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

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Research Questions

- What is responsible for the declining population of Southern Resident Killer Whales? (SRKW)
  - Has booming international trade with Asia created a boom in vessels disturbing killer whales?
  - Is there evidence that vessel km in a habitat affect the births and deaths of a long lived marine mammal?
  - What policies could/should we use to lessen or eliminate the impact?

Plan for Today

- Preview of Results
- Review the relevant History and Biology of Killer Whales (KW)
- Introduce competing hypotheses.
- Generate measures of vessel km travelled in the SRKW critical habitat
- Investigate whether vessel km add to conventional demographic and environmental determinants of births three different ways

A Preview of Results

- Vessel km travelled within the SRKW has increased tremendously post 1998. Average km travelled by large commercial vessels rose by 800,000 km/year or 46% over pre-1998 levels.
- This increase in vessel km was driven primarily by changes in km for large Unitised Cargo (Container) Ships.
- Measures of km travelled by Unitised vessels drives SRKW births down and deaths up.
- The impacts are very large. Using the pre and post 1998 km as our metric for change, the odds of death rise by 30-40%; the odds of a successful birth fall by a similar amount.
- The impacts on the SRKW are by far the greatest, but the Northern Resident Killer Whales (NRKW) also seem to be affected.

What remains to be done?

- Alternative Treatment/Control Empirical Strategy.
- Metric for noise pollution yet to be included. A km is a km is a km...
- A smoking gun..
- Measures of km traversed in NRKW critical habitat not yet exploited.
- Calculations for costs of a go slow zone on trade.

Related Literature - Economics

- A contribution to our knowledge of the impact of international trade on the environment. Copeland, et al. forthcoming in the Handbook of International Economics.
- International Trade creates vessel trips which in turn creates a negative transboundary externality - disturbance to marine mammals.
- Most closely related work links trade to transport emissions created by air, rail and ocean shipping. Cristea, et al. 2013, Shapiro (2016)

Related Literature - Biology/Ecology

- 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. To my knowledge - there is currently no evidence linking this pollution to population impacts.
- 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.
- Related work in biology/ecology specifically studying KW population growth as a function of demographics and environmental conditions. Ford et al. 2005, Ford et al. 2010, Ward et al. 2009

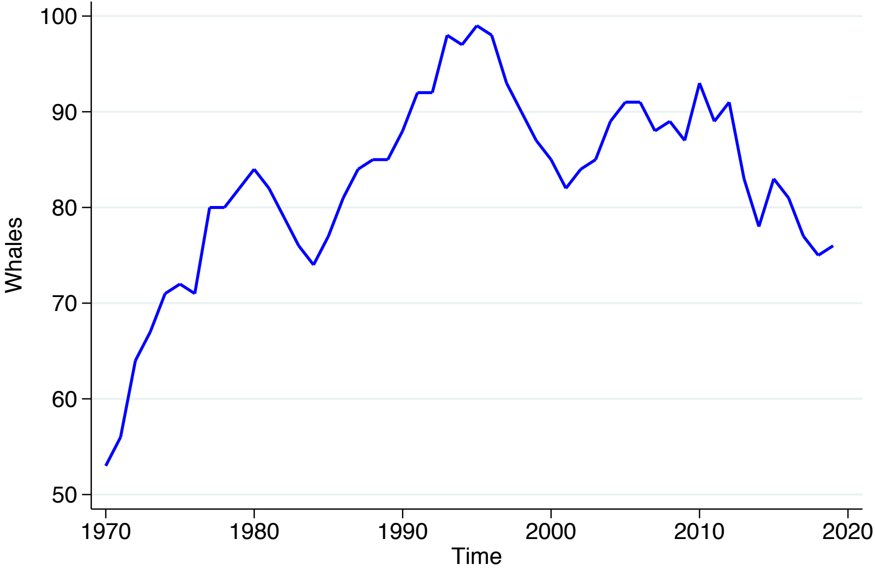
Killer Whale (Orcinus Orca)

Source: Southern Resident offshore Saturna Island, 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 under by both Canadian and US governments. 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 late 1990s. The NRKW has over 330 whales and is growing.

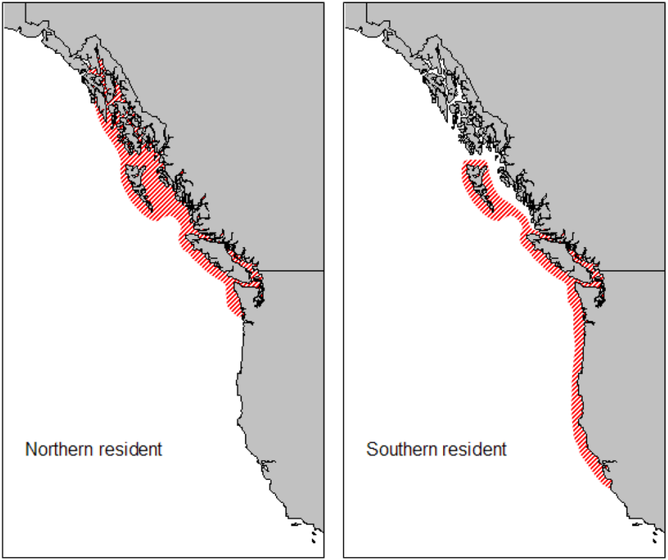
SRKW Population History



Biology

- 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 to follow Salmon.
- Live in family units called pods, comprised of several matrilines. Several pods make a clan; several clans make a population.
- Female whales can live to 80 or more years; Males typically 60 or less
- Gestation is 15-18 months
- Noise pollution can affect both communication (low frequency sounds) and echolocation (high frequency sounds).

Northern and Southern Habitats



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

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.

My Hypotheses

- Weak Conjecture: Growing vessel traffic tied to International trade creates attendant noise which has degraded the SRKW habitat lowering their ability to reproduce.

- Strong Conjecture: same as above, but now add that the NRKW are competing for prey, and this across population competition has magnified the negative impact of the vessel noise shock.

- Hypotheses come from the Competing Species Model of Lotkka-Volterra with noise shocks lowering carrying capacities.
  ▸ Competing Species Model

Data

Data collection by NOAA and DFO Scientists

Figure: Dog finding scat

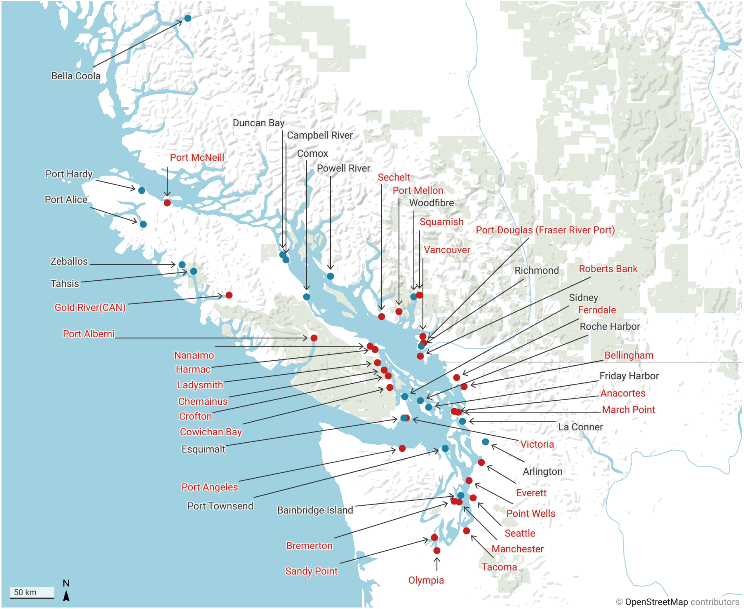
Methods of Data Collection: Whales and Ships

- Vessel and land based photo-identification surveys
- Acoustic monitoring of whales either stationary or on vessels.
- Tissue fragments and scale collected to identify prey; fecal matter to measure stress hormone levels, genetic signatures
- Very limited whale tagging and tracking. Some observational evidence on whale behaviour changes when vessels near.
- Underwater acoustic monitoring of vessel noise (Haro Strait, Pugeot Sound) and dissipation.
- Land and satellite tracking of ship movements in critical habitats possible since perhaps 2010.

My Methods: The Lloyd's List Data

- 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 all 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
- Some data missing; some is useless; it passes internal consistency checks

Area of Interest plus Ports

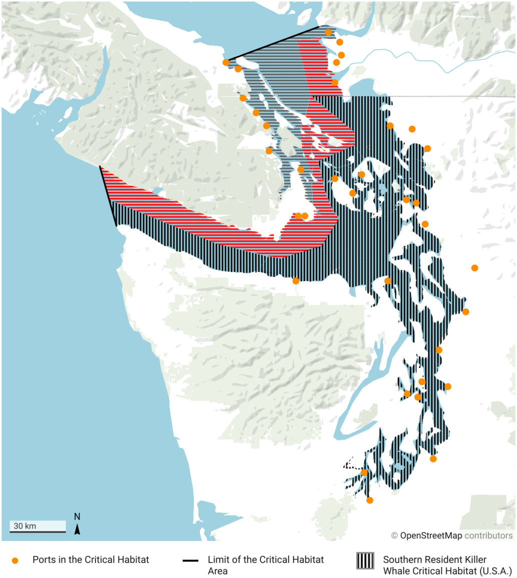


Other Data

- Complete record of all SRKW and NRKW in existence since 1977 together with births, deaths, pods, matrilines, etc.
- Extensive database of salmon available from Pacific Salmon Commission from early 1980s onward
- Additional cross checks provide by Pacific Pilotage data on BC coast
- Additional cross checks provided by Washington state Vessel Entry and Transit data.
- Distances between ports and portals obtained from Searoutes
- Spot checks on routes and vessels using Marine Traffic

Defining the Critical Habitat

Designated critical habitats for Southern Resident Killer Whales



Vessel Arithmetic

- 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 5 different types of trips
- Adding up km across trip types is akin to using value-added in National Income Accounting
- Exits to Foreign ports are not recorded, but all entries to the CH have to generate exits
- This budget balance imposes a type of Walras's Law for ships that allows me to calculate the scale of foreign destined trips.

Vessel Arithmetic Details

An Example: Trip Types

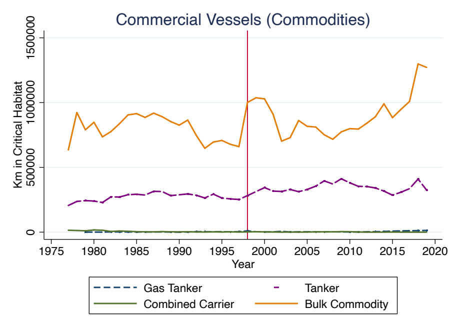
Result 1: From Walras Law

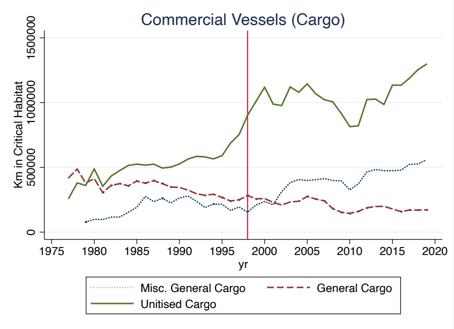
Departures by commercial vessels* from the ports in the Critical Habitat**, aggregated over 1977-2019

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





▸ Ship Types

Empirical Strategy

- Consider the Weak Conjecture first. It assumes within competition matters, but across population does not.
- Births and Deaths treated as Bernoulli random variables leading to logistic estimation
- Errors are clustered at the pod level
- Interactions used for population or gender specific effects. Age specific effects captured by higher-order polynomial.
- No control for potential vessel disturbance specific to NRKW along Johnstone Strait (in process) CH Maps

Baseline Demographic Determinants of Fertility

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

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

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

Magnitudes Births: Demographics and Environment

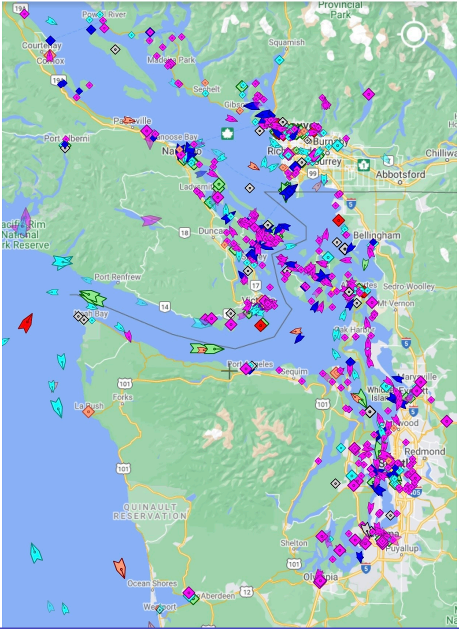
- NRKW indicator implies NRKW 20 year old female probability of birth is about .4; SRKW lower near .25. ▸ Predicted Probabilities

- Salmon indicator tells us that a 1 standard deviation increase in availability from its mean, raises the odds of calving by 11%. A great (2 std. dev) salmon year, 23%.

- Depletion effect coefficient indicates population size matters to growth. A 100 whale increase in population lowers the odds of calving by 20%.

- NRKW by Age interactions don't seem very important here.

Traffic in Salish Sea: Screen Shot from Marine Traffic



What we Know About Vessel Noise

- 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) vessel noise data
- 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 relevant measure of exposure?
- There appears to be no agreement on the proper way to aggregate across Vessels or adjust for Vessel characteristics to create an index of noise disturbance.

The Impact of Vessel Disturbance on Fertility

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

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

Distances are measured in million km.

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

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

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.
- If I just consider all km aggregated, the odds of a SRKW birth fall by 33% using this metric.
- 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 32%; and raises births in the NRKW!

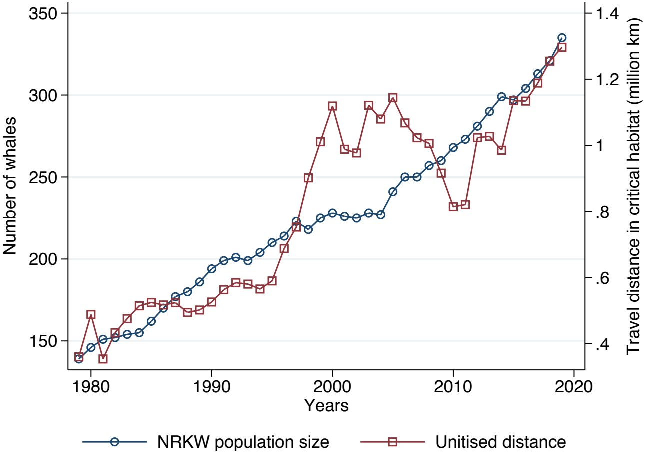
Alternative Approach I

Source: Brian Copeland Private collection

Exploiting Shocks to Vessel Km

- It is possible I am just finding a correlation between rising vessel km and falling population growth.
- Perhaps, but relative impacts on NRKW and SRKW is consistent with causation.
- Perhaps, but relative impacts of Unitised vs other Commercial Vessels is also consistent with causation
- However, if they are competing species then the most important excluded factor, that is also growing over time, is the population of the NRKW.

Correlation or Causation



First difference Impacts on Births

	I.	II.	III.
Constant	-17.58^{***}	-17.59^{***}	-17.58^{***}
	(1.46)	(1.42)	(1.46)
Age	2.80^{***}	2.79^{***}	2.80^{***}
	(0.29)	(0.28)	(0.29)
Age^2	-0.16^{***}	-0.16^{***}	-0.16^{***}
	(0.02)	(0.02)	(0.02)
Age^3	0.004^{***}	0.004^{***}	0.004^{***}
	(0.001)	(0.001)	(0.001)
Age^4	-0.00004^{***}	-0.00003^{***}	-0.00004^{***}
	(0.0000)	(0.0000)	(0.0000)
L1.Within-Competition	-0.002^{*}	-0.002^{*}	-0.002^{*}
	(0.001)	(0.001)	(0.001)
L1.Across-Competition	-0.01^{***}	-0.01^{***}	-0.01^{***}
	(0.00)	(0.00)	(0.00)
L1.Salmon Abundance	0.29^{**}	0.32^{***}	0.29^{**}
	(0.12)	(0.11)	(0.12)
L1.Δ Total Unitised km	-3.24^{***}	-3.29^{***}	0.02
	(0.71)	(0.67)	(0.67)
L1.ΔTotal Unitised km $\times$ NRKW	3.25^{***}	3.30^{***}	
	(0.98)	(0.95)	
L1.ΔTotal Unitised km $\times$ J pod			-3.78^{***}
			(0.71)
L1.ΔTotal Unitised km $\times$ K pod			-1.03
			(0.70)
L1.ΔTotal Unitised km $\times$ L pod			-3.97^{***}
			(0.66)
ΔTotal Unitised km		-1.23	
		(0.90)	
ΔTotal Unitised km $\times$ NRKW		0.21	
		(1.09)	
N	5,707	5,707	5,707
Log likelihood	-1403.76	-1402.39	-1403.35

Standard errors are clustered at the pod level and appear in parentheses. $^{***}: p < 0.01$, $^{**}: p < 0.05$, $^{*}: p < 0.1$
Distances are measured in million km.
[a]: Δ denotes first differences.
[b]: N records the number of female-whale-years for births; all whale years for deaths.

Within and Across Competition

- Demographic and Salmon determinants remain stable across specifications.
- Across Competition seems to matter quite a bit, so does Within competition
- Change in Unitised km matters for the SRKW but not for the North
- Change in Unitised km is negative for all Southern pods, J, K, L.
- Largely consistent with earlier results.

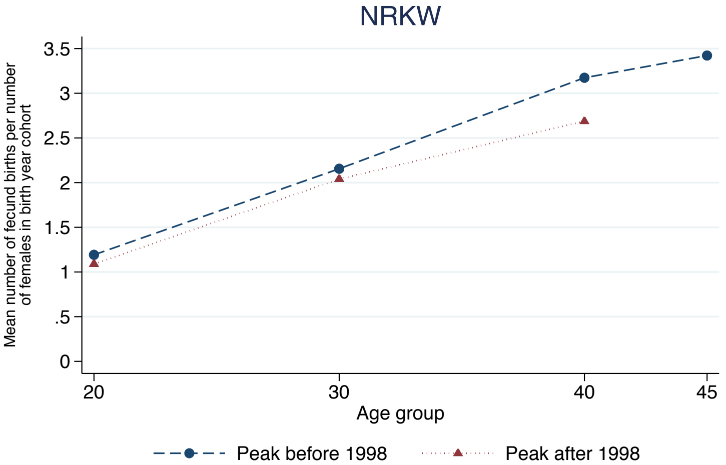
Alternative Approach II

Source: Brian Copeland Private collection

Exploiting Cohort Information

- Group 10 year of birth female whale Cohorts into those that reached peak reproductive year of age 20 before and after 1998
- Calculate Total fertility rate profiles for the two synthetic - before and after - cohorts.
- TFR will, in theory, reflect changes in fertility directly, and changes in mortality indirectly
- Also provides information about likely extinction

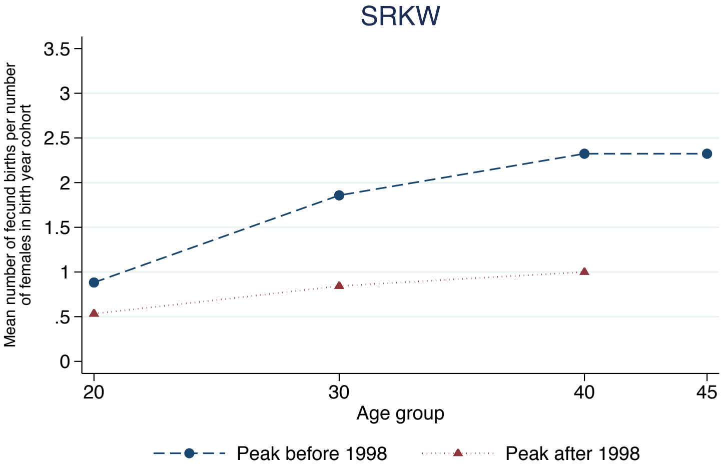
NRKW Synthetic Whale Cohorts



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

Lifetime Surviving to One year births

SRKW Synthetic Whale Cohorts



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

Lifetime Surviving to One year births

Conclusion

- Used simple economic theory and statistics to offer a credible explanation for the slow motion extinction of the SRKW based on booming international trade post 1998, causing increased vessel disturbance to whales in their critical habitat.
- Estimated impacts on births and deaths are large. Three alternative methods gave similar results.
- Still much to do: evaluate the robustness of results, alternative hypotheses, and develop a policy response cost calculation example
- My method for calculating vessel disturbance in marine environments may be useful to other researchers studying noise pollution and its effect on marine mammals.