The Orca Conjecture

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The Tragedy of the Commons

The population problem has no technical solution; it requires a fundamental extension in morality.

Garrett Hardin

The author is professor of biology, University of California, Santa Barbara. This article is based on a presidential address presented before the meeting of the Pacific Division of the American Association for the Advancement of Science at Utah State University, Logan, 25 June 1968.

Hardin's Approach

- Hardin, who was a biologist, used a well established economic model, to generate a well known result.
- Hardin used little to no data, and made several bold predictions.
- Hardin's dismal conclusions are forever tied to the catchy title of his Presidential Address.
- Essentially the same result was published 14 years earlier by the Canadian Resource Economist - H. Scott Gordon (1954).
- H. Scott Gordon is a Past President of the Canadian Economics Association (1977-78).

The Empire Strikes Back

- I will use a well established biological model, to generate a well known result.
- I will use more than 5 million observations on vessel movements, salmon fish stocks, a complete census of both Northern and Southern Resident killer whales, etc. to make one bold prediction.
- I also have a dismal conclusion, and a very catchy title for my Presidential Address.
- None of the results I will show you today appear anywhere else, although some of them will appear in a companion paper by M. Scott Taylor - a Past President of the Canadian Economics Association (2019-2020)

History, Geography and Photography of Killer Whales (Orcinus Orca)

Orca Breaching off Saturna Island

Source: Brian Copeland Private collection

A Pod off Vancouver Harbour

Source: Center for Whale Research, 2020

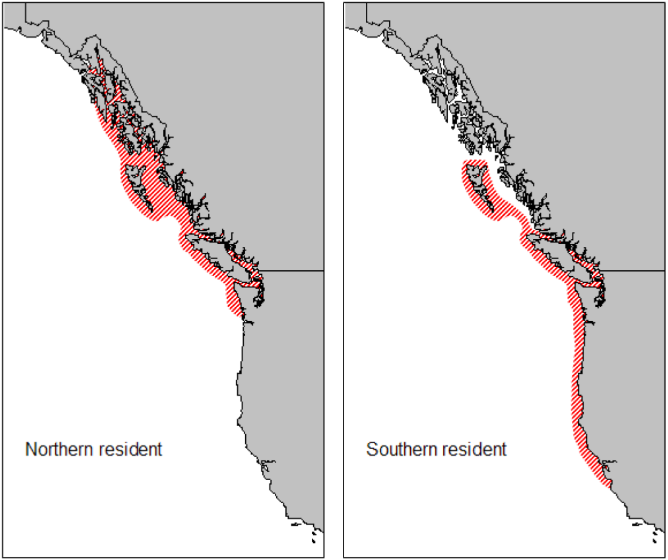
Orca Watching off Saturna Island

Source: Brian Copeland Private collection

History

- Previous to the early 1960s Killer Whales were feared, despised and routinely shot by fishermen and boaters.
- A fortuitous live capture altered many of these beliefs and a live capture and display industry was born.
- In the early 1970s, live capture was regulated and then banned. Despite this there are approximately 20 KW still in captivity today in North America. Many more in Europe and Asia.
- By the late 1990s, KW were protected by both Canadian and US governments, and were listed as Species at Risk or Endangered species in the early 2000s. The SRKW is endangered; the NRKW is listed as threatened.
- Currently, the SRKW has 74 whales remaining from a peak of nearly 100 in the middle of the 1990s. The NRKW has over 300 whales and is growing.

Northern and Southern Ranges

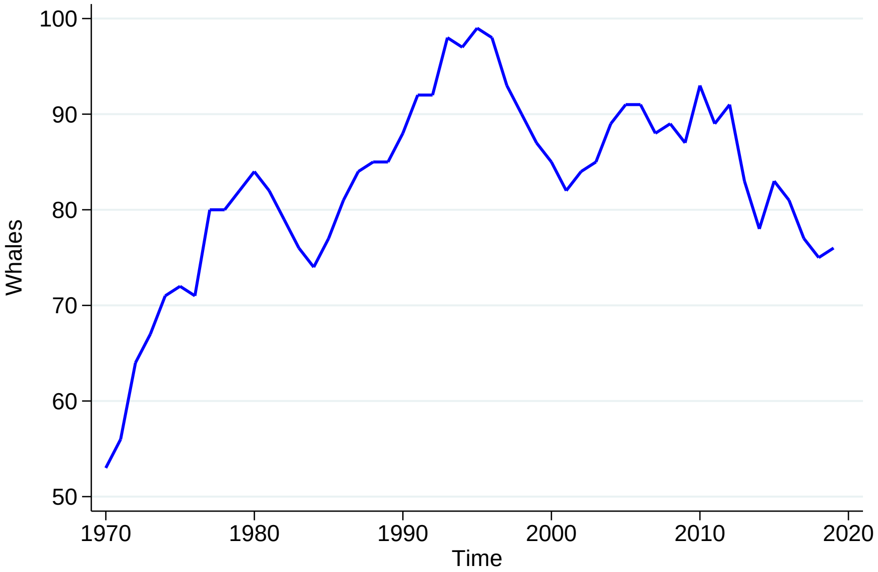


Known geographical ranges of northern (left) and southern (right) resident killer whales. Extent of movement offshore is unknown. Source: Figure 1. in Ford (2006)

The Problem with the Southern Residents

- The Southern Resident population has been on a long downward trend since the mid to late 1990s.
- The current population size is about where it was in the mid 1970s when the live capture industry was still active.
- Its age and sex composition is worrisome.
- In contrast to the Southern Residents, the Northern Residents have experienced almost continuous growth since the late 1970s.

SRKW Population History



Three Main Suspects

- A lack of prey, sometimes linked to declining Salmon returns on the Columbia River and dams on its tributary the Snake River.
- Vessel disturbance from whale watching and large Commercial Vessels.
- PCBs and other long lived contaminants leaching into the marine environment and then magnified by bio-accumulation.
- Despite literally tens of millions of dollars of research, the Debate over what to do with, or for, the Southern Residents is going nowhere fast.

The Orca Conjecture

The Conjecture

- Booming 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.
- The shock was asymmetric, affecting the the Southern Resident Killer whales more than their Northern counterparts.
- This asymmetric shock was magnified by the Competing Species model of Lottka-Volterra, and has now placed the Southern Resident Killer Whales on a slow-motion path to extinction.

Divide and Conquer

- This paper when published will contain the Conjecture, summary statistics, several simulations, and an introduction to the issue of Marine Pollution and International Trade.
- The companion paper - Trade, Competitive Exclusion, and the Slow motion extinction of the Southern Resident Killer Whales - contains the novel methods and empirics behind the work presented here (currently in process with an ETA of late June).
- Also in process is an Online Supplementary Data Appendix co-authored with my excellent Phd student Fruzsina Mayer (additional research support provided by MA students Chetan Sharma and Samira Ayache)

My Five Step Method for Today

- Review the relevant Biology of Killer Whales (KW) with a focus on the NRKW and SRKW populations.
- Use the Lotka-Volterra competing species model to show how an correlated shock to their habitats affects population outcomes.
- Show that measures of vessel km travelled in the relevant critical habitats have indeed changed drastically over the sample period.
- Cite evidence that vessels do disturb whales, and provide evidence that higher vessel km within a habitat lowers KW births.
- Argue the net result of these changes is to lower SRKW total fertility well below replacement, implying extinction is inevitable.

Tremendous Debt owed to the Biology/Ecology literature

- Recently there has been a recognition of the scale and potential importance of underwater noise pollution. There is now a large body of scientific work measuring noise disturbances from vessels, and some work studying their effects on KW.
- To my knowledge - there is currently no evidence linking this form of pollution to population impacts on whales of any sort.
- There is a huge literature created, and supported by, NOAA and Fisheries and Oceans Canada to support the listings of KW as endangered, to establish Recovery plans etc. Very detailed, very useful. Canadian Scientists at DFO have played a leading role in much of this research.
- Some related empirical work in biology/ecology studying KW population growth as a function of demographics and environmental conditions. Ford et al. 2005, Ford et al. 2010, Ward et al. 2009

I. Biology

Source: Brian Copeland Private collection

Biology A.

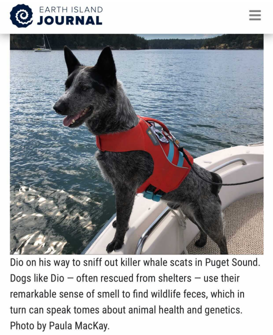
- There are three types of KW populations worldwide: Resident, Transient (Biggs) and Offshore.
- The NRKW and SRKW are Resident killer whales. These populations do not interact, interbreed nor share a common dialect.
- Resident whales eat fish, primarily Chinook (King) salmon and to some extent migrate along the coast to follow Salmon.
- Identified at surface by unique markings on dorsal fin and saddle patch (M. Biggs); identified below water by uniqueness of calls used for communication (J. Ford).
- Communication between whales occurs via low frequency tones; when hunting they use echolocation with high frequency very fast clicks to locate and identify prey.

Biology B.

- Males are roughly 30% larger than females. Sexual dimorphism. Males 8 meters, 6,600 kgs; Females 6 meters, 4500 kgs
- Live in family units called pods, comprised of several matrilines. Born into a matriline and you die in the matriline. Several pods make a clan; several clans make a population.
- Female whales can live to 60 or more years; Males typically 40 or less
- Gestation is 15-18 months, nursing and natal care lasts another 18 months. Female reproductive years start at 10 and ends close to 40, peak at 20. Conception, on average, in July-August.

Critical Habitats

Data collection by NOAA and DFO Scientists

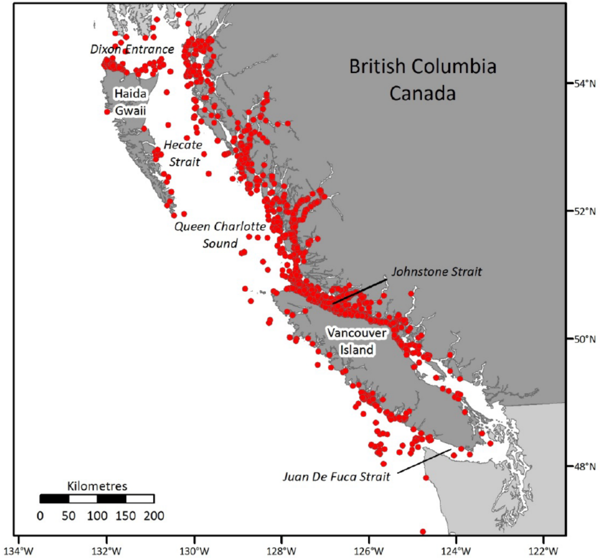


Left: Photo by Paula MacKay from here. Right: Screenshot from BBCTwo video

Typical Methods

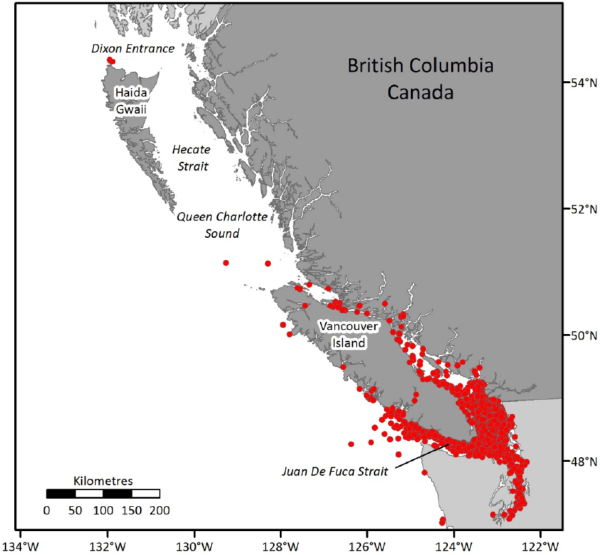
- Vessel and land based photo-identification surveys.
- Acoustic monitoring either stationary or on vessels.
- Tissue fragments and scale collected at predation sites. Fecal matter at surface. Useful to identify prey selectivity, stress hormone levels, genetic signatures of both whales and prey.
- Very limited whale tagging and tracking devices. Some underwater photo and videography.

NRKW Sightings



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

SRKW Sightings



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

The NRKW Critical Habitat

Northern Resident Killer Whale Critical Habitat

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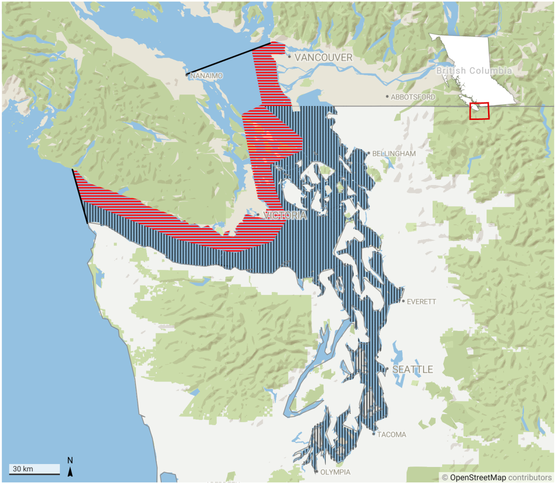
The SRKW Critical Habitat

SRKW Critical Habitat



— Limit of Critical Habitat Area   SRKW Critical Habitat (CAN)   SRKW Critical Habitat (USA)

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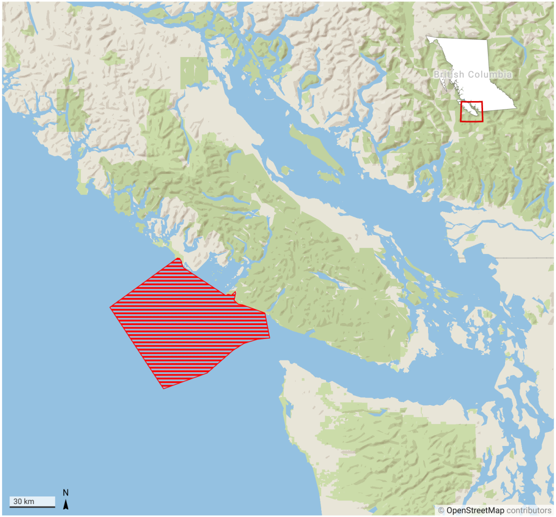
The New (2018) Shared Critical Habitat

New Killer Whale Critical Habitat



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II. Theory

Source: Brian Copeland Private collection

Lotka-Volterra Competing Species Model

Assumptions

- Populations do not interbreed with each other.
- Populations do not interfere or mix with one another.
- Populations share habitat and compete for prey.
- Growth is density dependent.

Modelling Competing Populations (Species)

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

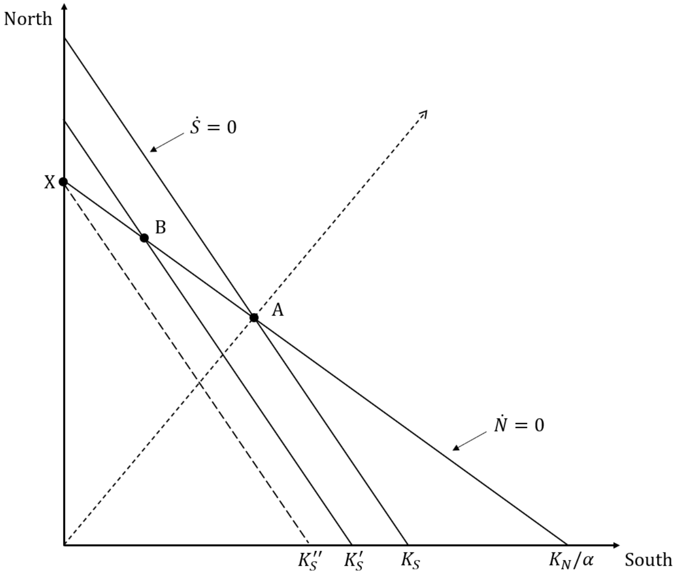
$$\frac{dS}{dt} = rS[1 - \frac{S}{K_S} - \frac{\beta N}{K_S}] \quad (2)$$

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

Its Simpler to Think in Terms of Economics

- The isoclines are just full employment constraints for the carrying capacities $K_N = N + \alpha S$ and $K_S = S + \beta N$.
- If Northern whales are intensive in their use of the Northern Carrying Capacity then $1 > \alpha$.
- If Southern whales are intensive in their use of the Southern Carrying Capacity, then $1 > \beta$.
- If each is intensive in its use of its own core habitat, the interior steady state is globally stable.

The Competitive Exclusion Principle: Gause's Law (1934)



Conclusion from Theory (Biology or Economics)

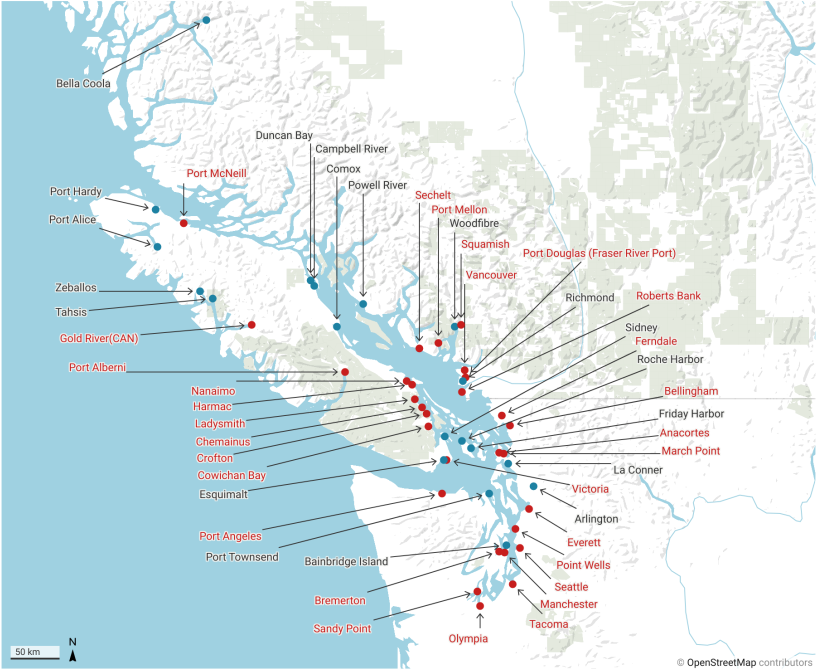
- Common shocks lead to common responses (Salmon availability; PCB pollution?)
- Asymmetric shocks lead to very different, and magnified, responses.
- The impact of a Correlated shock = common shock plus asymmetric shock
- One path to SRKW extinction is an correlated shock to both carrying capacities, magnified by competitive exclusion.

III. Vessel Movement

Source: Brian Copeland Private collection

My Methods: Data from Lloyd's List Intelligence Unit

- Data from 1977-2019 includes *all* vessel landings at 121 West coast ports in North America.
- Gives number of vessels of certain type X, landing in port Y, during month Z. Does not identify vessel per se.
- Also includes last two ports for most vessel landings
- Over 1.8 million landings and over 5 million vessel movements
- Additional data on vessel characteristics by port/month/type including dead weight tons, length, age, and TEUs


Bella Coola
Duncan Bay
Campbell River
Comox
Powell River
Port McNeill
Port Hardy
Port Alice
Sechelt
Port Mellon
Woodfibre
Squamish
Port Douglas (Fraser River Port)
Vancouver
Zeballos
Tahsis
Gold River(CAN)
Richmond
Roberts Bank
Sidney
Ferndale
Roche Harbor
Port Alberni
Nanaimo
Harmac
Ladysmith
Chemainus
Crofton
Cowichan Bay
Esquimalt
Bellingham
Friday Harbor
Anacortes
March Point
La Conner
Victoria
Arlington
Port Angeles
Port Townsend
Everett
Point Wells
Bainbridge Island
Seattle
Bremerton
Manchester
Sandy Point
Tacoma
Olympia
50 km
N
© OpenStreetMap contributors

How to Calculate Vessel Km in Habitats

Use Two Insights from Economics

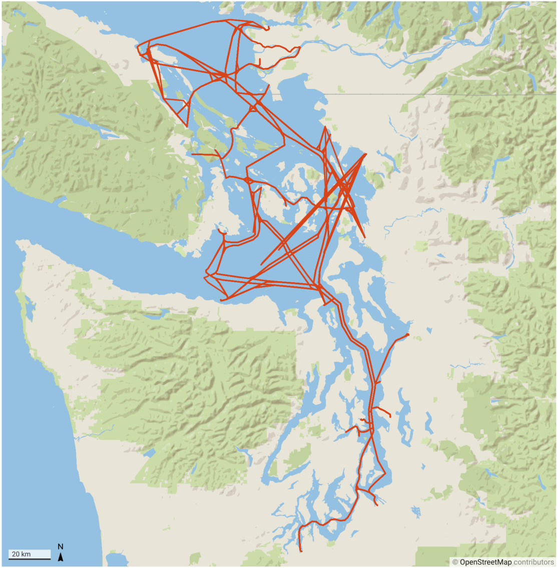
- Landings alone overestimate km traversed in the critical habitat by large amounts. An observed landing at Vancouver Harbour does not represent 280 km travelled in the CH if it just moved from the Fraser river port

- To calculate km in the CH, I define different types of trips: incoming, outgoing, within, passthrough, and foreign outgoing

- Adding up km across trip types is akin to computing value-added in National Income Accounting. A Port is like an Industry. A trip is a sale from an intermediate producer (previous port) to a final good producer (current port).

- Exits to Foreign ports are not recorded, but all entries to the CH have to generate exits. This is Budget Balance. Walras's Law then allows me to calculate the magnitude of trips leaving for foreign ports.

Tracking Vessels without Satellites! Within Trips



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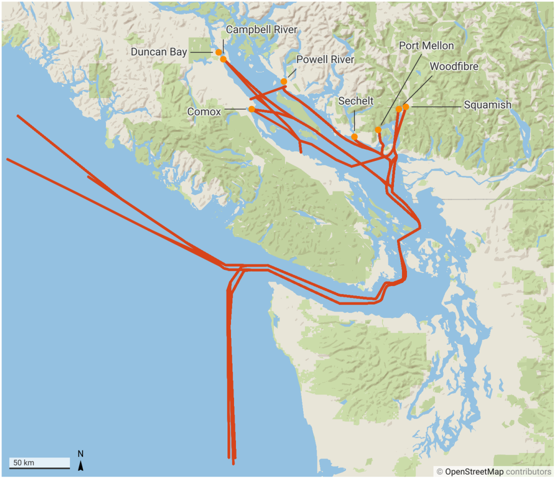
Incoming/Outgoing Trips

Pass Through Trips



Georgia Strait ports

Created with Datawrapper

Result 1: From Walras's Law

Table: 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.

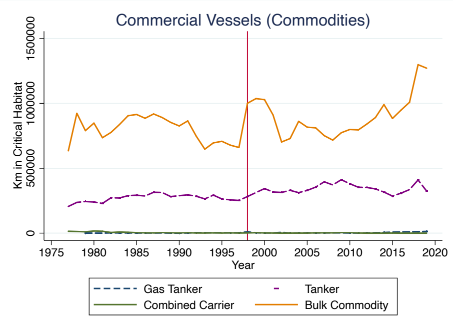
**: Including Orcas Is. (U.S.A.) and Vancouver Anchorage (Canada).

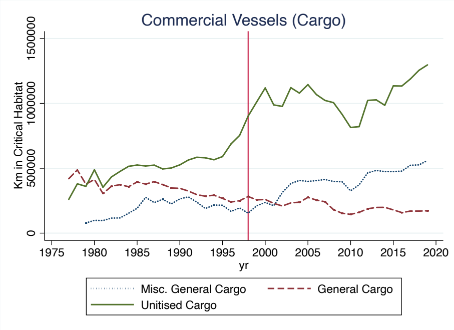
[a]: Goes from Canada to Canada and from U.S. to U.S.; arrival port may be outside the critical habitat

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

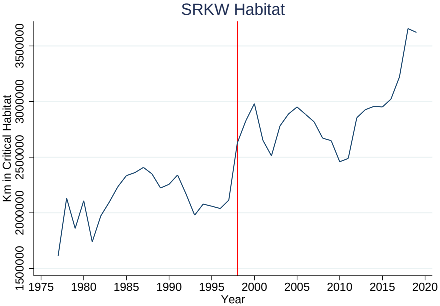
[c]: Goes from Canada and from U.S. to third country

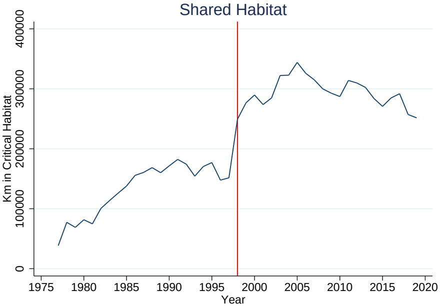
Result 2: Distances in the SRKW Critical Habitat





Total Commercial km within Two Critical Habitats





In Numbers

All Commercial Vessels, All Year
Average Km/year through Critical Habitats

	1977-1998	1998-2019	Percentage change
SRKW Habitat	2,117,513	2,882,156	36.1%*
Shared Habitat	133,002.5	293,161.1	120.4%*

*: Difference in means is statistically significant.

IV. Does Vessel Disturbance affect KW populations?

Source: Brian Copeland Private collection

What we Know

- Vessel's emit sounds at frequencies KW use for both communication and echolocation. Hall et al. (1972)
- Measured noise disturbances from Marine Vessels in situ are significant and long lasting. McKenna et al. (2012)
- Unitised vessels are the loudest; other large commercial vessels similar. Speed matters. Veirs et al. (2016)
- Whale behavior changes when vessels are near. Diving, socializing, foraging. There is an Energetic cost. Williams et al. (2002, 2014).
- Constant high amplitude background noise can drive KW from an area. Morton et al. (2002).

What we don't know

- We don't know if these disturbances add up to a change in whale populations. Does it lower births, raise deaths? Both?
- We don't know how to measure a Vessel's disturbance on KW. Is it ship length and its displacement?; is it time in the vicinity, or is it just noise? What is the Treatment?
- There is no agreement on the proper way to aggregate across Vessels or adjust for Vessel characteristics to create an index of noise disturbance.
- Difficult to design a treatment and control empirical strategy when your treatment group is mobile, mostly underwater, and disappears for long stretches of time.

My Method

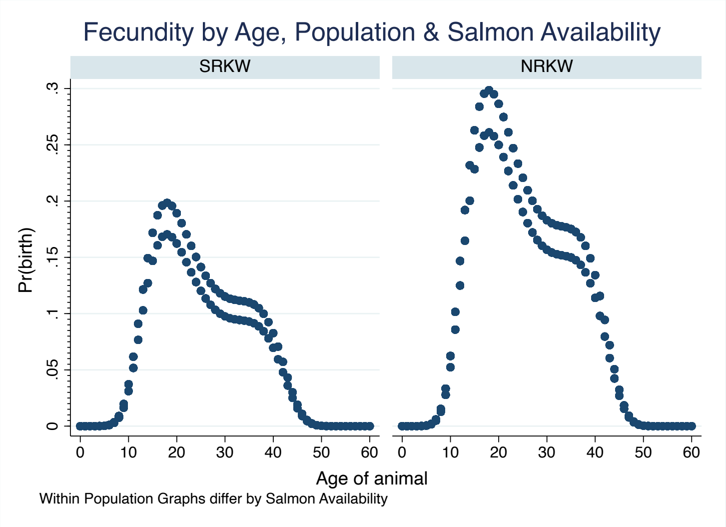
- Develop a model of population change already used by biologists.
- Use Vessel km in the critical habitat as my measure of disturbance
- Explore how three different sources of variation in the disturbance data affect births
- Births treated as Bernoulli random variables leading to logistic estimation
- Interactions used for population or gender specific effects
- A useful exploratory first step

Additional Data

- Complete record of all SRKW and NRKW in existence since 1977 together with births, deaths, pods, matrilines, etc.
- Approximately, 12,000 whale year observations. (DFO, CRW, Orca sightings network)
- Extensive database of salmon stock measures from the Pacific Salmon Commission 1979-2017.
- Three major stock indices (NBC, SEAK, WCVI) that reflect conditions at 30 Chinook indicator stocks.

Demographics and Salmon Availability Only

Predicted Probabilities of Birth



The Impact of Vessel Disturbance on Fertility

	I.	II.	III.	IV.	V.	VI.
Constant	−17.658***	−16.847***	−17.935***	−17.635***	−18.085***	−17.918***
	(1.033)	(1.385)	(1.211)	(1.363)	(1.246)	(1.374)
Age	2.741***	2.744***	2.730***	2.733***	2.732***	2.739***
	(0.246)	(0.247)	(0.243)	(0.245)	(0.243)	(0.249)
Age^2	−0.158***	−0.159***	−0.157***	−0.158***	−0.158***	−0.158***
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)
Age^3	0.0039***	0.0039***	0.0038***	0.0039***	0.004***	0.004***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Age^4	−0.00003***	−0.00003***	−0.00003***	−0.00003***	−0.00003***	−0.00003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
NRKW	0.565***	−0.491***	0.566***	0.149***	0.552***	0.282***
	(0.014)	(0.000)	(0.014)	(0.000)	(0.009)	(0.000)
Salmon index high	0.048	0.051	0.059	0.058	0.023	0.021
	(0.036)	(0.032)	(0.037)	(0.039)	(0.042)	(0.044)
Salmon index low	−0.192**	−0.187**	−0.157*	-0.153	−0.180**	−0.178**
	(0.077)	(0.083)	(0.095)	(0.099)	(0.081)	(0.082)
Depletion effect	−0.00035***	−0.00034***	−0.00037***	−0.00037***	−0.00093***	−0.00094***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
SRKW Vessel km	−0.263*	−0.586***				
	(0.140)	(0.003)				
SRKW Vessel km × NRKW		0.416***				
		(0.001)				
SRKW Unitised km			−0.428**	−0.816***		
			(0.202)	(0.015)		
SRKW Unitised km × NRKW				0.515***		
				(0.005)		
Shared Vessel km					-0.261	−1.121***
					(0.374)	(0.081)
Shared Vessel km × NRKW						1.181***
						(0.016)
Age × NRKW	No	No	No	No	No	No
N	5820	5820	5820	5820	5820	5820
Log likelihood	-1434.55	-1433.19	-1434.72	-1433.92	-1436.9136	-1436.5669

Standard errors in parentheses. *** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$
Distances are measured in million km.
In the regressions where "Total Unitised km" is also included on the right hand side, "Total Vessel km" is the vessel total less the distance traveled by unitised vessels.

Magnitudes Births: Vessel Disturbance Effects

- Need a base case to consider. Km travelled went from a yearly average of 2.1 million to 2.9 million over the 1977-1998 vs 1998-2019 periods.
- Total Commercial km rose .8 million, but of this about .5 is increased km by Unitised vessels; the remainder is all others.
- Using this metric, then Unitised vessel km lower the odds of calving in the SRKW by about 30%; lowers it in the NRKW by half this amount
- If I just consider all km aggregated, the odds of a SRKW birth fall by 38%.
- To put this in perspective, a one std deviation below average Salmon year lowers the odds of a birth by 18%.

V. Extinction

Source: Brian Copeland Private collection

Extinction

- Biologists have very complicated stochastic models they use to predict the liklihood of extinction. There is an entire subfield and literature dedicated to it.
- I am going to do something much simpler and very transparent. It is based on two observations.
- Observation 1: Killer whales are sexually dimorphic. This suggests dominant males may be the only reproducers. Recent genetic sampling in fact reveals two males are responsible for over 50% of Southern Resident births.
- Observation 2: Any population with a total fertility rate (permanently) below replacement is destined for extinction.

NRKW Synthetic Whale Cohorts

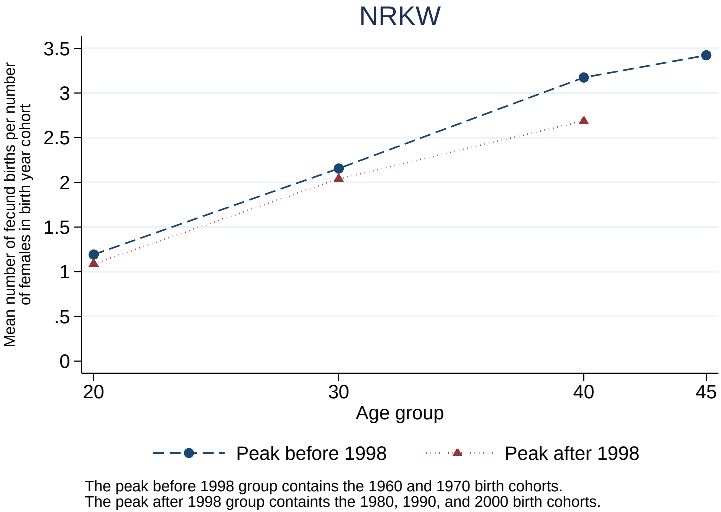


Figure: Lifetime Surviving to One year births

SRKW Synthetic Whale Cohorts

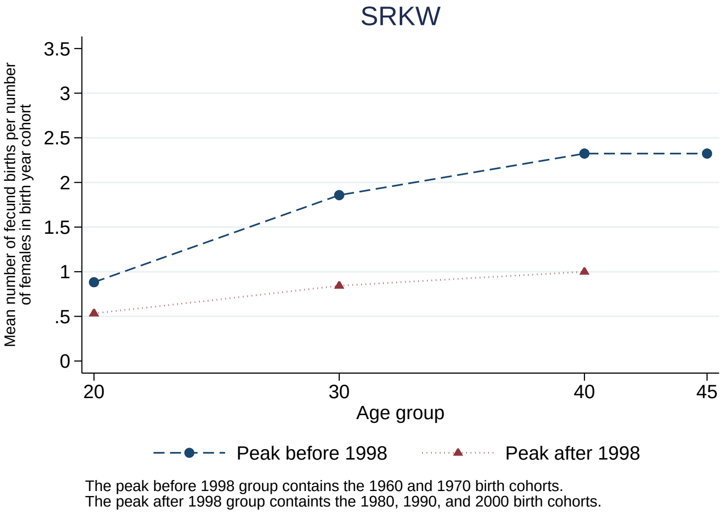


Figure: Lifetime Surviving to One year births

Conclusions

Some Good News - Some Bad

- Used simple economic theory and data to offer a credible explanation for the long term decline of the SRKW population.
- The data shows Commercial vessel km travelled in KW critical habitats show a very large post 1998 increase.
- A large shock to the quality of critical habitats caused by vessel traffic is magnified by the dynamics of Competitive Exclusion and can drive the SRKW to extinction.
- An analysis of whale cohorts shows that, absent a large change in circumstances, the SRKW are on a slow motion path to extinction.

Thank you

Source: Brian Copeland Private collection

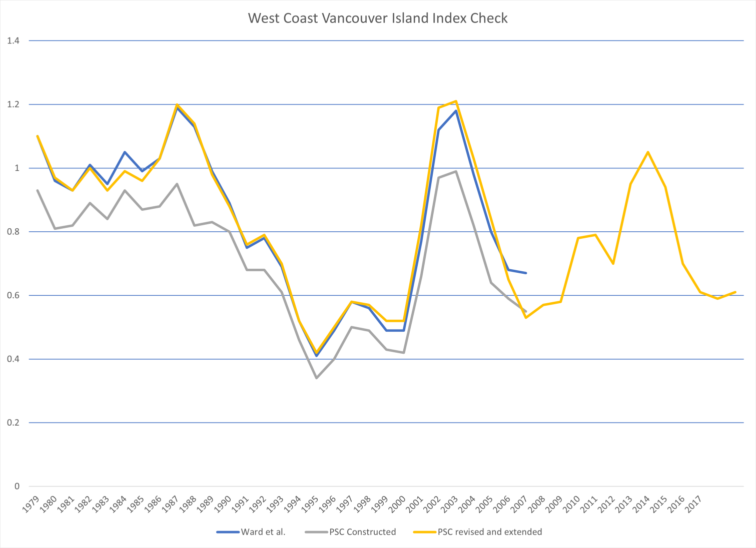
Alternatives: Persistent Organic Pollutants

- PCBs production/import/sale was banned by both US and Canadian governments in the late 1970s, although release to the environment and storage were not regulated until the mid 1980s. Nor was it stripped from existing machinery, etc.
- PCB pollution that is already in the marine environment, plus that leaching into the Salish Sea, raises levels of PCBs in other marine mammals (seals, sea lions,etc.)
- There are elevated levels of PCBs in Killer whales; these levels are sufficiently high to impair reproduction in seals, but unknown effects on KW.
- Highest concentrations are however in Transient Killer whales and those populations are growing rapidly.

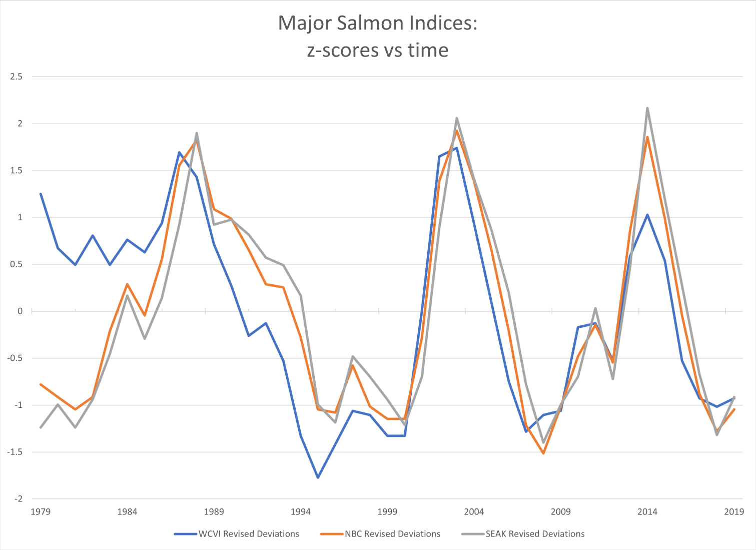
Alternatives: Lack of Prey

- Salmon returns have been falling since the 1960s, but have been relatively constant since 1980.
- WCVI stocks, which are important to the KW, are perhaps 30% on average below their late 1970s mean.
- NBC and SEAK stocks are 20% above their means.
- Movements in the three major Chinook indicators are highly correlated. Salmon have had several years well above (1 std deviation above) these means but the SRKW did not recover.

Salmon


West Coast Vancouver Island Index Check
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Ward et al.
PSC Constructed
PSC revised and extended

Salmon


Major Salmon Indices:
z-scores vs time
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1979
1984
1989
1994
1999
2004
2009
2014
2019
WCVI Revised Deviations
NBC Revised Deviations
SEAK Revised Deviations