein lies the contradiction.

In order to reconcile the broad features of the two population histories with the weak conjecture requires we assume an incredibly large and permanent vessel disturbance shock lowered the quality of the Southern habitat to perhaps 10% of its previous value. The implication of this assumption is shown in figure 12. The two populations start at their respective 1979 levels, and I impose a very severe negative shock to the SRKW carrying capacity in 1998, leaving it at only 10% of its former value. The NRKW is unaffected by the shock and grows to a little above 330 in 2019; the SRKW immediately falls and reaches approximately 74 whales in 2019. Despite the very sizeable shock, however, the SRKW will not go extinct under the weak conjecture.

Although the evidence I presented earlier on vessel traffic, kilometres and composition shows a large increase and suggest a significant impact could be expected, I find it very hard to believe the SRKW critical habitat has been degraded to only 10% of its former value. I take the size of the shock needed to match current whale numbers to be the contradiction and conclude the weak conjecture is at odds with the broad features of the data.

While a more complicated model of growth may of course alter these conclusions, and a more nuanced calibration may also affect the results somewhat, the scale of the contradiction is so large that it is hard to believe that reasonable departures are going to fix this problem. Occam's razor suggests

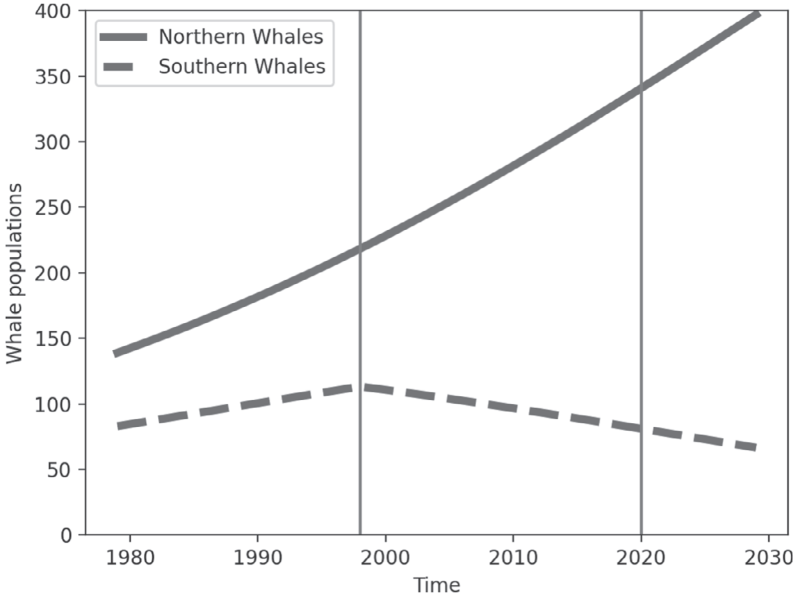

FIGURE 13 The strong conjecture with extinction

we adopt the simplest solution to this conundrum—which is, of course, to allow for across-population competition and evaluate the strong conjecture.

The key challenge is generating persistently negative growth for the SRKW in the face of recovering salmon abundance and almost continuous growth in the NRKW. The simplest way to effect this change is to assume they are in fact competing populations. To proceed directly, recall from (5) that extinction for the SRKW would occur if, post shock, ${K_S}^* - \beta K_N \leq 0$, where ${K_S}^*$ is the new carrying capacity after the shock. Let ${K_S}^* = \gamma K_S$, so γ represents the reduction in the quality of the habitat caused by vessel disturbance. I assume $\gamma = 0.4$ so vessel disturbance lowers the productivity of the SRKW carrying capacity by 60%. Given our already calibrated values for the two carrying capacities, this implies the competition coefficient β needs to exceed only 0.25 to cause the extinction of the SRKW. While this extent of competition is not great given the extent of overlap in their habitats, it generates a painfully slow path towards extinction. In order to drive population downward fast enough to meet its 2019 value of 74 requires a $\beta = 0.75$ or three times that needed to generate extinction.

This possibility is shown in figure 13. Again the shock is applied in 1998 but now it is a still, very large, 60% decline in the carrying capacity. I also set $\beta = 0.75$ and, by 2019, the populations are close to their observed values.[23]

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[23] I also set $\alpha = 0$. Choosing a positive value just reinforces the argument by requiring an even larger shock or larger β.

Eventually, the NRKW reach their carrying capacity of 850, while the SRKW approach zero.

Putting these observations together leads to a somewhat painful conclusion: if the NRKW and SRKW evolve independently, as in the weak conjecture, then the fall in the SRKW carrying capacity required to drive populations down to match current levels is too large to be credible. Assuming they are competing species makes it far easier to generate falling SRKW population levels with even a relatively small value for across-population competition. Matching the pace of decline after 1998, however, requires a much higher value—a value that is consistent only with the shock placing the SRKW on a slow-motion path towards extinction.[24]

6. Conclusions

I have used simple economic theory and data to offer a credible explanation for the long-term decline of the SRKW population. The explanation I offered was formalized in the weak and strong versions of the orca conjecture. To be precise about the conjecture, I employed the Lotka–Volterra model of competing species to develop the weak and strong versions and discipline later inferences drawn from simulations. The key theoretical result is that a negative shock that falls primarily on one population is magnified by across-population competition to become much more potent. Even a relatively small shock can push a system from one with mutual co-existence to one featuring extinction of the SRKW.

To identify a large and permanent shock, I exploited new data on vessel arrivals to ports in the SRKW critical habitat. Using this data, I showed that vessel arrivals at ports within the habitat rose by the 46% in the post-1998 period relative to the 1977–1997 period. While this increase in arrivals is suggestive, I then went further to show that constructed measures of the vessel kilometres travelled within the critical habitat also rose by 36% post 1998. Finally, not only did vessel kilometres rise but also the composition of these kilometres changed drastically. The share of unitized cargo ships doubled from 21% to 42%. Because unitized vessels are the fastest and nosiest of all commercial vessels, this shift in the composition of traffic may well be as important as the increase in arrivals or vessel kilometres.

I then returned to the model to investigate whether broad features of the data are better explained by the weak or strong conjecture. By adopting parameter values drawn from published studies in the literature, combined

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[24] In Taylor (2021), I come to the same conclusion by examining cohorts of female whales who reached their years of maximum reproductive potential either pre or post 1998. I show the pre-1998 SRKW cohorts had a total fertility rate well above replacement, but the post-1998 cohorts have a total fertility rate well below replacement, implying they are on a path to extinction. In contrast, the NRKW whale cohorts pre and post 1998 differed very little.

with knowledge of current and past conditions, I first showed that the precipitous decline of the SRKW post 2000 is very difficult to explain with a vessel disturbance shock alone if the two populations do not compete for prey. I also argued that, while salmon availability is very important to population growth, the available data from the Pacific Salmon Commission show variability in salmon availability and not overall decline post 1998.

One possible conclusion is that the Lotka–Volterra model, or the logistic growth model underlying it, is just not up to the task—a more complicated model taking into account the population's composition (juveniles, mature males, breeding age females and senescent females) and the impact of the initial "cropping" by the display industry are needed. At some level, this is clearly true—the Lotka–Volterra model is a caricature of a complex dynamic general equilibrium system. However, rather than abandon it, I chose to follow the principle of Occam's razor by adding only the possibility of across-population competition to investigate its effect. With this one change, I am able to replicate broad features of both the NRKW and SRKW population histories but only with parameter values that also come with the uncomfortable conclusion that vessel shocks, post 1998, have placed the SRKW on a slow-motion path towards extinction.

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