Noisy Trade: The Impact of Shipping Noise on Marine Mammals

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KW Photographs from Brian Copeland Private collection.

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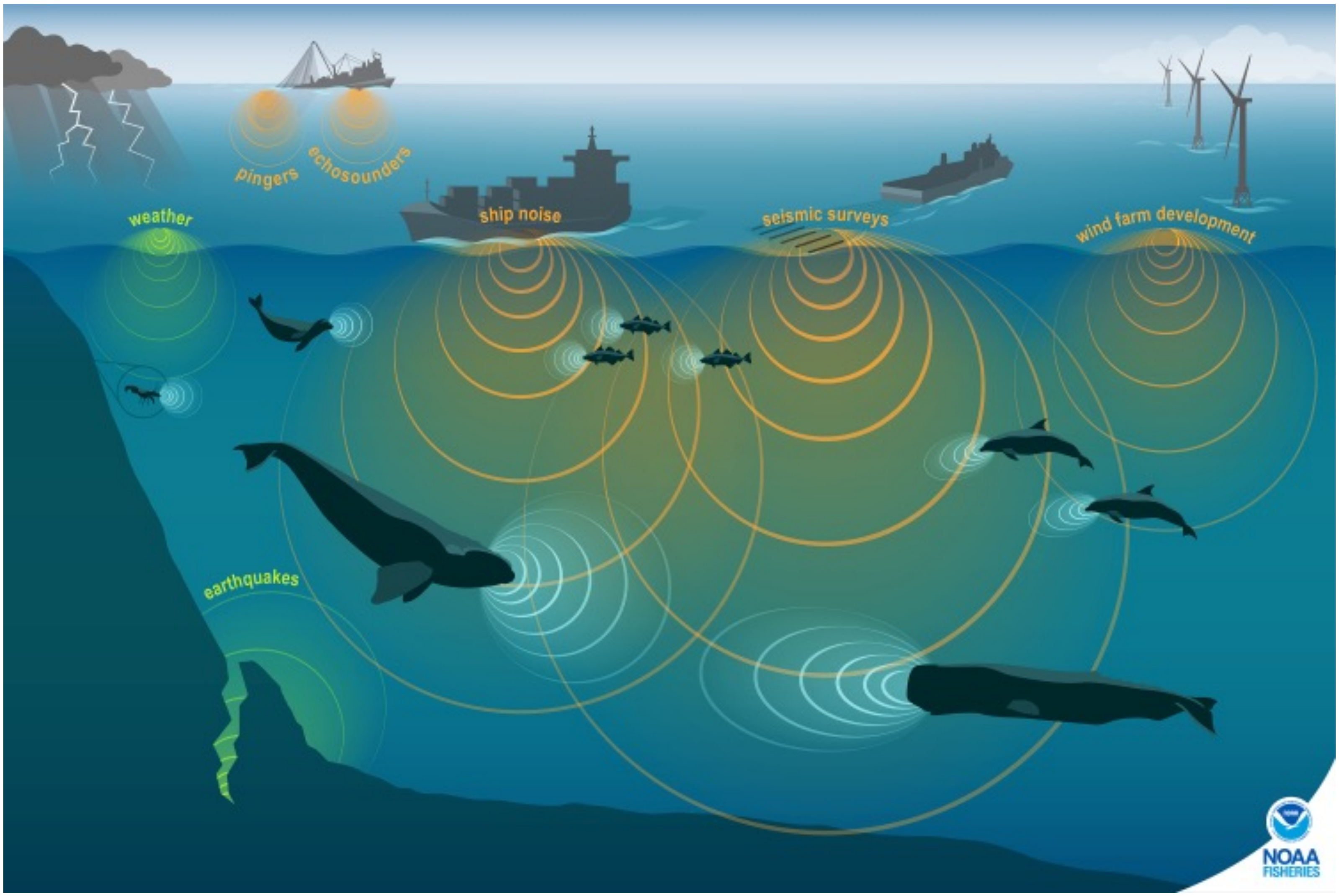
Research Questions

- How can we evaluate the impact of noise disturbances on marine mammals?
- Has vessel noise from vessel traffic had a measurable impact on Killer Whale populations? What should we do about it?
- Could these methods be employed elsewhere? Offshore wind turbines, deep sea mining, or other whale populations?

Whales Worldwide

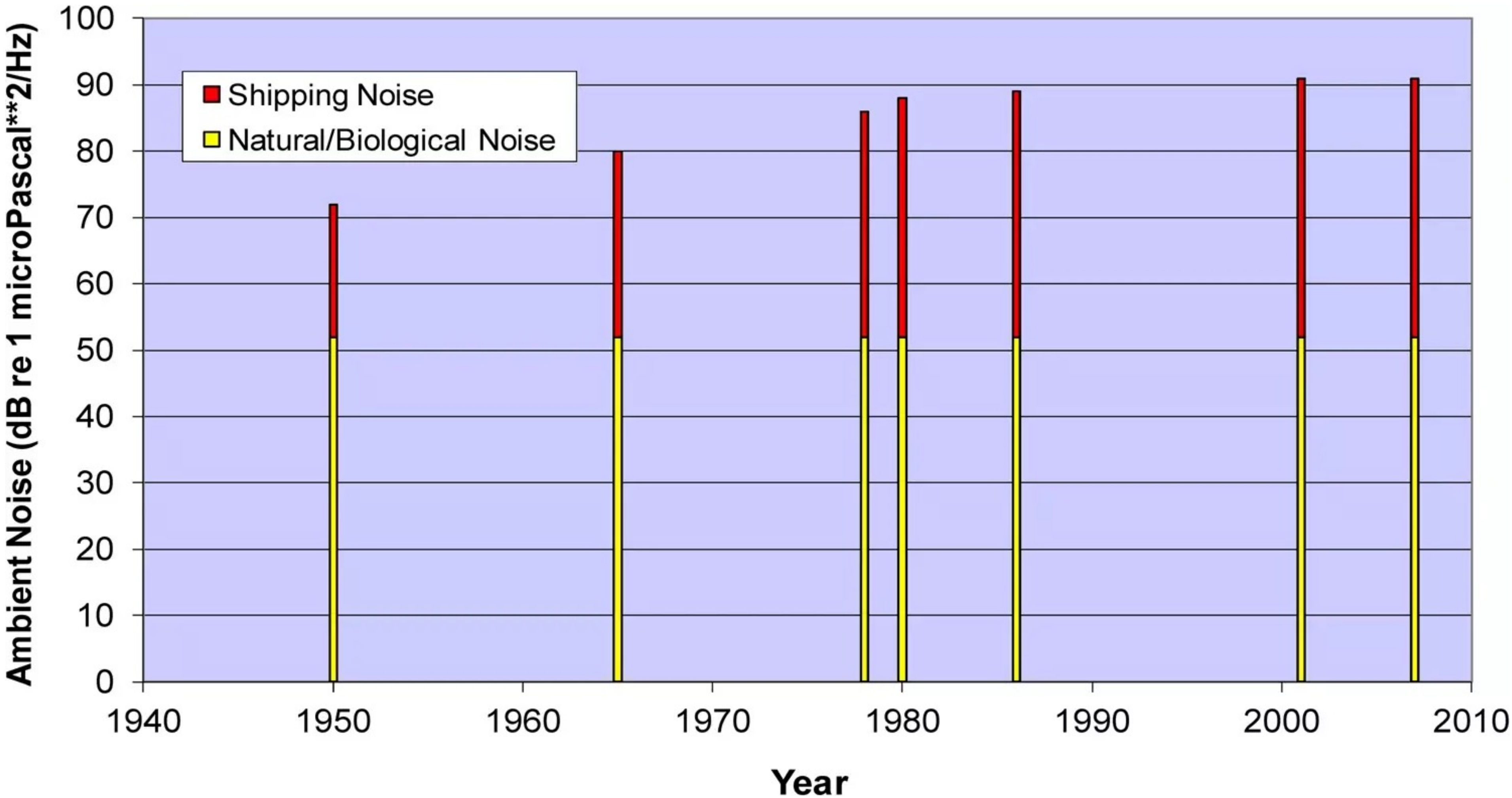
- There are a little over 90 species of Cetacea; 40 or so more sub-populations.
- 6/13 of the Great Whales are vulnerable to extinction.
- 19/33 of Canada’s Whales are at risk.
- 72 are threatened, vulnerable, endangered, or critically endangered by IUCN Red List > 50%.

Noise Pollution Sources and Impacts

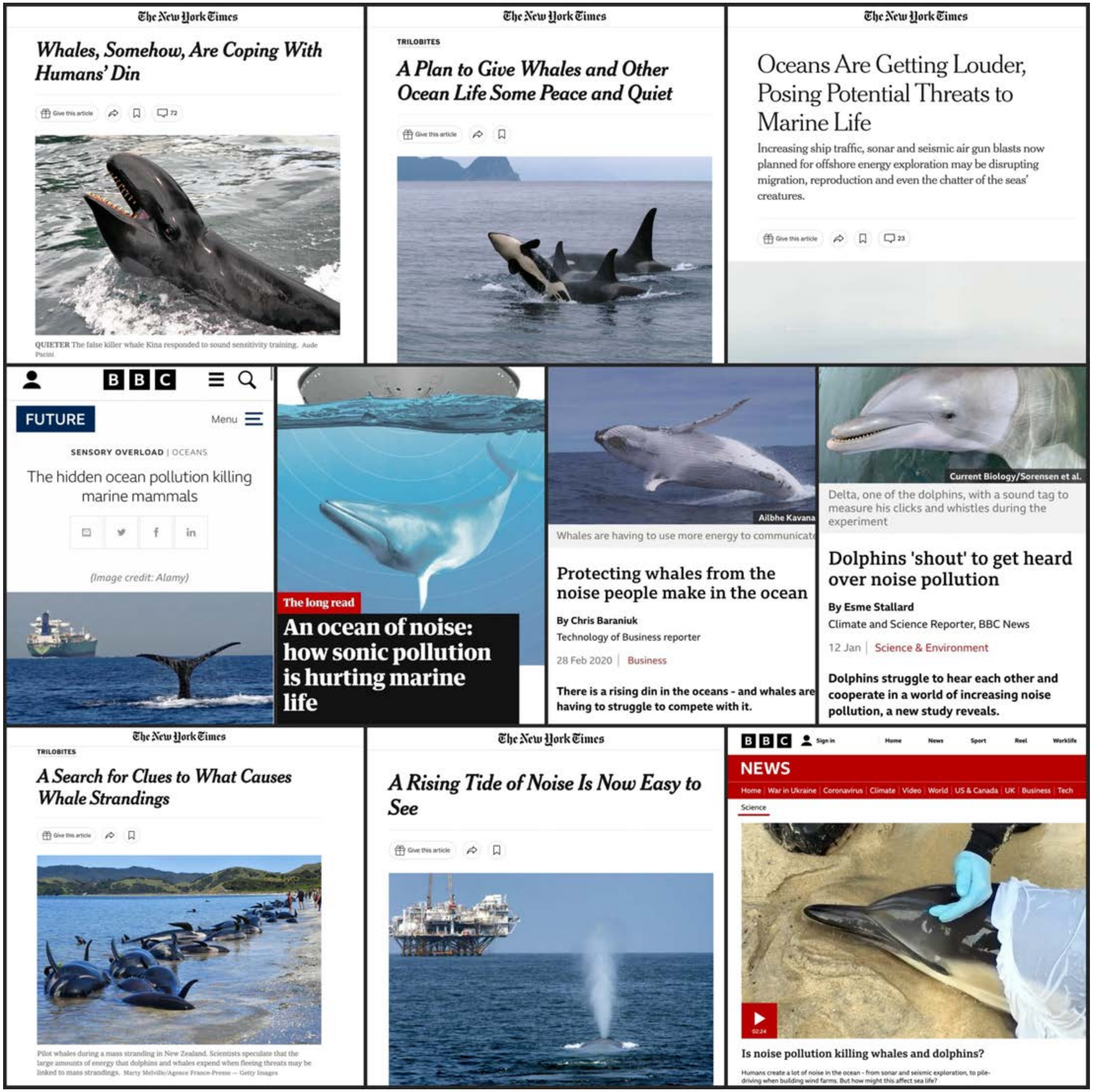


Source: NOAA

Noise Against Time



Source: Frisk (2012)


The New York Times
Whales, Somehow, Are Coping With Humans' Din
QUIETER The false killer whale Kina responded to sound sensitivity training.
The New York Times
TRILOBITES
A Plan to Give Whales and Other Ocean Life Some Peace and Quiet
The New York Times
Oceans Are Getting Louder, Posing Potential Threats to Marine Life
Increasing ship traffic, sonar and seismic air gun blasts now planned for offshore energy exploration may be disrupting migration, reproduction and even the chatter of the seas' creatures.
BBC
FUTURE
Menu
SENSORY OVERLOAD | OCEANS
The hidden ocean pollution killing marine mammals
(Image credit: Alamy)
The long read
An ocean of noise: how sonic pollution is hurting marine life
Ailbhe Kavana
Whales are having to use more energy to communicate
Protecting whales from the noise people make in the ocean
By Chris Baraniuk
Technology of Business reporter
28 Feb 2020 | Business
There is a rising din in the oceans - and whales are having to struggle to compete with it.
Current Biology/Sorensen et al.
Delta, one of the dolphins, with a sound tag to measure his clicks and whistles during the experiment
Dolphins 'shout' to get heard over noise pollution
By Esme Stallard
Climate and Science Reporter, BBC News
12 Jan | Science & Environment
Dolphins struggle to hear each other and cooperate in a world of increasing noise pollution, a new study reveals.
The New York Times
TRILOBITES
A Search for Clues to What Causes Whale Strandings
Pilot whales during a mass stranding in New Zealand. Scientists speculate that the large amounts of energy that dolphins and whales expend when fleeing threats may be linked to mass strandings.
The New York Times
A Rising Tide of Noise Is Now Easy to See
BBC
NEWS
Home | War in Ukraine | Coronavirus | Climate | Video | World | US & Canada | UK | Business | Tech
Science
Is noise pollution killing whales and dolphins?
Humans create a lot of noise in the ocean - from sonar and seismic exploration, to pile-driving when building wind farms. But how might this affect sea life?

Today's Talk

- Biology and History of Killer Whales.

- Describe Data and Research Design.

- Develop models of KW demographics: births/deaths.
  Evaluate impact of Vessel traffic shocks on KW.

- Develop a Sound Exposure model.
  Evaluate the impact of Noise disturbance shocks on KW.

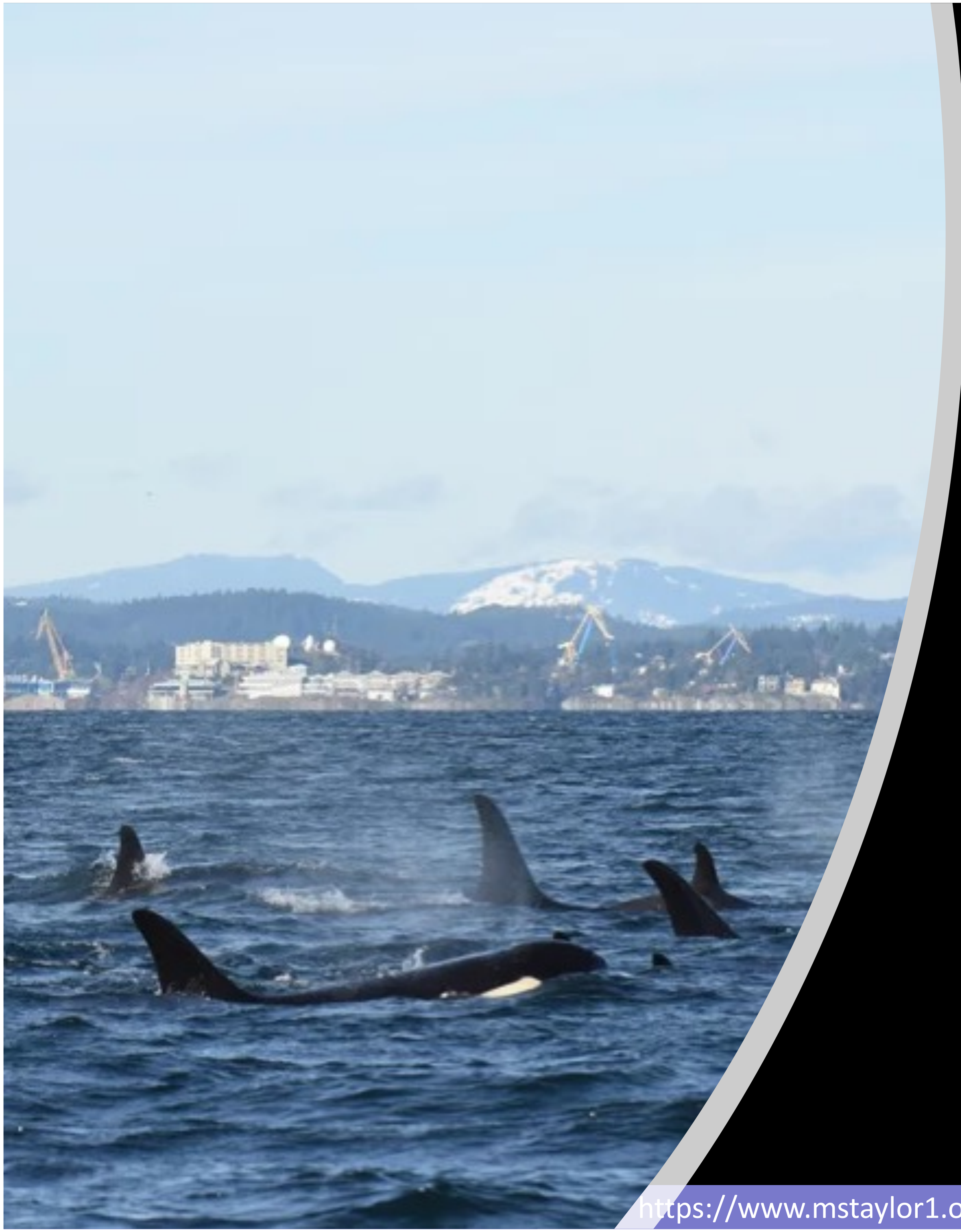
- Policy: Can good Environmental policy Save the Whales?

Debts owed

- Large literature using pollution shocks to identify human health impacts. See Greenstone et al. 2009, Graff Zivin et al. 2013 for reviews. We follow their methods.

- Taylor (2021a) invented the methods needed to construct the Vessel Traffic data and reported summary statistics.

- Empirical work in biology/ecology relates KW population growth to demographic determinants and some ocean environmental conditions. (Ford et al. 2005, Ford et al. 2010, Ward et al. 2009)

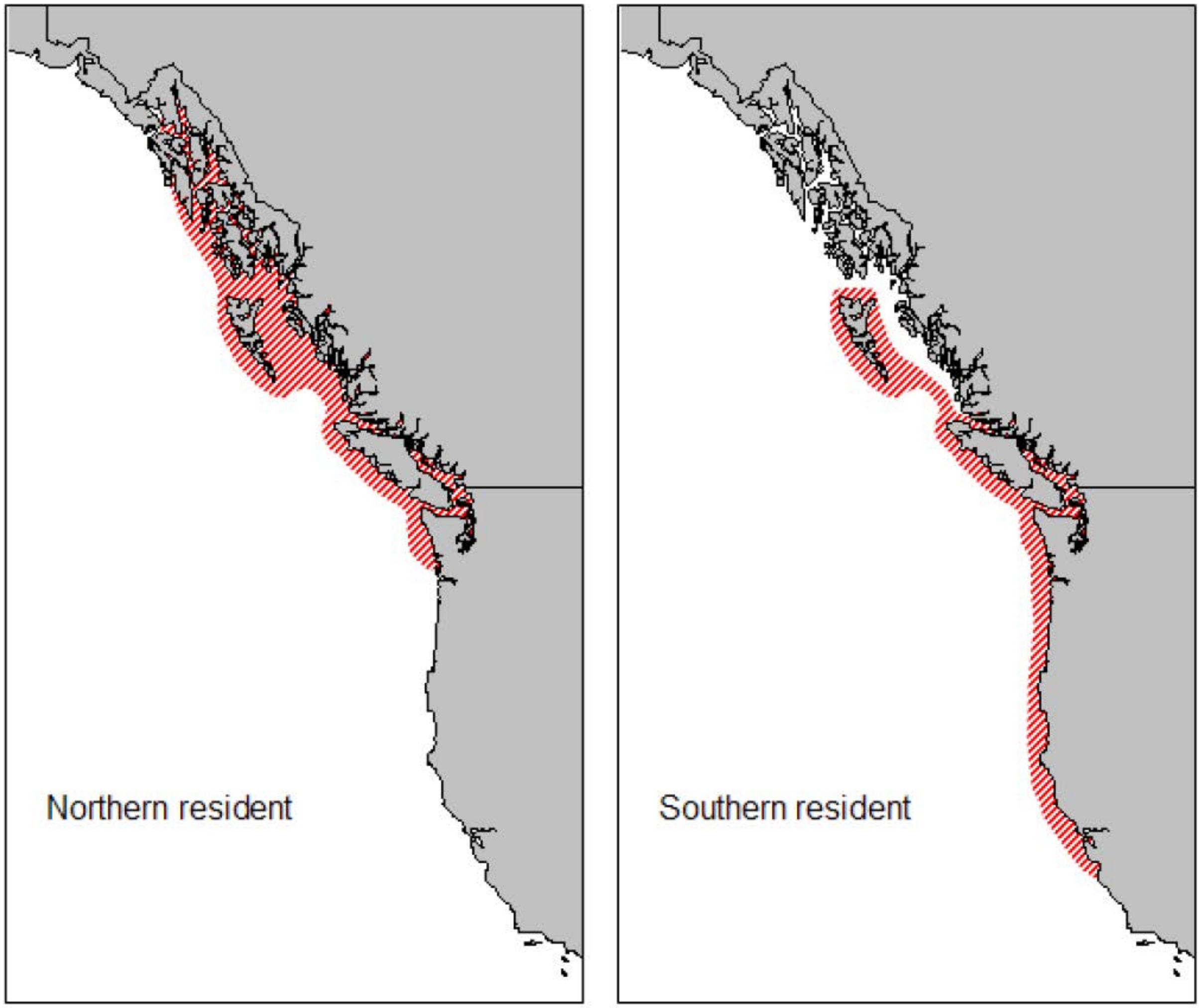


History

History

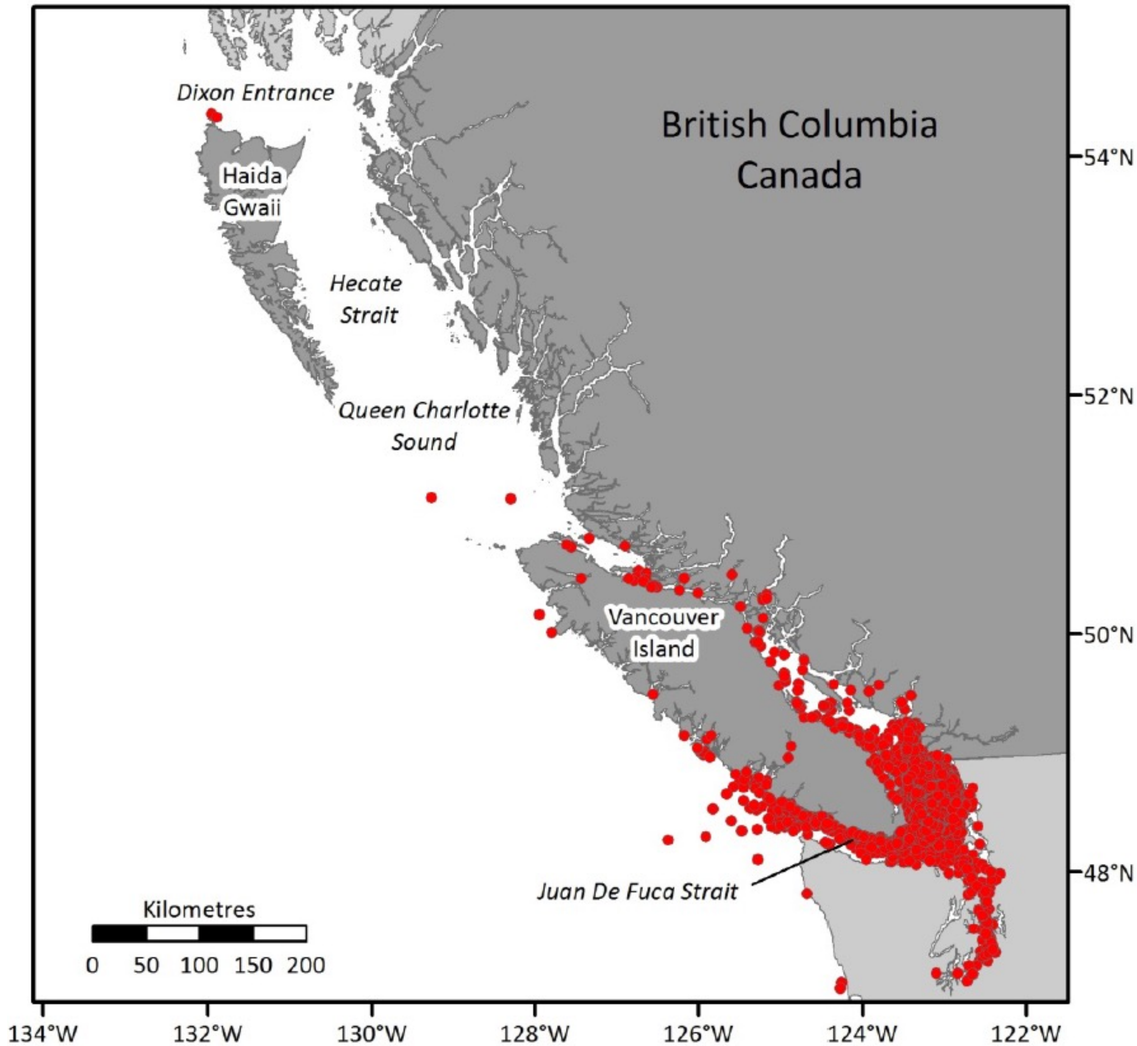
- July 16th, 1964: A small killer whale was captured. The display industry started.
- Early 1970s: Live capture was regulated and then banned by 1980.
- Late 1990s: KW were protected by both Canadian and US governments.
- Early 2000s: KW were listed as Species at Risk (Canada) or Endangered species (US). The SRKW is endangered; the NRKW is listed as threatened.
- Today: SRKW has perhaps 74 whales, the NRKW 330.

Northern and Southern Ranges

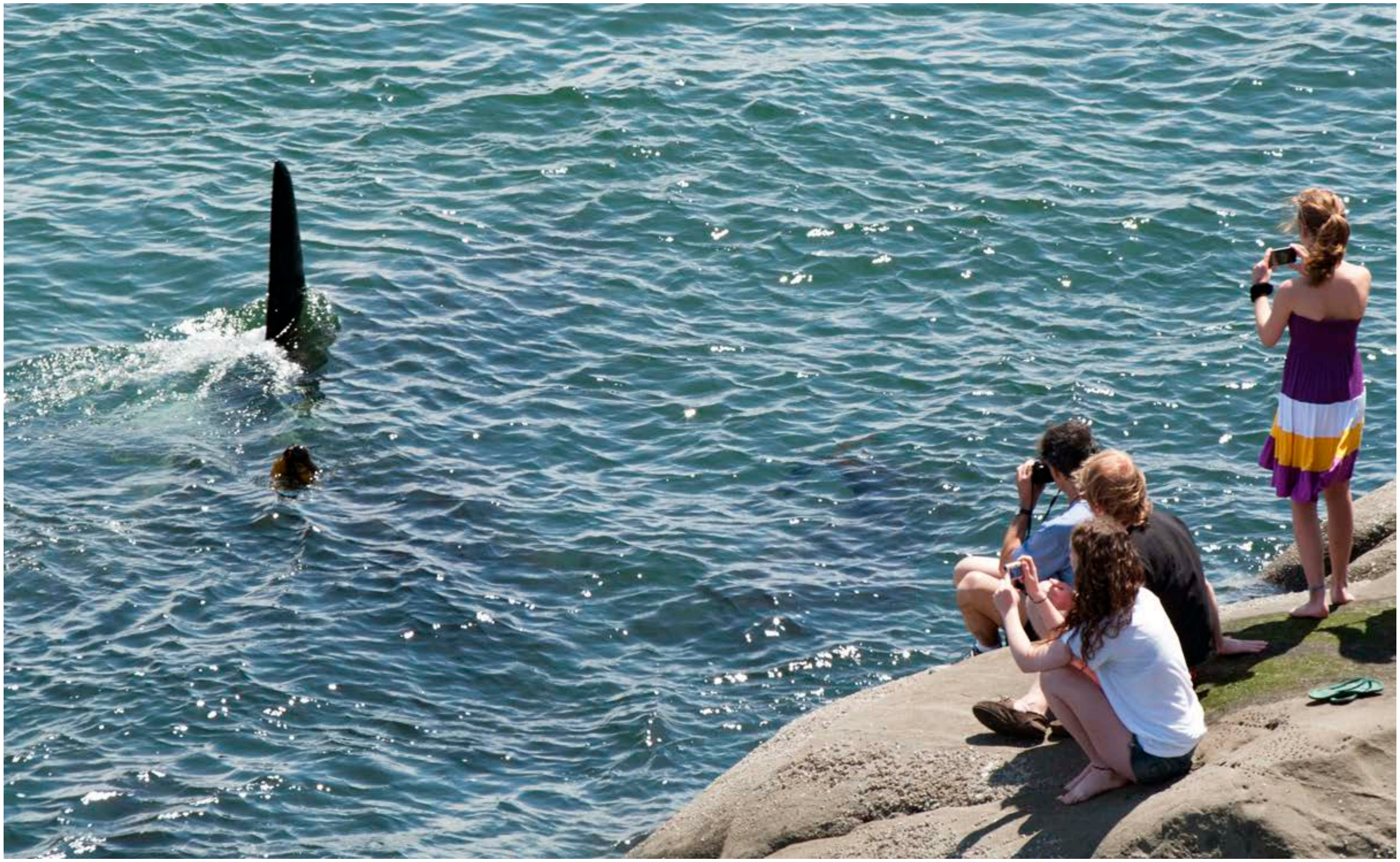


Known geographical ranges of northern (left) and southern (right) resident killer whales. Extent of movement offshore is unknown. Source: Figure 1. in Ford (2006)

SRKW Sightings



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



Orca Watching off Saturna Island

The Problem with the Southern Residents

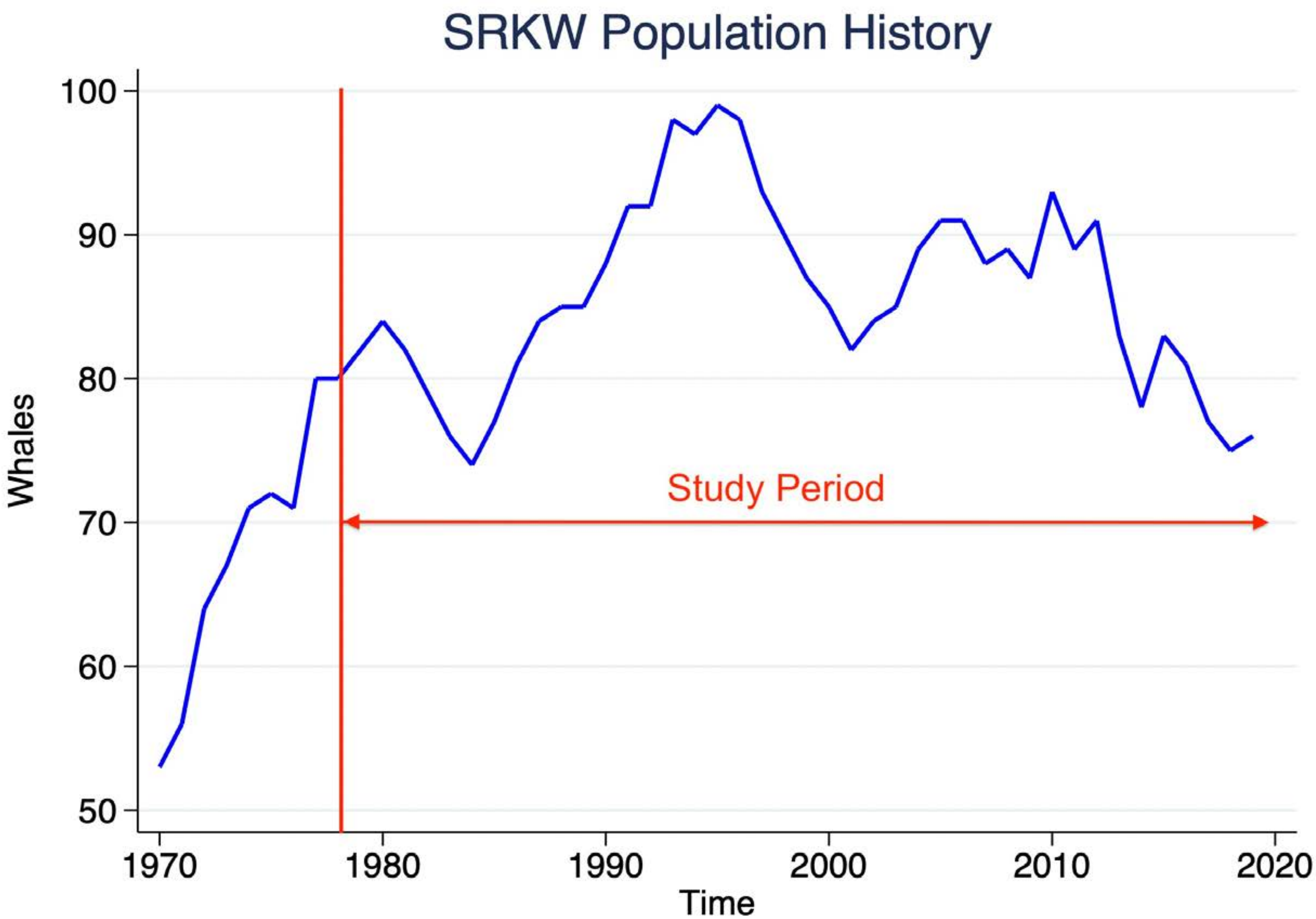
- The Southern Resident population has been on a long downward trend since the mid to late 1990s.

- 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.

The Southern Residents Plight



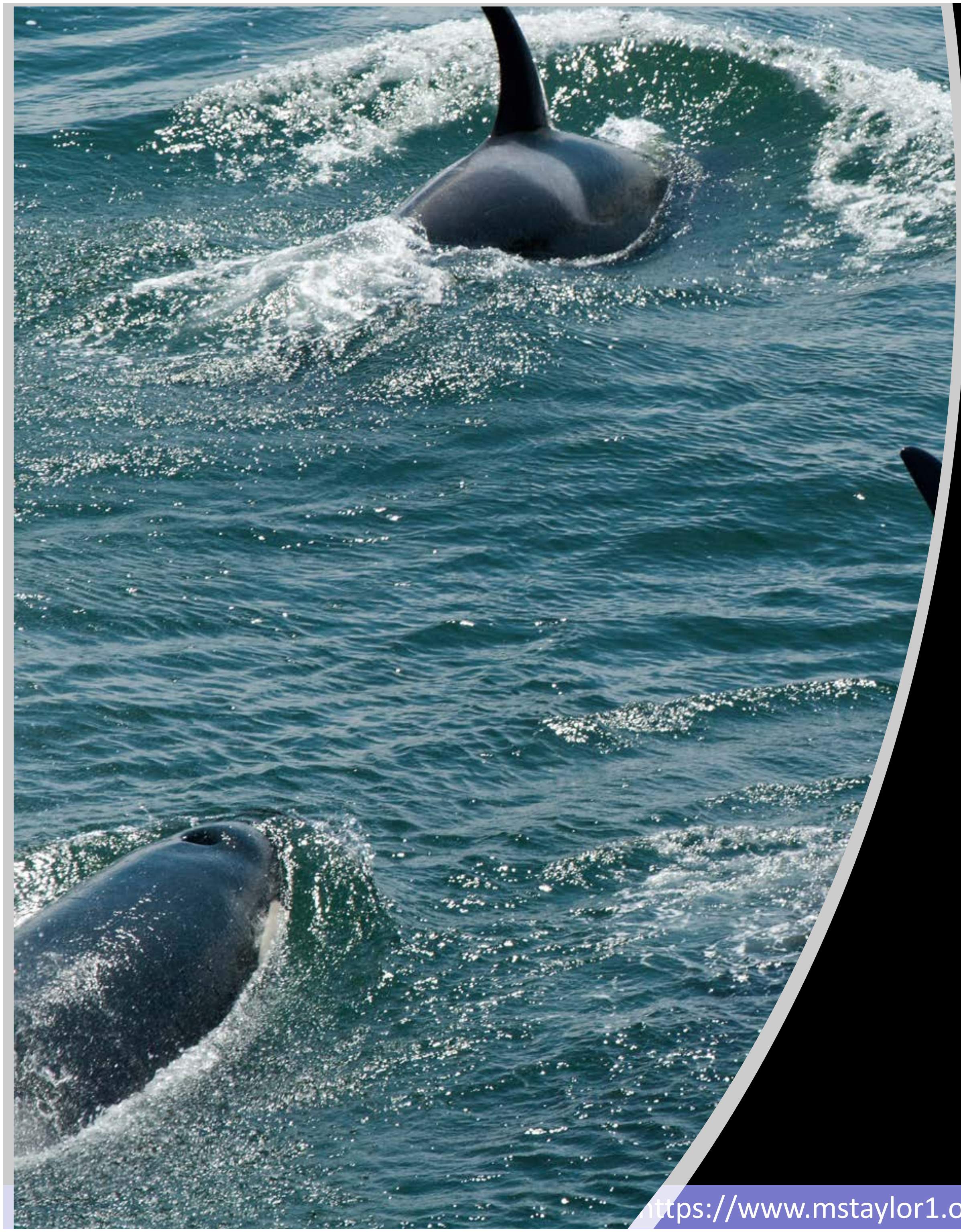
Three Main Suspects

- 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. There are three likely suspects.

- A lack of prey, sometimes linked to declining Salmon returns on the Columbia and Fraser Rivers and dams on tributary rivers.

- Vessel disturbances from whale watching and large Commercial Vessels.

- PCBs and other long-lived contaminants leaching into the marine environment and magnified by bioaccumulation.



Biology

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 along the coast to follow Salmon.
- 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

- Live in family units called pods, comprised of several matrilines. Born into a matriline and you die in the matriline.

- 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).

- Female whales can live to 60 or more years. Female reproductive years start at 10 and ends close to 40. Males live 40 or less years.

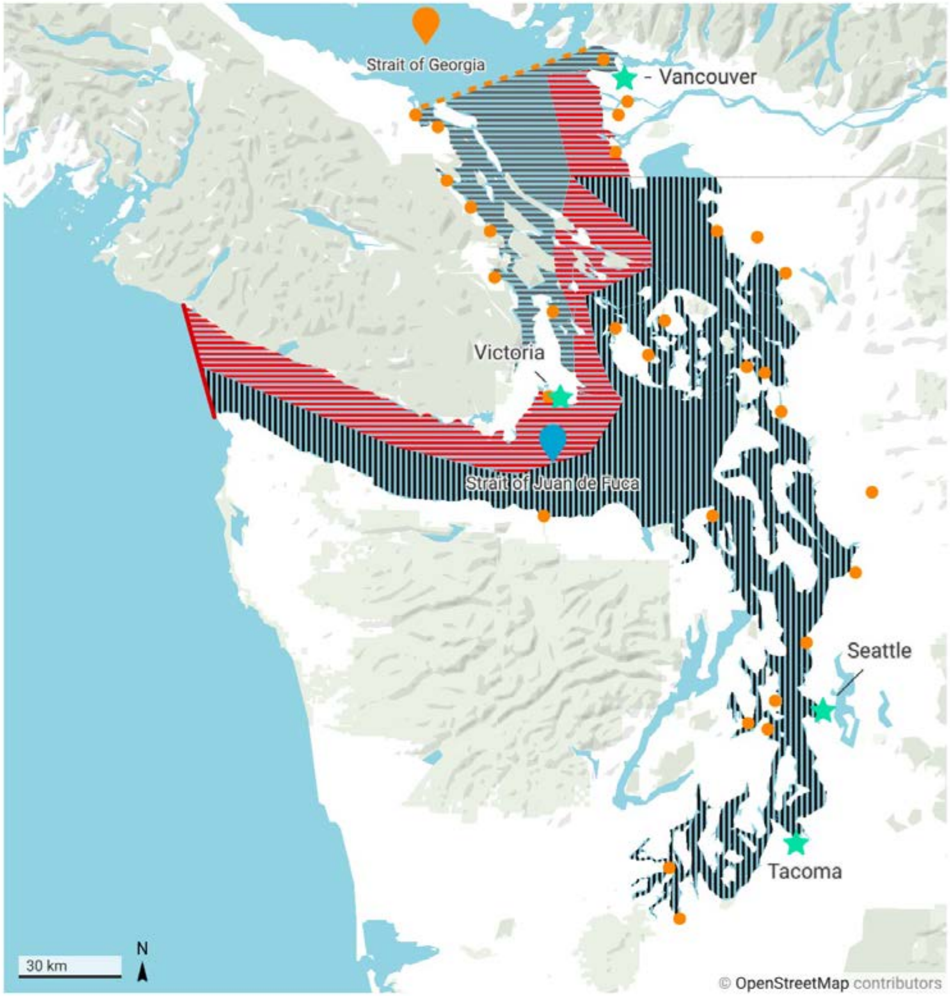
- Gestation is 15-18 months, nursing and natal care lasts another 18 months. Conception, on average, in spring/summer months year previous to births.

Is Vessel Noise Important for KW?

- 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)
- 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)

8 Facts to Frame the Argument

#1. The Critical Habitat contains 31 Ports



Ports in the Critical Habitat
Ferry Line
Swiftsure Line
Southern Resident Killer Whale Critical Habitat (U.S.A.)
Southern Resident Killer Whale Critical Habitat (CAN)
Southern Resident Killer Whale Critical Habitat plus

The Lloyd’s List Data

- Data from 1977-2019 includes all vessel landings at 121 West coast ports in North America (Lloyd's List Intelligence Unit).
- 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.

#2. The Growth in Vessel Traffic is Huge

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

Source: Taylor (2021a)

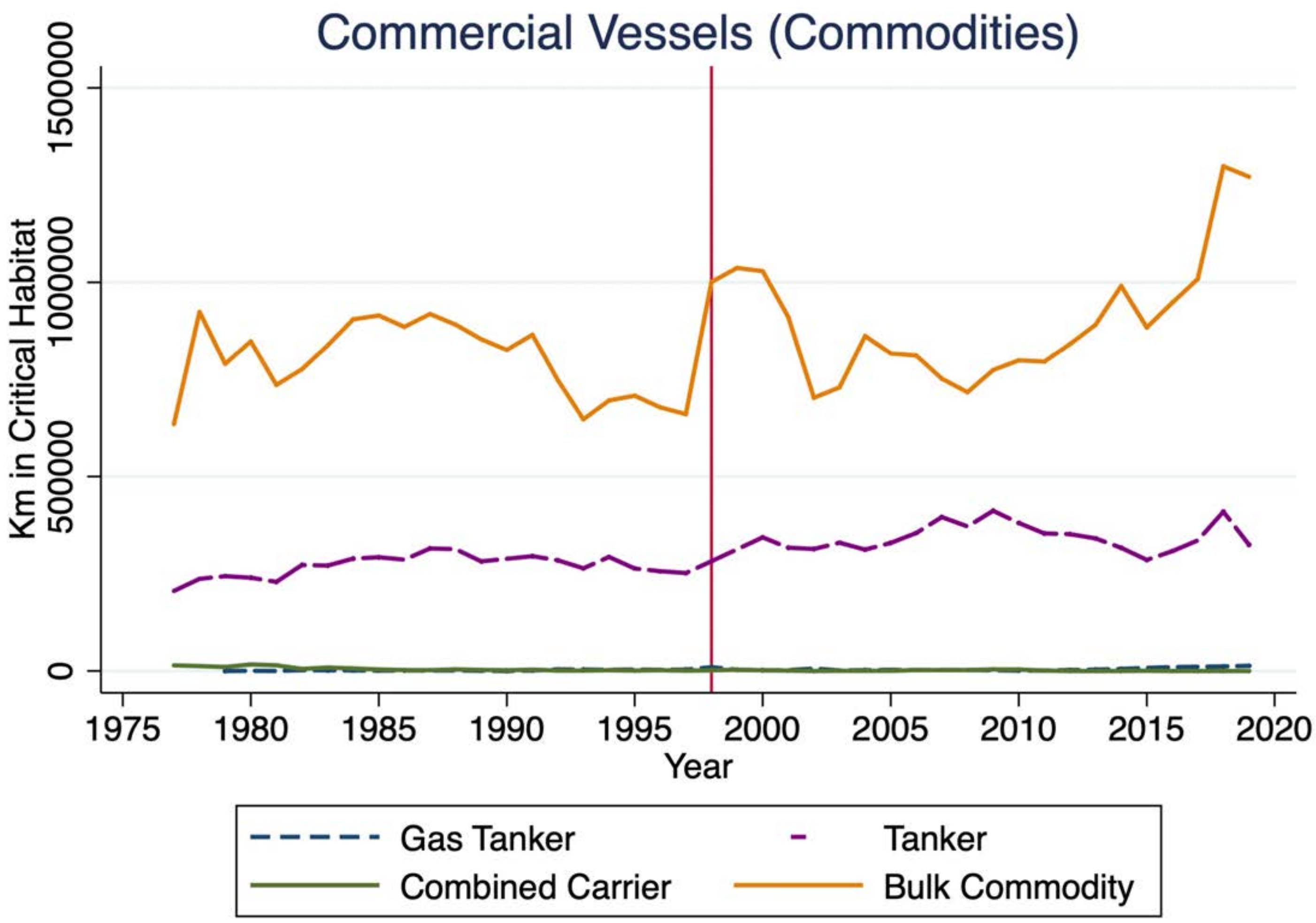
#3. The Composition of Vessel Traffic Changed Dramatically

Table 2: Landings at Critical Habitat ports by Vessel Type

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

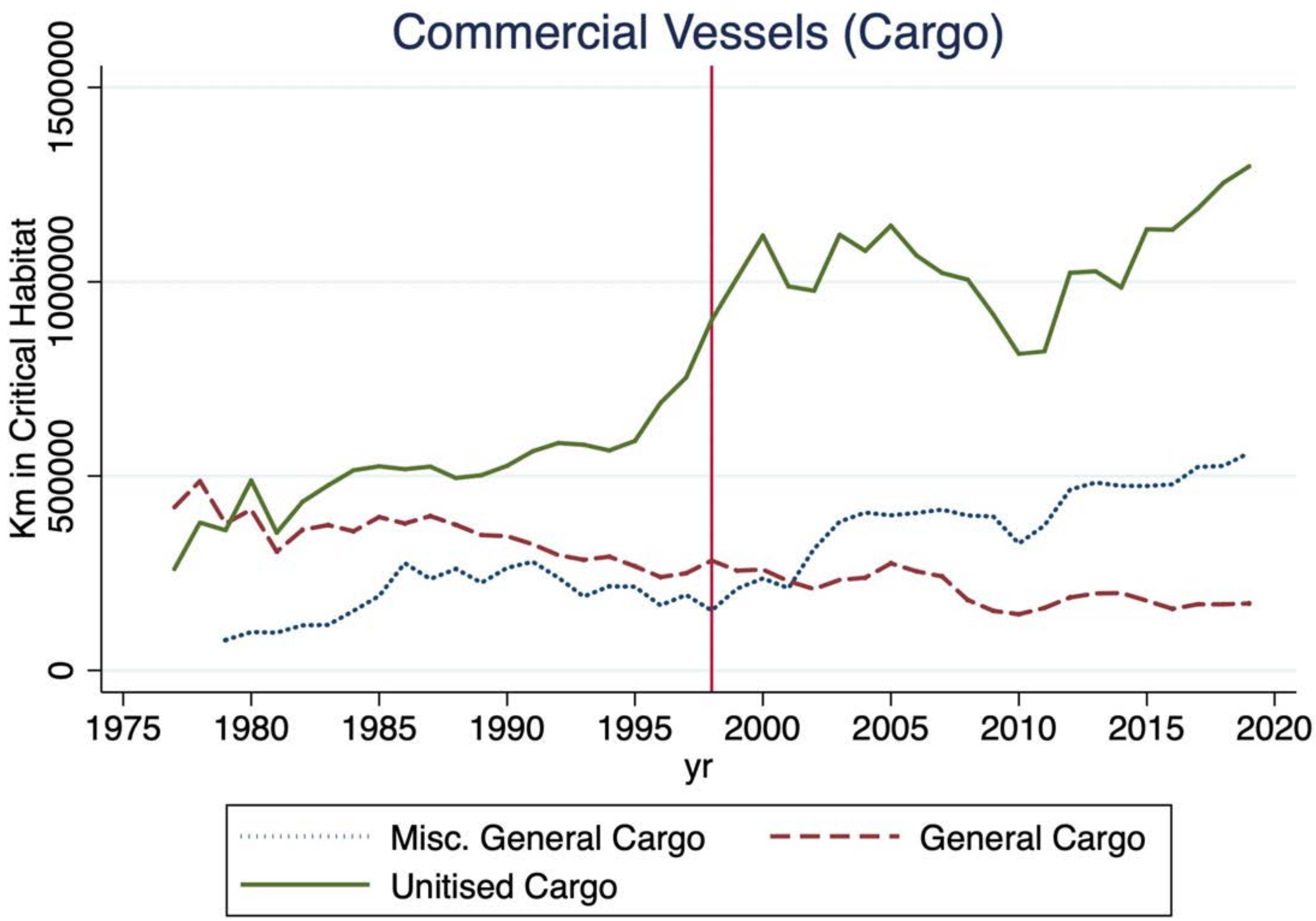
Source: Taylor (2021a)

#4a. The Vessel km Traveled in the CH has more than Doubled



Source: Taylor (2021a)

#4b. The Vessel km Traveled in the CH has more than Doubled



Source: Taylor (2021a)

Vessel Movement Summary

- Annual km in CH, by large commercial vessels, grew from 1.5 million to 3.5 million.

- The change in traffic comes from growing international trade with Asia.

- The composition of the Vessels changed radically. Container ships doubled their share.

#5. The Nosiest Vessels are Container Ships

Table 3: Relative Vessel Disturbance (1 km)

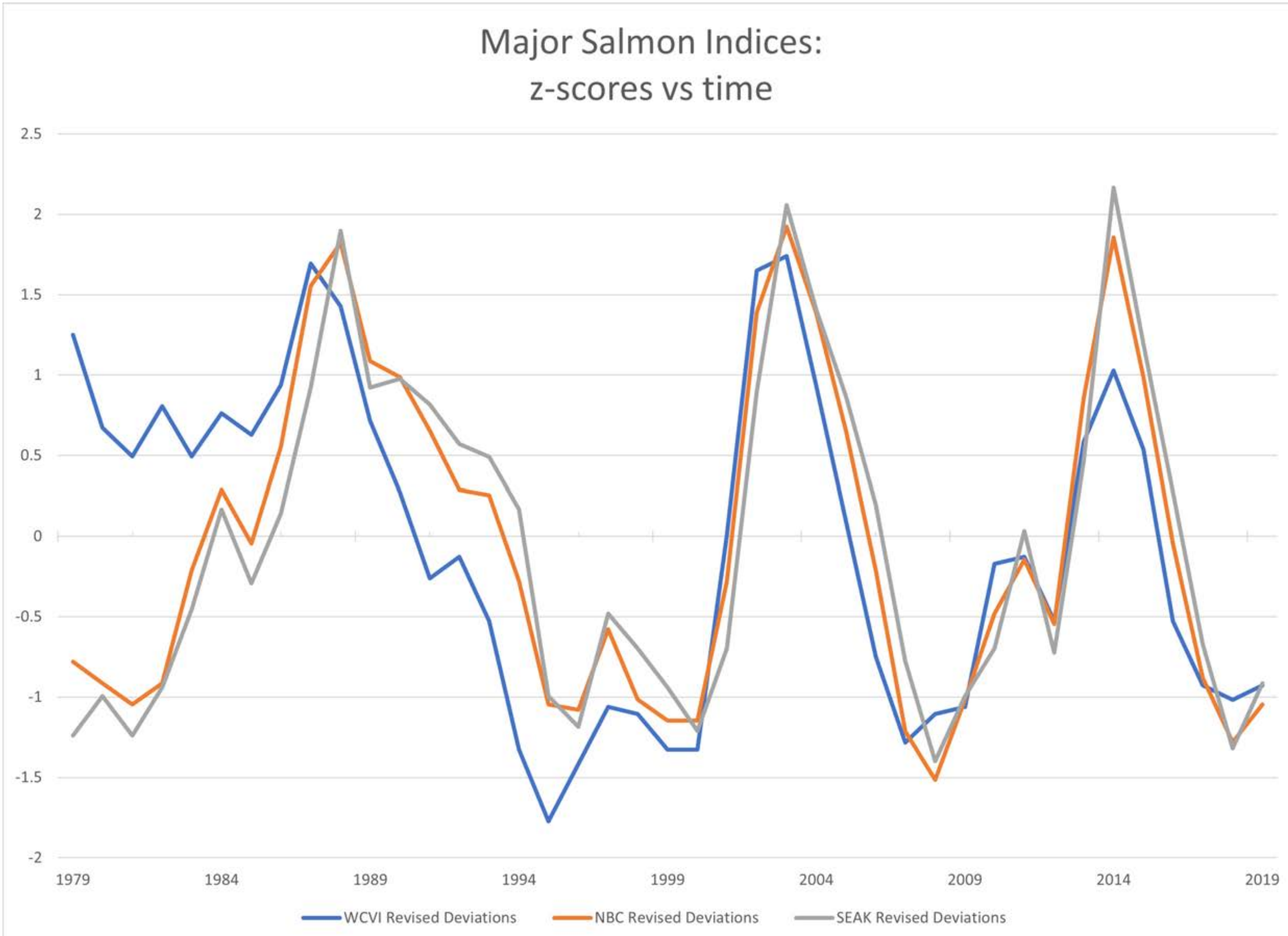
Vessel type	Predicted source level $\hat{SL}$	Relative Disturbance
Bulk carrier 200-	173.35	1.00
Bulk carrier 200-250	172.58	0.77
Bulk carrier 250+	177.24	3.76
Cargo 150-	174.39	1.46
Cargo 150+	175.62	2.05
Container ship 250-	176.02	1.87
Container ship 250-320	178.72	4.49
Container ship 320+	180.26	7.55
Tanker 165-	173.52	1.05
Tanker 165+	175.65	2.20
Vehicle carrier	175.68	1.81
Tug	171.11	0.77
Fishing	165.35	0.10
Military	163.62	0.03
Miscellaneous	163.15	0.04
Passenger	167.08	0.11
Pleasure craft	166.65	0.11
Research	167.12	0.14

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

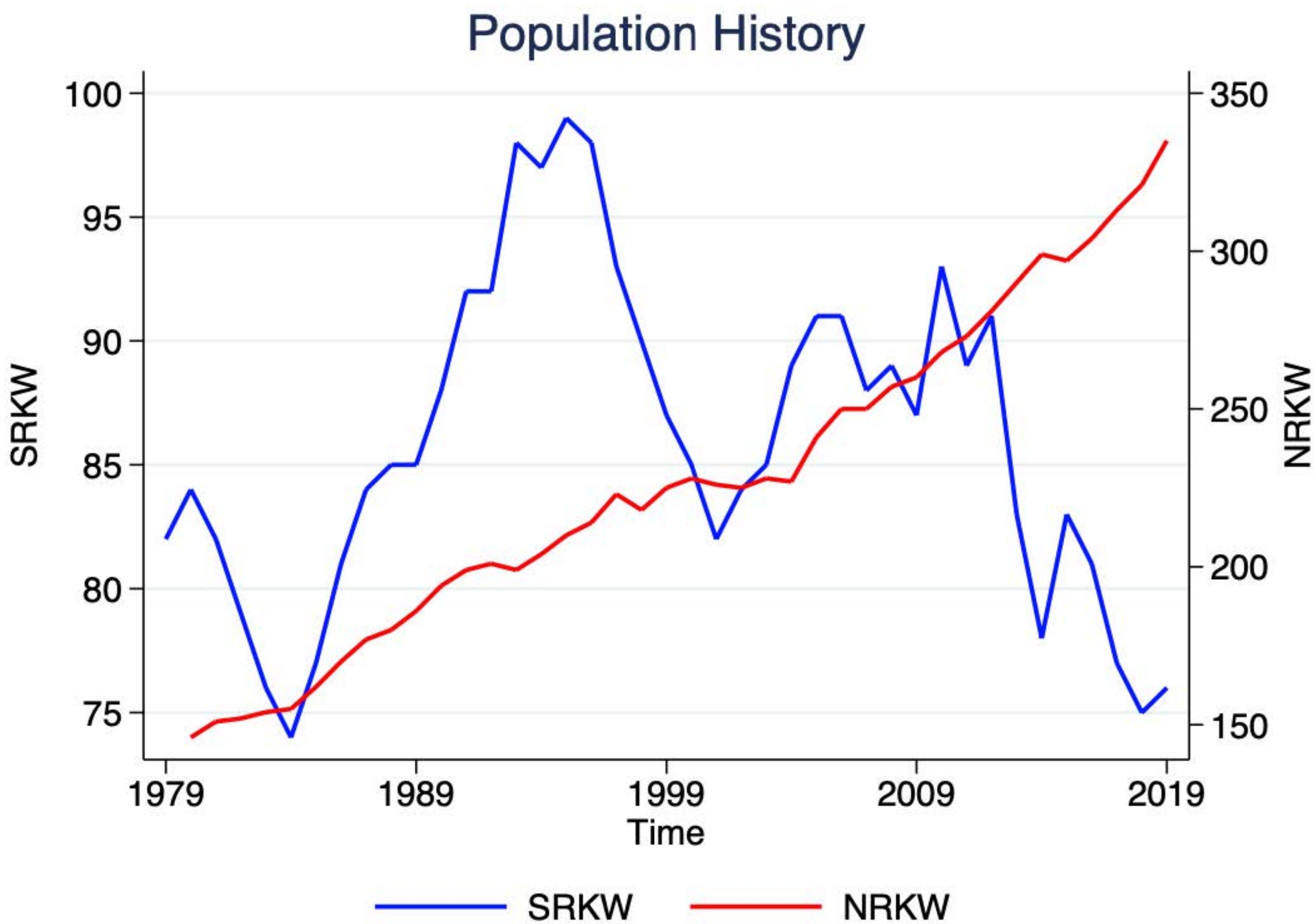
Vessel Noise Data

- Almost 3,000 observations from two existing studies.
- Data collected opportunistically – sample is random. One was collected in the SRKW critical habitat.
- Vessel noise measured via hydrophone/s placed on ocean floor at given distance from shipping lanes. Authors estimate source level, SL, noise at ship.
- Use AIS to identify vessels, other industry sources to get vessel characteristics.

#6. The Availability of Salmon is Cyclical



#7. The SRKW Population Decline is Unique



#8a. Conflict is Inevitable

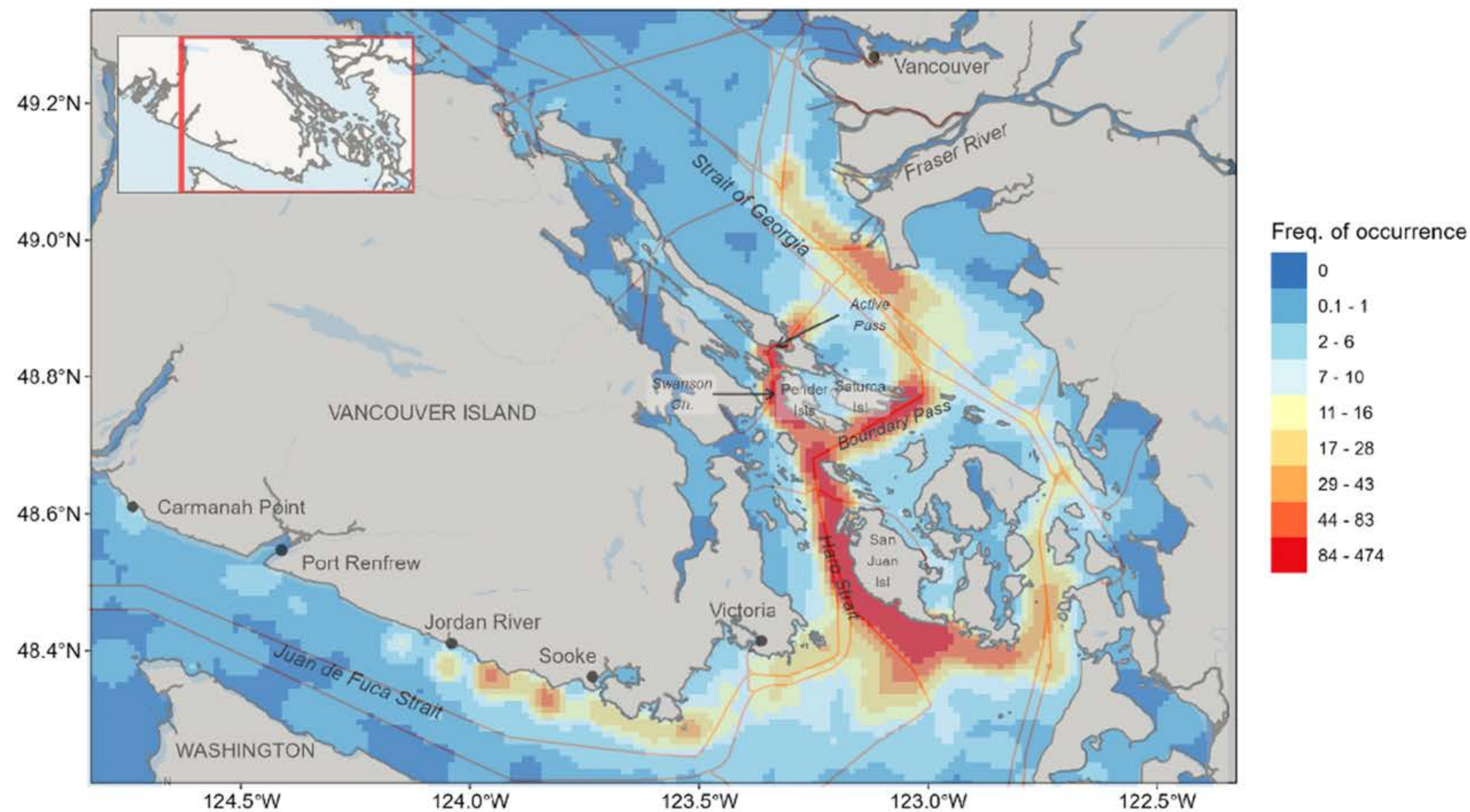


Figure 9. Annual frequency of SRKW occurrence from May to October as predicted by the 2009-2018 platform of opportunity (BC Cetacean Sightings Network/OrcaMaster) sightings fit to a Kernel Density model.

#8b. Conflict is Inevitable

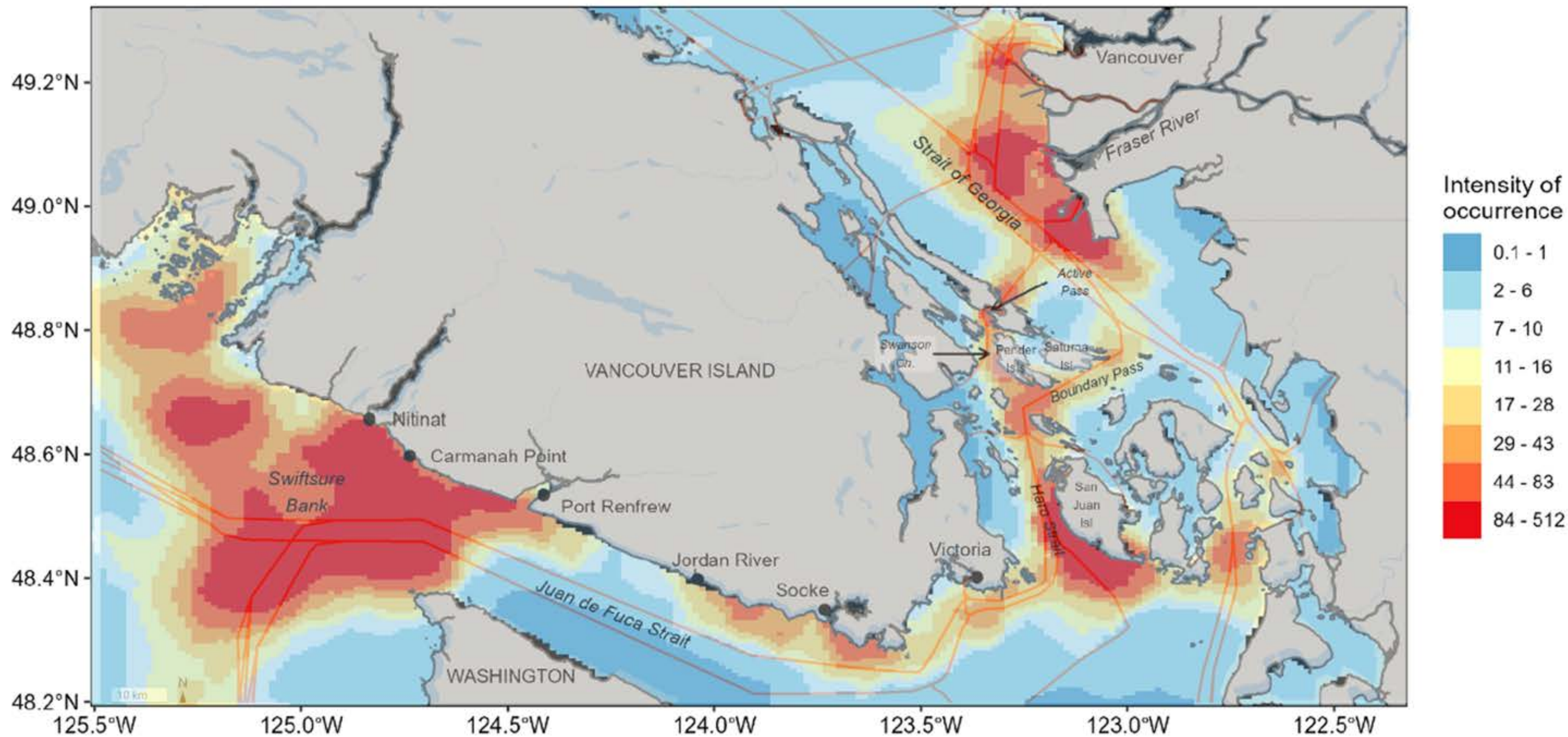
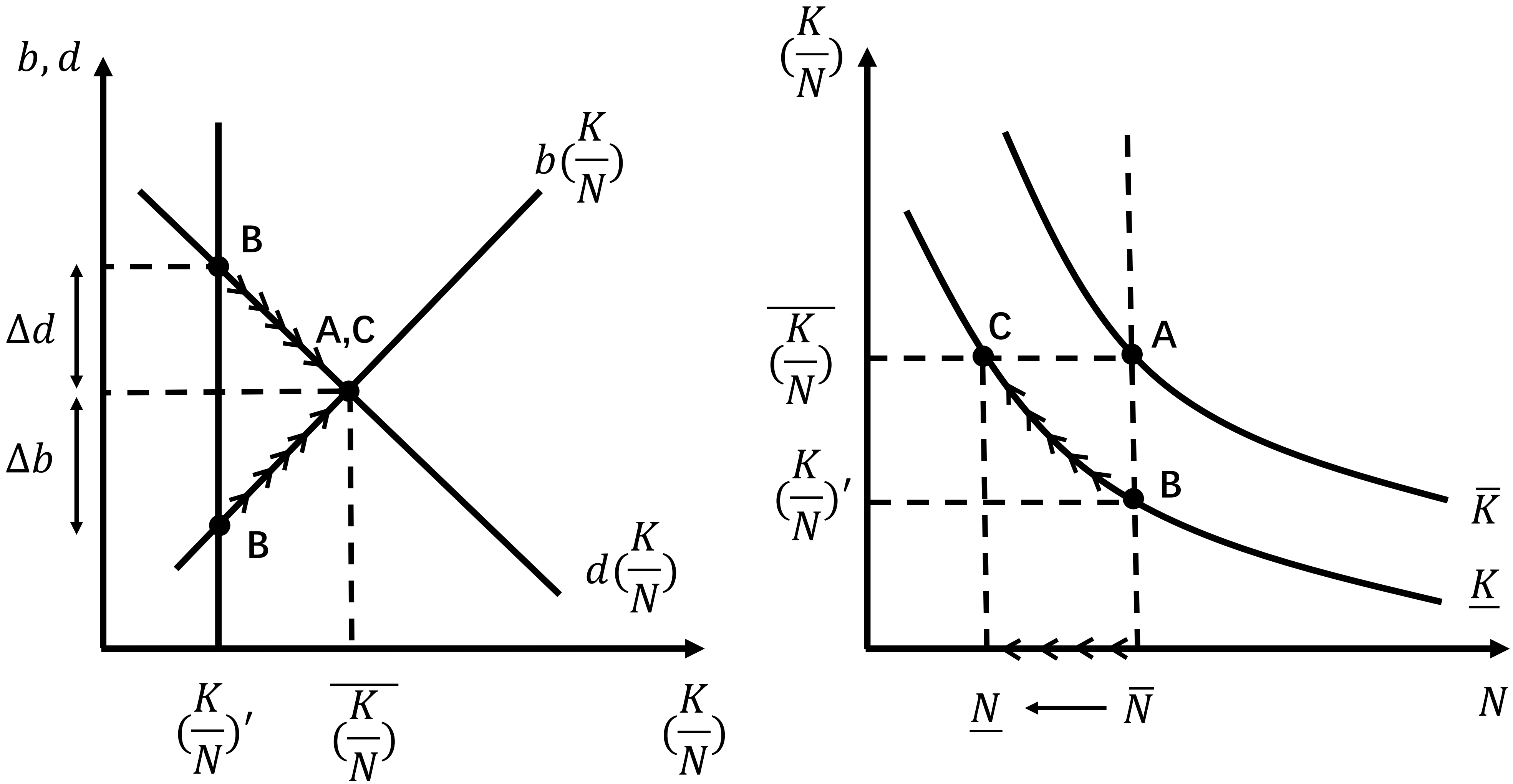


Figure 11. Annual SRKW intensity of occurrence as estimated by the SRKW occurrence model using combined WW and DFO data for May to October, 2009—2020.

Research Design

How could Noise Pollution from Vessels lower KW populations?



Constructed from std. logistic growth function dN/dt = rN(1-N/K)

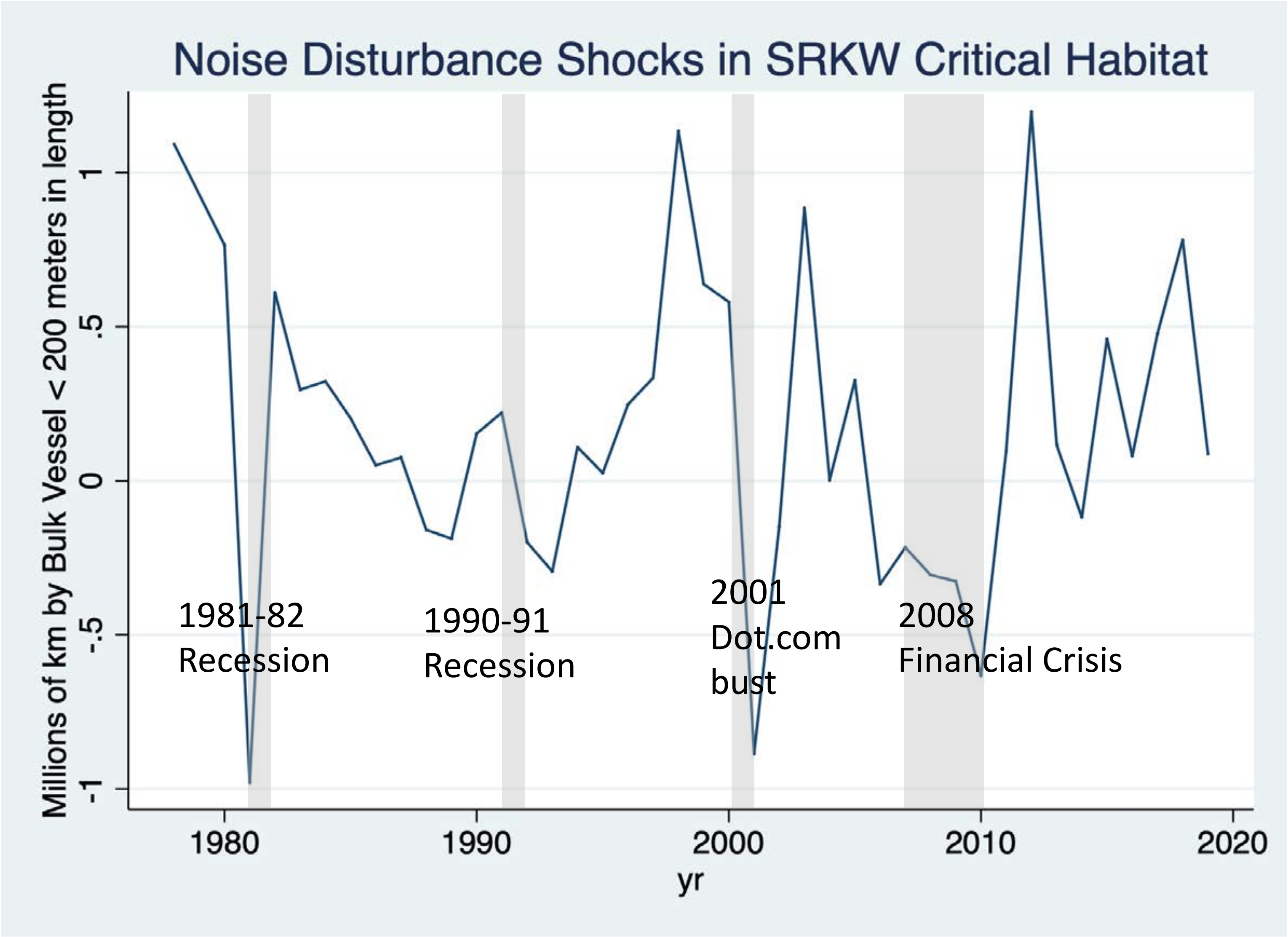
Quasi-experimental Research Design

- Compare the fertility and mortality, of otherwise identical Killer whales, who are exposed to greater or lesser amounts of noise pollution.

- Condition on large set of demographic, prey and competition variables. Ensures like-to-like comparisons.

- Use “pollution shocks” to eliminate avoidance and fixed effects for sorting. Ensures treatment dosage is unrelated to other health attributes.

Noise Disturbance Shocks in SRKW Critical Habitat



Covariate Balance

	Mean age of female whales		male whales		Mean sex ratio		Mean population		Mean aggregate salmon abundance	
	NRKW	SRKW	NRKW	SRKW	NRKW	SRKW	NRKW	SRKW	NRKW	SRKW
Negative shock	21.58	28.2	15.41	14.08	1.40	1.76	196	85.75	3.04	3.04
Control	22.27	28.57	15.83	14.98	1.41	1.54	229.23	87.33	3.59	3.59
Positive shock	22.8	28.25	16.14	14.65	1.44	1.61	224.43	85.43	3.12	3.12

Control years: noise disturbance shocks of type 1 are within one standard deviation of their mean. Positive (negative) shocks: noise disturbance shocks are more than one standard deviation above (below) their mean.
Negative shock years: 1979, 1981, 2001, 2010. Positive shock years: 1980, 1982, 1998, 1999, 2003, 2012, 2018.
***: significant at 1% level, ** significant at 5% level, *: significant at 10% level.

Killer Whale Demographics

Data for Demographics

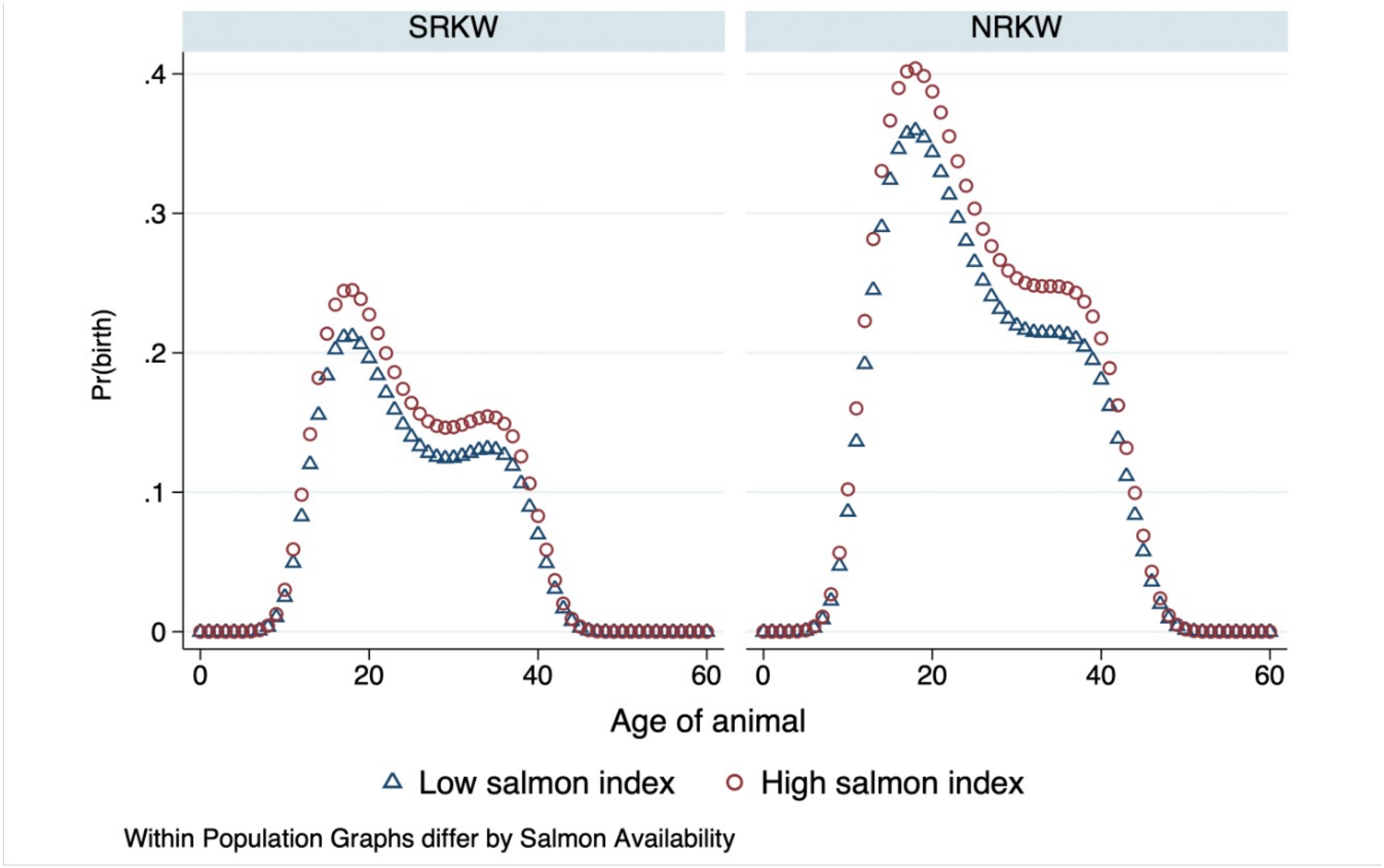
- Complete record of all SRKW and NRKW in existence since 1977 together with births, deaths, pods, matrilines, etc.
- Approximately, 12,000 whale year observations. (DFO, CRW, Orca sightings network)
- Extensive database of salmon stock measures from the Pacific Salmon Commission 1979-2017. Three major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

Baseline Demographic Determinants of Fertility Conditional Logit Estimation

	I.	II.	III.	IV.	V.
Age	2.80	2.82	2.83	2.85	3.98
	0.000	0.000	0.000	0.000	0.000
Age^2	−0.16	−0.16	−0.16	−0.16	−0.24
	0.000	0.000	0.000	0.000	0.000
Age^3	0.004	0.004	0.004	0.004	0.006
	0.000	0.000	0.000	0.000	0.000
Age^4	−0.00004	−0.00004	−0.00004	−0.00004	−0.00005
	0.000	0.000	0.000	0.000	0.000
L1.Salmon abundance		0.36	0.32	0.29	0.28
		0.005	0.011	0.023	0.031
L1.Within competition			−0.003	−0.004	−0.003
			0.004	0.002	0.003
L1.Across competition				−0.01	−0.01
				0.000	0.000
Matriline FE	Yes	Yes	Yes	Yes	Yes
NRKW × Age	No	No	No	No	Yes
N	5527	5379	5379	5379	5379
Log-likelihood	-1268.75	-1242.09	-1238.79	-1234.29	-1231.48
Groups dropped	20	21	21	21	21

Standard errors are clustered at the pod level. P-values appear under the coefficient.
N records the number of female-whale-years
Groups dropped: "clogit" drops animals with an outcome variable that is either 0 or 1 for all their observations.

Fecundity by Age, Population, and Salmon Availability



Magnitudes

- One std. deviation increase in Salmon Abundance:

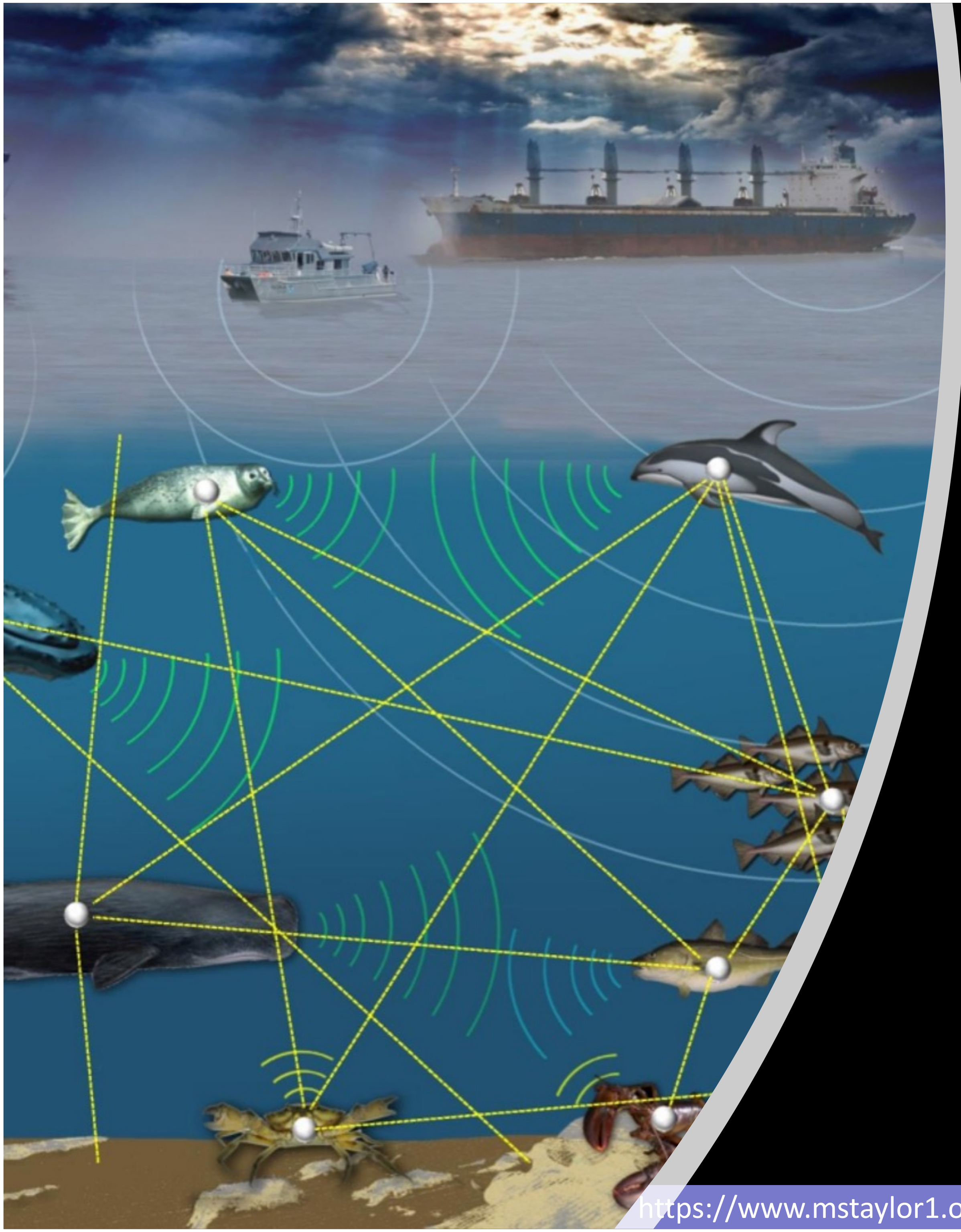
  Raises odds of birth by 10.6%

  Lowers odds of death by 17.1%

- A 50-whale within-population increase :

  Lowers odds of births by 14%

  Raises odds of death by 10.5%



Noise Disturbance Shocks: Naïve

Vessel km shocks & Fertility Conditional Logit Estimation

	I.	II.	III.	IV.	V.
L1.Δ Total Vessel km	−0.68				
	0.000				
L1.Δ Total Vessel km × NRKW	0.84				
	0.004				
L1.Δ Other Vessel km		0.83			
		0.268			
L1.Δ Other Vessel km × NRKW		−0.404			
		0.657			
L1.Δ Unitised km		−4.01	−3.25	−3.32	−0.13
		0.006	0.000	0.000	0.844
L1.Δ Unitised km × NRKW		3.55	3.12	3.18	
		0.042	0.004	0.003	
Δ Unitised km				−1.31	
				0.101	
Δ Unitised km × NRKW				0.42	
				0.682	
L1.Δ Unitised km × J pod					−4.53
					0.000
L1.Δ Unitised km × K pod					−0.47
					0.489
L1.Δ Unitised km × L pod					−3.58
					0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes
N	5379	5379	5379	5379	5379
Log likelihood	-1230.61	-1227.8	-1228.68	-1227.5	-1228.12
Groups dropped	21	21	21	21	21

Standard errors are clustered at the pod level and appear under the coefficient.
Distances are measured in million km.
Δ denotes first differences.
N records the number of female-whale-years for births; all whale years for deaths.

All demographic model variable estimates are suppressed.

Magnitudes

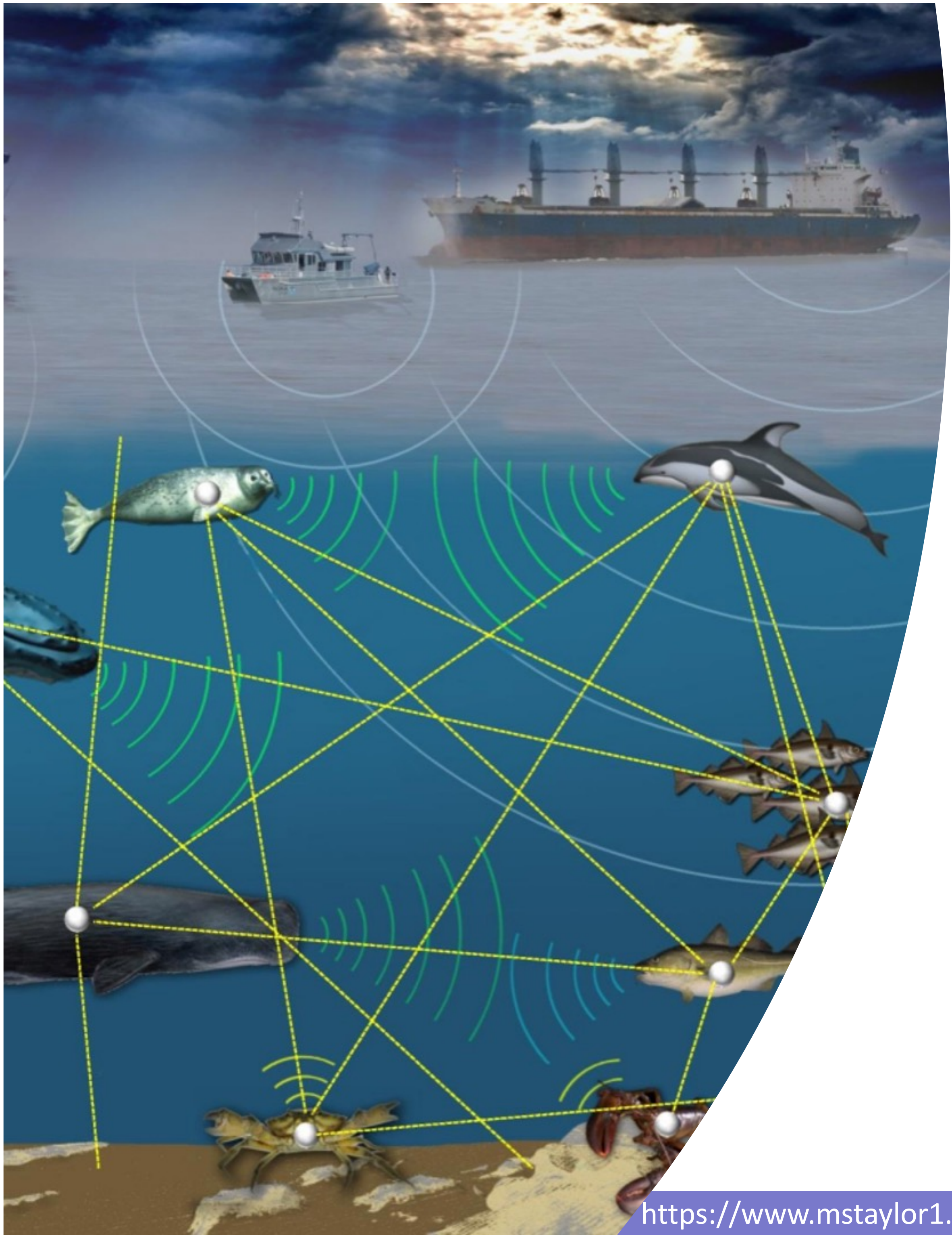
- One std. deviation increase in Unitised Vessel Traffic km:

  Lowers odds of birth by 22%

  Raises odds of death by 13%

  spread over this and next year.

- You need a greater than Two std. deviation increase in Salmon abundance to compensate for births.



Noise Disturbance Shocks: Sophisticated

Noise shock Sophisticated

- Estimate SL radiated by specific ship type, length, vintage, and speed.
- Calculate vessel’s disturbance given sound exposure model.
- Weigh vessel km by these new relative disturbance measures.
- The annual change in this metric becomes our new noise disturbance shock.

Noise disturbance shocks & Fertility Conditional Logit Estimation

	Noise disturbance 1			Noise disturbance 2		
	I.	II.	III.	IV.	V.	VI.
L1.Δ Distance weighted by noise	−0.46	−0.49	0.03	−0.40	−0.42	0.03
	0.000	0.000	0.737	0.000	0.000	0.753
L1.Δ Distance weighted by noise × NRKW	0.50	0.53		0.43	0.45	
	0.001	0.000		0.001	0.000	
Δ Distance weighted by noise		−0.37			−0.31	
		0.005			0.006	
Δ Distance weighted by noise × NRKW		0.26			0.21	
		0.210			0.223	
L1.Δ Distance weighted by noise × J pod			−0.76			−0.65
			0.000			0.000
L1.Δ Distance weighted by noise × K pod			−0.24			−0.22
			0.022			0.016
L1.Δ Distance weighted by noise × L pod			−0.48			−0.41
			0.000			0.000
NRKW × Age	Yes	Yes	Yes	Yes	Yes	Yes
N	5379	5379	5379	5379	5379	5379
Log likelihood	-1229.77	-1228.46	-1229.54	-1229.72	-1228.43	-1229.51
Groups dropped	21	21	21	21	21	21

Standard errors are clustered at the pod level. P-values appear under the coefficient.
Distances are measured in million km.
Δ denotes first differences.
N records the number of female-whale-years for births; all whale years for deaths.
Groups dropped: "clogit" drops animals with an outcome variable that is either 0 or 1 for all their observations.

Noise disturbance I uses wide vessel categories and length as explanatory variables; Noise disturbance II uses narrow vessel categories defined by length.

Vessel Type matters
Small Bulk Vessels have little impact

- 50,000 increase in annual km by Bulk vessels < 200 meters in length. Aggregating all SRKW pods, Column IV, estimates:

Lowers odds of birth by 3%

Raises odds of death by 2.2%

spread over this and next year.

Vessel Type Matters
Large Unitised Vessels have a Large Impact

- 50,000 increase in annual km by Unitised Vessel > 320 meters in length.

- Aggregating across all SRKW pods, our estimates imply:

Lowers odds of birth by 22%

Raises odds of death by 18%

spread over this and next year.

Policy Options

Can Economics Save the Whales?

Is Vessel Noise Important Enough?

- Using our theory and estimates we can solve for the long run – steady state - elasticity of SRKW numbers to a change in noise disturbance.

- Estimates of this elasticity vary across specifications, but are centered around -.3

- Noise levels in the Salish increased by 100% from the first five years of our sample in 1977 to the last five years ending in 2019.

Ignoring Noise is not an Option

- A 100% permanent change in noise pollution implies SRKW fall by 30% in the long run.
- Noise pollution has degraded the whales' acoustic environment lowering the carrying capacity of the Salish Sea by 30%.
- Ignoring noise pollution is not a realistic option.

How to Save the Whales

- Step One: Minimize the costs of sustaining any KW population via noise abatement/salmon restoration.
- Step Two: Construct the supply curve for KW Conservation; estimate the Marginal willingness to pay (Demand curve) for Conservation. Combine.
- Step Three: Implement noise pollution pricing via a permit system, maintain salmon restoration and experiment with stringency. Permit system fixes noise level which is important for recovery.

How to Save the Whales

- Our Theory says, a sustainable long run population size equals carrying capacity, K.
- Our Estimates tell us that Salmon restoration, S_A, and lowering noise pollution via abatement, N_A, are substitutes in raising whale populations.
- These imply an implicit function $K = K(N_A, S_R)$.

Relative Productivity: Salmon Restoration vs. Noise Abatement

Table 11: Relative Productivity of Restoration versus Noise Abatement

One σ Δ in Vessel km	Versus a Δ σ increase in Salmon Abundance
Bulk carrier 200-	0.47
Bulk carrier 250+	1.77
Cargo 150+	0.96
Container ship 250-	0.88
Container ship 250-320	2.11
Container ship 320+	3.55
Tanker 165+	1.03
Vehicle carrier	0.85

Notes: Calculations use the estimated coefficients from Column II, Table 9 & 10. (Noise disturbance shocks & Fertility/Mortality)

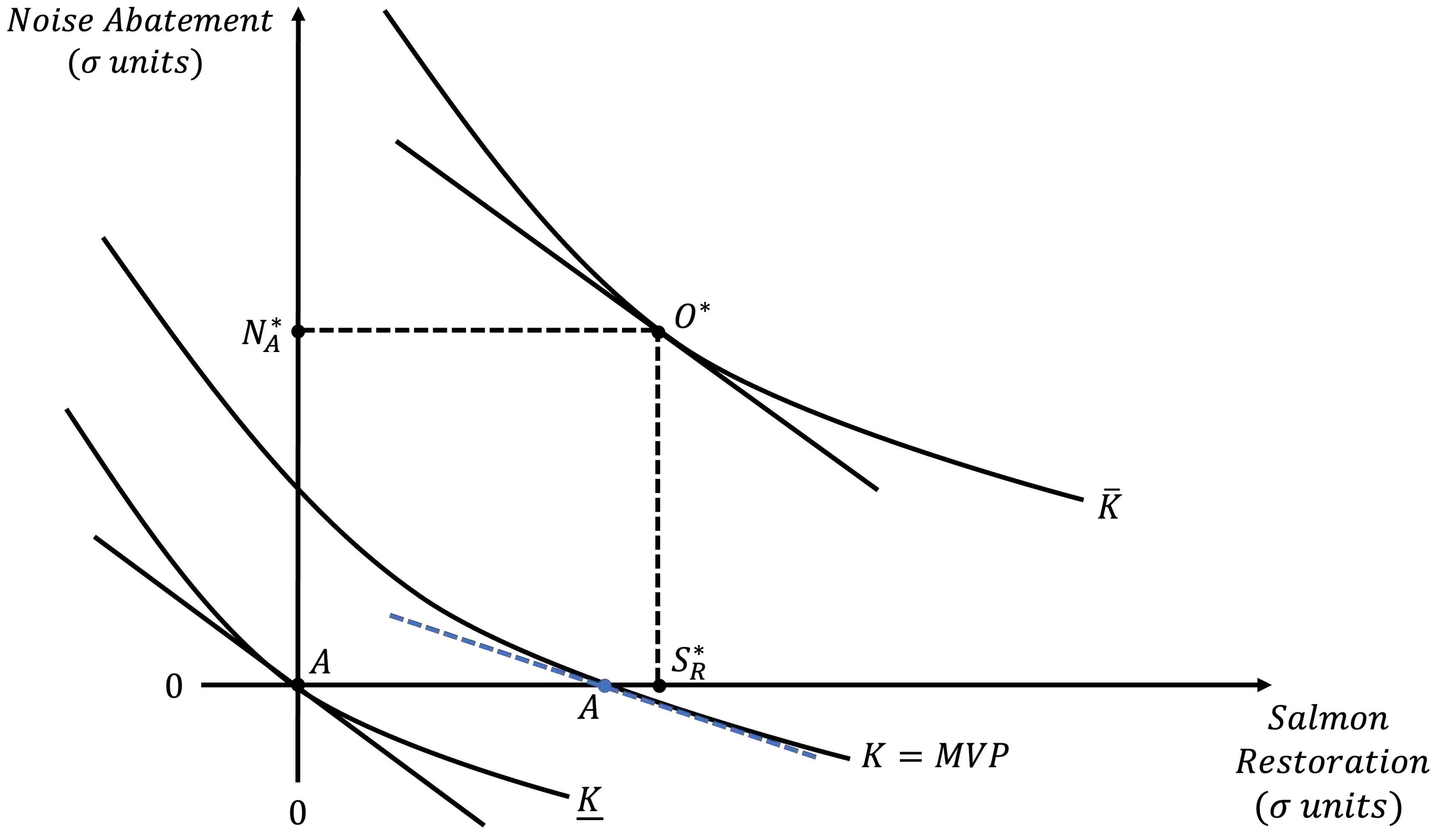
Cost Minimization

$$\text{Min } TC = \tau N_A + \rho S_R$$

$$subject\ to\text{: } K(N_A, S_R) \geq \underline{K}$$

- We know $K(0, S_R) < \text{MVP}$ minimum viable population
- We also know the slope of $\mathrm{K}(0, \mathrm{S_R})$ at axis.
- We also know the minimized cost function will be convex in K
- Call this cost function $C(\tau, \rho, K)$
- We are implicitly assuming Noise is a well-mixed pollutant.

Cost Minimization



Marginal cost of KW recovery is the implied marginal cost from resulting cost function $C(\tau, \rho, K)$; that is, $C_K(\tau, \rho, K) > 0$.

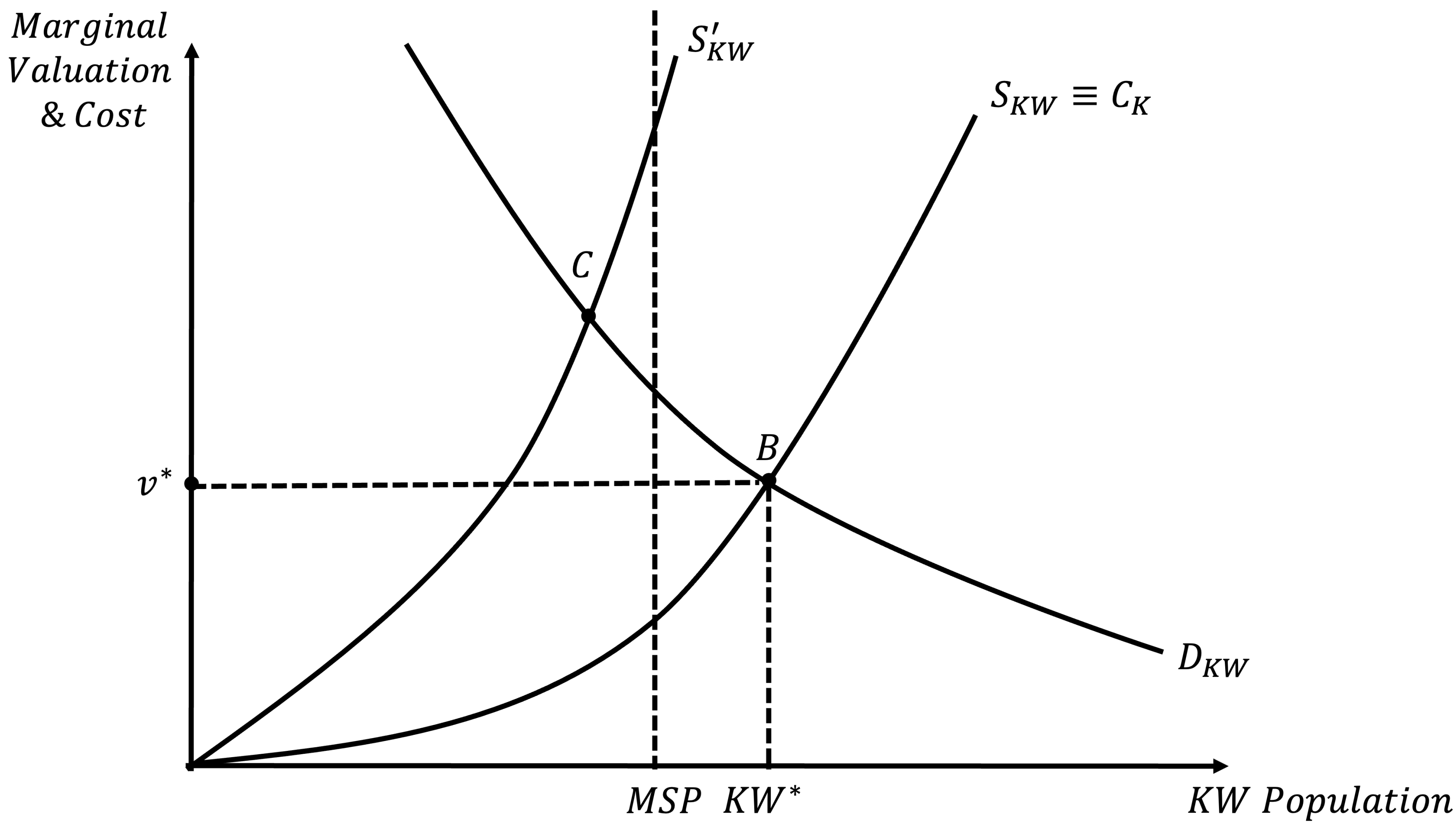
Step two: Construct Supply and Demand for Conservation

- Marginal cost of noise reduction is currently unknown, but ship owners can alter speed, vintage, size, vessel type, engine configuration, and over the longer run design changes could occur. Fleet adjustments also possible.

- Current annual costs of Salmon Restoration, across both the US and Canada, are in the hundreds of million dollar per year.

- Marginal benefit of conserving the Southern Residents comes from non-consumption use values arising from tourism, intrinsic values and existence values and has been estimated. An average US household is willing to pay $110/year for ten years for full recovery.

The First-Best Solution



Step Three: Price noise pollution (details in companion paper)

- Create a unit to measure and price noise disturbance.
- Indicate to ship owners the required units (permits) needed for any given trip and vessel type employed based on industry averages.
- Use AIS to identify incoming ships to verify destination and vessel type matches permit relinquished.
- Auction an initial allotment of permits equal to some base year with given noise disturbance. Observe, experiment and iterate.

Conclusions

- Vessel noise pollution shocks measured by disturbance, lowers births and raises deaths.
- No feasible level of salmon restoration will bring the SRKW back if vessel noise is left unchecked.
- Price noise pollution! Iterate towards first best.
- Applications to other noise sources and other whale populations are feasible given tools created.

Thank You

Source: Brian Copeland Private Collection

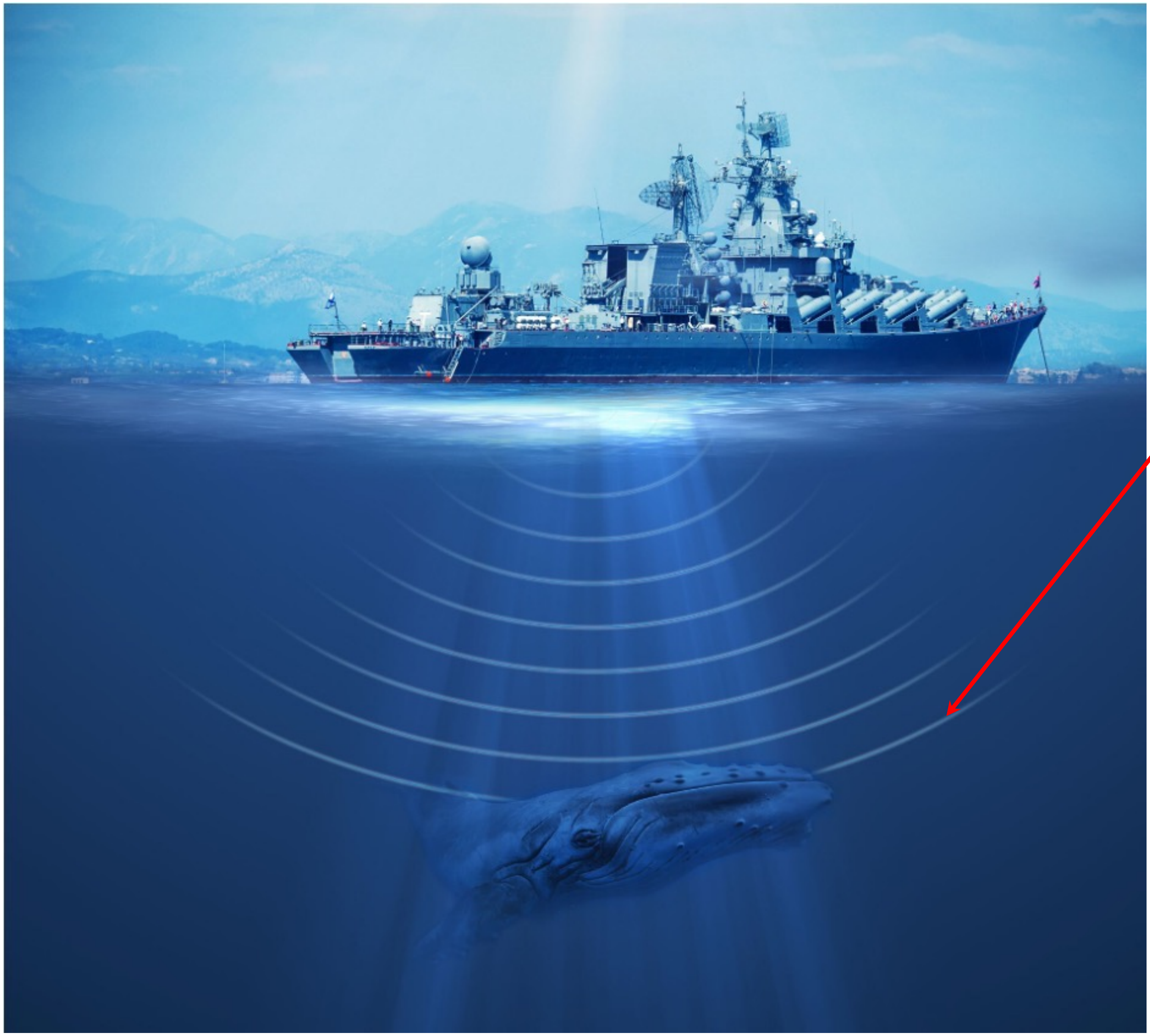
Additional Slides

Sound Exposure Model

- A1. Sound dissipates spherically.
- A2. Disturbance is binary: zero or 1.
- A3. Inverse-square law plus threshold determines size of disturbance bubble.
- A4. Vessels are acoustically isolated.

More detail

This Whale is Disturbed



Threshold

Simulation

Data for Vessel Noise

- Almost 3,000 observations from two existing studies.
- Data collected opportunistically – sample is random. One was collected in the SRKW critical habitat.
- Vessel noise measured via hydrophone/s placed on ocean floor at given distance from shipping lanes. Authors estimate source level, SL, noise at ship.
- Use AIS to identify vessels, other industry sources to get vessel characteristics.

Making disturbances Vessel specific

- We run simple cross-sectional regressions relating SL to vessel characteristics.
- Vessel characteristics are as vessel class (Bulk, Container, etc.), length, dwt, average speed, and age.
- Empirical model generates estimates of the SL noise that we match with vessels in our sample.
- Our findings are (mostly) consistent with earlier authors' observations drawn from graphs or bivariate regressions.

Relative Vessel Disturbance (1 km)

Vessel type	Relative Disturbance
Bulk carrier 200-	1.00
Bulk carrier 200-250	0.77
Bulk carrier 250+	3.76
Cargo 150-	1.46
Cargo 150+	2.05
Container ship 250-	1.87
Container ship 250-320	4.49
Container ship 320+	7.55
Tanker 165-	1.05
Tanker 165+	2.20
Vehicle carrier	1.81
Tug	0.77
Fishing	0.10
Military	0.03
Miscellaneous	0.04
Passenger	0.11
Pleasure craft	0.11
Research	0.14

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