Using temporal genomic contrasts to understand Pacific herring population recovery following the Exxon Valdez oil spill

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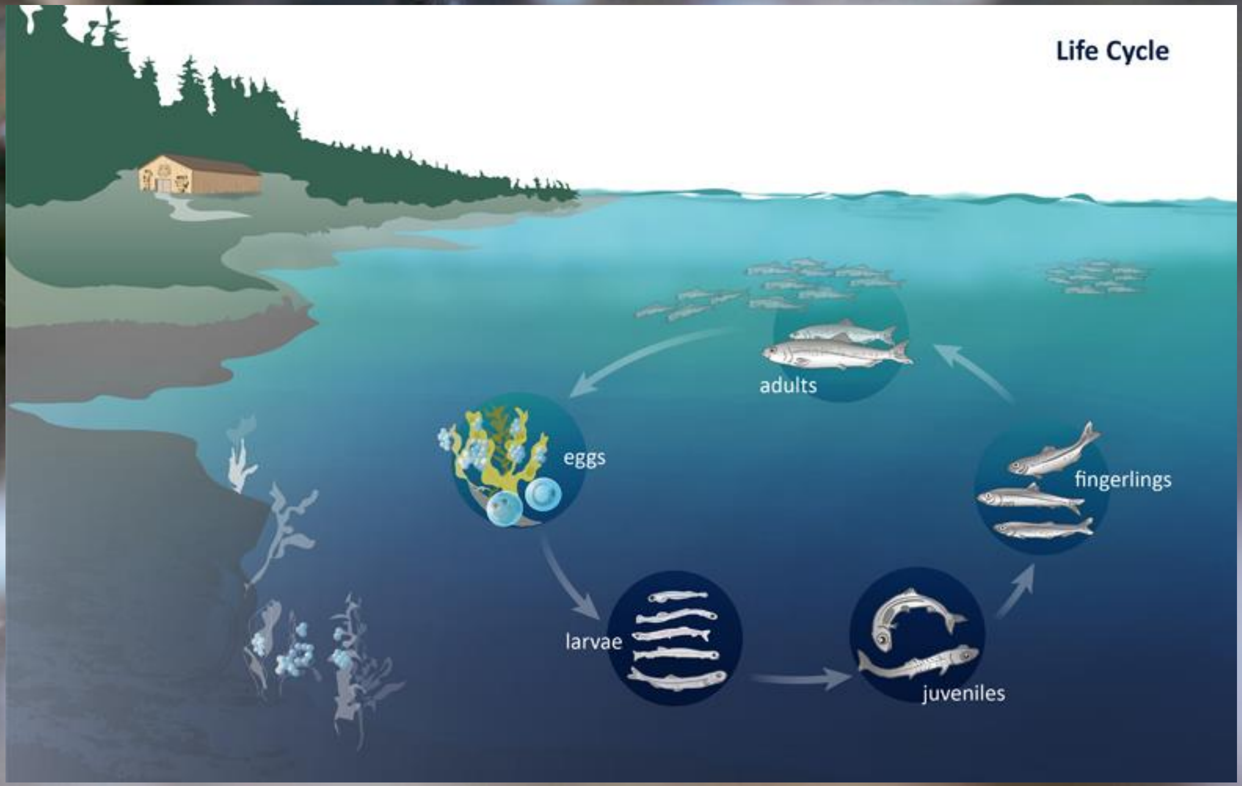
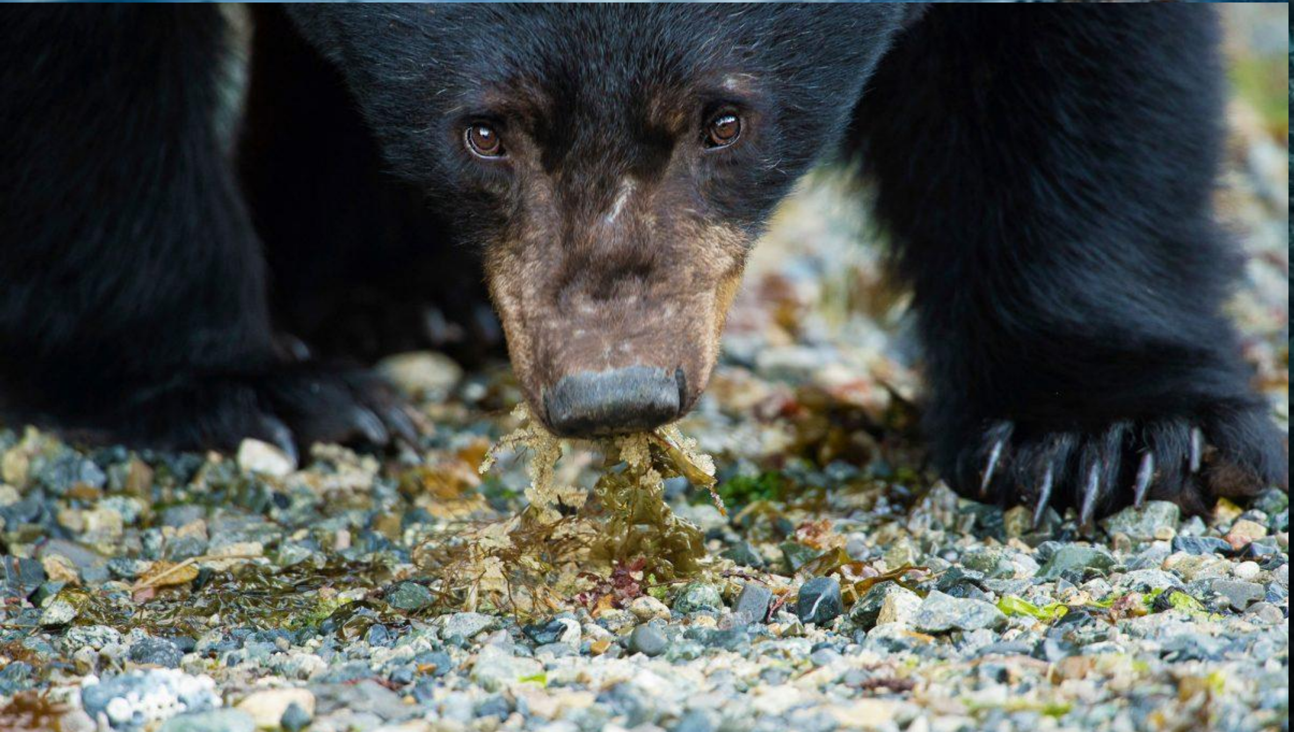
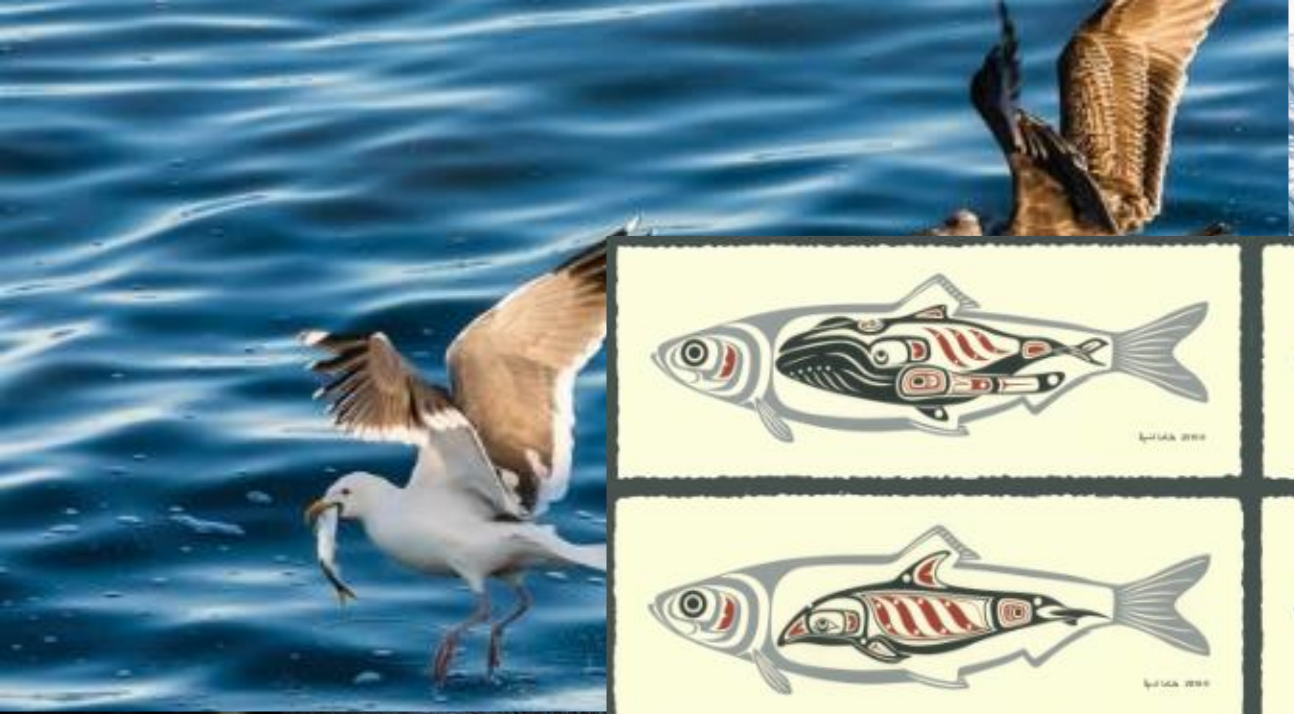
UCDAVIS
UNIVERSITY OF CALIFORNIA

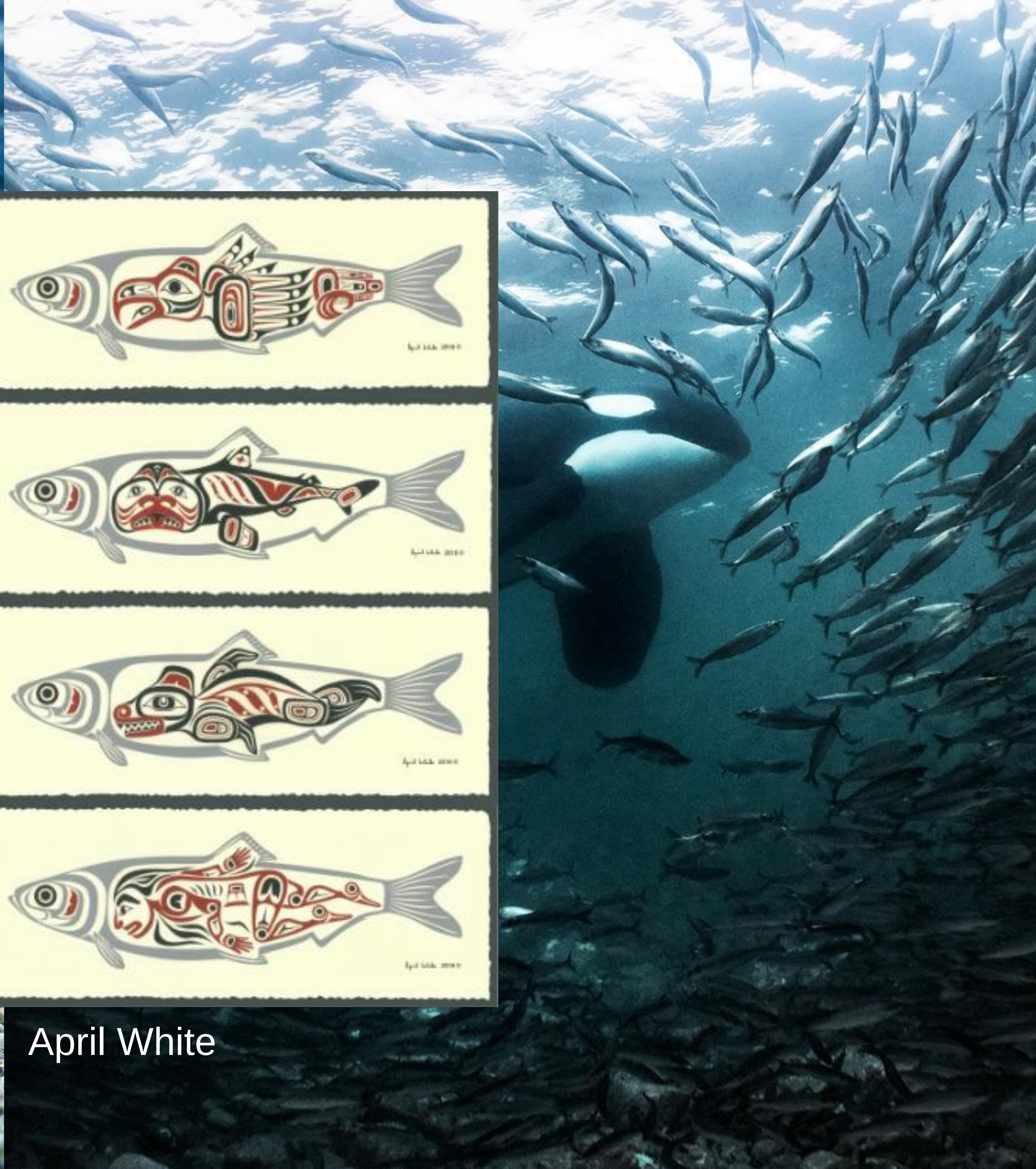
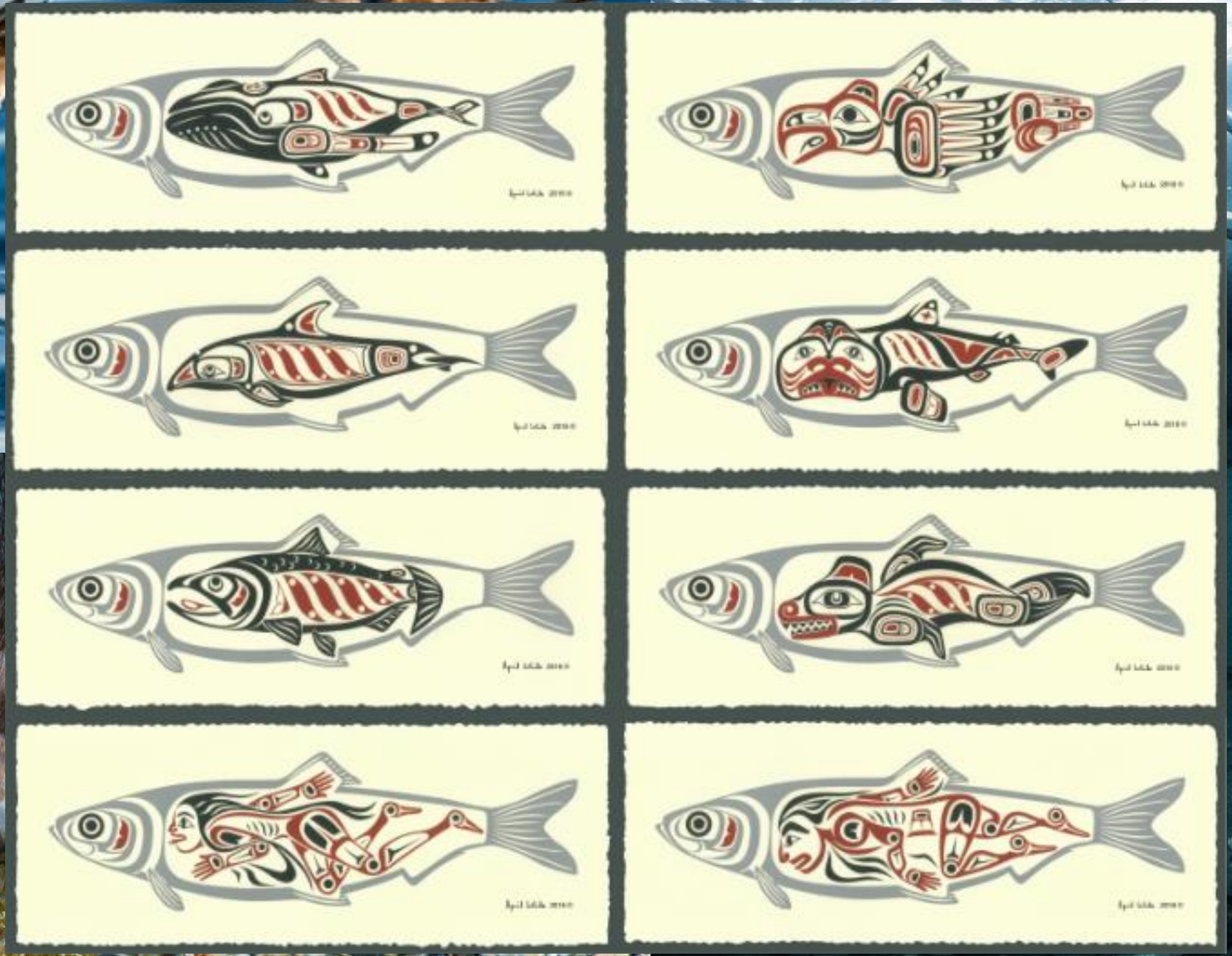
Video credit: Karac Lindsay

Video credit: Ian McAllister



April White

Pacific herring and humans

Harvested by coastal indigenous communities

Main export:
dry-salted

1882
First commercial
fisheries in Alaska

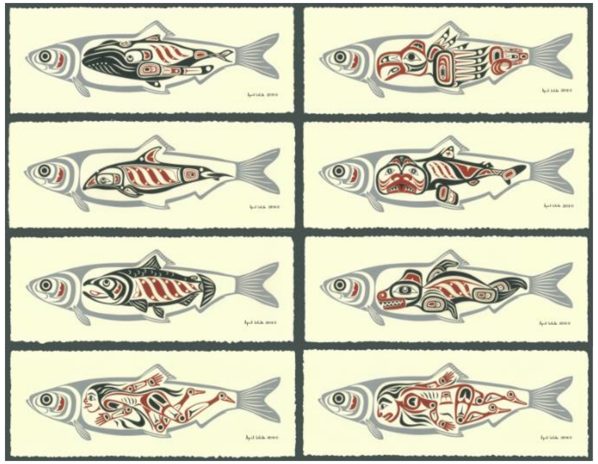
Main export:
meal and oil

1930s

Main export:
roe/spawn on kelp and bait

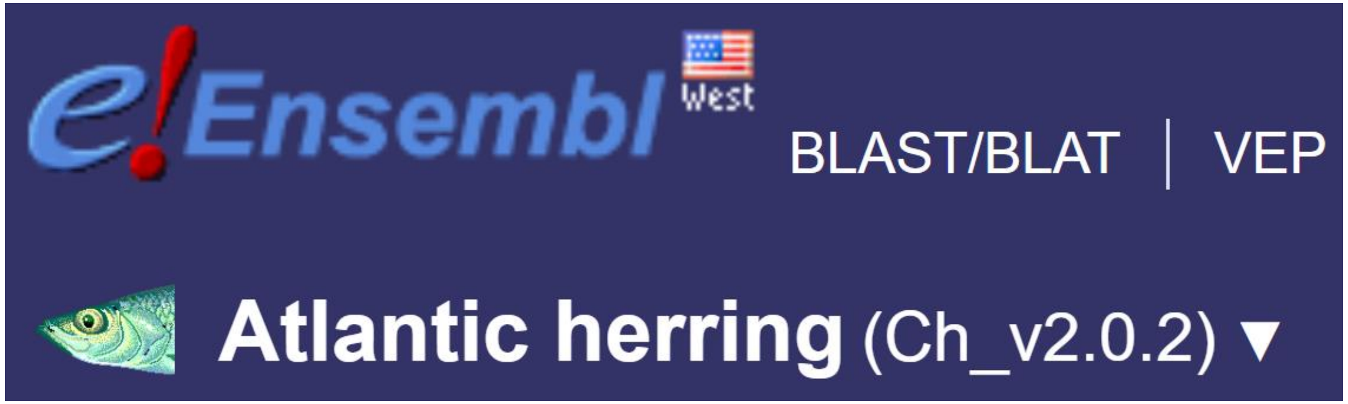
1960s

Present



Atlantic herring: A model for population genetics

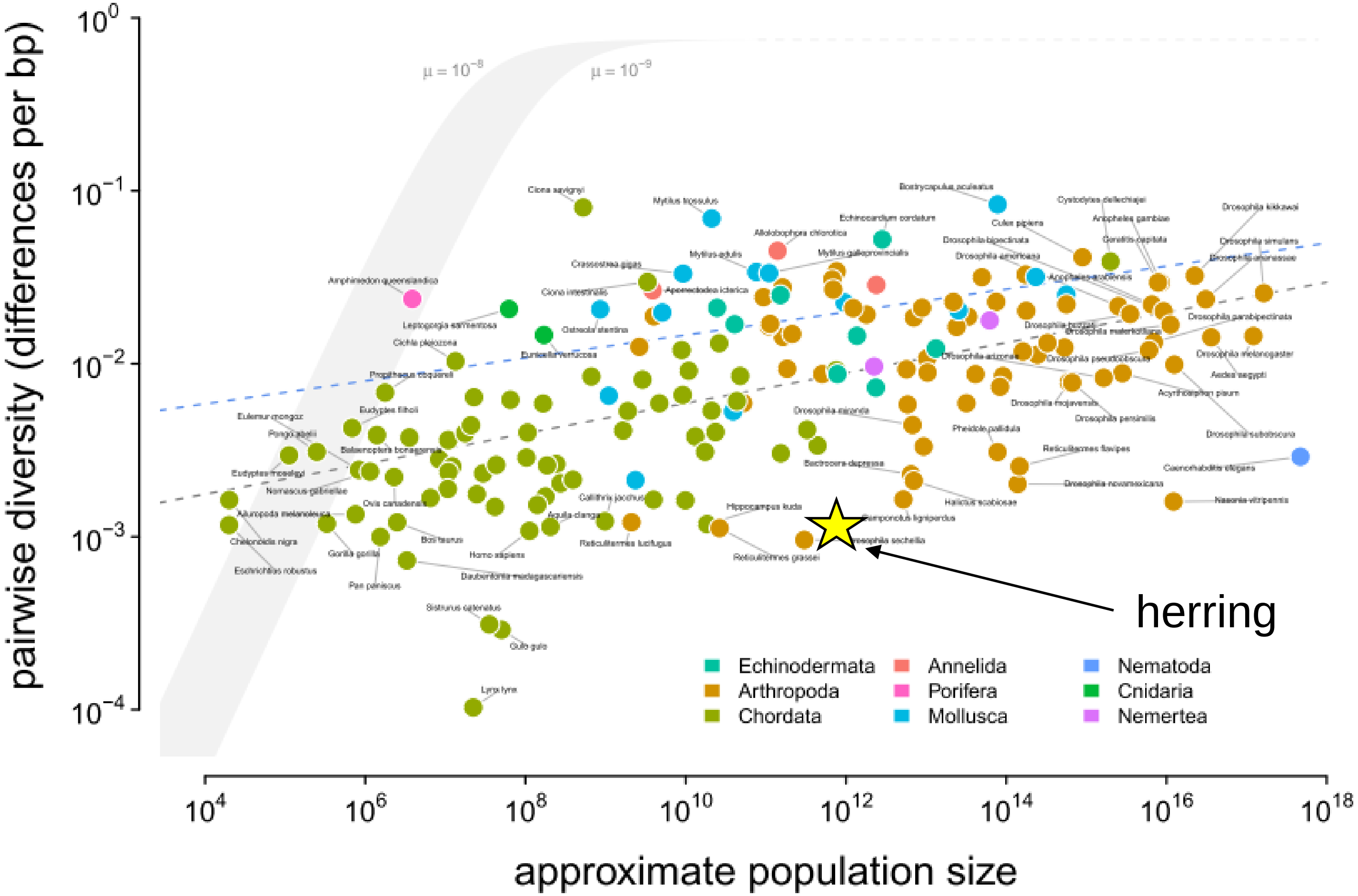
- Giant population size
- Random mating
- Chromosome-level genome assembly
- Mutation rate (2×10^{-9})
- Moderate nucleotide diversity (π = 0.3%)
- Tiny Ne/Nc ratio (10^5 / 10^{12})



Feng et al. 2017, *elife.* Pettersson et al. 2019 *Genome Research*

Lewontin’s Paradox

Vince Buffalo

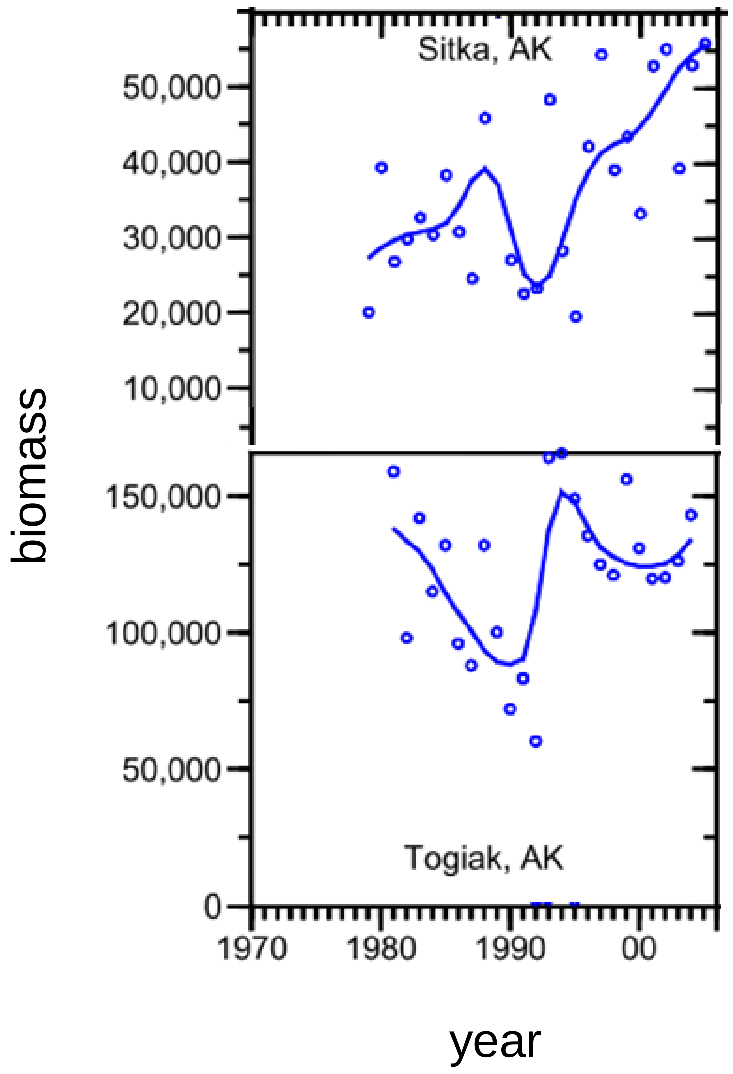


Buffalo 2021, *bioRxiv*

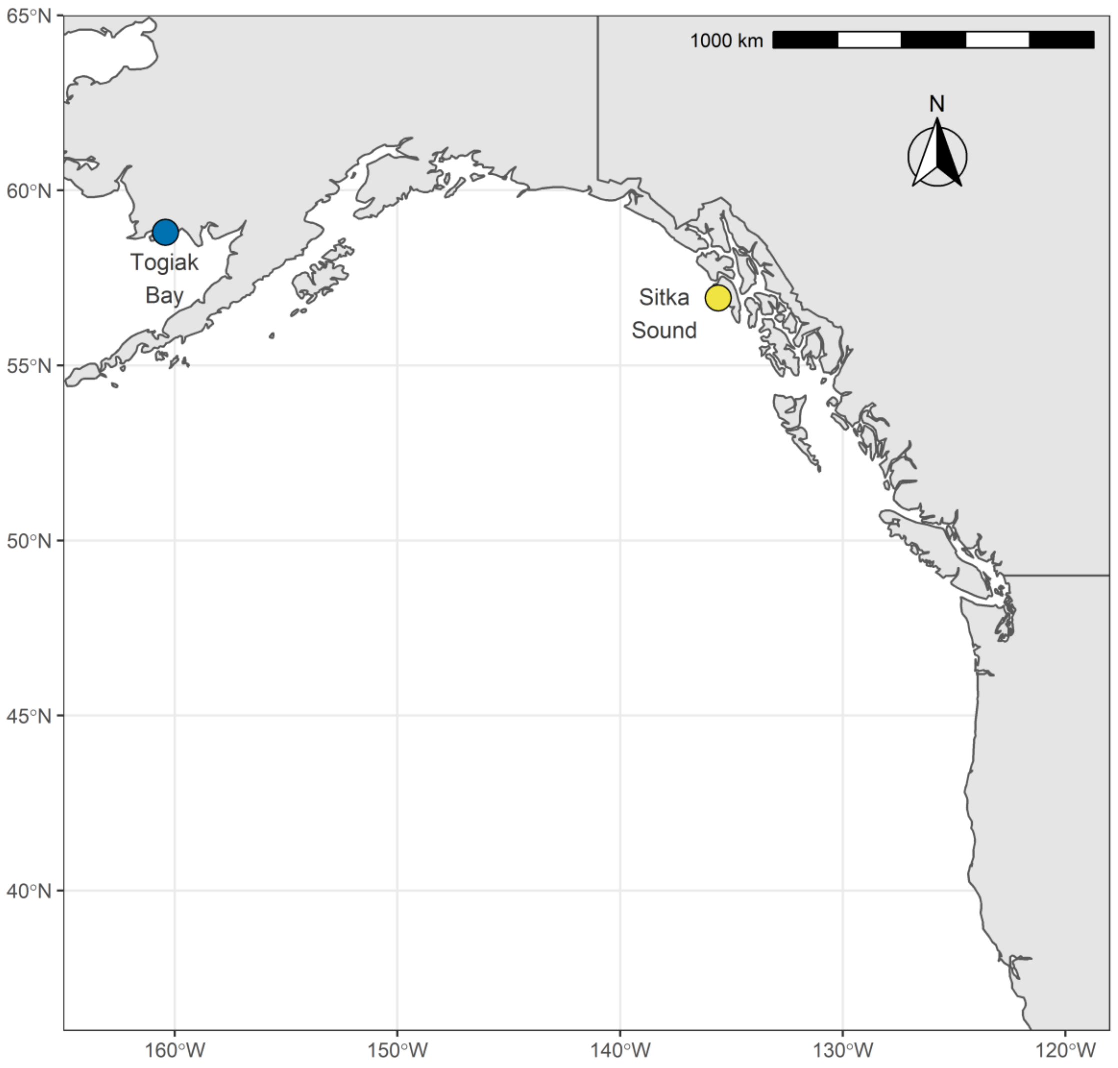
Outline

- Genetic variation underlying pollution resistance and susceptibility to disease.
- Inversions underlying local adaptation.

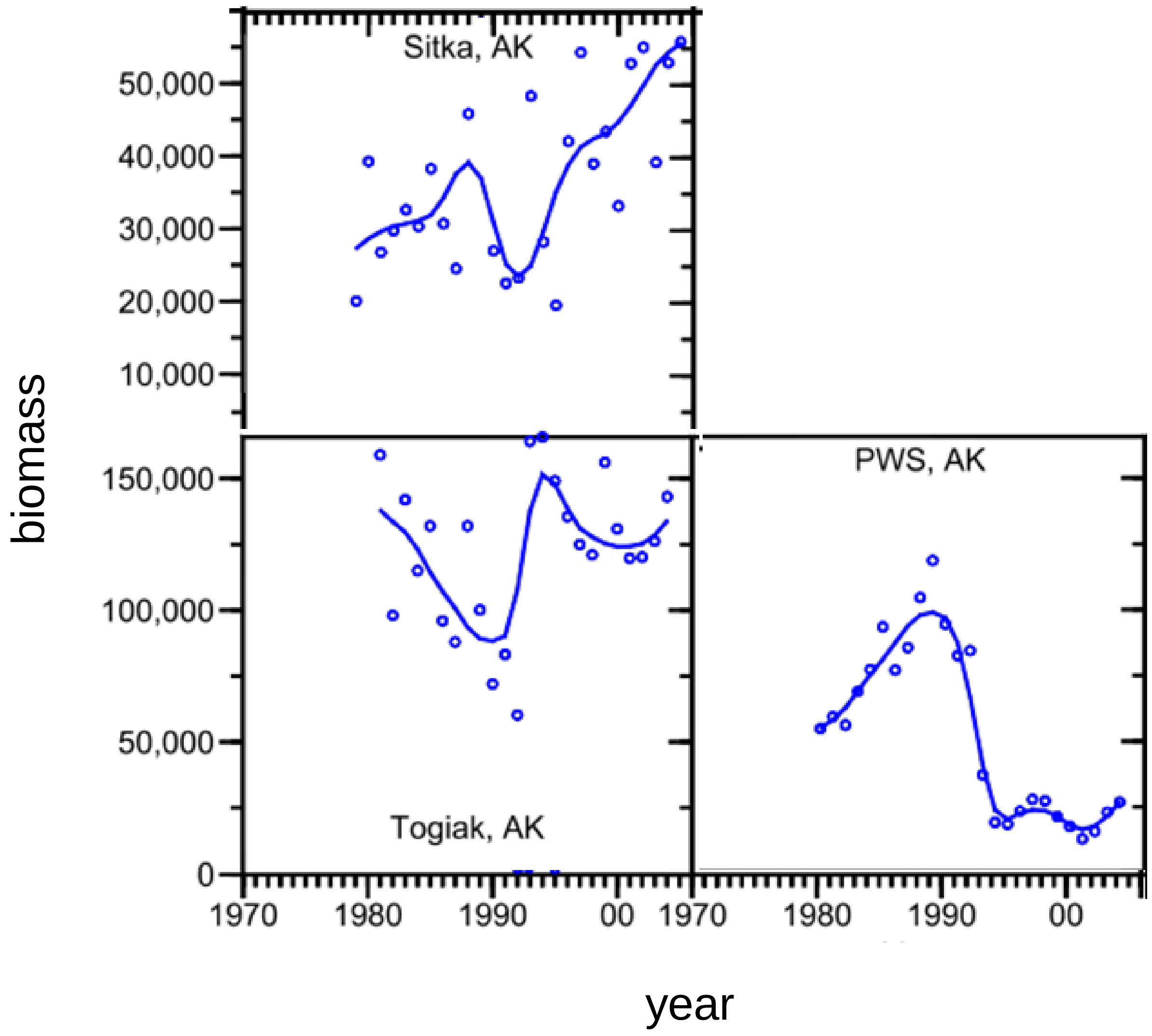
Population collapse and recovery

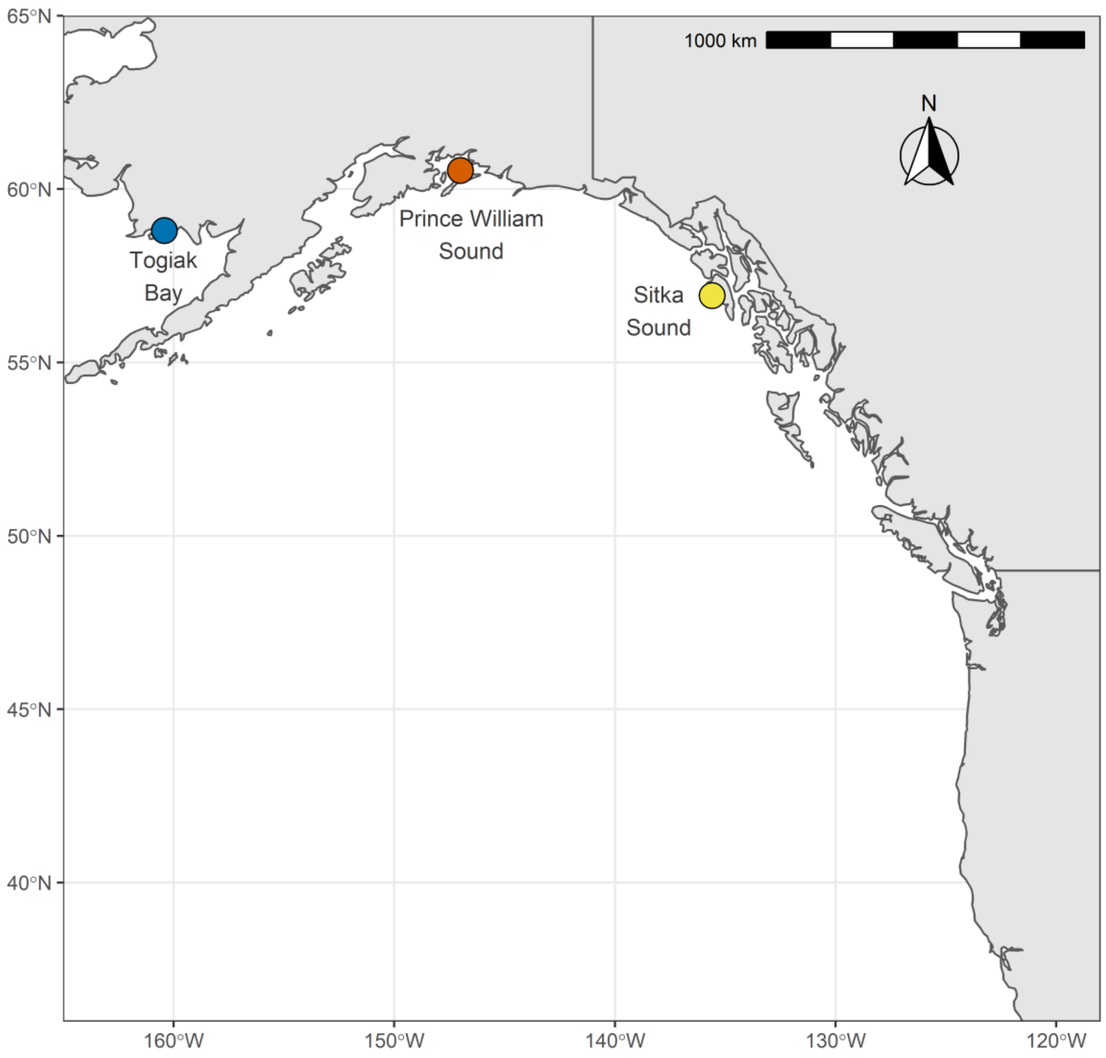


Rice and Carls 2007, *EVOS Report*



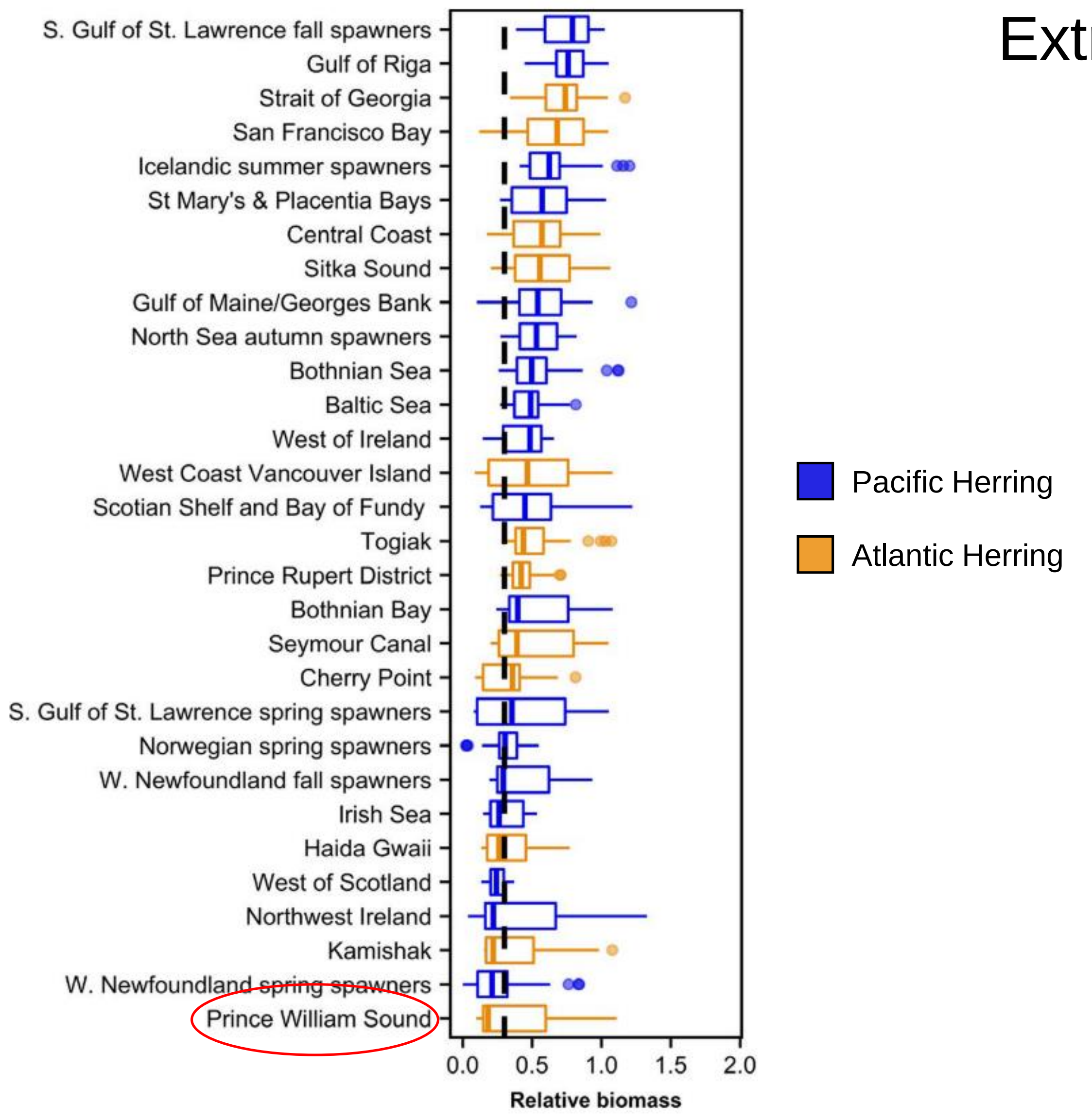
No recovery in Prince William Sound (PWS)





Rice and Carls 2007, *EVOS Report*

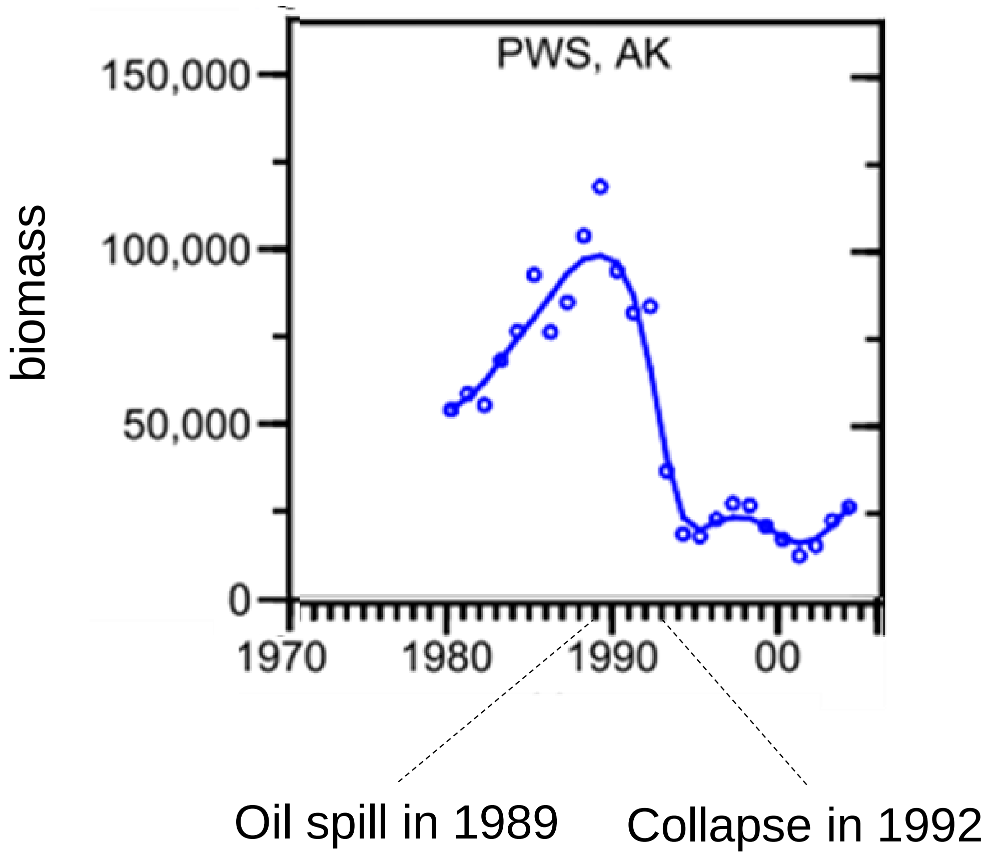
Extreme population collapse in Prince William Sound



Trochta et al. 2020, *Fish and Fisheries*

Exxon Valdez oil spill

Exxon Valdez oil spill



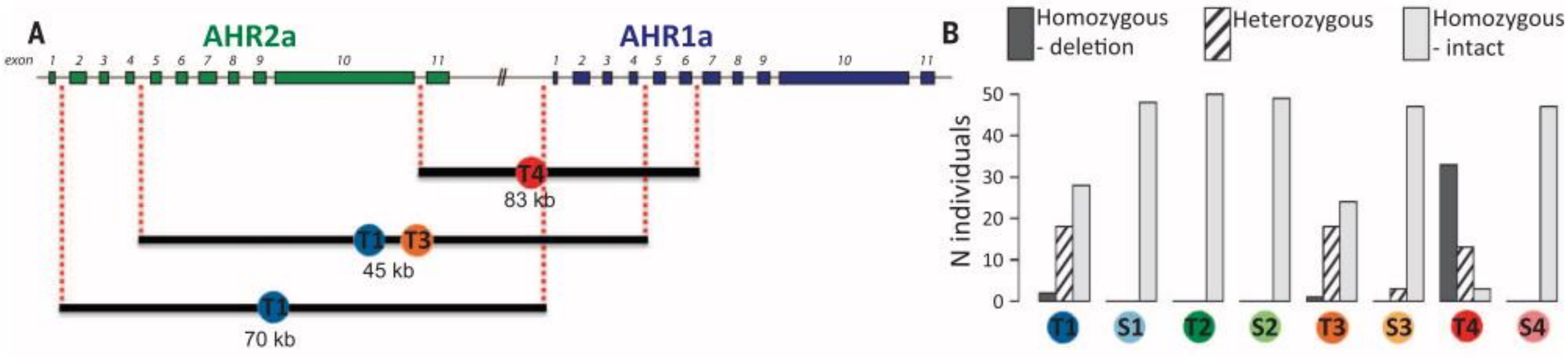
Disease: Viral hemorrhagic septicemia virus (VHSV) and *Ichthyophonus hoferi* (Ick)

VHSV prevalence up to 14%
Deadly at early life stages

Ichthyophonus prevalence up to 51%
Deadly at later life stages

Marty et al. 2010, *Diseases of Aquatic Organisms*
Photos: Paul Hershberger

Adaptation to pollution through loss-of-function mutations



Reid et al. 2016, *Science*

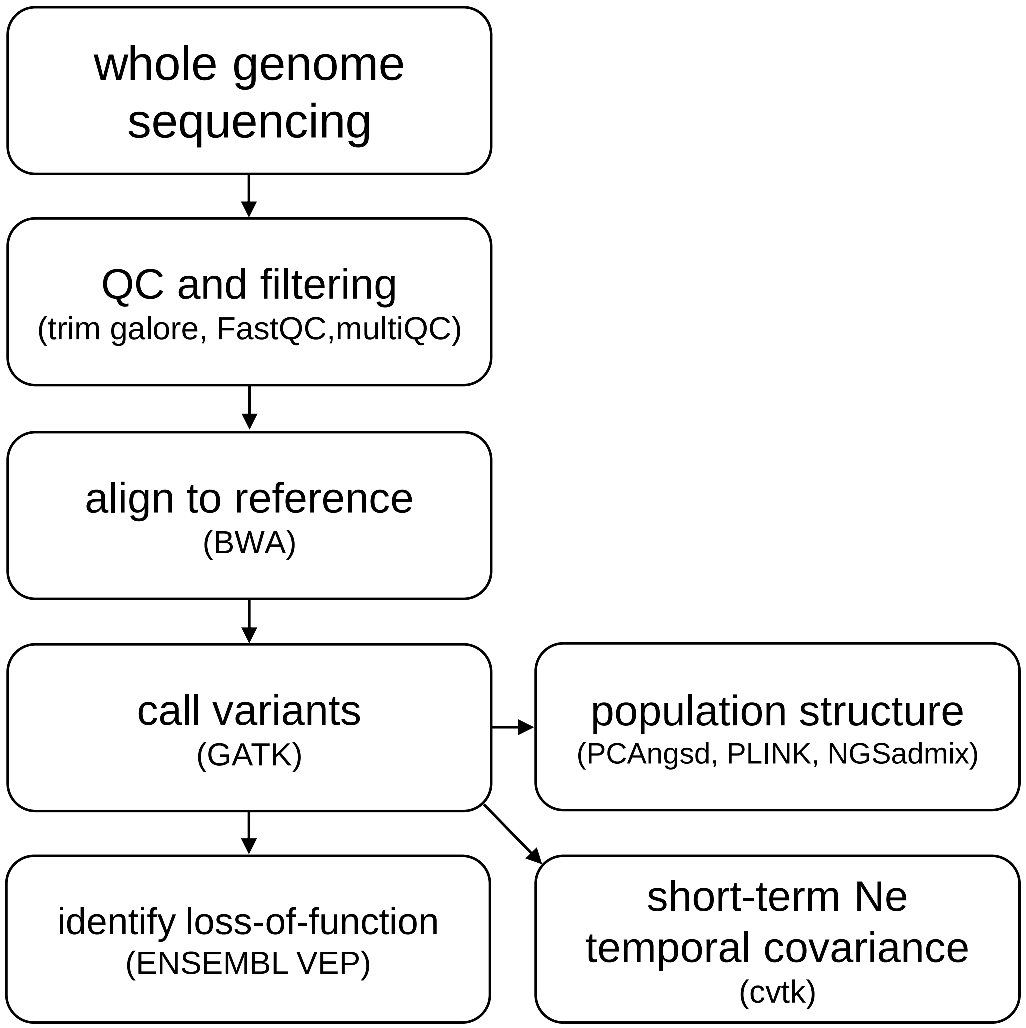
Increased mutation load following population collapse

- Mutation load: a measure largely determined by a reduction in fitness contributed by deleterious mutations across the entire genome.
- A bottleneck can increase mutation load because drift is stronger.
- A bottleneck can cause larger increases in the total load when population size recovers slowly.

Lohr and Hagg 2015, *Evolution.* Kirkpatrick and Jarne 2000, *The American Naturalist*

Are there genetic factors limiting population recovery in Prince William Sound?

Low coverage sequencing of 1100 Pacific herring to identify genetic variation limiting population recovery



Acknowledgements

whole genome sequencing

QC and filtering
(trim galore, FastQC, multiQC)

align to reference
(BWA)

call variants
(GATK)

population structure
(PCAngsd, PLINK, NGSadmix)

identify loss-of-function
(ENSEMBL VEP)

short-term Ne
temporal covariance
(cvtk)

Libraries prepared by Jenn Roach and Elias Oziolor

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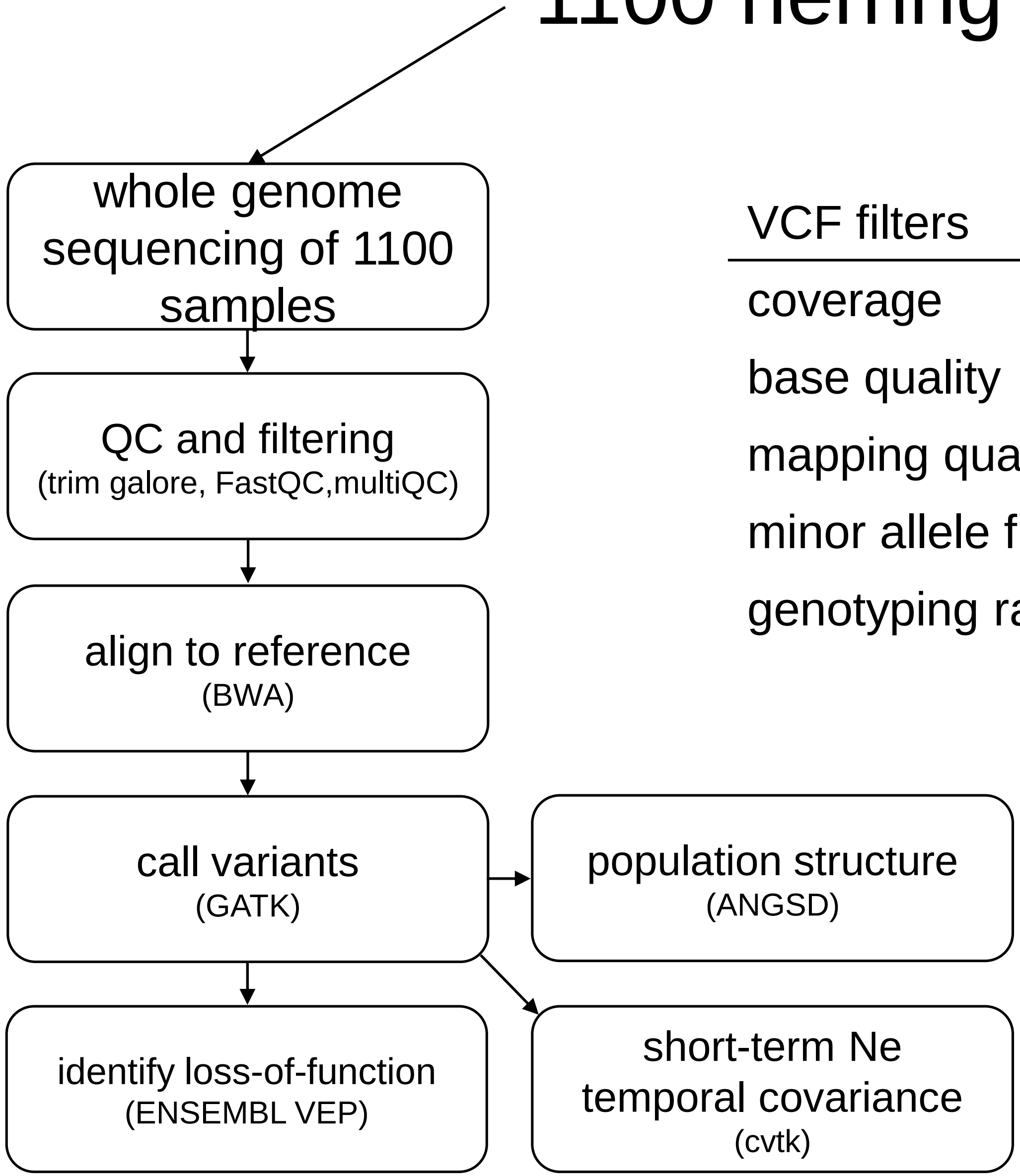
Vince Buffalo

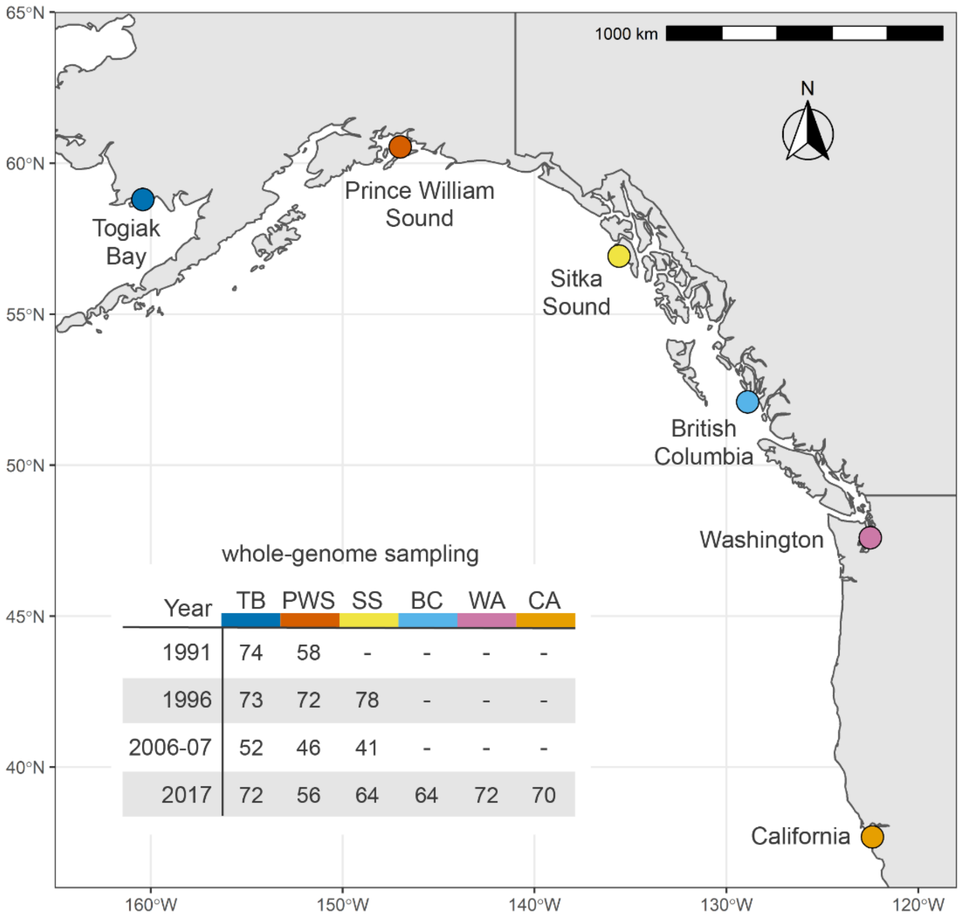
1100 herring genomes (1.2x)



VCF filters	
coverage	between 600 and 2000
base quality	>20
mapping quality	>30
minor allele freq.	>5%
genotyping rate	>50%

200,000 SNPs

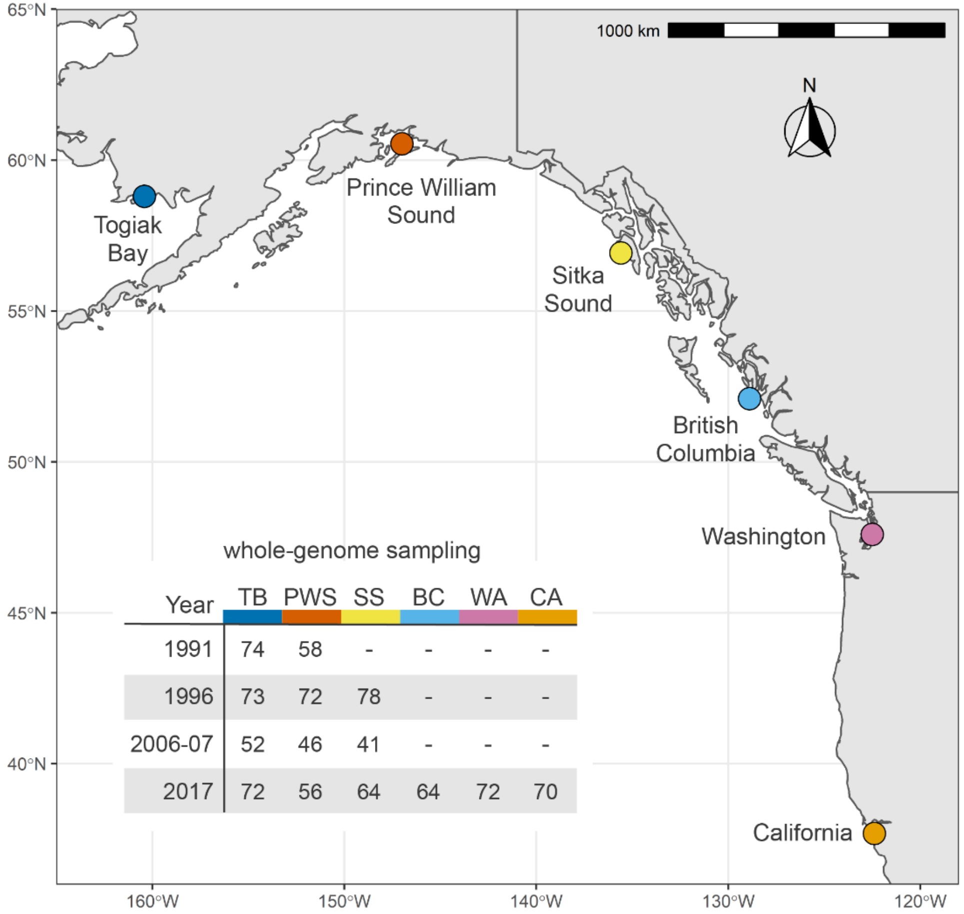
Population sampling



Year	TB	PWS	SS	BC	WA	CA
1991	74	58	-	-	-	-
1996	73	72	78	-	-	-
2006-07	52	46	41	-	-	-
2017	72	56	64	64	72	70

- None of the pre-collapse samples collected in 1991 were exposed to oil as embryos.
- A subset of the post-collapse samples collected in 1996 descended from oil spill survivors.
- None of the post-collapse samples collected in 2007 and 2017 were directly exposed to oil.

Population structure



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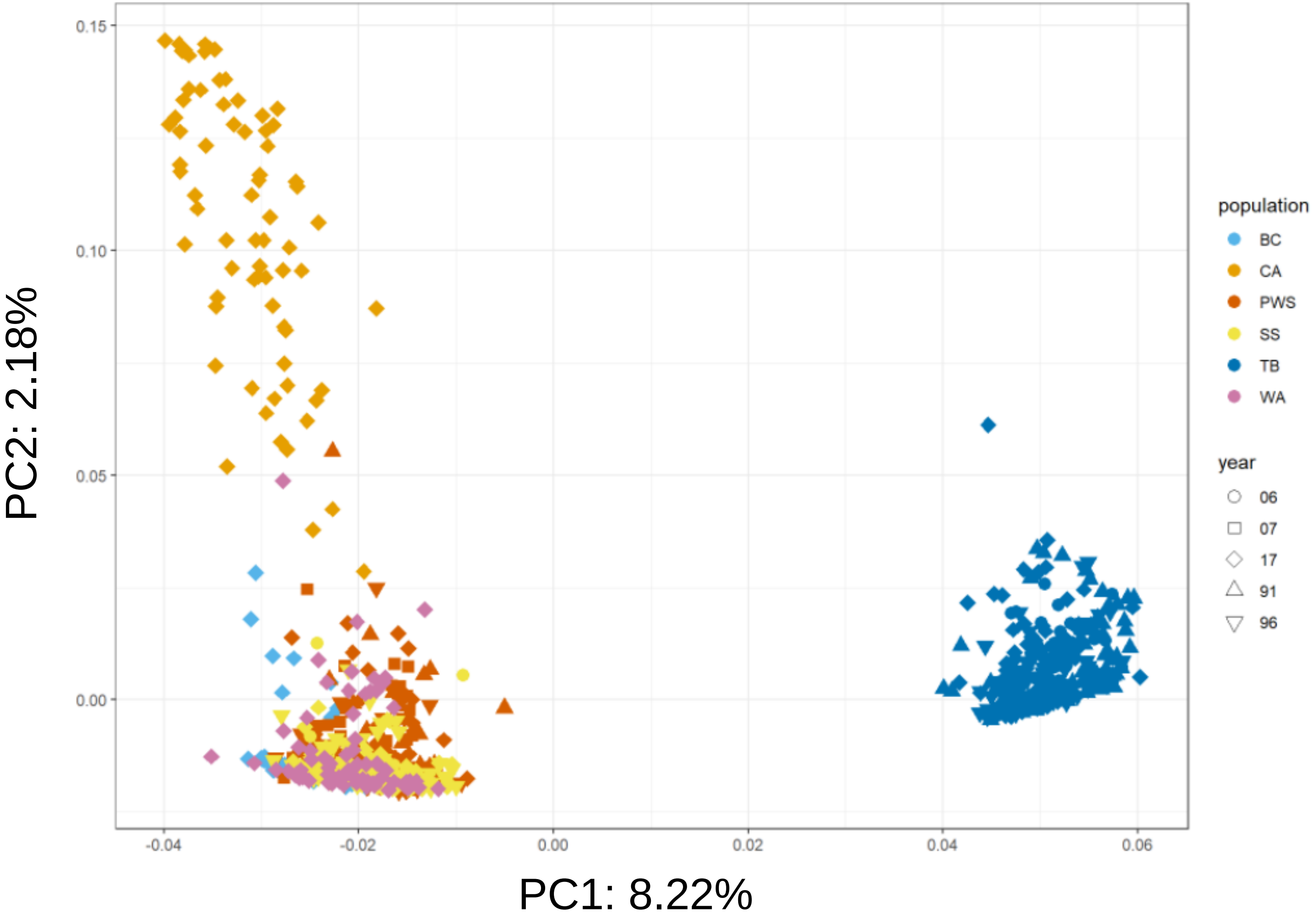
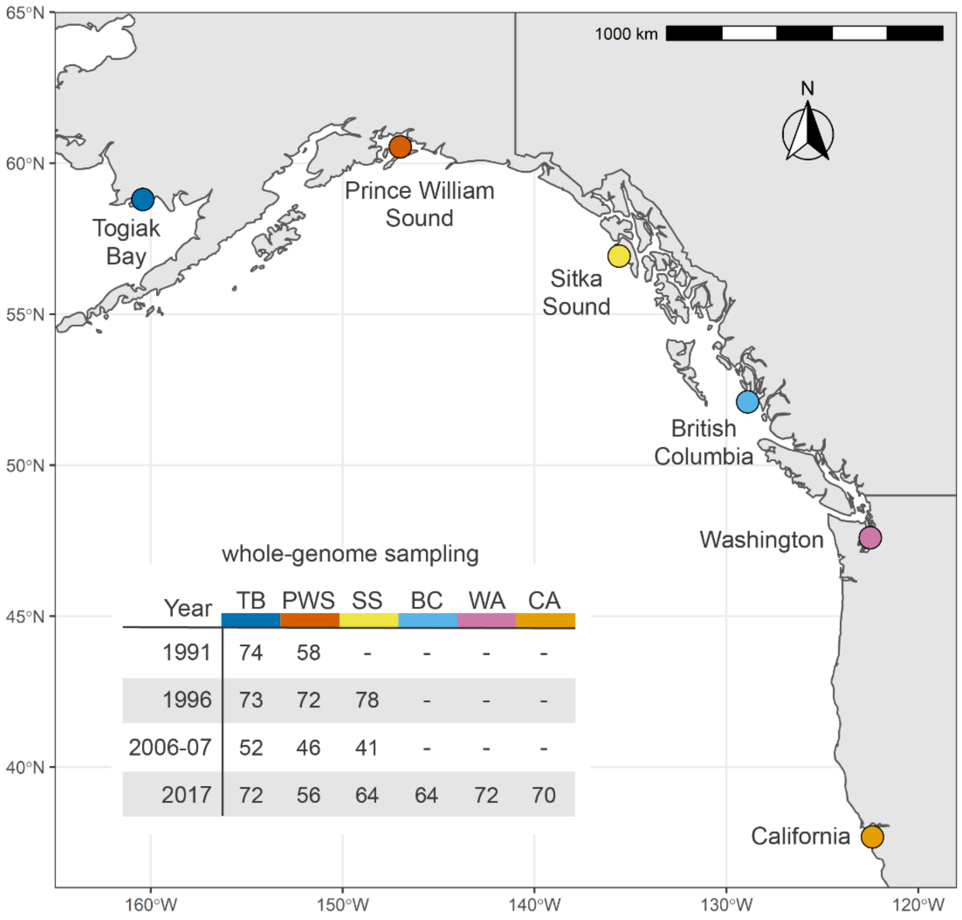


Nucleotide Diversity



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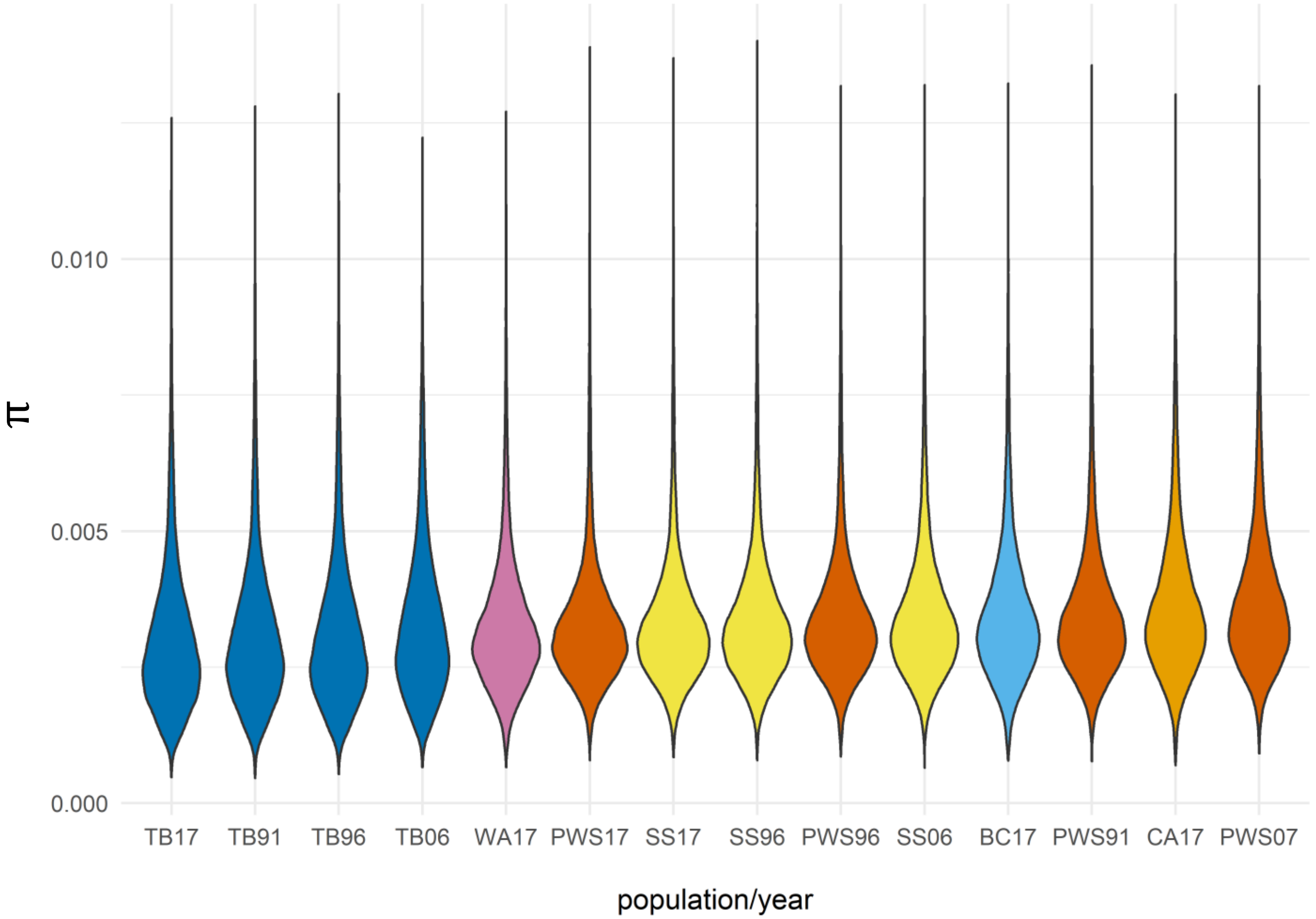
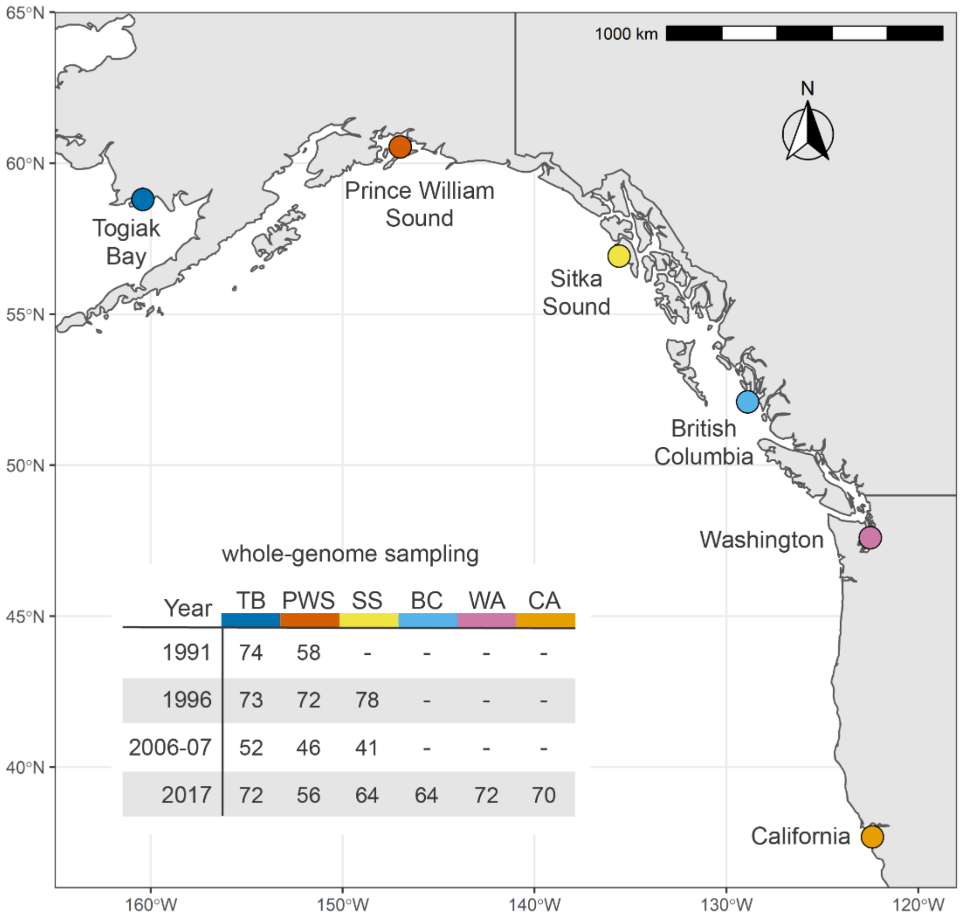
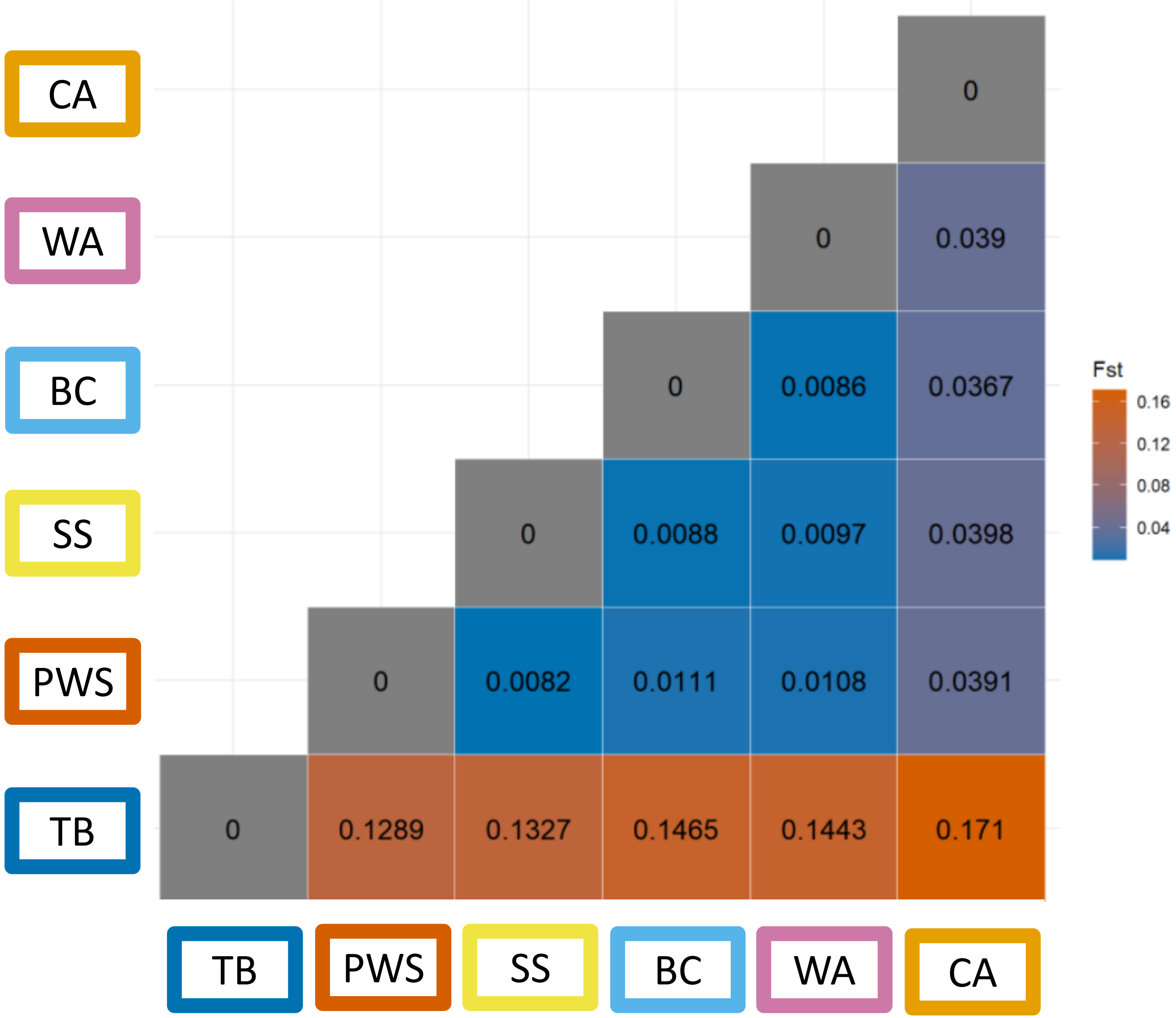
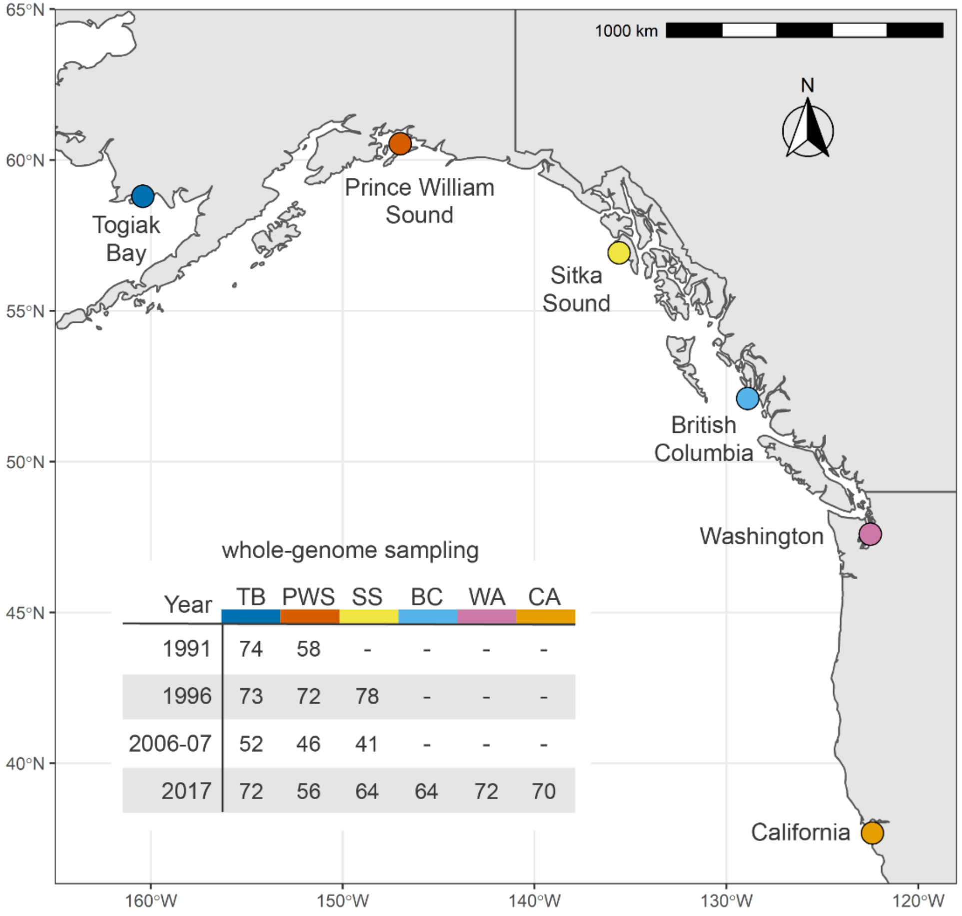


Fst: 2017 comparisons





LD decay



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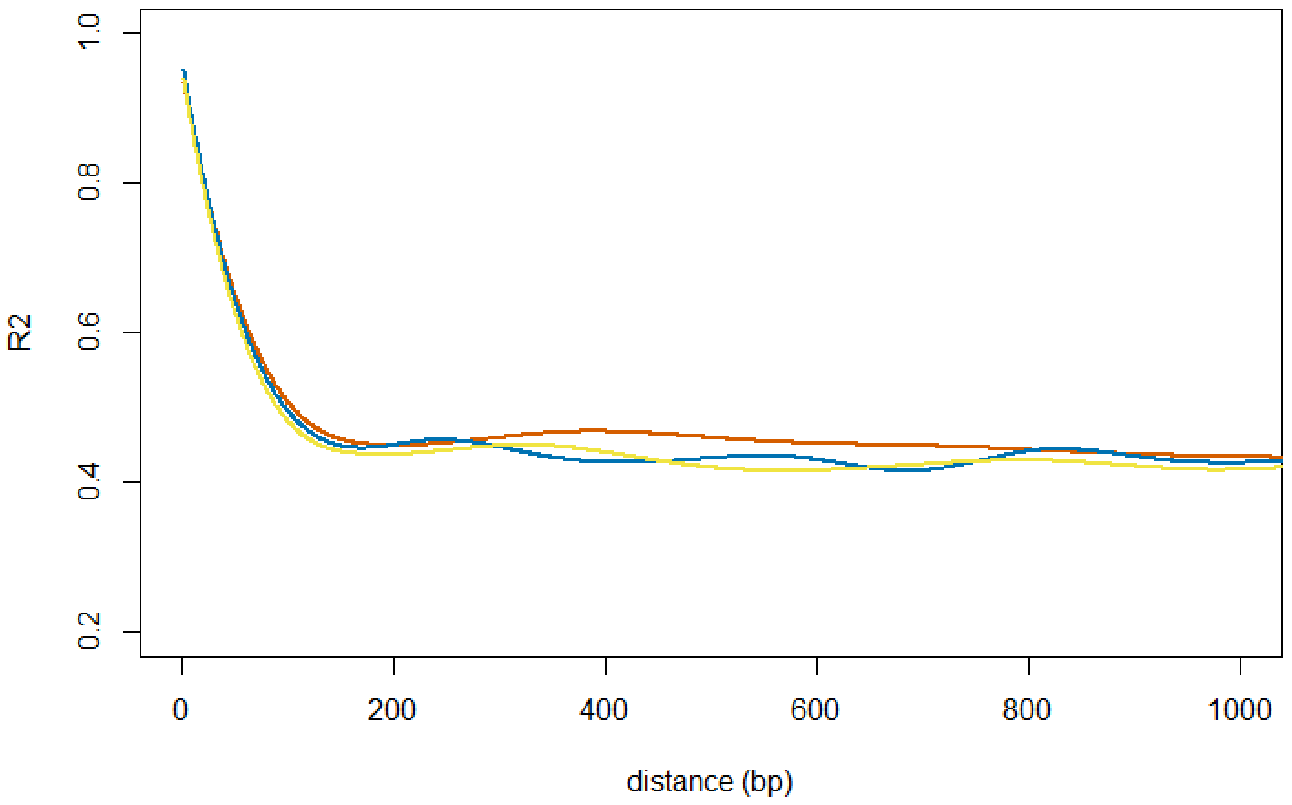


Population collapse

Motivation

- Half of egg biomass in 1989 was within the trajectory of spilled oil that would have occurred at harmful concentrations.

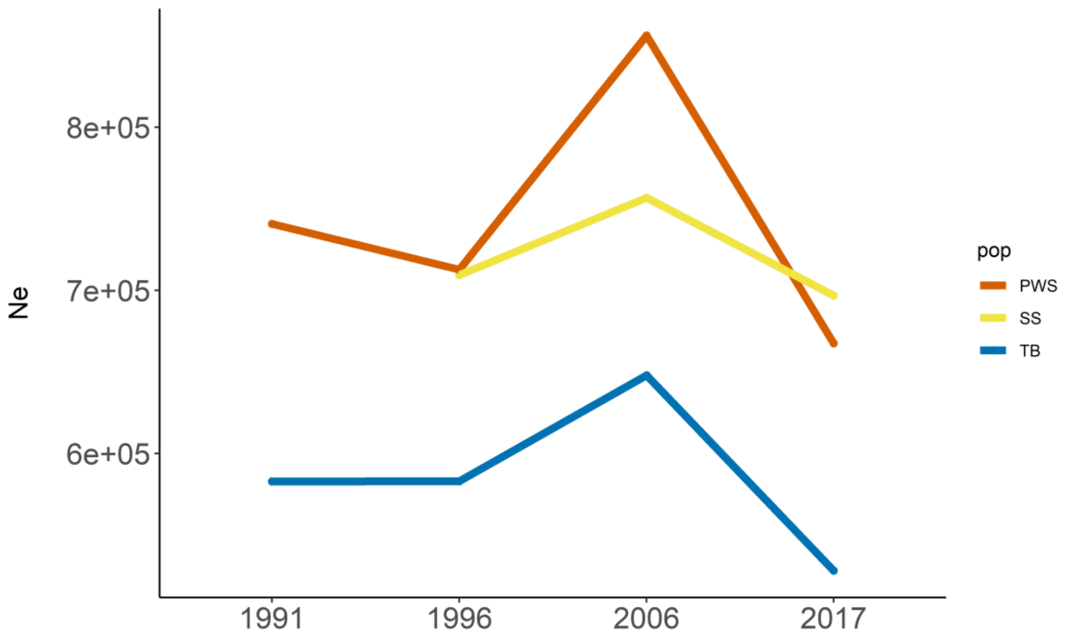
Hypothesis

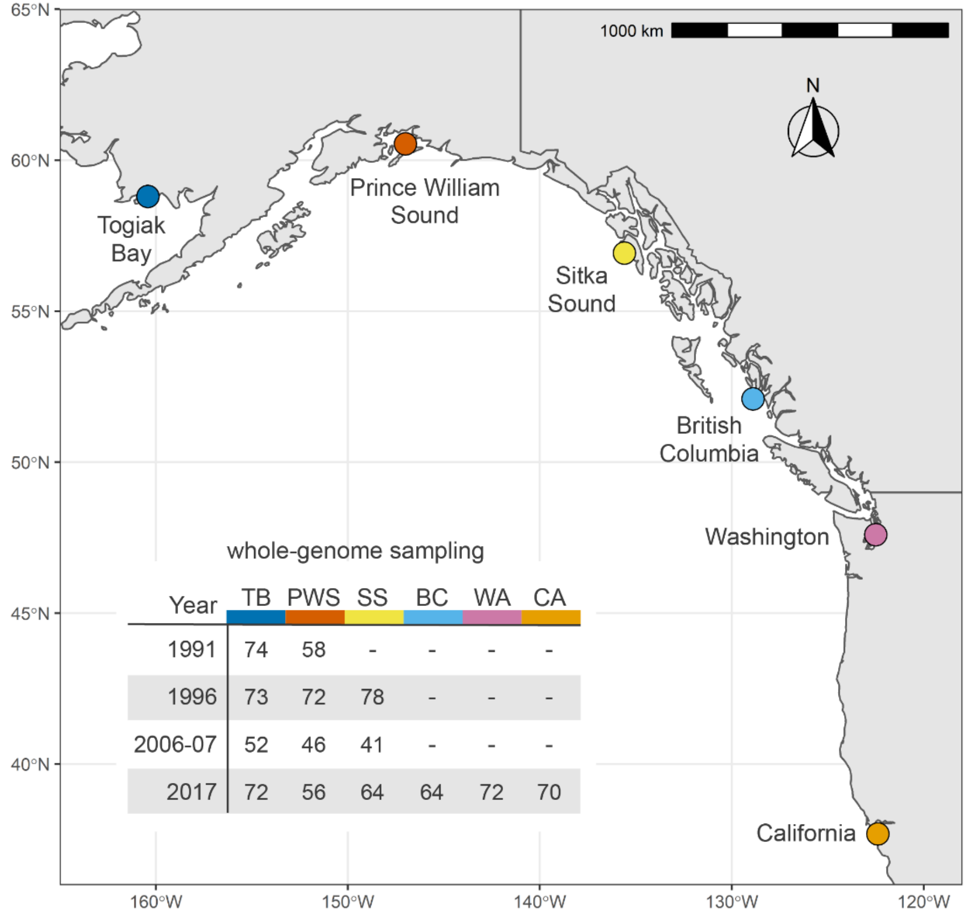
- PWS should show a larger decline in effective population size post-spill compared to nearby populations.

Effective population size changes through time

$\Theta = 4N_e\mu$

$t \ll N_e$





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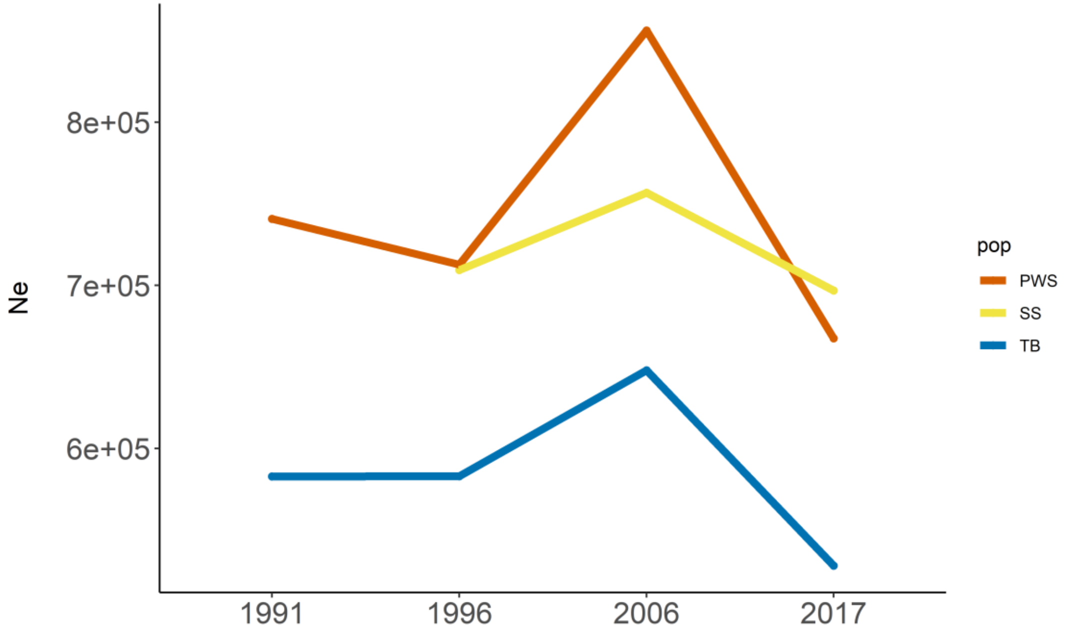
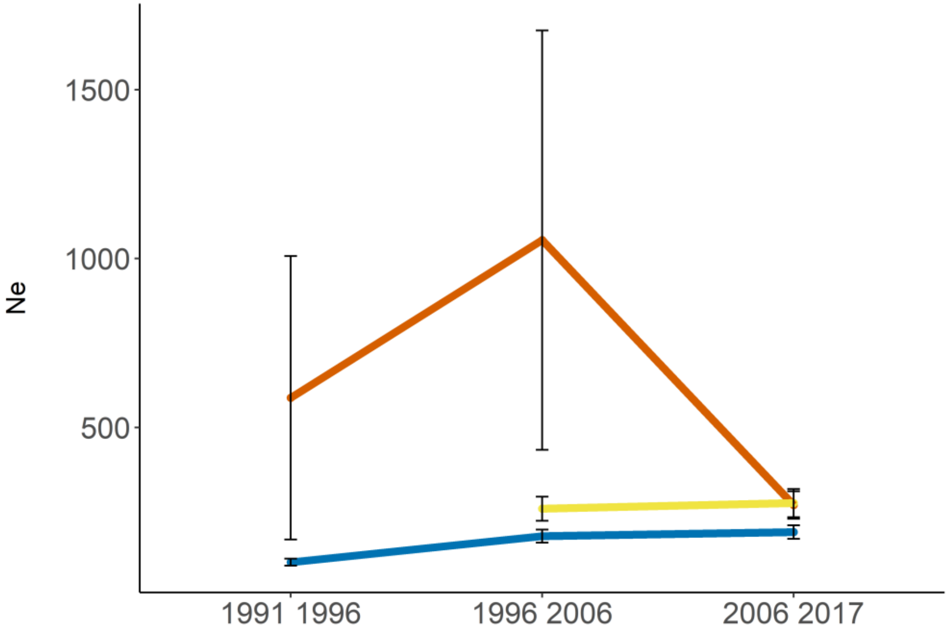


variance in the temporal changes of allele frequency (F)

$F \propto 1/N_e$



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- PWS may show a higher frequency of deleterious alleles post-spill.

Are loss-of-function alleles more common after the oil spill?

input .bed file with Ref and Alt alleles

↓

Ensembl Variant Effect Predictor

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input .bed file with Ref and Alt alleles

↓

Ensembl Variant Effect Predictor

Atlantic herring
reference genome

24,095 coding genes

Are loss-of-function alleles more common after the oil spill?

input .bed file with Ref and Alt alleles

↓

Ensembl Variant Effect Predictor

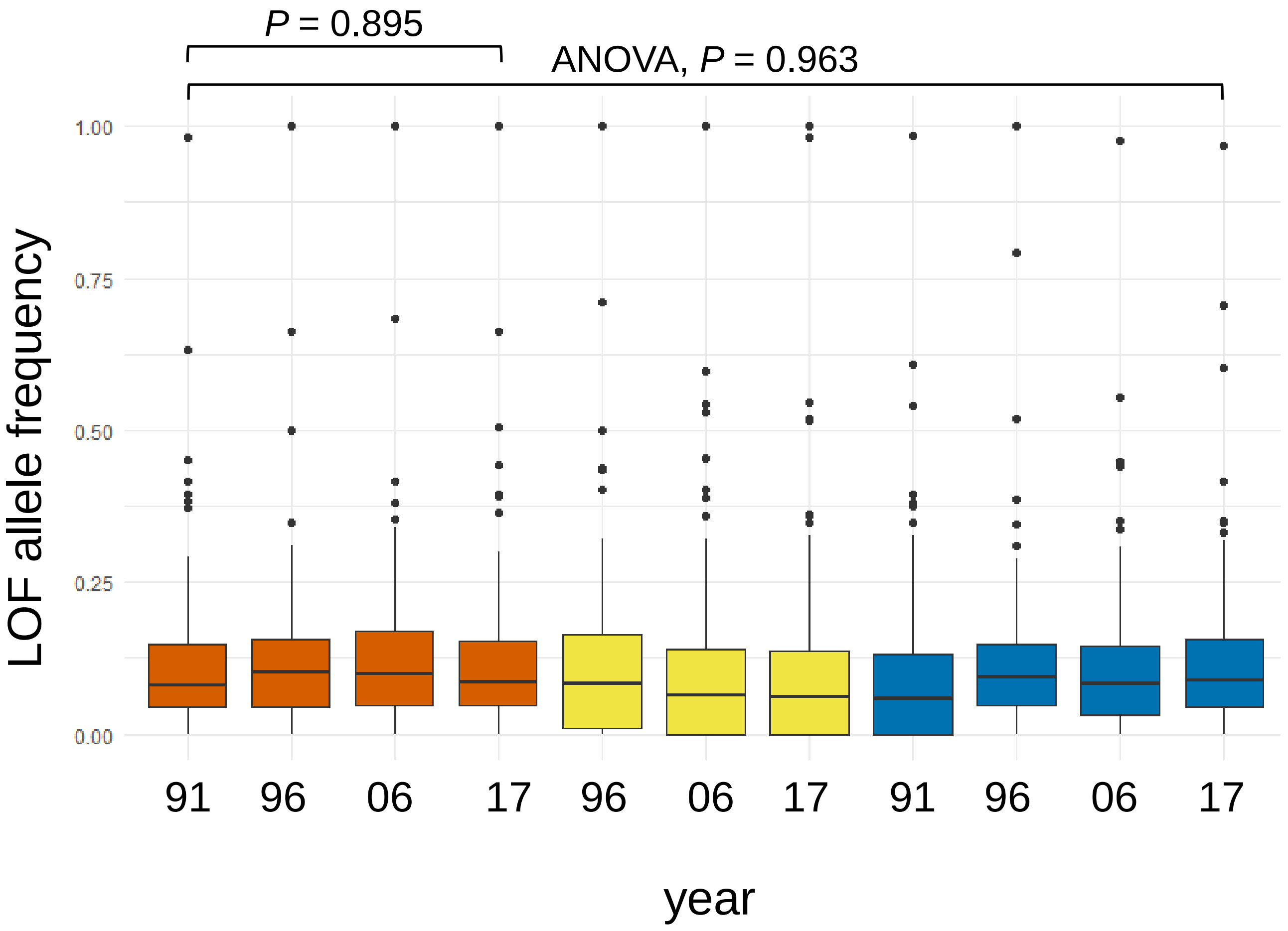
↓

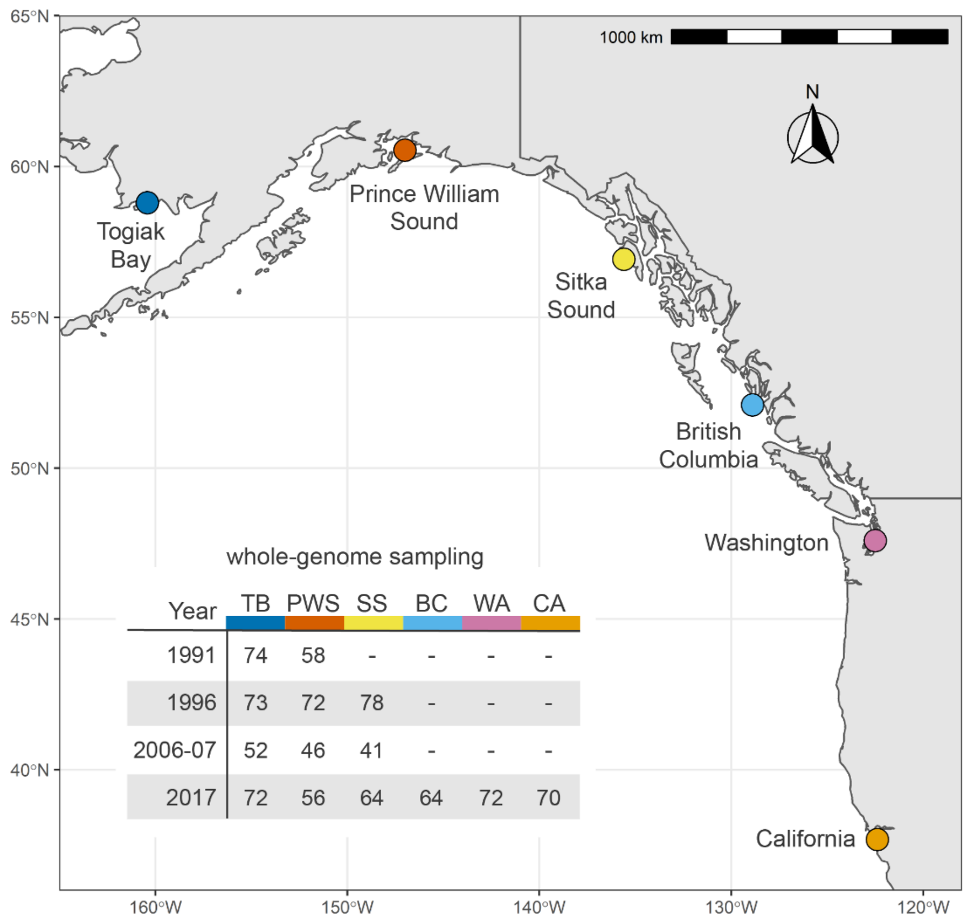
stop gained	190
stop lost	40
start lost	30

Atlantic herring
reference genome

24,095 coding genes

Frequency of loss-of-function alleles across populations





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- PWS may show genetic signatures of fluctuating selection pressures.

Population recovery

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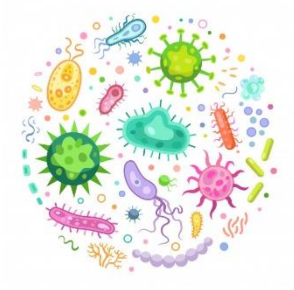
1991-1996

1996-2017



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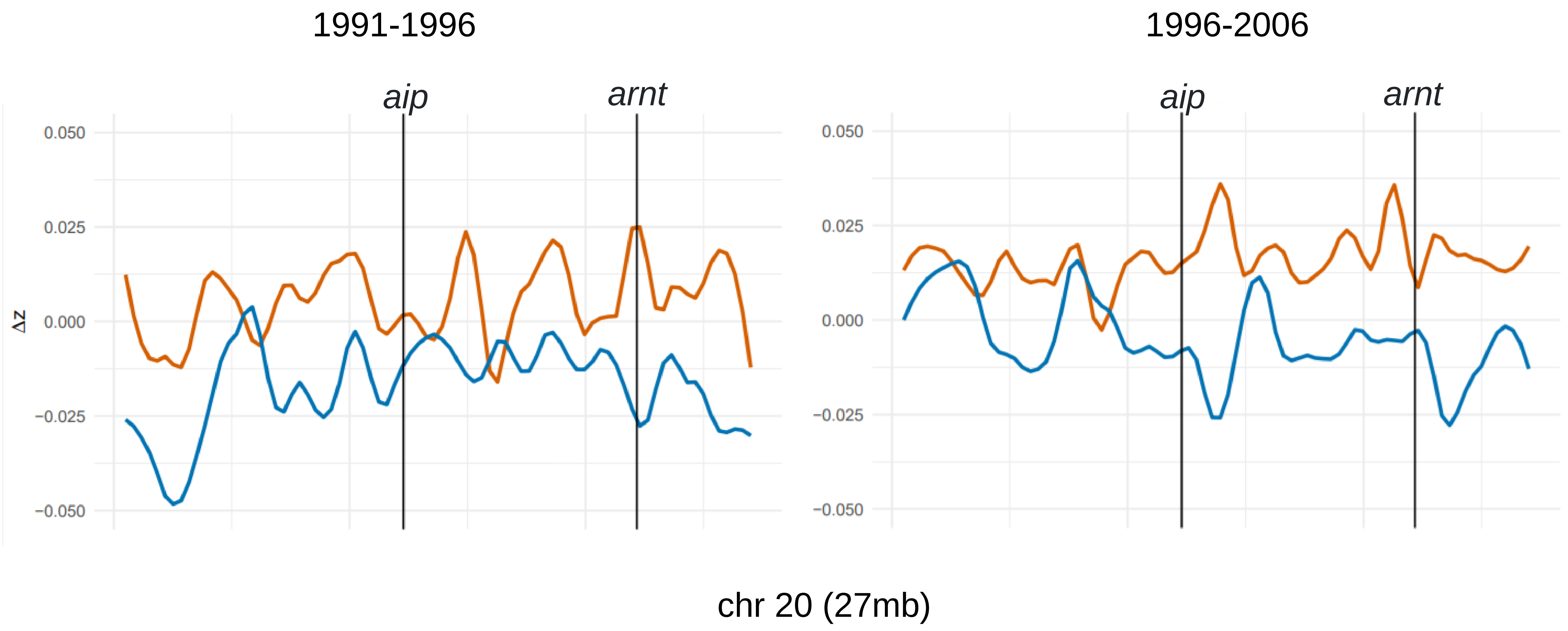
Measuring temporal shifts in allele frequency to identify fluctuating selection

year	major allele frequency p	minor allele frequency q
1991	0.9	0.1
1996	0.7	0.3
2006	0.9	0.1

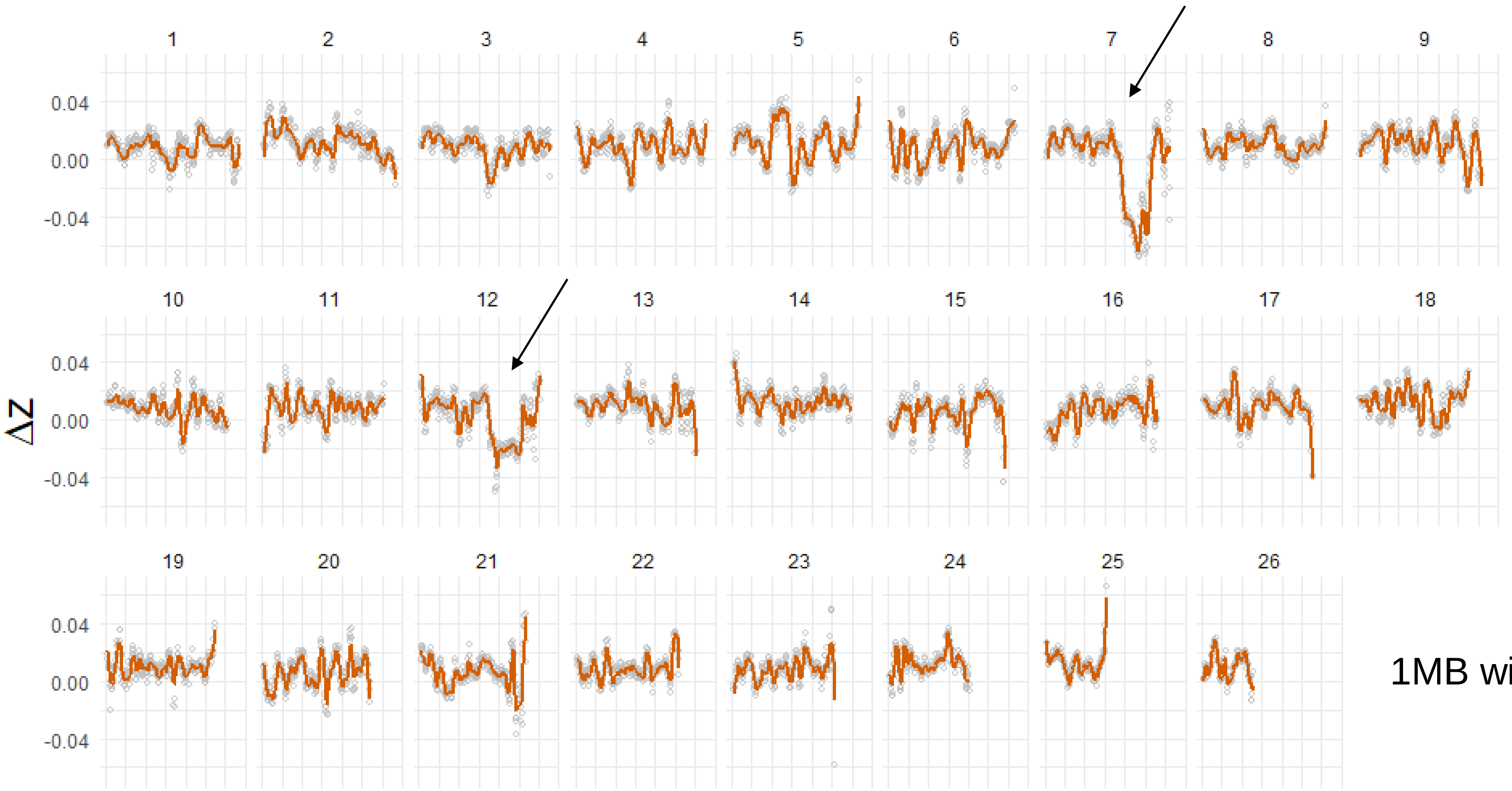
$$\Delta z = \text{arcsine}\left(\sqrt{q_{\text{t}1}}\right) - \text{arcsine}\left(\sqrt{q_{\text{t}0}}\right)$$

Temporal shifts in allele frequency near AHR signaling genes

Prince William Sound and Togiak Bay

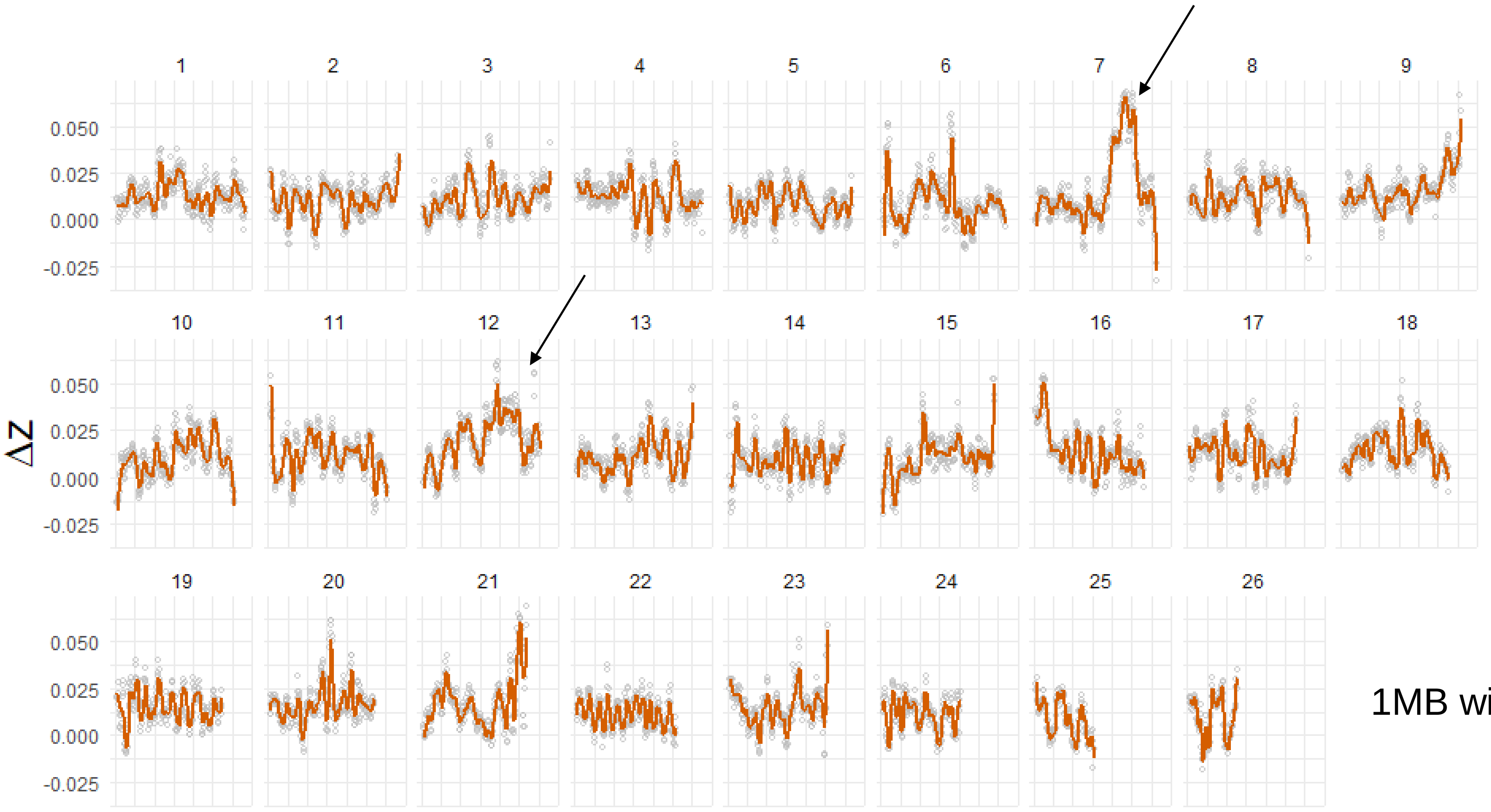


Temporal shifts in allele frequency between 1991 and 1996 Prince William Sound



1MB windows

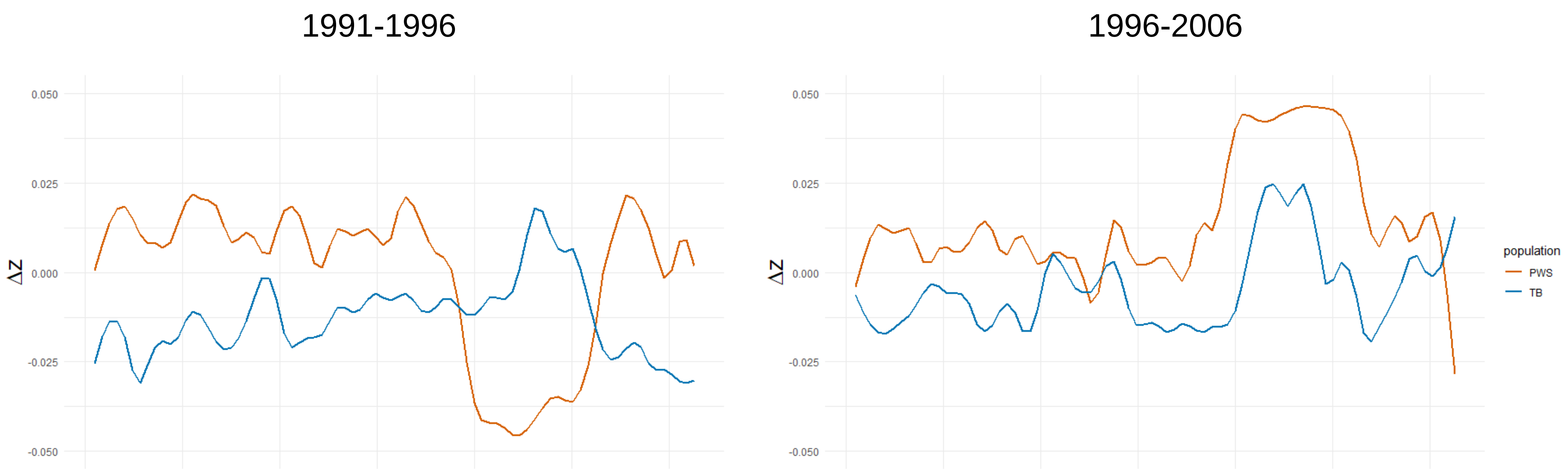
Temporal shifts in allele frequency between 1996 and 2006 Prince William Sound



1MB windows

Fluctuating selection in Prince William Sound?

Prince William Sound and Togiak Bay

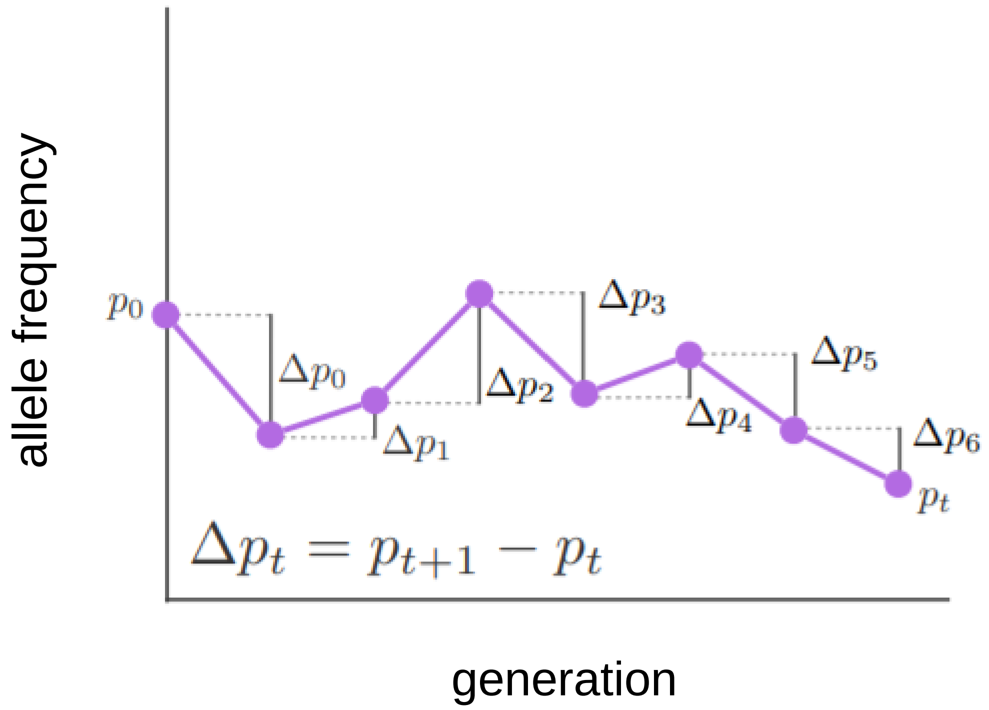


chr 7 (30mb)

Temporal covariance in allele frequency change

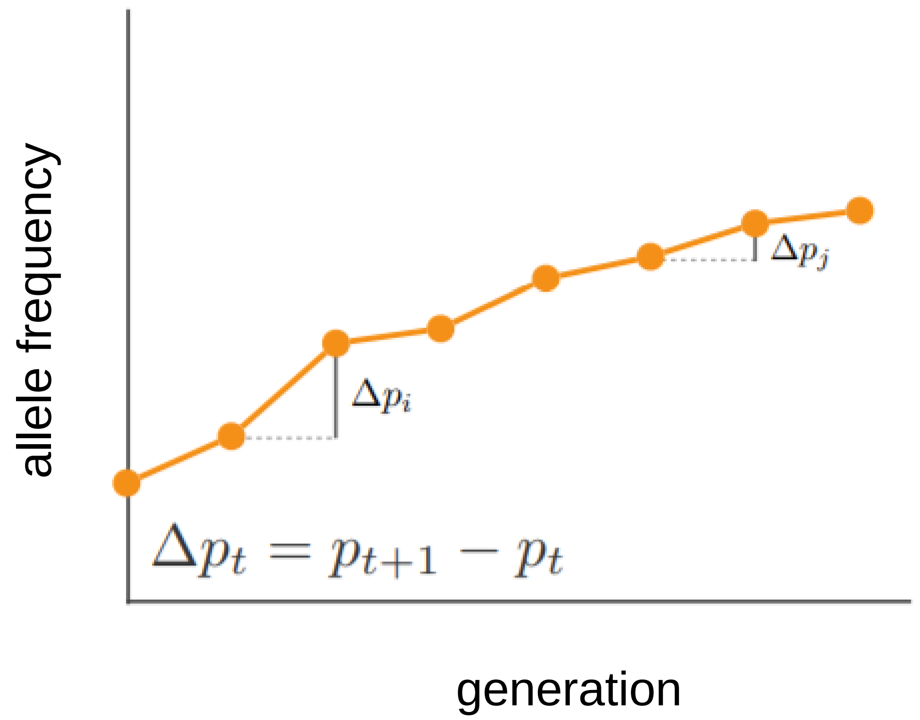
Under Drift

$$\mathrm{Cov}(\Delta p_i, \Delta p_j) = 0$$



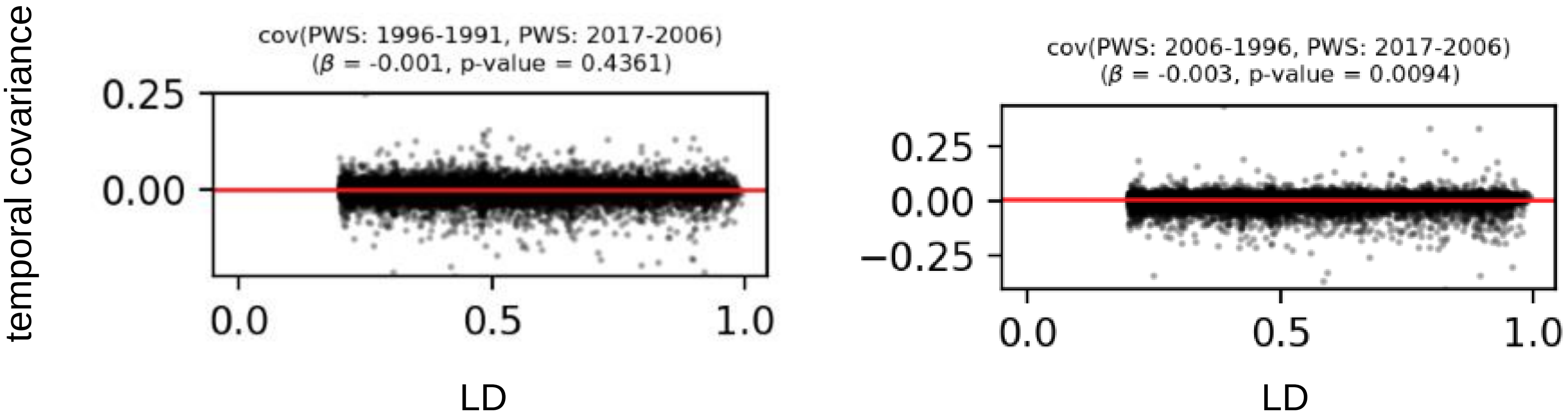
Under Directional Selection

$$\mathrm{Cov}(\Delta p_i, \Delta p_j) > 0$$



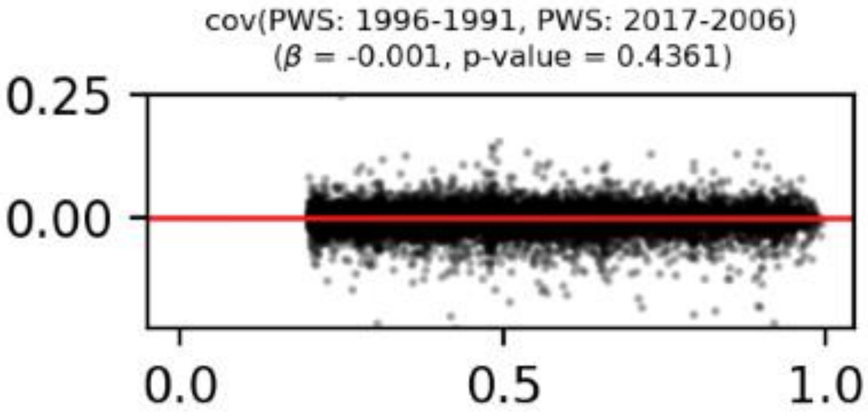
Buffalo and Coop 2019, *Genetics*

Signs of linked selection post-spill using temporal covariance in allele frequency changes

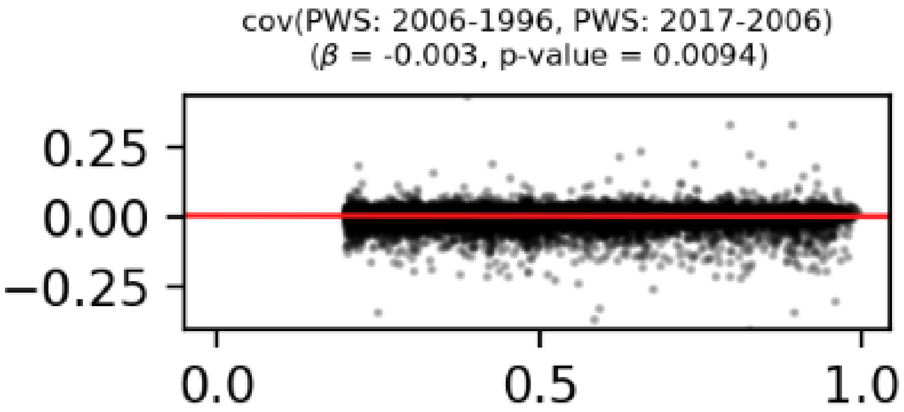


Signs of linked selection post-spill using temporal covariance in allele frequency changes

temporal covariance



LD



LD

1991-1996

1996-2017

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- PWS may show a higher frequency of deleterious alleles post-spill.
- PWS may show genetic signatures of fluctuating selection pressures.

Takeaways

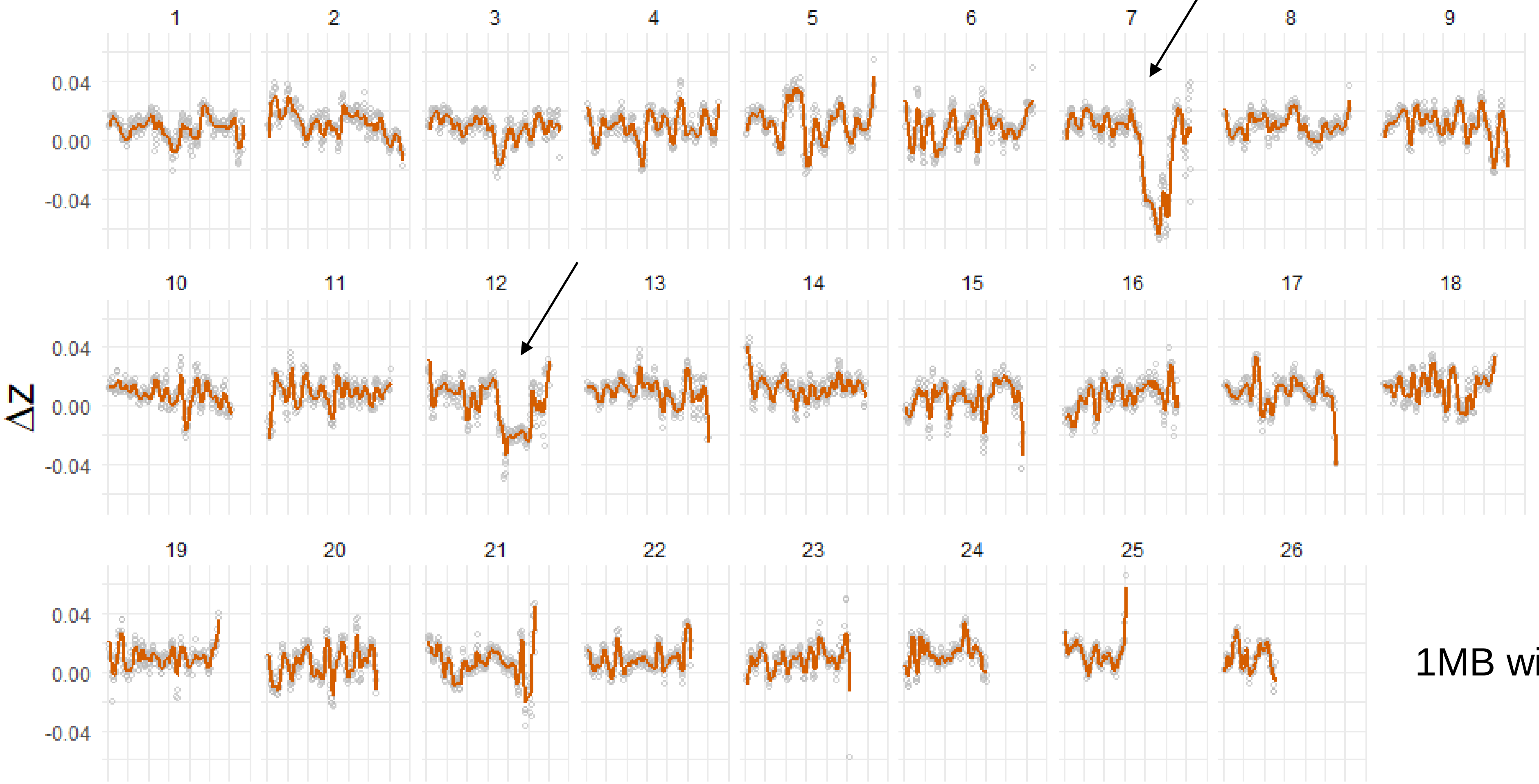
- The Prince William Sound population shows a decline in effective population size between 1991 and 2017.
- Loss-of-function mutations are not more common in Prince William Sound after the oil spill, suggesting that lack of population recovery is not driven by an overall increase in mutation load.
- Temporal changes in allele frequency are consistent with fluctuating selection pressures in Prince William Sound.

Outline

- Genetic variation underlying pollution resistance and susceptibility to disease.

- Inversions underlying local adaptation.

Temporal shifts in allele frequency between 1991 and 1996 Prince William Sound



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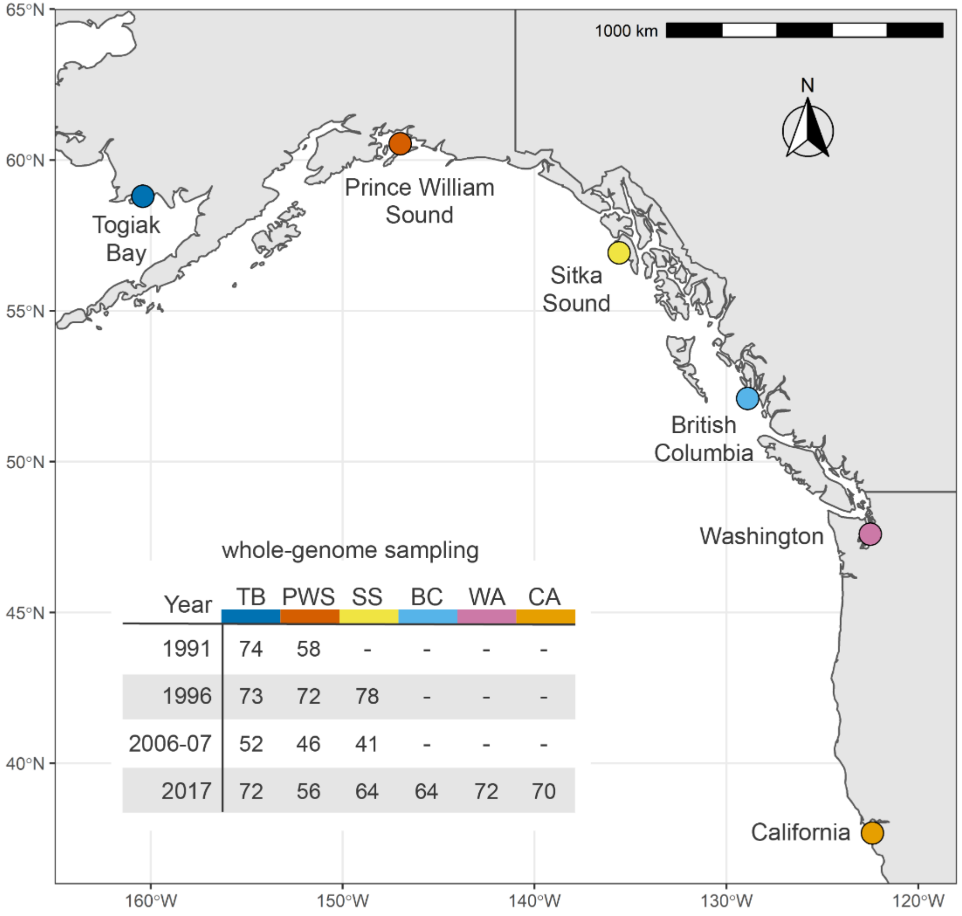
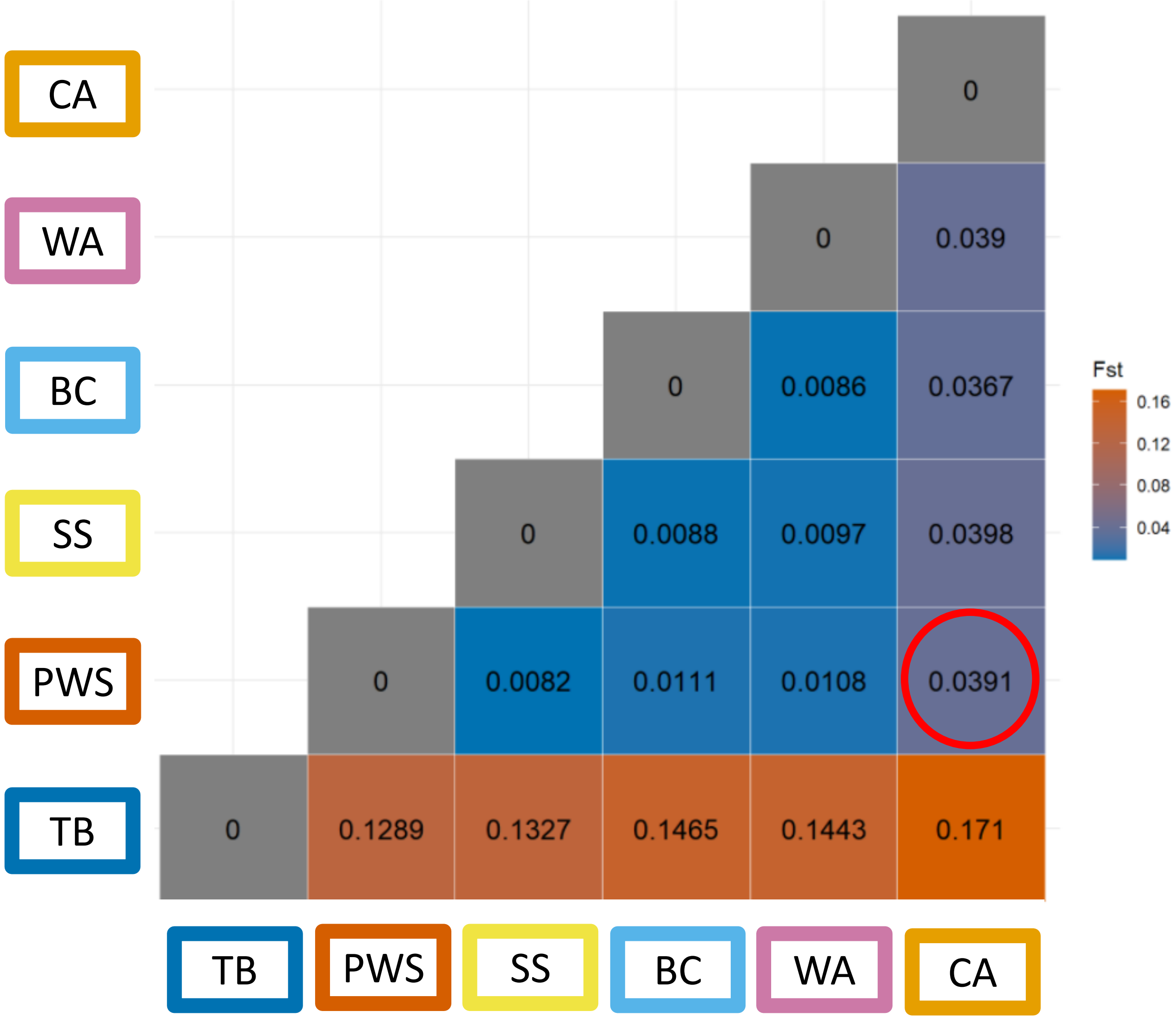
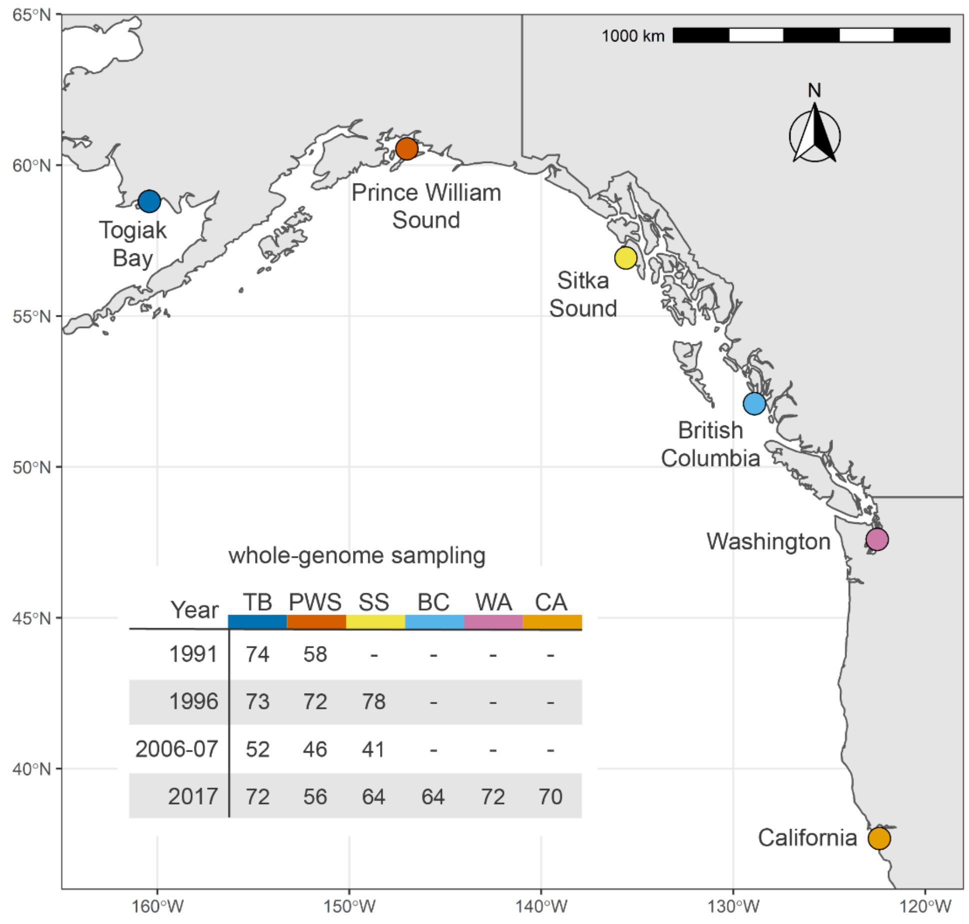
Fst: 2017 comparisons





Fst

California vs. Prince William Sound



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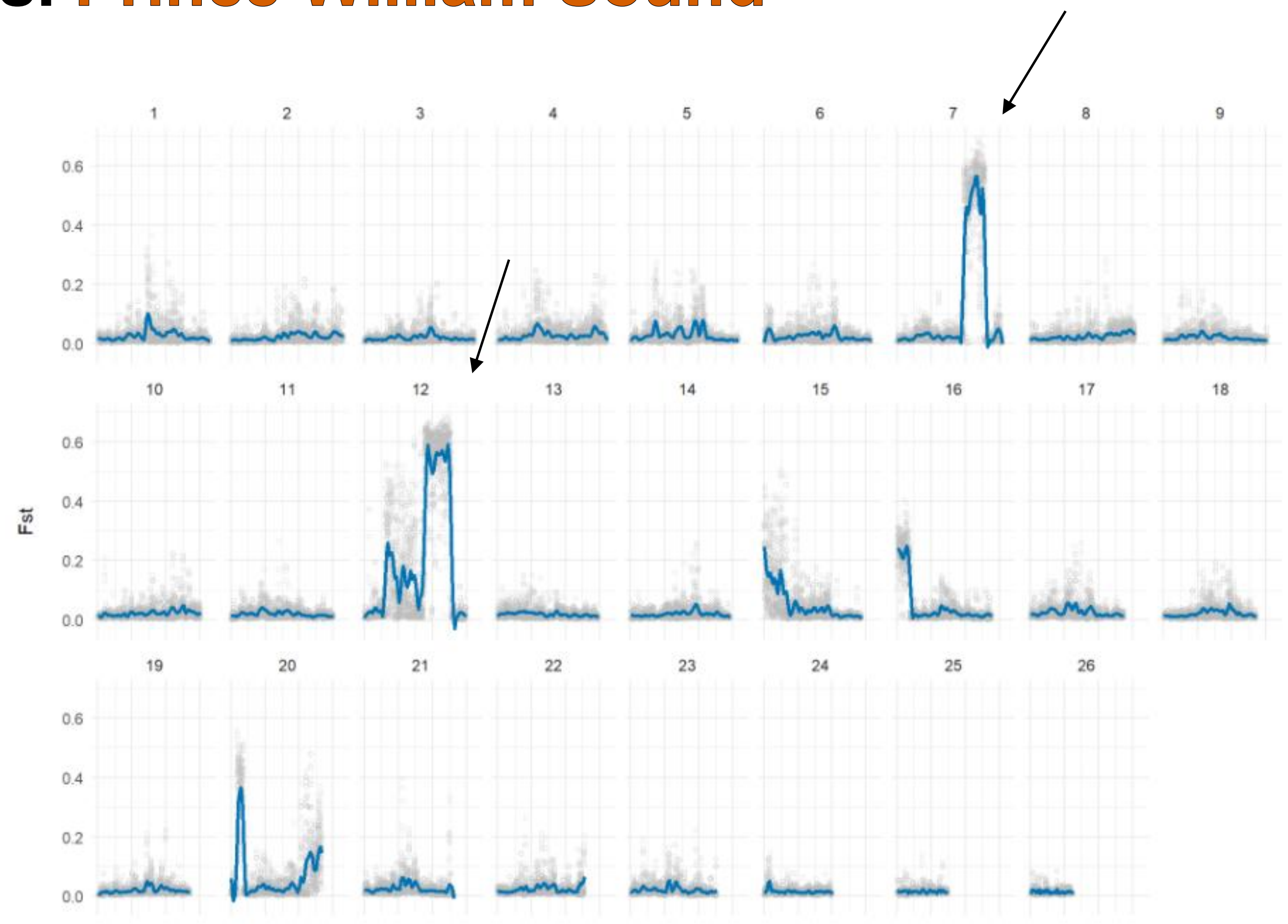
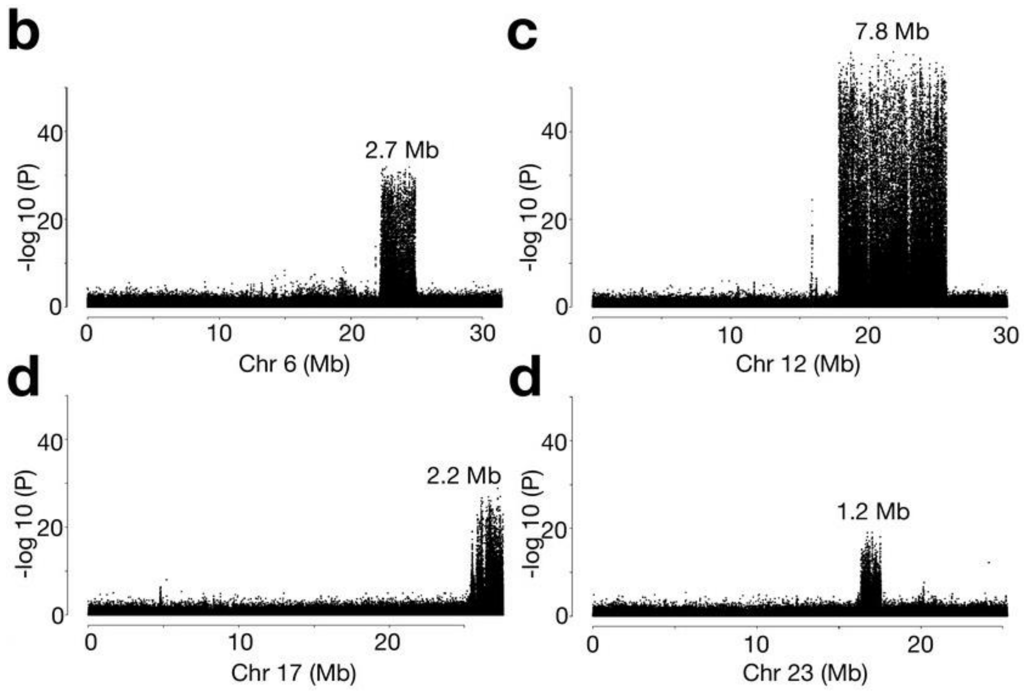
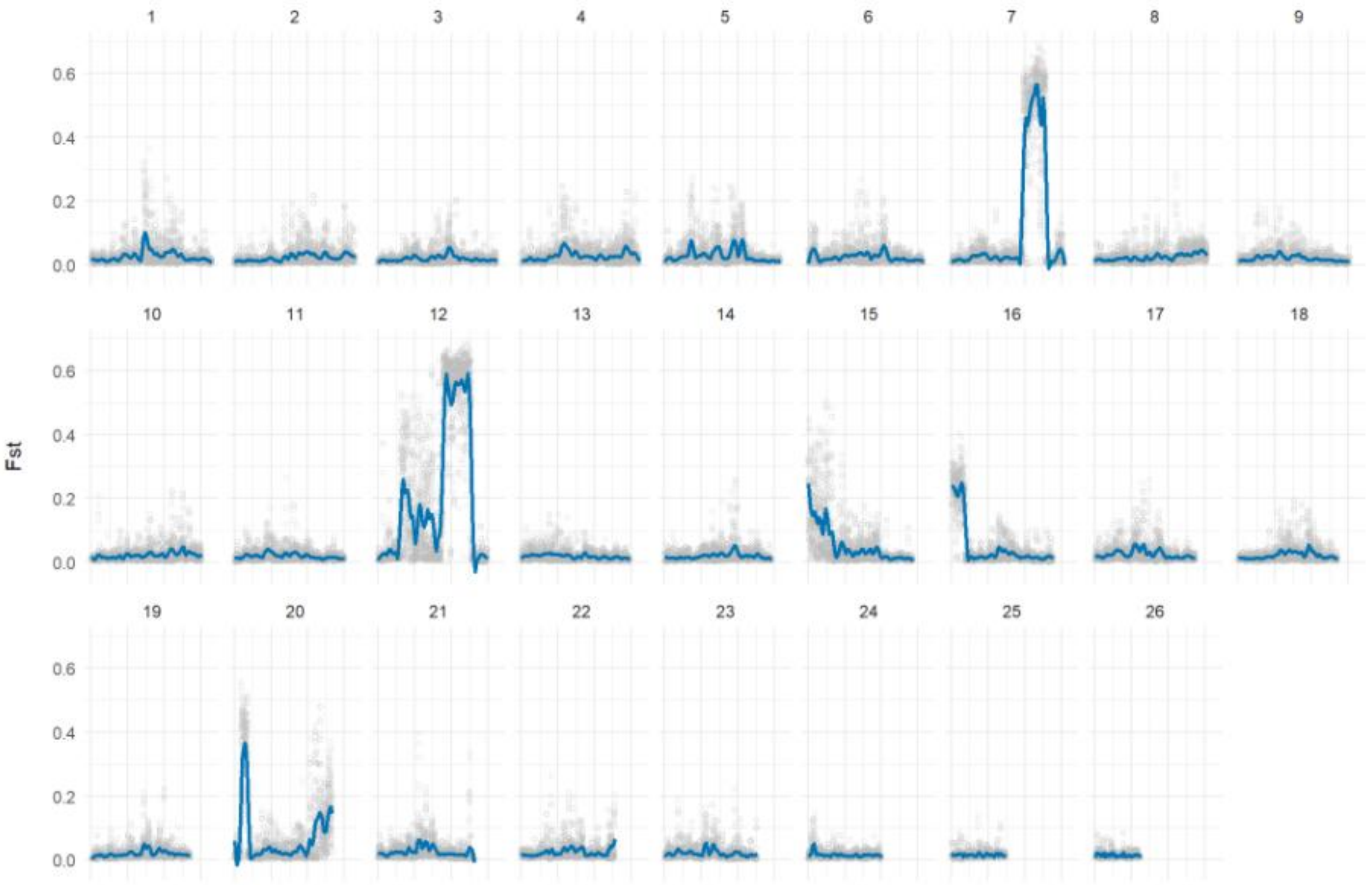


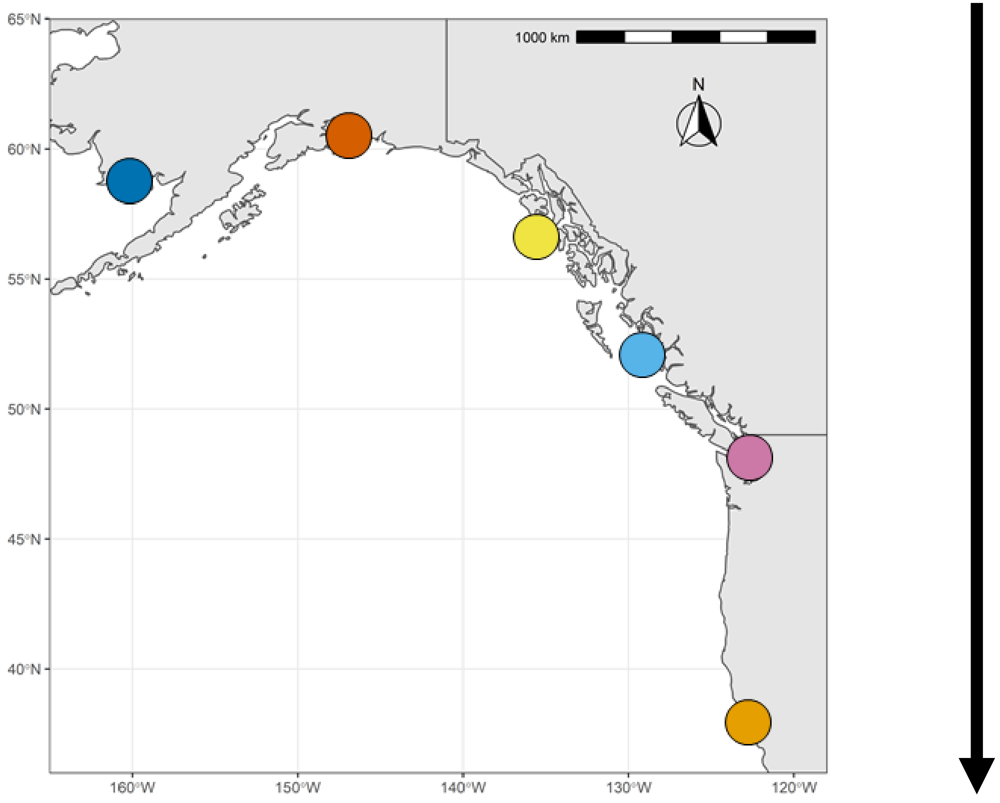
Recent discovery of inversions in Atlantic herring





Han et al. 2020, *elife*

Latitudinal differences between populations

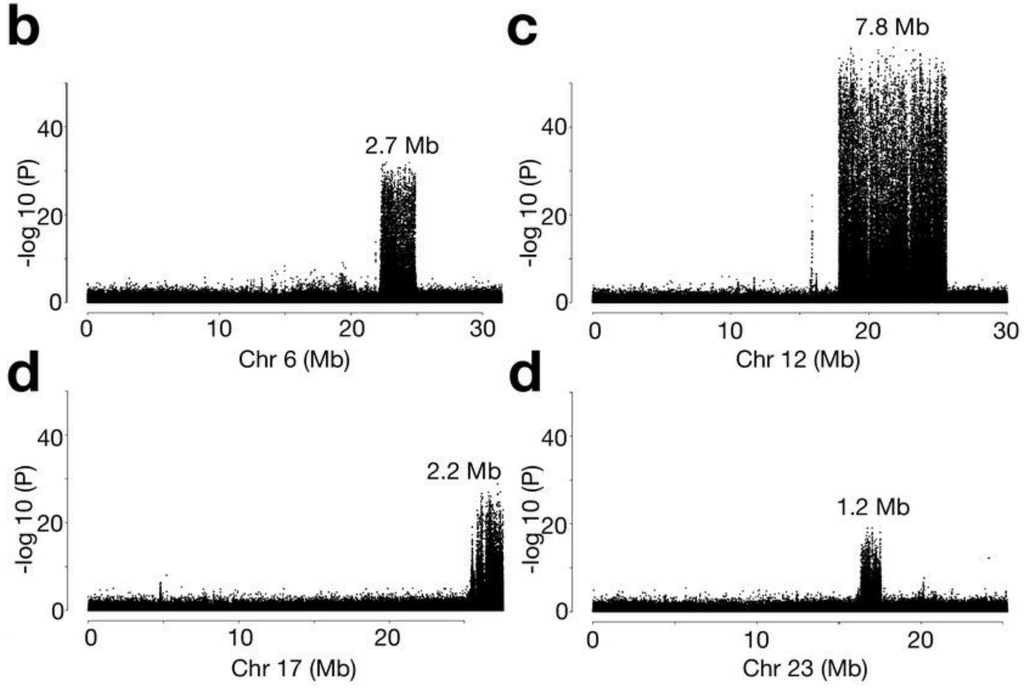


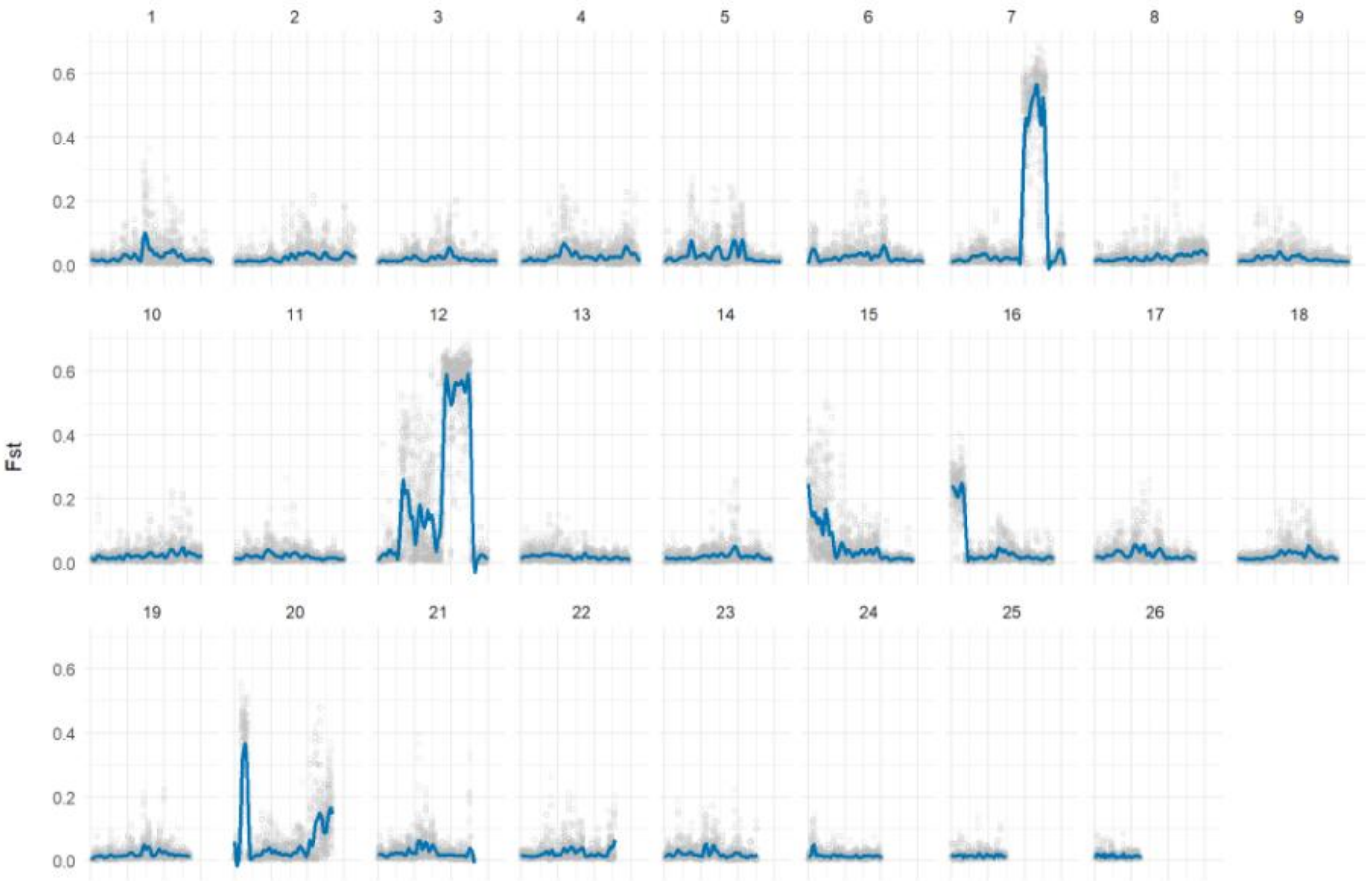
Trends from North to South

- smaller size
- sexually mature earlier
- spawn earlier in the year
- die younger

Hay et al. 2008, *Progress in Oceanography*

Local adaptation driven by supergenes?

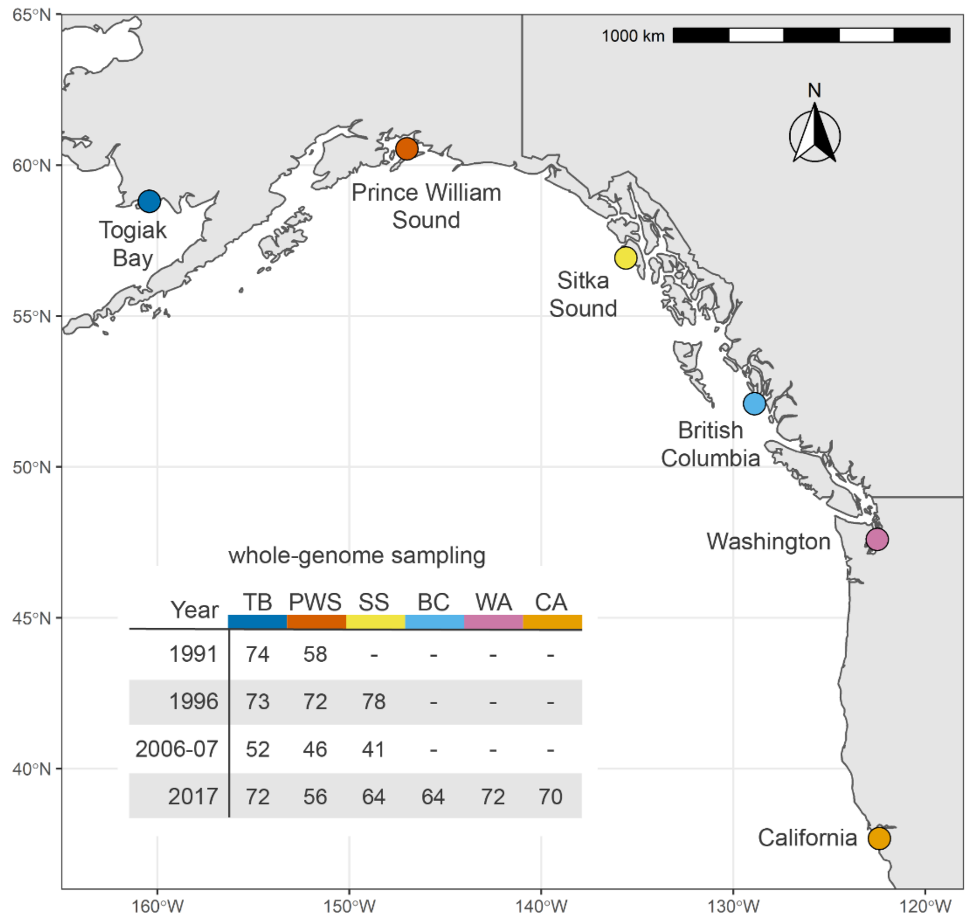




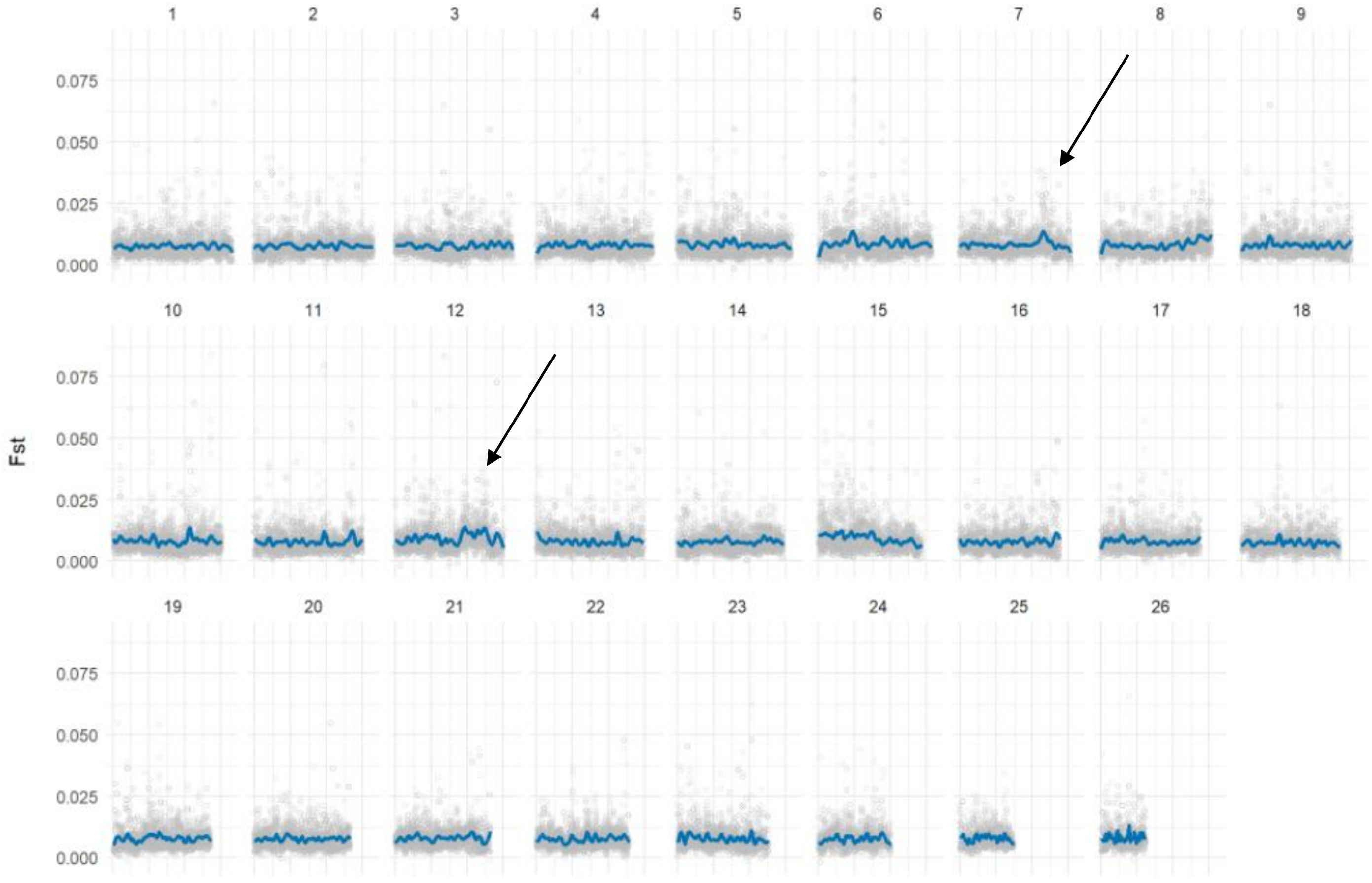
Han et al 2020, *elife*

Fst

Prince William Sound vs. Sitka Sound



Year	TB	PWS	SS	BC	WA	CA
1991	74	58	-	-	-	-
1996	73	72	78	-	-	-
2006-07	52	46	41	-	-	-
2017	72	56	64	64	72	70



Takeaways

- Putative inversions are segregating at high frequency in the California population.
- Parallel ecological adaptations in Pacific and Atlantic herring may result from similar genetic mechanisms.
- Inversions may also play a role in slow population recovery in Prince William Sound.

Whitehead Lab: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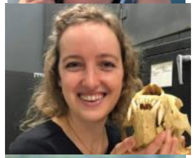
Jenn Roach


Nichole McNabb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Thanks!
Questions?

Exxon Valdez Oil Spill
Trustee Council

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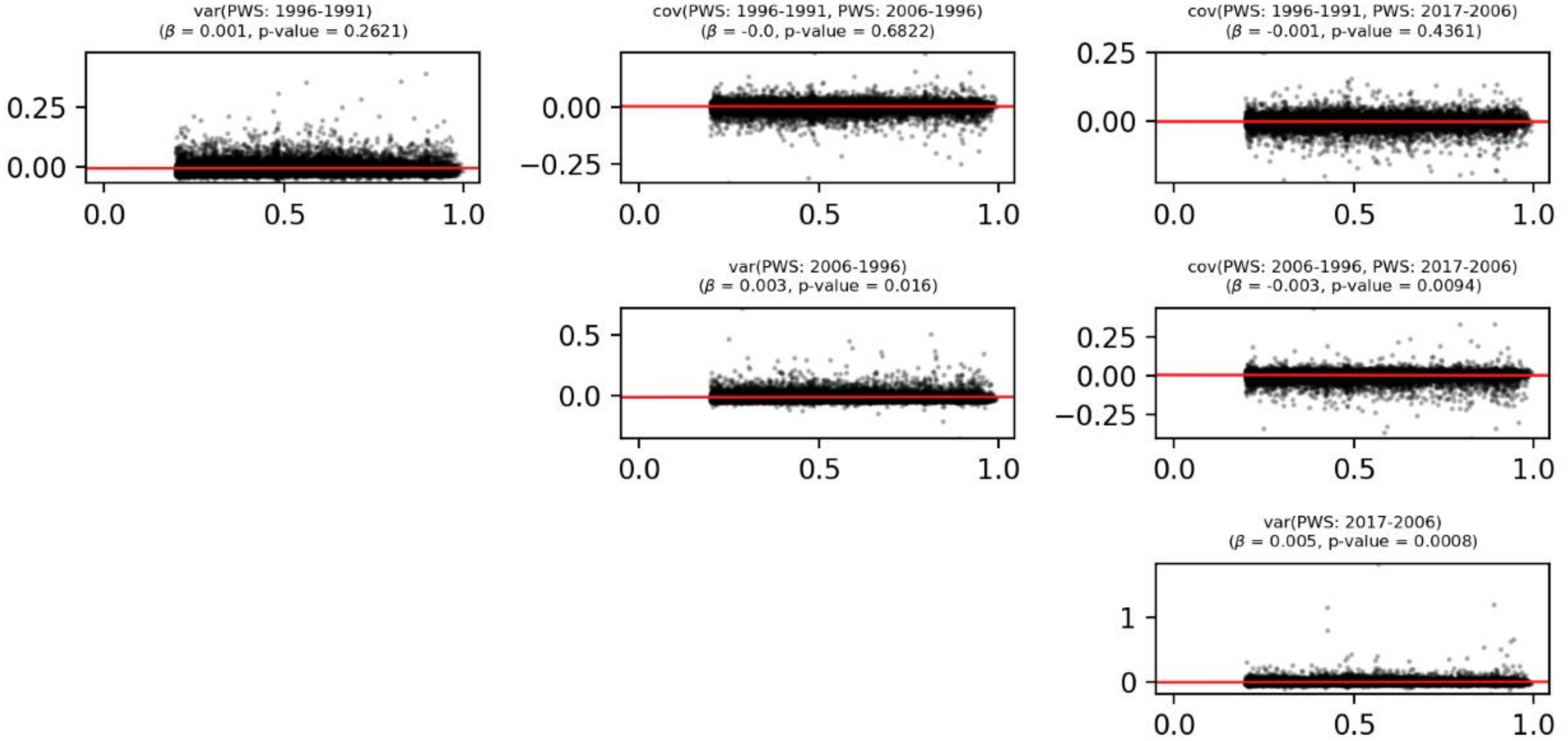
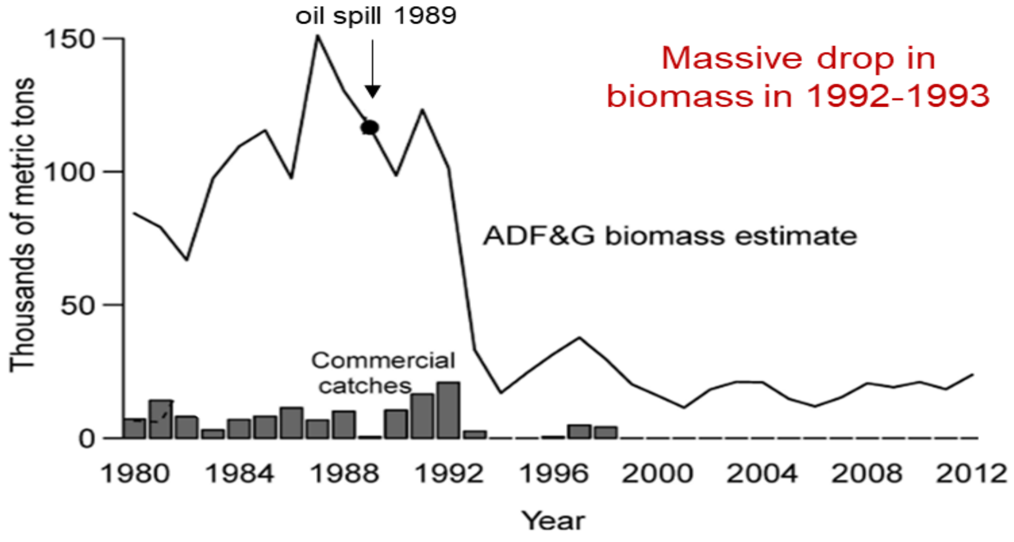
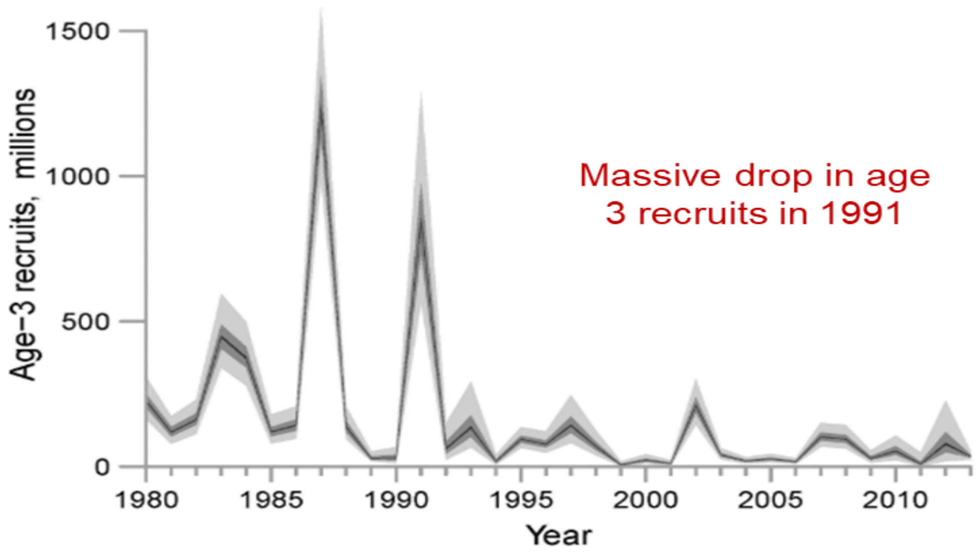
Temporal covariance in allele frequency change

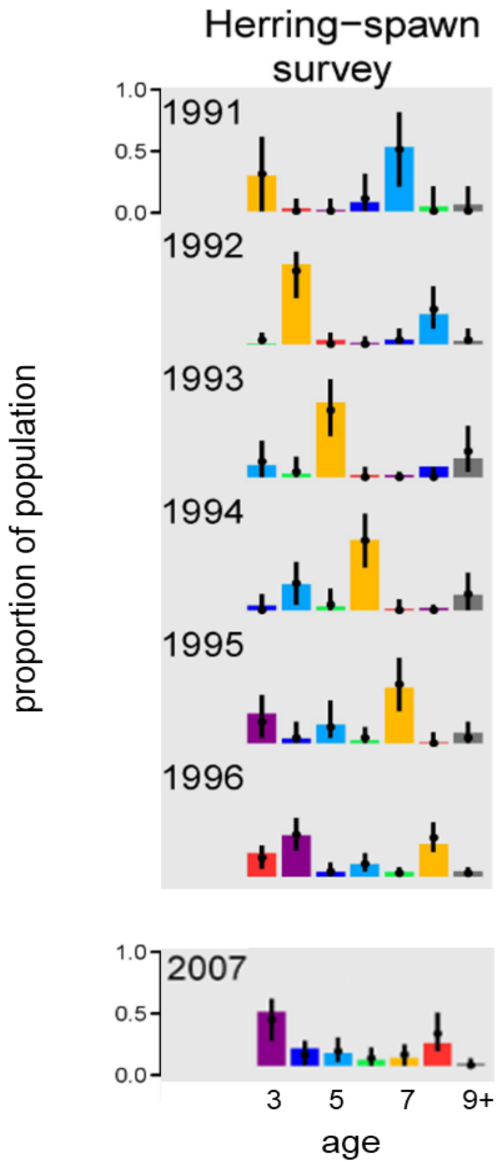




Massive drop in biomass in 1992-1993



Massive drop in age 3 recruits in 1991



Majority 1984 and 1988 year class

VERY small 1989 year class (green)

Majority 2004 year class

Population genetics: Fst

Prince William Sound vs. Togiak Bay