Shellfish environmental memory

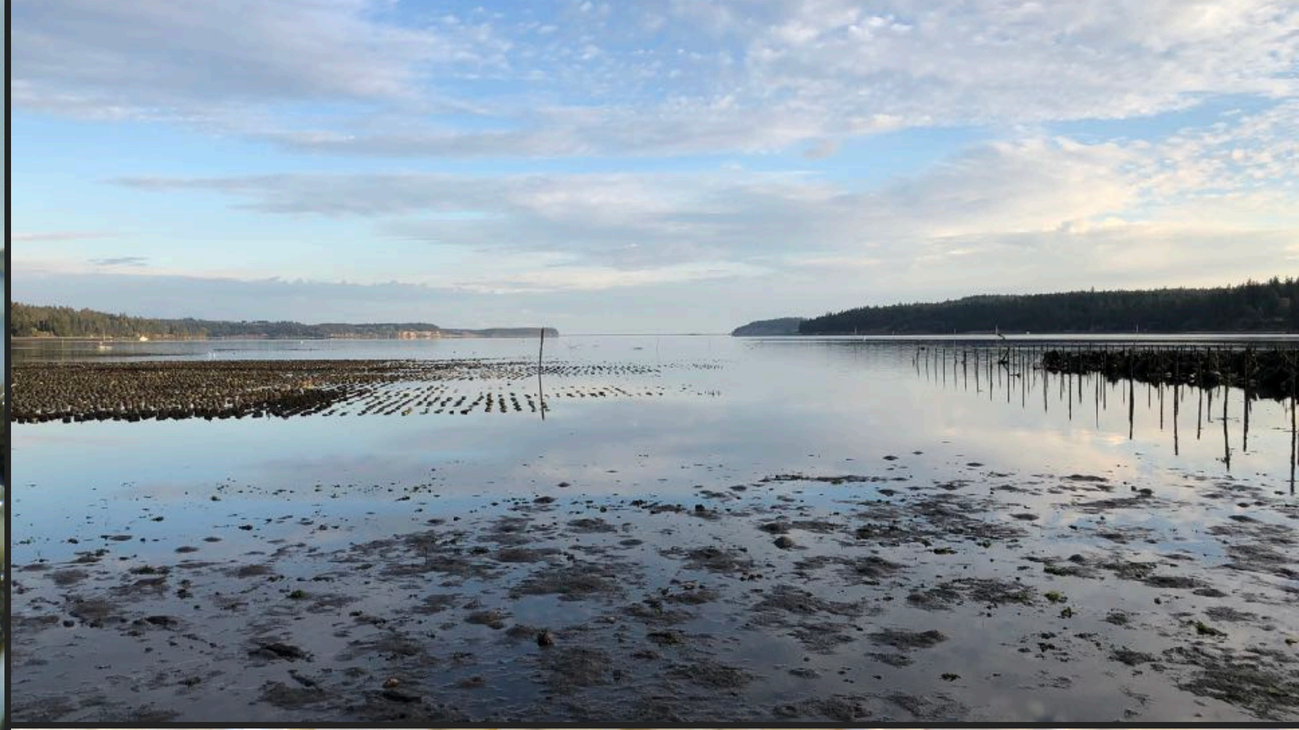
Implications and opportunities

Ariana Huffmyer
Steven Roberts


FHL


FHL


FHL

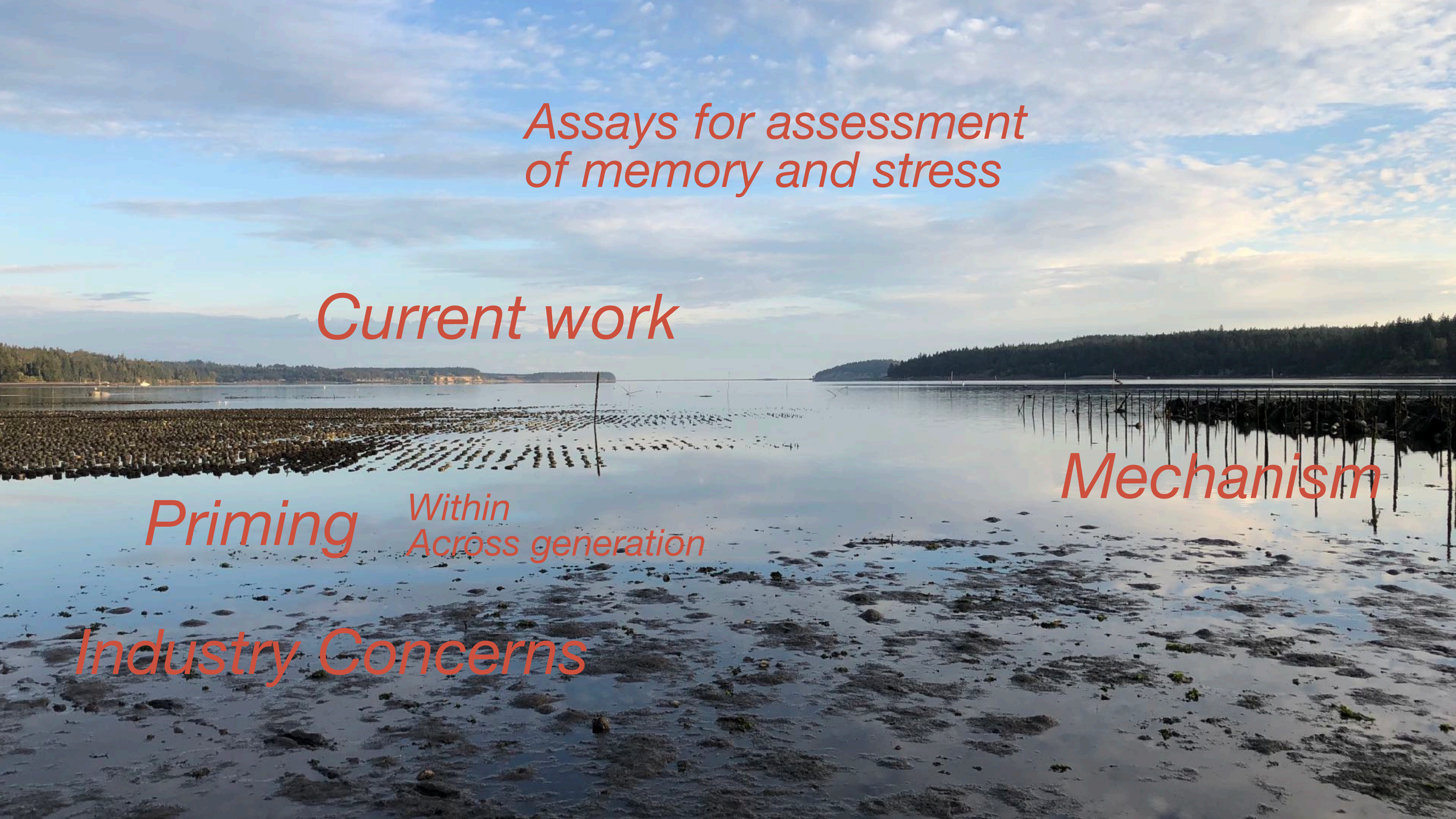


Industry Concerns


Priming
Within
Across generation
Industry Concerns


Mechanism
Priming
Within
Across generation
Industry Concerns


Current work
Priming
Within
Across generation
Mechanism
Industry Concerns


Assays for assessment
of memory and stress
Current work
Priming
Within
Across generation
Mechanism
Industry Concerns

Industry Concerns

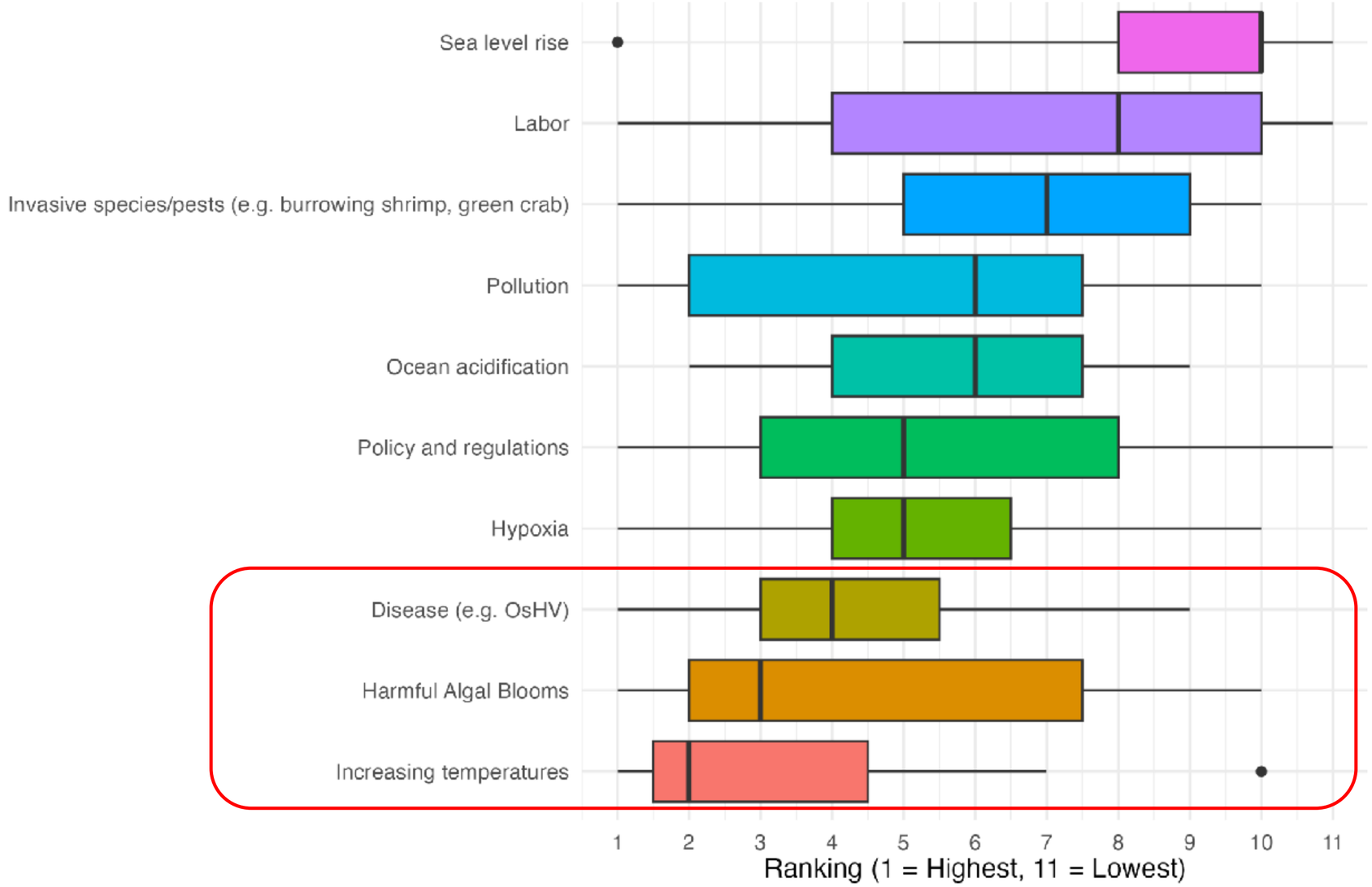
Grower Survey:
Perceptions of threats and proposed adaptation strategies

- 2024 requested input from industry
- 20-30 min interview:
  - Ranking threats
  - Input on leveraging environmental memory as an adaptation strategy
- *Huge thank you to those who participated!* Manuscript is in review

AQUATIC AND FISHERY SCIENCES
UNIVERSITY of WASHINGTON

Connor Lewis-Smith

Grower Survey:
Perceptions of threats and proposed adaptation strategies



Environmental Priming

Would you consider implementing environmental priming in your hatchery?

Response	Percentage
Yes, immediately	7%
Yes, but after other growers try it	7%
Yes, but after reviewing literature supporting the practice	64%
No	21%

Would you pay more for primed seed?

Response	Percentage
Yes, immediately	0%
Yes, starting with a test plot	17%
Yes, but after other growers try it	7%
Yes, but after reviewing data supporting the practice	53%
No	23%

Environmental Priming

78% of hatcheries would consider adopting environmental priming practices, most only after reviewing supportive literature

70% of respondents would be willing to pay more for primed seed, most only after a test plot or supportive literature

Would you consider implementing environmental priming in your hatchery?

Response	Percentage
Yes, immediately	7%
Yes, but after other growers try it	7%
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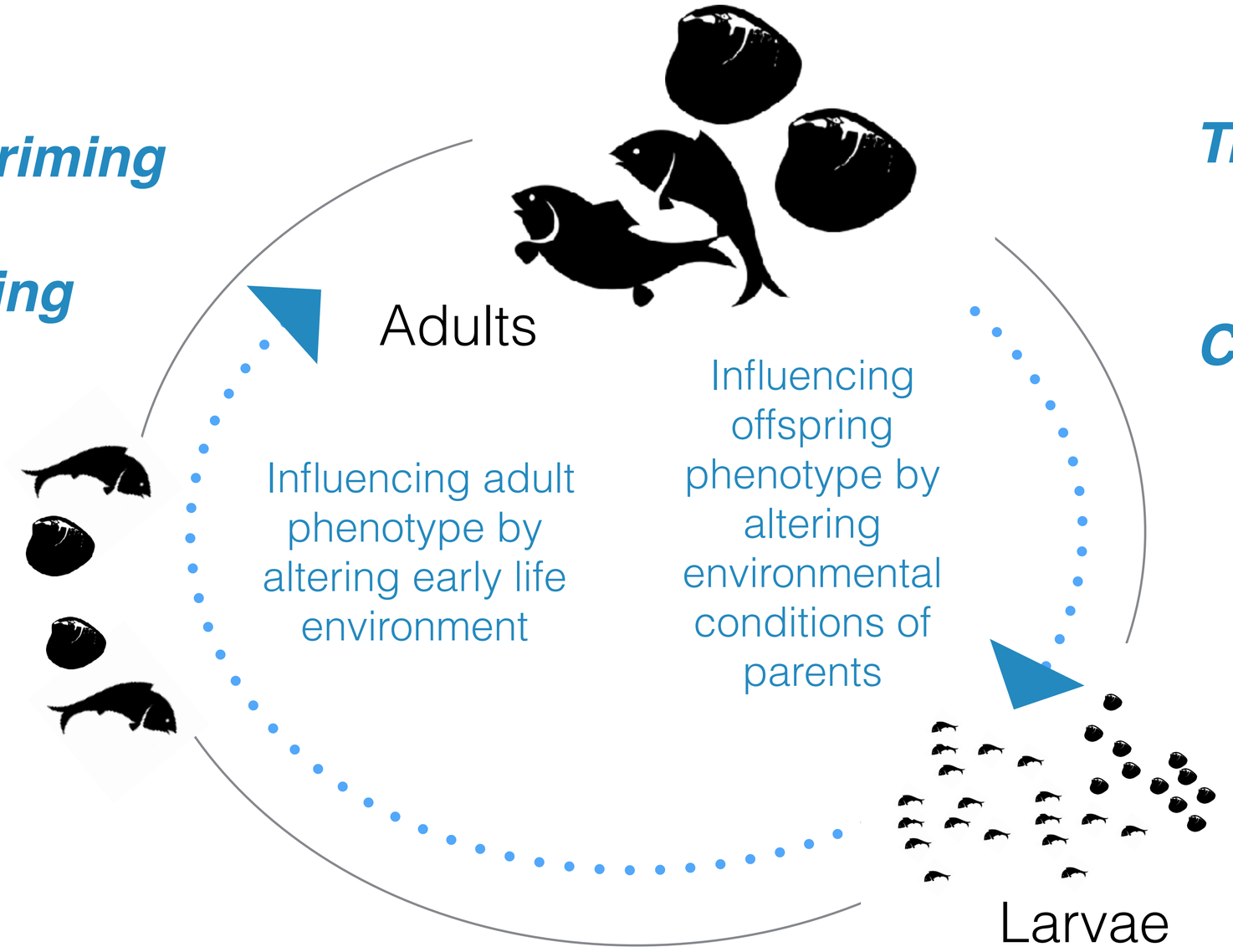
Priming
Industry Concerns

Early-life Priming

Hardening

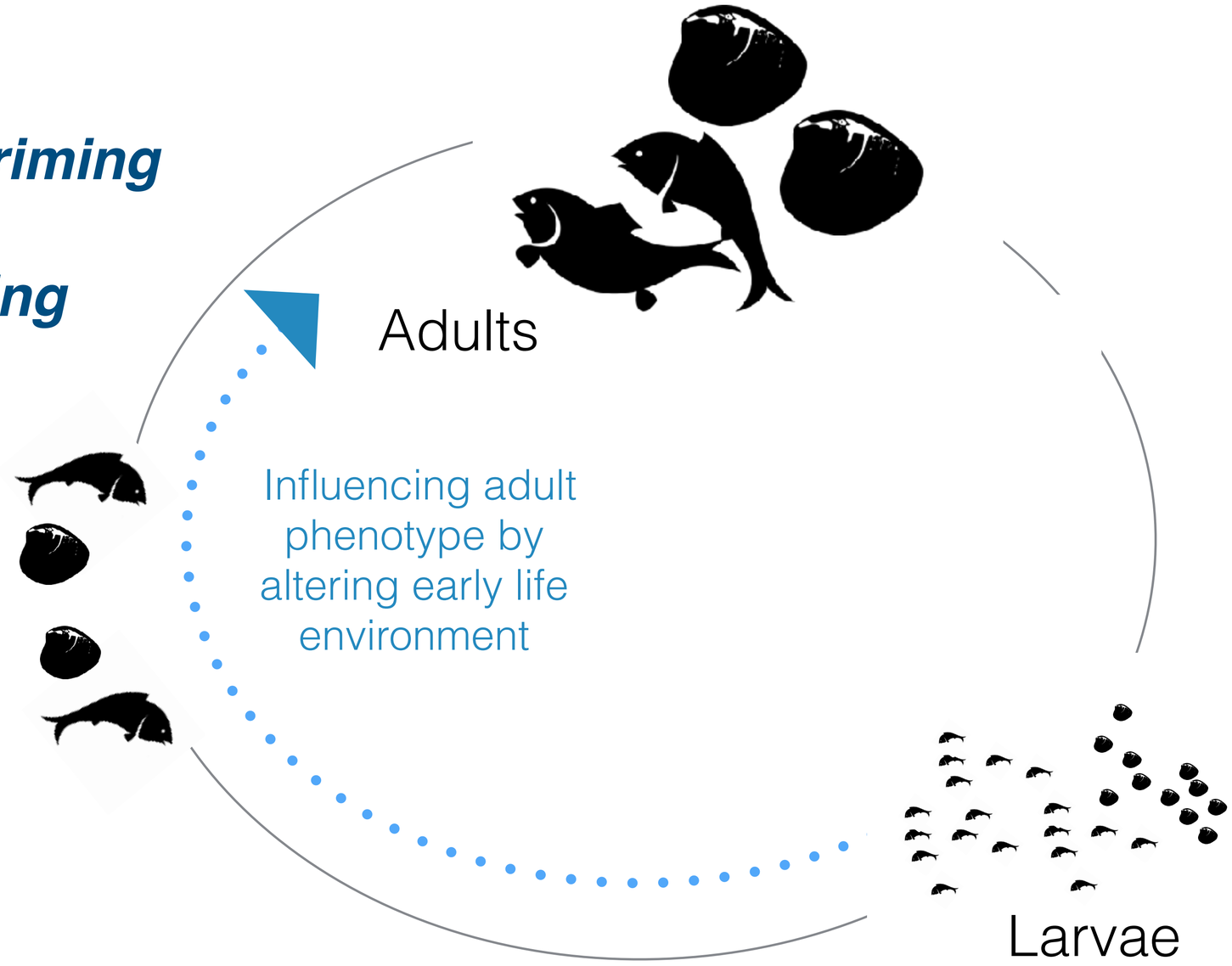


Transgenerational Plasticity

Carry-over effects

Early-life Priming

Hardening



Early-life Priming

Hardening

Trends in
Plant Science

Special issue: Climate change and sustainability I

Review

Priming crops for the future: rewiring stress memory

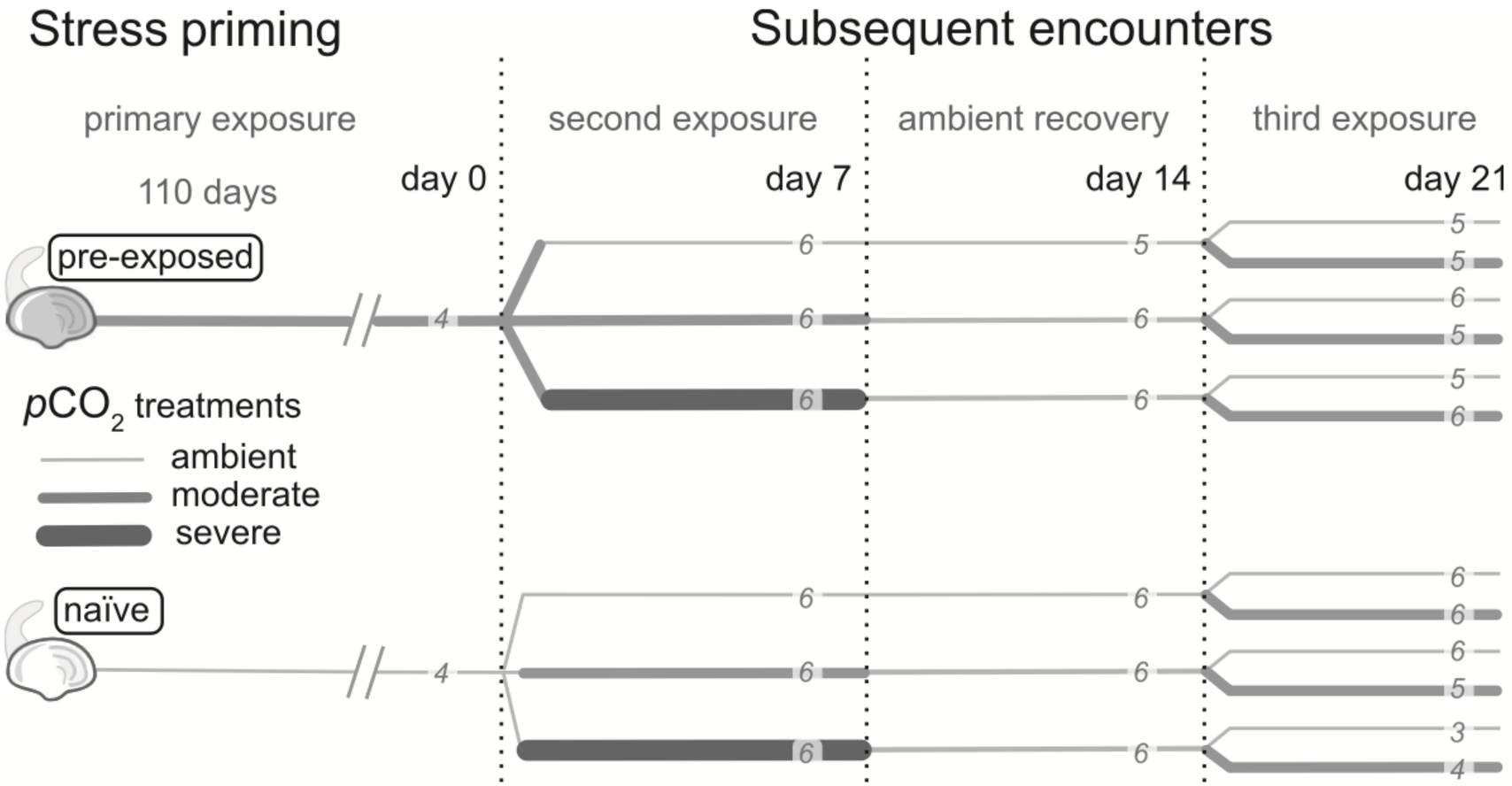
Haipei Liu [1], Amanda J. Able [1] and Jason A. Able [1,@,*]

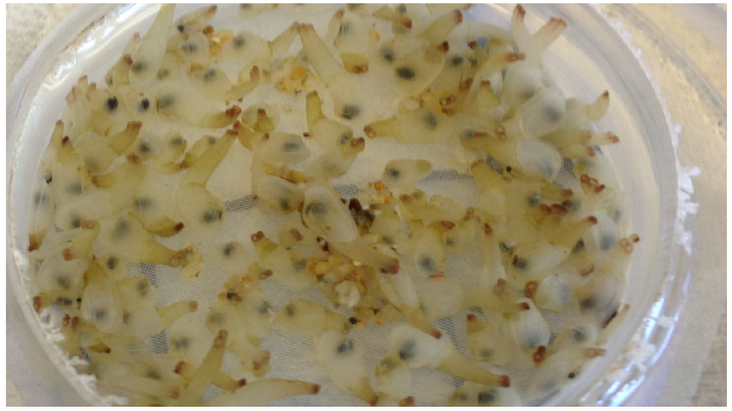
Cross-stress priming success relies on synergistic stress signaling pathways being shared across stresses varying in nature and intensity.

Geoduck Clams

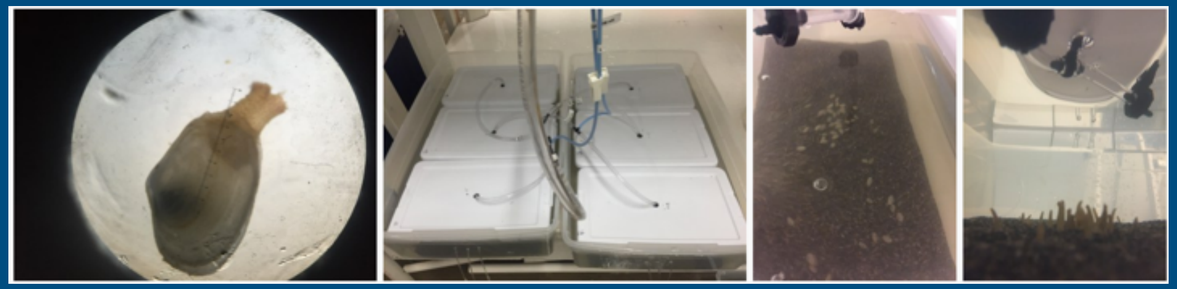
Repeat exposure to hypercapnic seawater modifies growth and oxidative status in a tolerant burrowing clam

Samuel J. Gurr[1,*], Shelly A. Wanamaker[2], Brent Vadopalas[3], Steven B. Roberts[2] and Hollie M. Putnam[1]

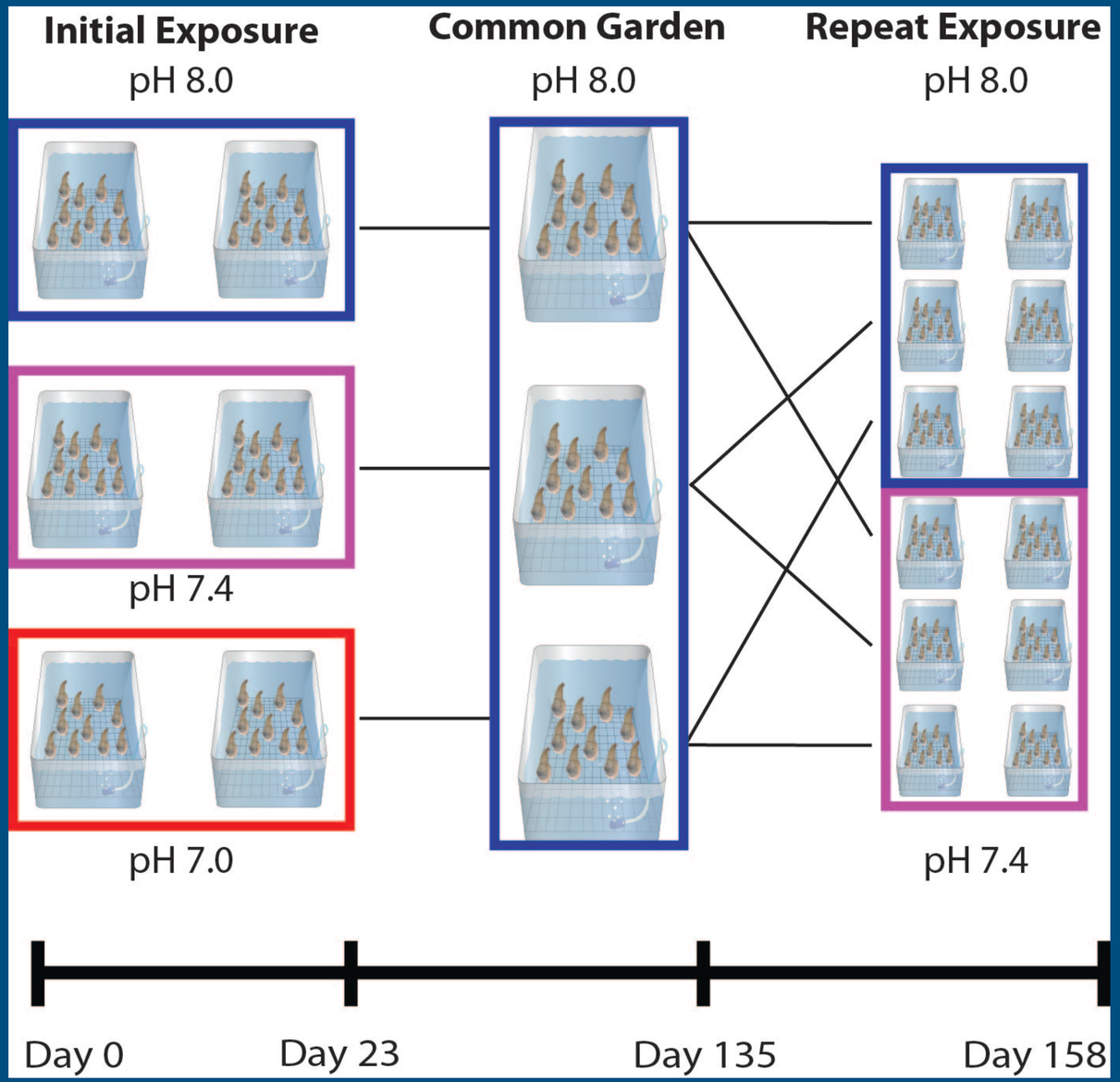




GEODUCKS CLAMS

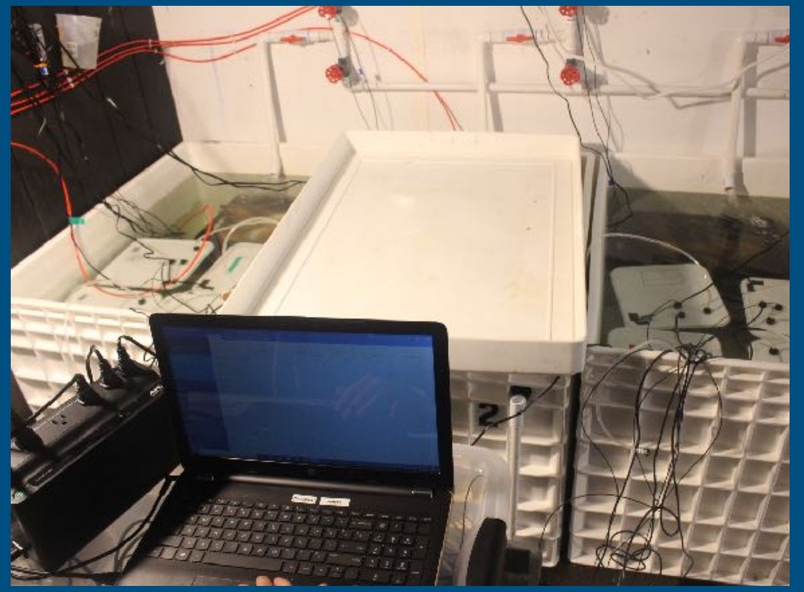


- Does conditioning to low pH confer tolerance within a generation?



HOLLIE PUTNAM, SAM GURR, BRENT VADOPALAS, SHELLY TRIGG, JAMESTOWN S'KLALLAM TRIBE

GEODUCKS CLAMS



GEODUCKS CLAMS

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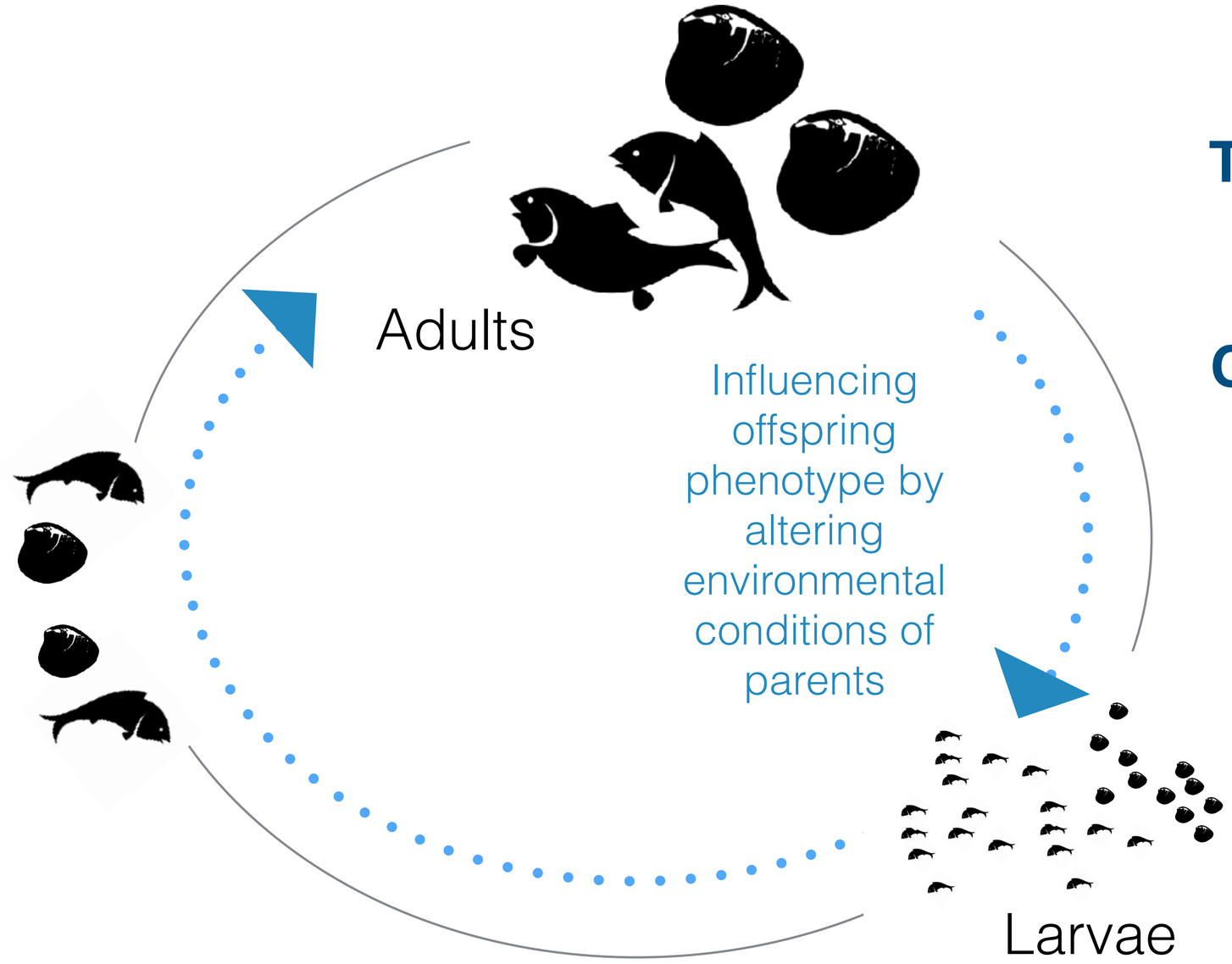
Priming
Across generation
Industry Concerns



Transgenerational Plasticity

Carry-over effects

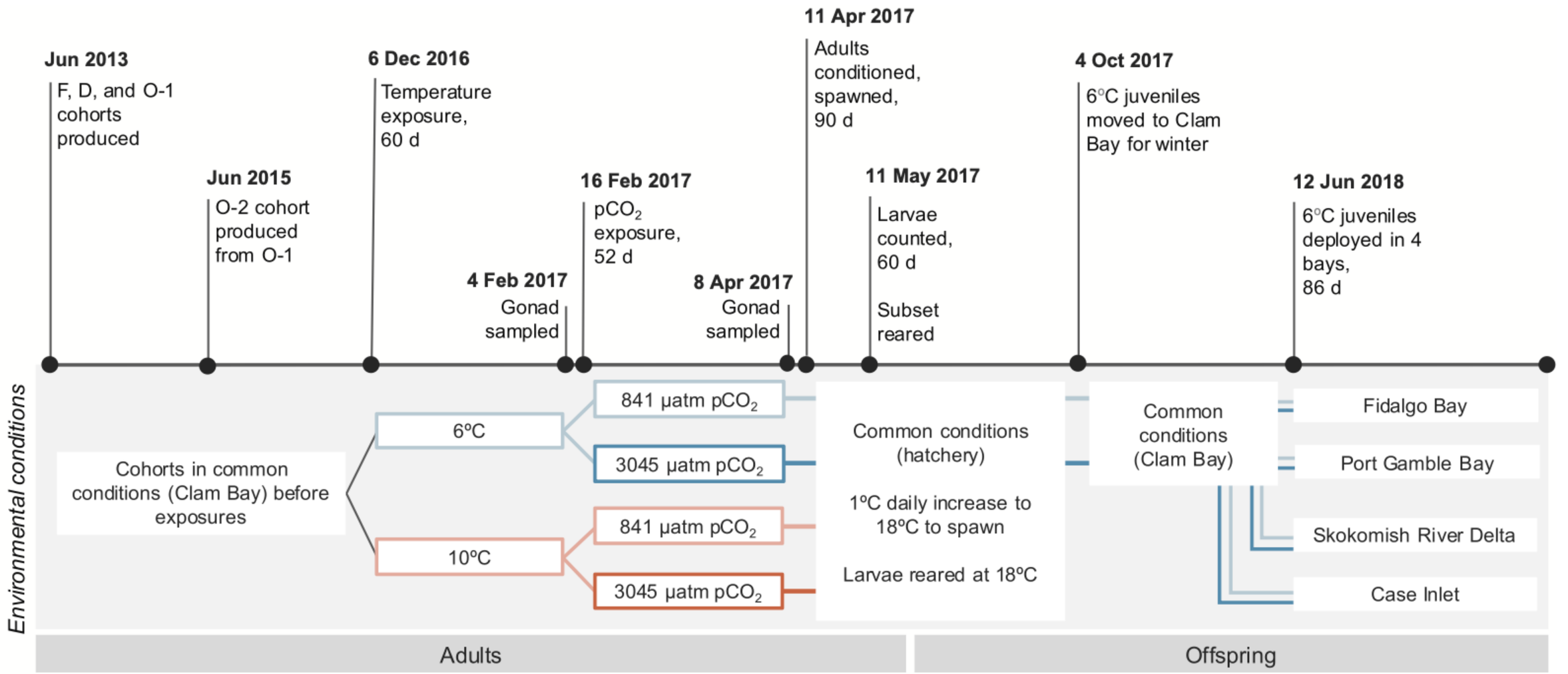
EFFECTS OF TEMPERATURE AND OA IN OLYMPIA OYSTER POPULATIONS

- Oysters were held at **two temperature regimes** (6°C and 10°C) for 60 days in December
- A differential pCO2 exposure was **carried out after the temperature treatment ended**. Held at ambient pCO2 (841 µatm) or high pCO2 (3045 µatm) for 52 days, during the Winter.

Carryover effects of temperature and pCO_2 across multiple Olympia oyster populations

Laura H. Spencer,[1] Yaamini R. Venkataraman,[1] Ryan Crim,[2] Stuart Ryan,[2] Micah J. Horwith,[3] and Steven B. Roberts[1,4]

TEXT

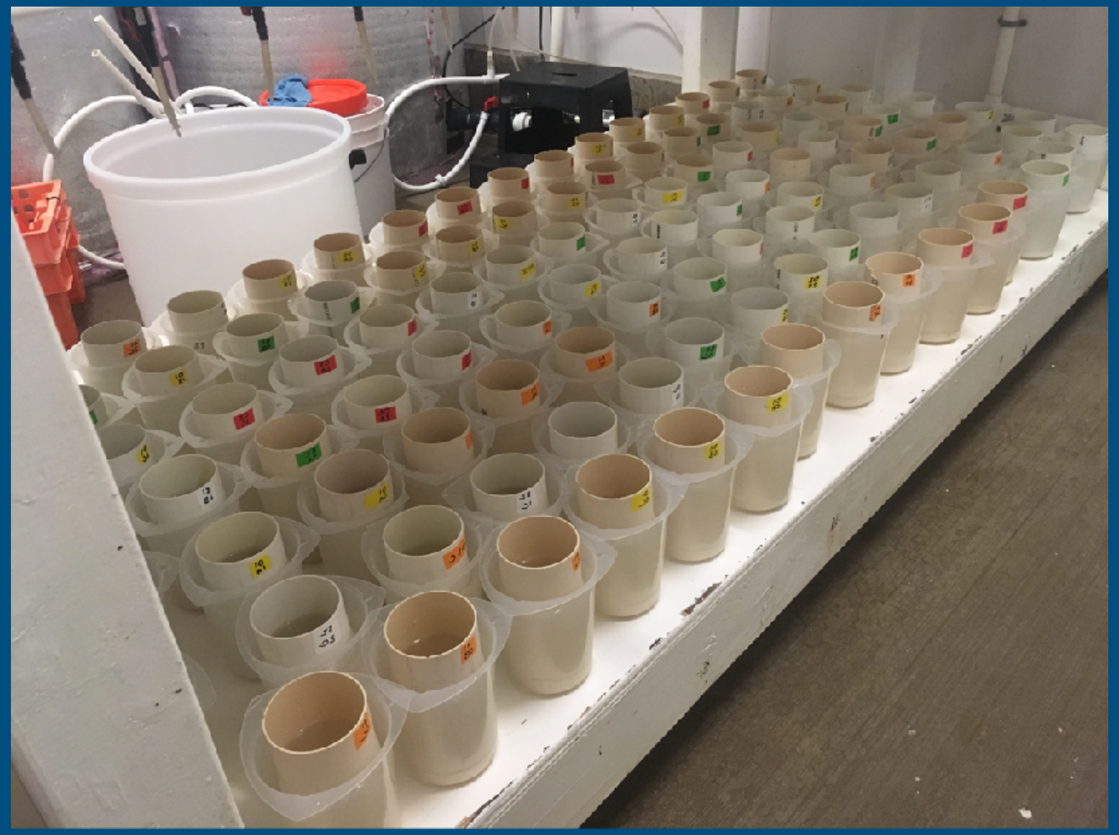

Jun 2013
F, D, and O-1 cohorts produced
Jun 2015
O-2 cohort produced from O-1
6 Dec 2016
Temperature exposure, 60 d
4 Feb 2017
Gonad sampled
16 Feb 2017
pCO2 exposure, 52 d
8 Apr 2017
Gonad sampled
11 Apr 2017
Adults conditioned, spawned, 90 d
11 May 2017
Larvae counted, 60 d
Subset reared
4 Oct 2017
6°C juveniles moved to Clam Bay for winter
12 Jun 2018
6°C juveniles deployed in 4 bays, 86 d
Environmental conditions
Cohorts in common conditions (Clam Bay) before exposures
6°C
10°C
841 µatm pCO2
3045 µatm pCO2
841 µatm pCO2
3045 µatm pCO2
Common conditions (hatchery)
1°C daily increase to 18°C to spawn
Larvae reared at 18°C
Common conditions (Clam Bay)
Fidalgo Bay
Port Gamble Bay
Skokomish River Delta
Case Inlet
Adults
Offspring

LAURA SPENCER

EFFECTS OF TEMPERATURE AND OA IN OLYMPIA OYSTER POPULATIONS

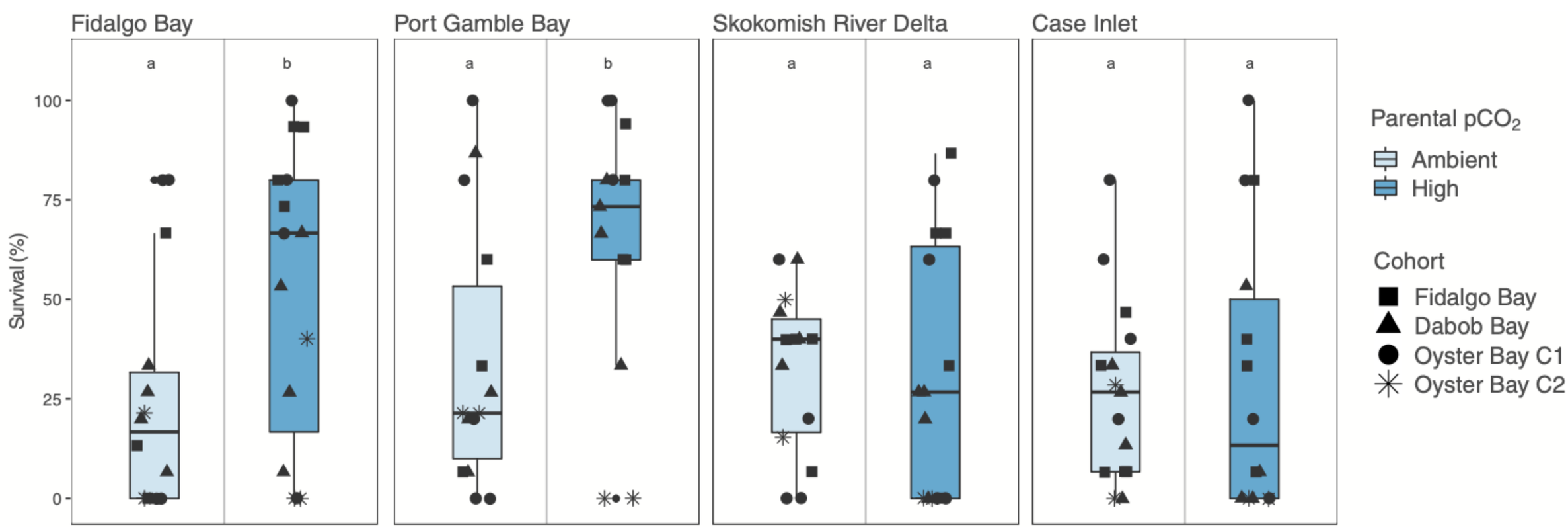
LAURA SPENCER

EFFECTS OF TEMPERATURE AND OA IN OLYMPIA OYSTER POPULATIONS



- Larval release occurred earlier in warm-exposed oysters
- Winter warming conditions increased larval production
- No effects on larval survival were detected
- **Juveniles of parents exposed to elevated pCO_2 had higher survival rates in the natural environment**

EFFECTS OF OA IN OLYMPIA OYSTER POPULATIONS



Eastern Oyster

LIMNOLOGY
and
OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 67, 2022, 1732–1745

doi: 10.1002/lno.12162

Parental exposure of Eastern oysters (*Crassostrea virginica*) to elevated pCO_2 mitigates its negative effects on early larval shell growth and morphology

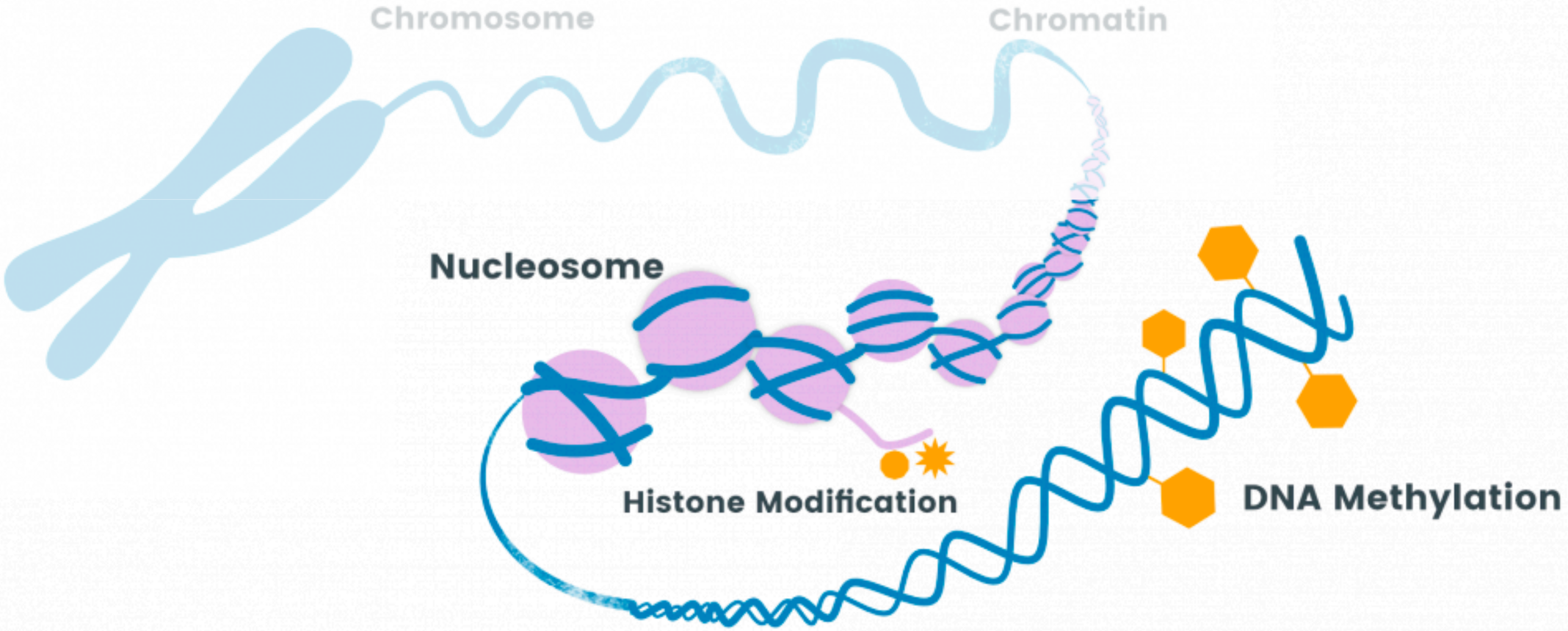
Elise M. McNally, * Alan M. Downey-Wall, F. Dylan Titmuss, Camila Cortina, Kathleen Lotterhos, Justin B. Ries

Department of Marine and Environmental Sciences, Marine Science Center, Northeastern University, Nahant, Massachusetts

Transgenerational plasticity in early larval shell growth and morphology, but not in survival, in response to the parental pCO2 exposure. Larvae from parents exposed to elevated pCO2 exhibited faster shell growth rates than larvae from control parents, with this effect being significantly larger when larvae were grown under elevated pCO2


Mechanism
Priming
Within
Across generation
Industry Concerns

ALTERS THE PHENOTYPE (WITHOUT CHANGING DNA CODE); HERITABLE



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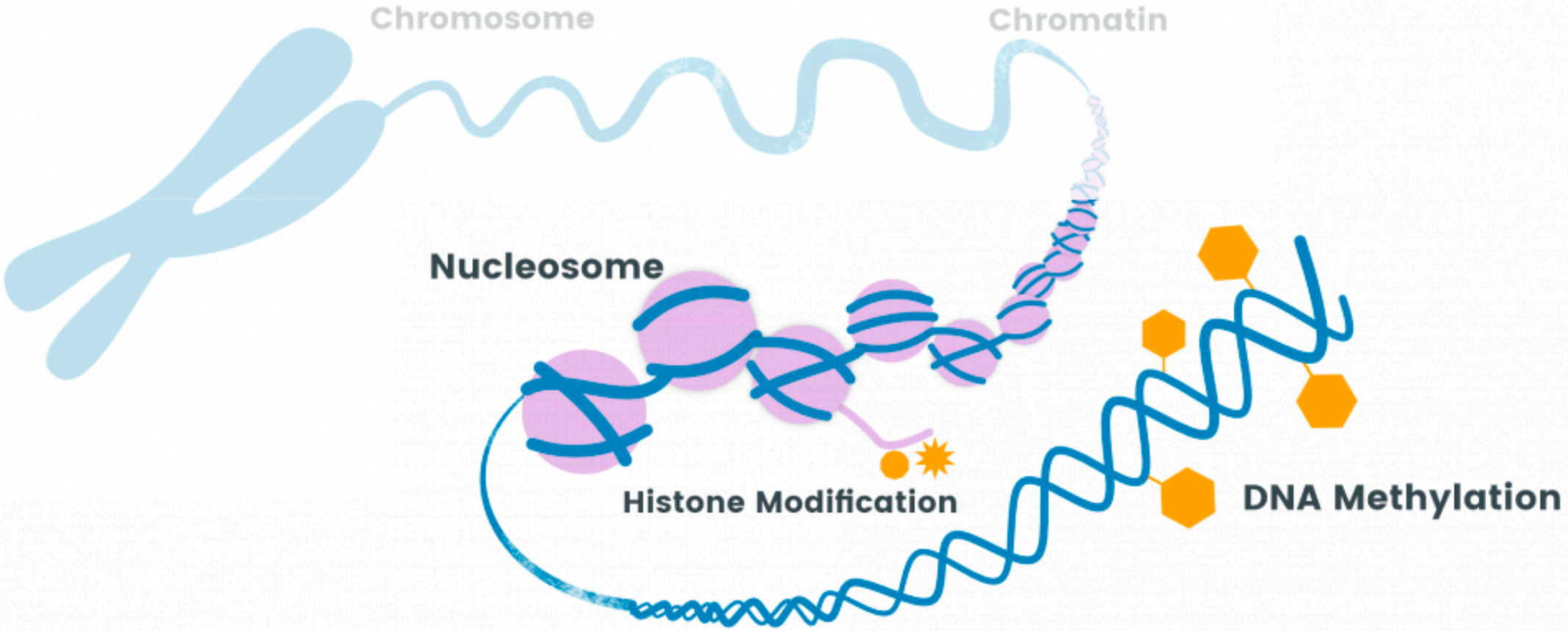
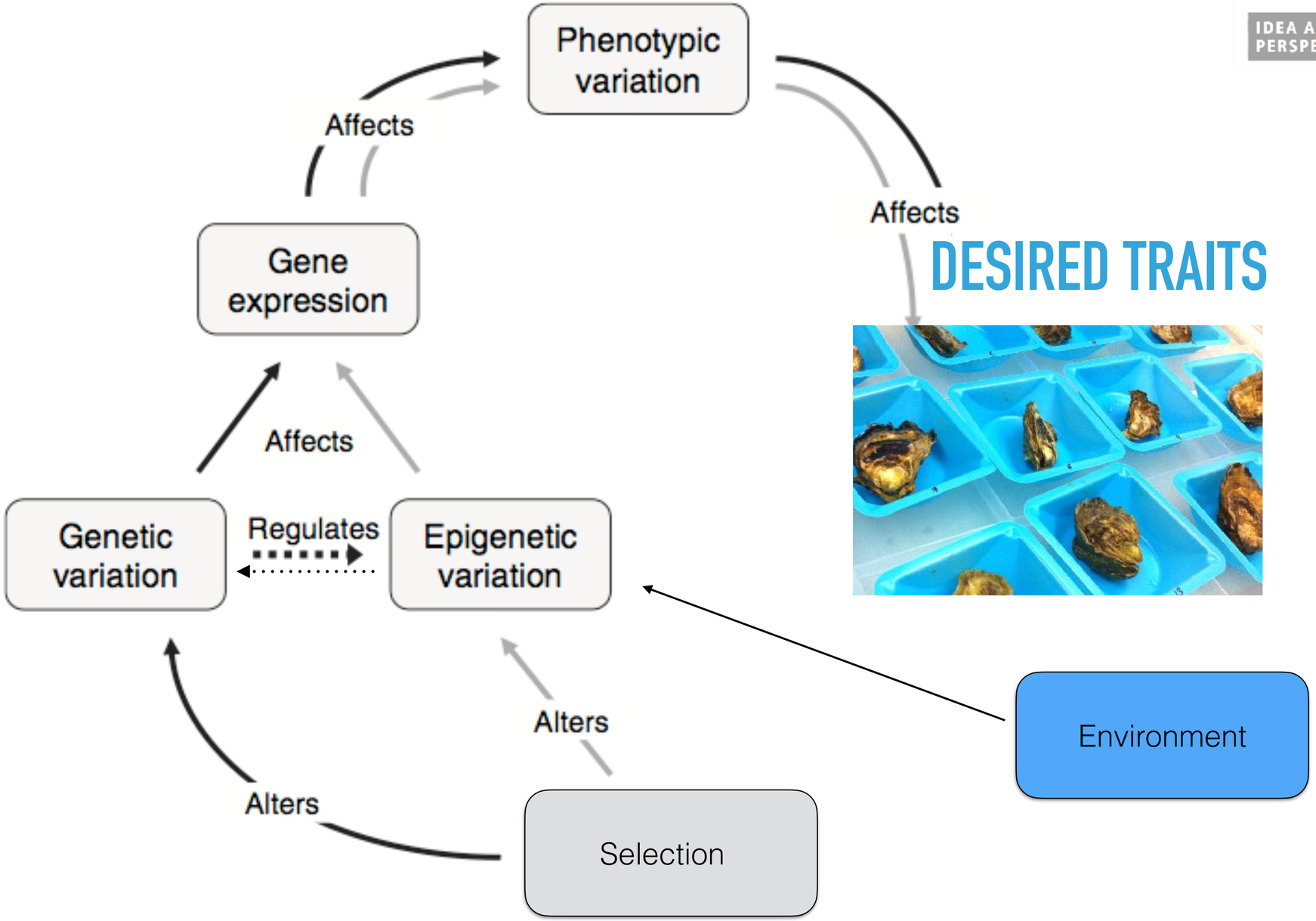


CAN BE INDUCED WITH ENVIRONMENTAL MANIPULATION

ECOLOGICAL EPIGENETICS

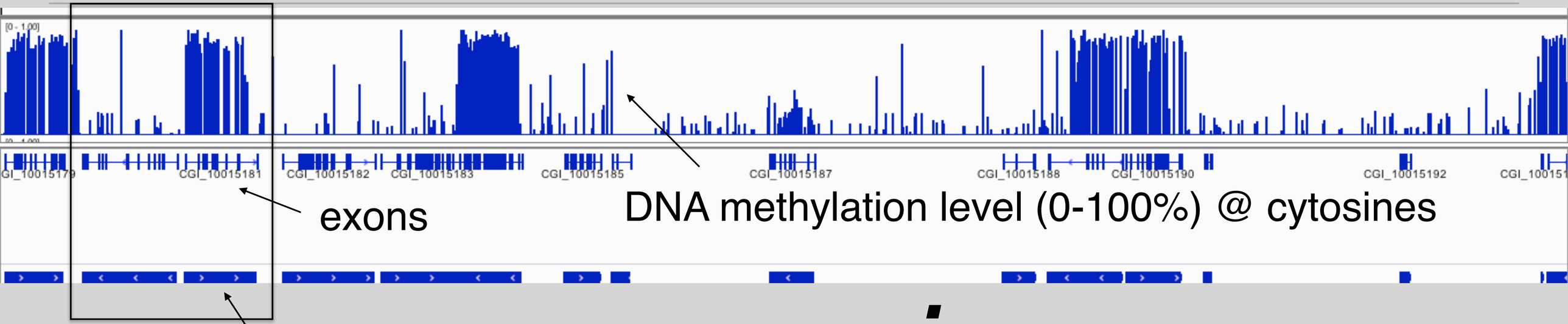


Ecology Letters, (2008) **11**: 106–115 doi: 10.1111/j.1461-0248.2007.01130.x

IDEA AND PERSPECTIVE

Epigenetics for ecologists

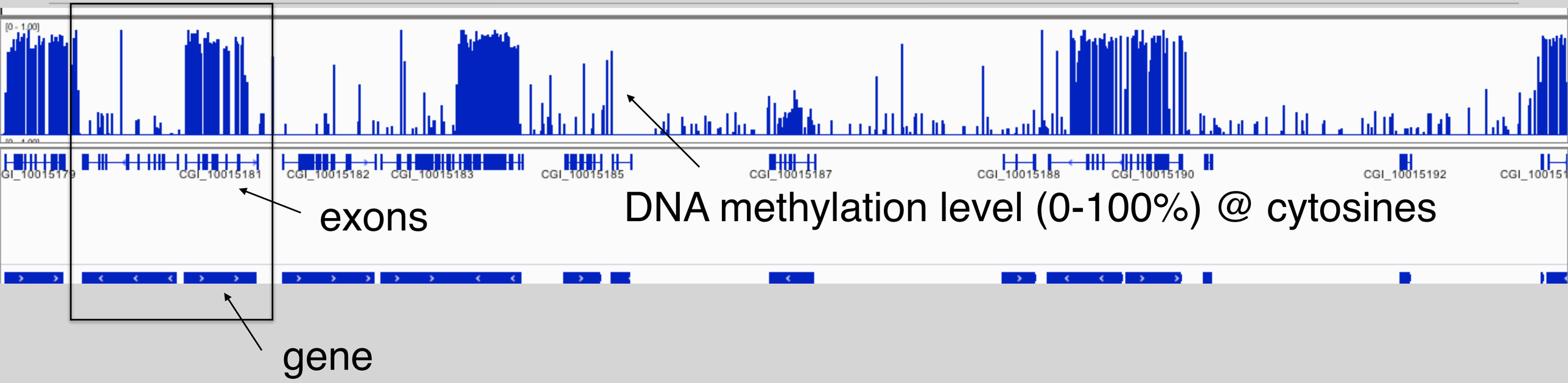
DESIRED TRAITS

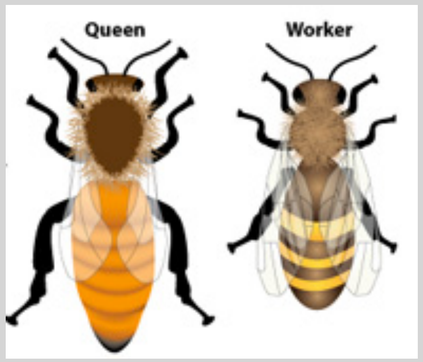


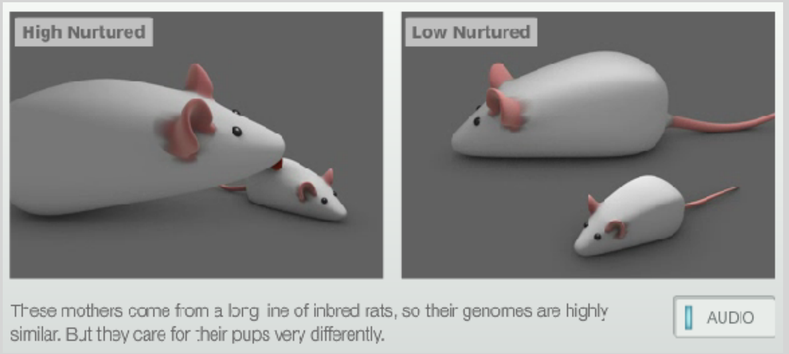
mosaic

associated with gene bodies

METHYLATION LANDSCAPE IN MARINE INVERTEBRATES







Four Dimensionalities

Targeted Regulation

Stochastic Regulation

Reliable Transcription

Spurious Transcription

Four Dimensionalities

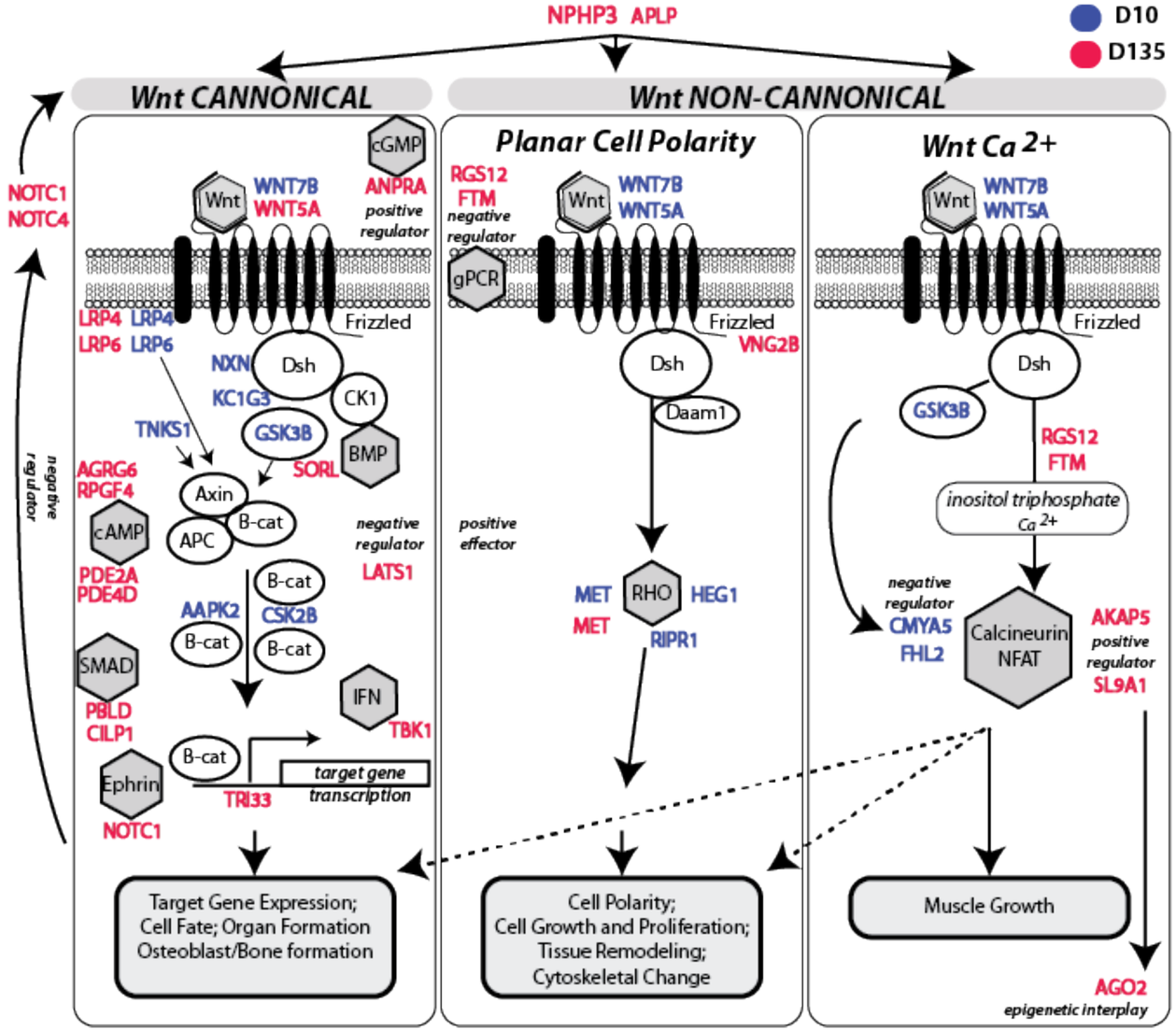
- Evolutionary
- Life History Driven
- Constitutive

Four Dimensionalities

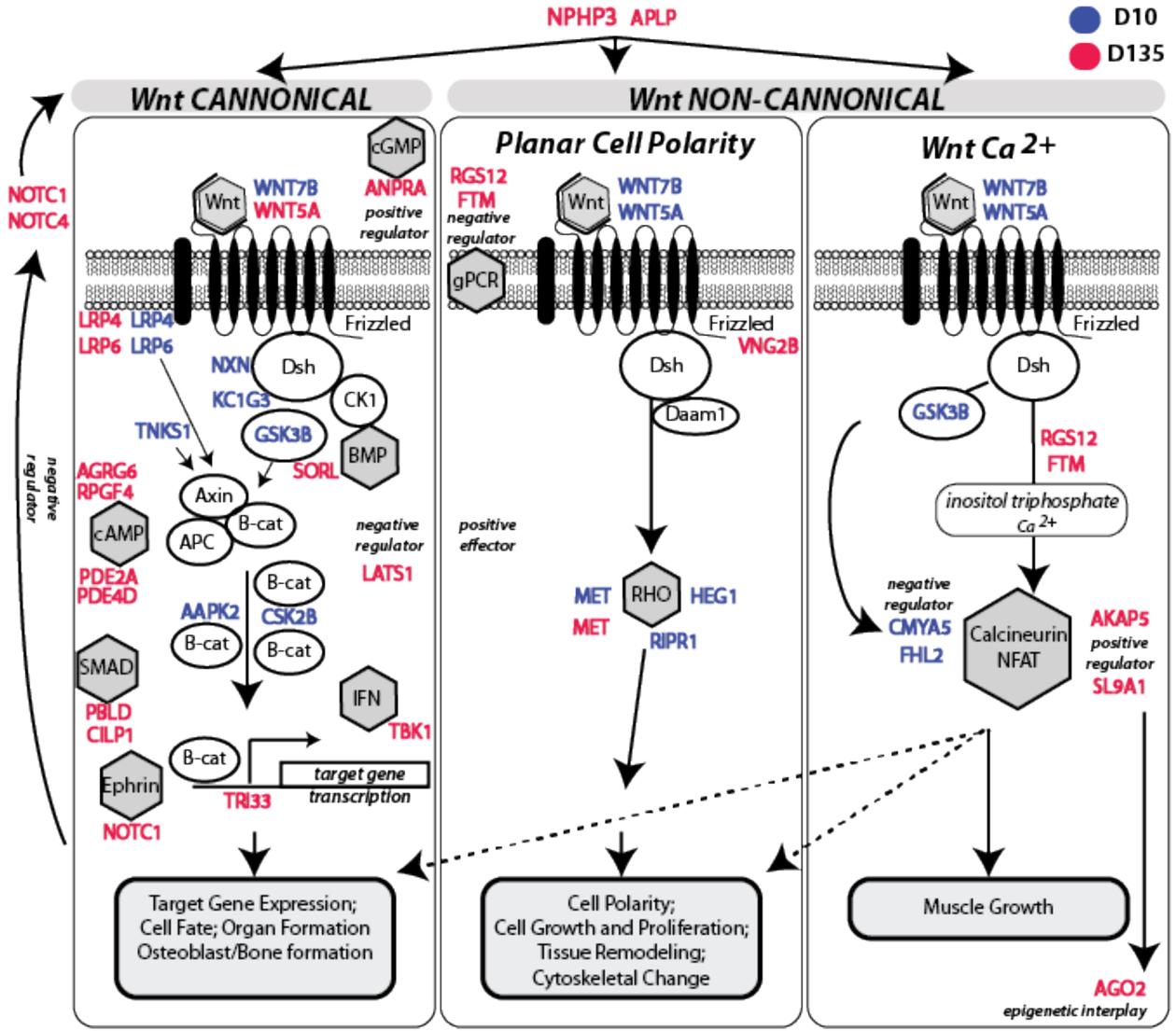
- Distinct Lineage
- Experiential
- Inducible

- Evolutionary
- Life History Driven
- Constitutive

GEODUCKS AND OA



GEODUCKS AND OA



New Results

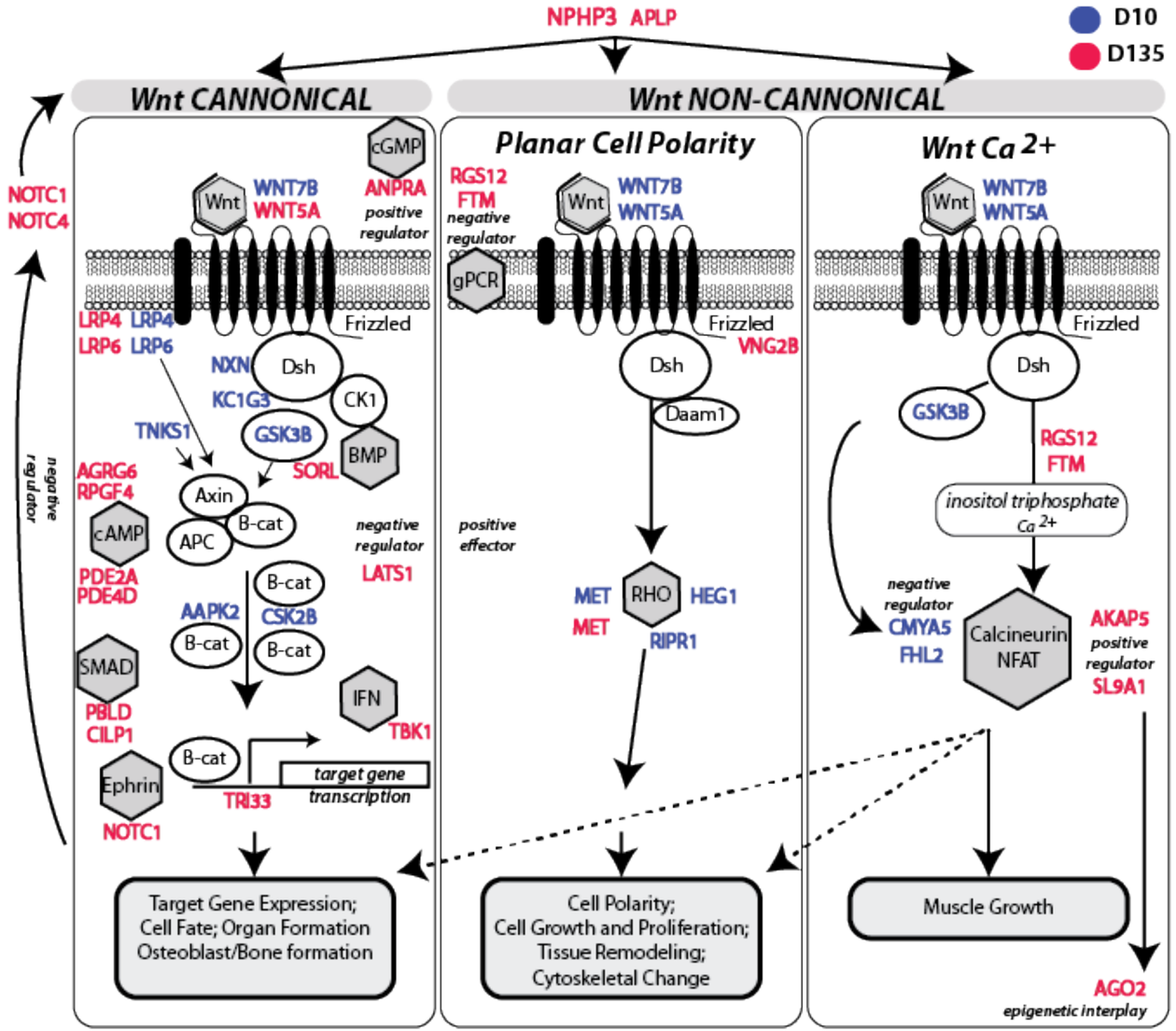
Follow this preprint

Dynamic DNA methylation contributes to carryover effects and beneficial acclimatization in geoduck clams

Hollie M. Putnam, Shelly A. Trigg, Samuel J. White, Laura H. Spencer, Brent Vadopalas, Aparna Natarajan, Jonathan Hetzel, Erich Jaeger, Jonathan Soohoo, Cristian Gallardo-Escárate, Frederick W. Goetz, Steven B. Roberts

doi: https://doi.org/10.1101/2022.06.24.497506

GEODUCKS AND OA



Following four months of ambient common-garden conditions, **juveniles initially exposed to low pH compensatorily grew larger**, with DNA methylation indicative of these phenotypic differences, demonstrating epigenetic carryover effects persisted months after initial exposure.

EPIGENETIC MECHANISM INVOLVED?

LIMNOLOGY
and
OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 67, 2022, 1732–1745

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Parental exposure of Eastern oysters (*Crassostrea virginica*) to elevated pCO_2 mitigates its negative effects on early larval shell growth and morphology

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Department of Marine and Environmental Sciences, Marine Science Center, Northeastern University, Nahant, Massachusetts

EPIGENETIC MECHANISM INVOLVED?

DNA methylation correlates with transcriptional noise in response to elevated pCO_2 in the eastern oyster (*Crassostrea virginica*)

Yaamini R. Venkataraman[1]*, Ariana S. Huffmyer[2,3], Samuel J. White[2], Alan Downey-Wall[4], Jill Ashey[3], Danielle M. Becker[3], Zachary Bengtsson[2], Hollie M. Putnam[3], Emma Strand[3,5], Javier A. Rodríguez-Casariego[6], Shelly A. Wanamaker[5], Kathleen E. Lotterhos[7], Steven B. Roberts[2]

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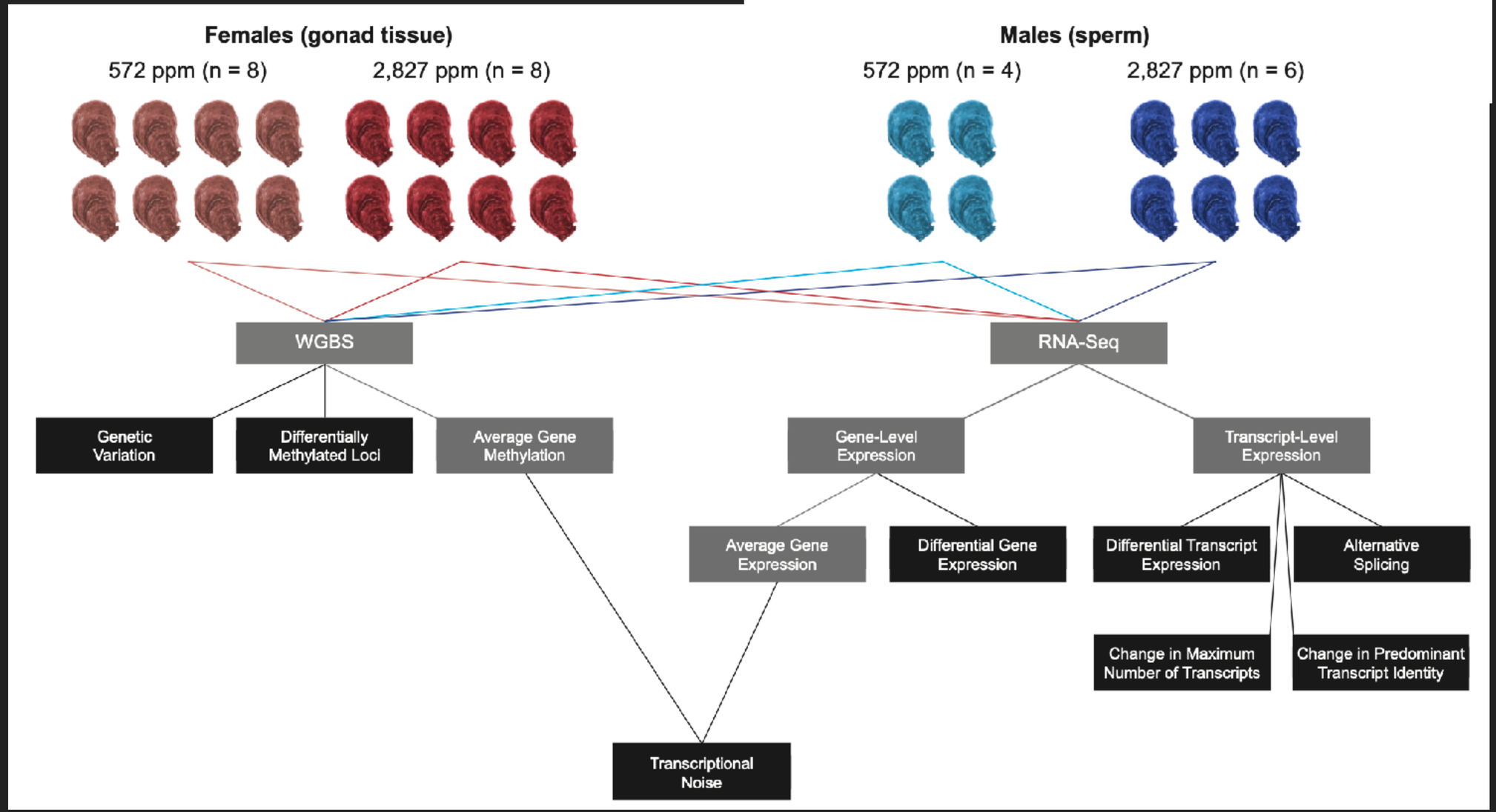

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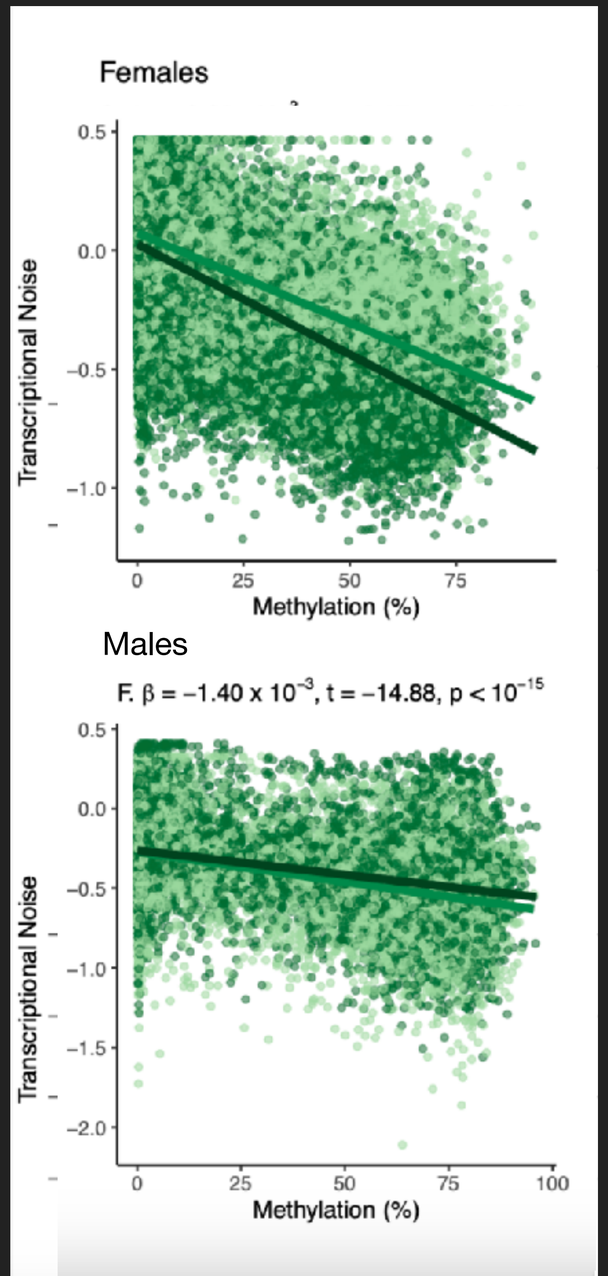
Gene body methylation impacts maximum number of transcripts expressed per gene and changes in the predominant transcript expressed. Elevated pCO2 exposure increased gene expression variability (transcriptional noise) in males but decreased noise in females, suggesting a sex-specific role of methylation in gene expression regulation.

VENKATARAMAN: DNA METHYLATION CORRELATES WITH TRANSCRIPTIONAL NOISE



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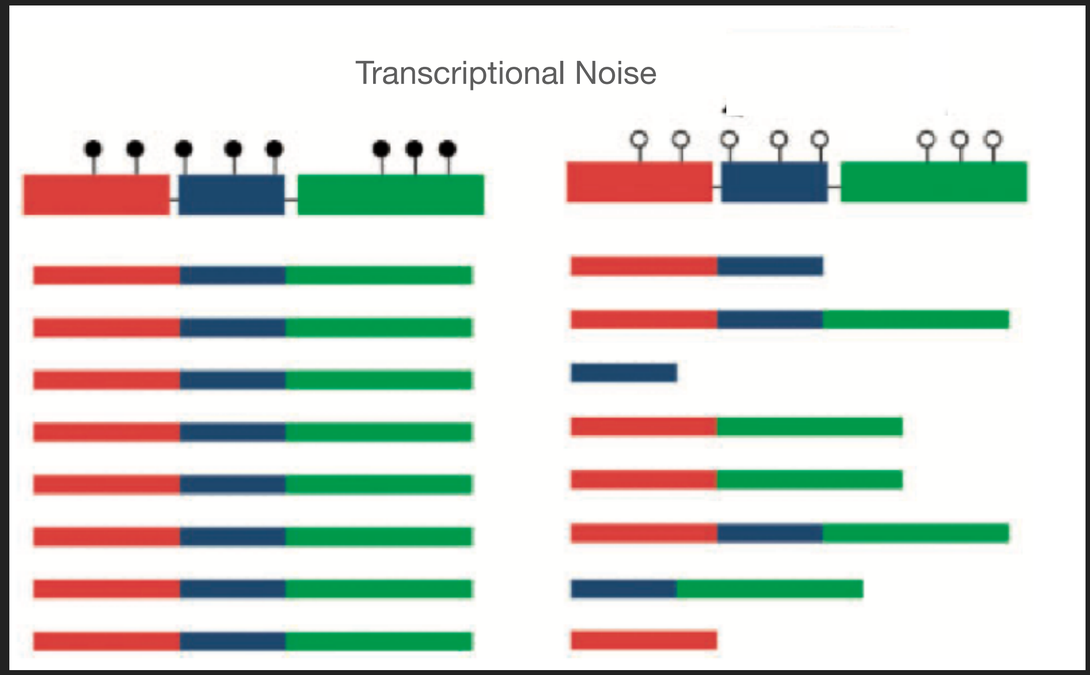

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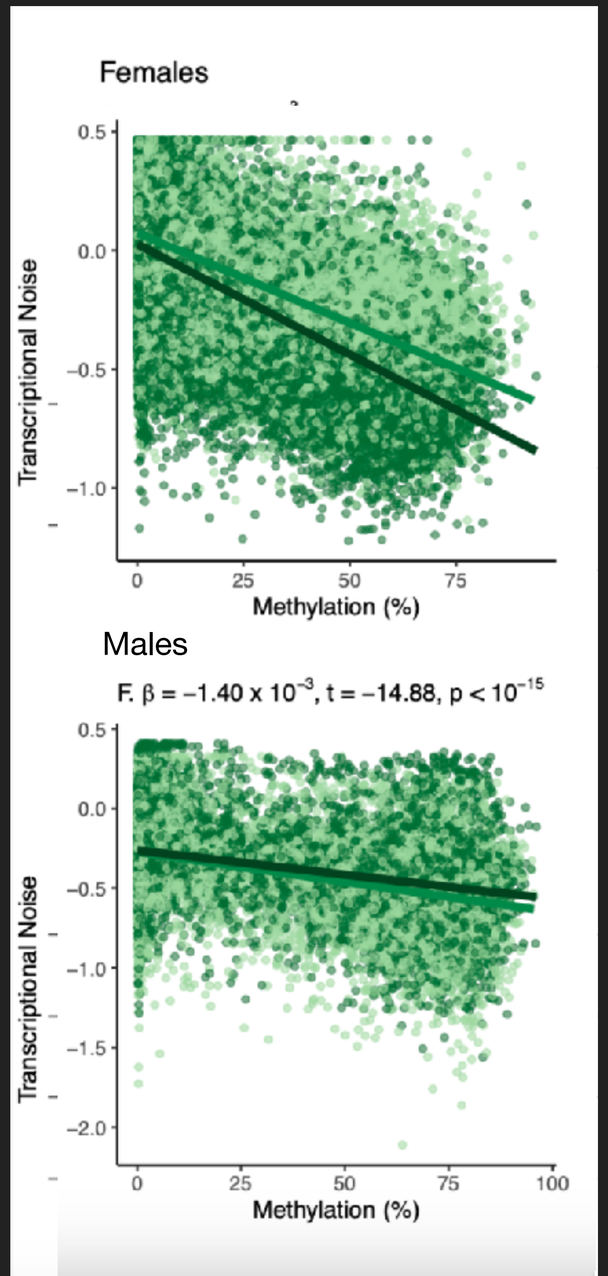

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Methylation has a genome-wide regulatory role, effectively maintaining gene expression homeostasis in reproductive tissues under elevated pCO2 by reducing transcriptional noise.

The relationship between methylation and transcriptional noise was different between female reproductive tissue and sperm: male oysters required higher levels of methylation to achieve similar reductions in transcriptional noise when compared to female oysters.

Epigenetic maintenance of reproduction could confer intergenerational resilience to environmental perturbations.

VENKATARAMAN: DNA METHYLATION CORRELATES WITH TRANSCRIPTIONAL NOISE

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Males

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Looking at Offspring now

Moms

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Epigenetic maintenance of reproduction could confer intergenerational resilience to environmental perturbations.

EXCITING?
COMPLEX
‘LAYER’ OF RESILIENCE

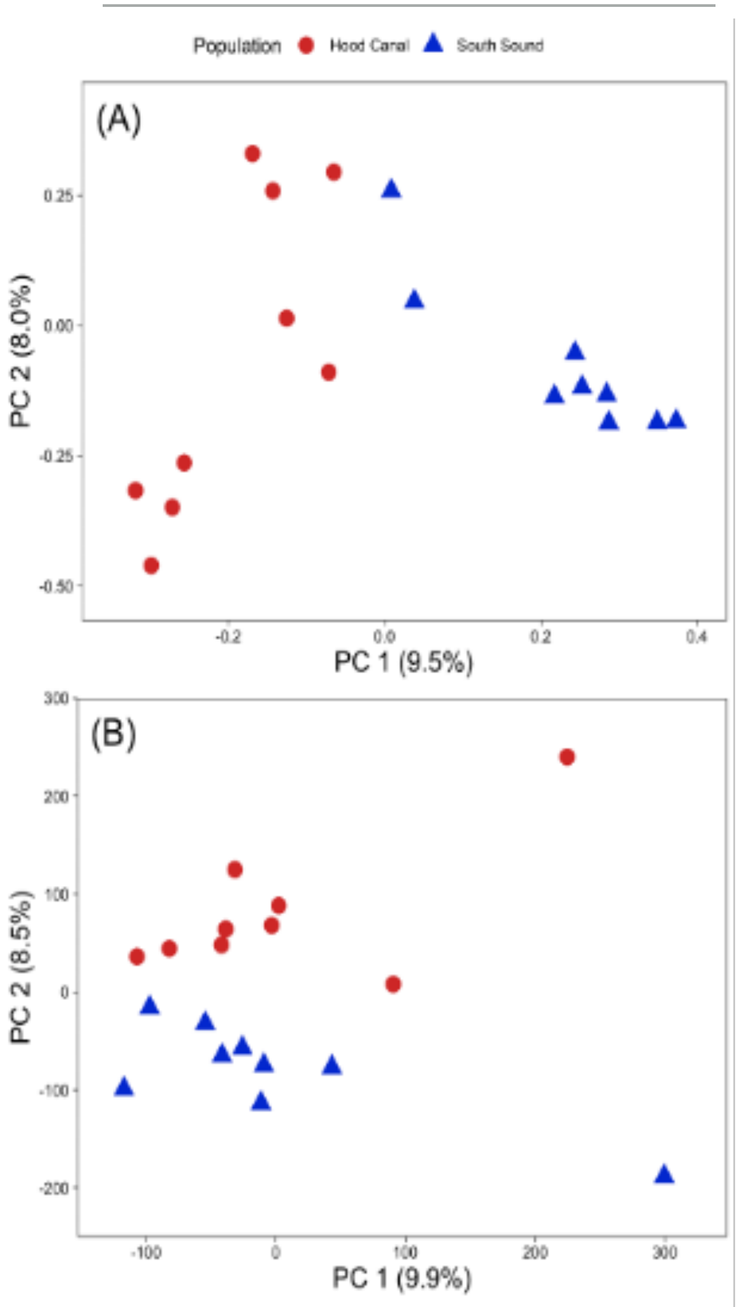
Epigenetic and Genetic Population Structure is Coupled in a Marine Invertebrate

Katherine Silliman [1,†], Laura H. Spencer [2,†], Samuel J. White[2], and Steven B. Roberts [2,*]

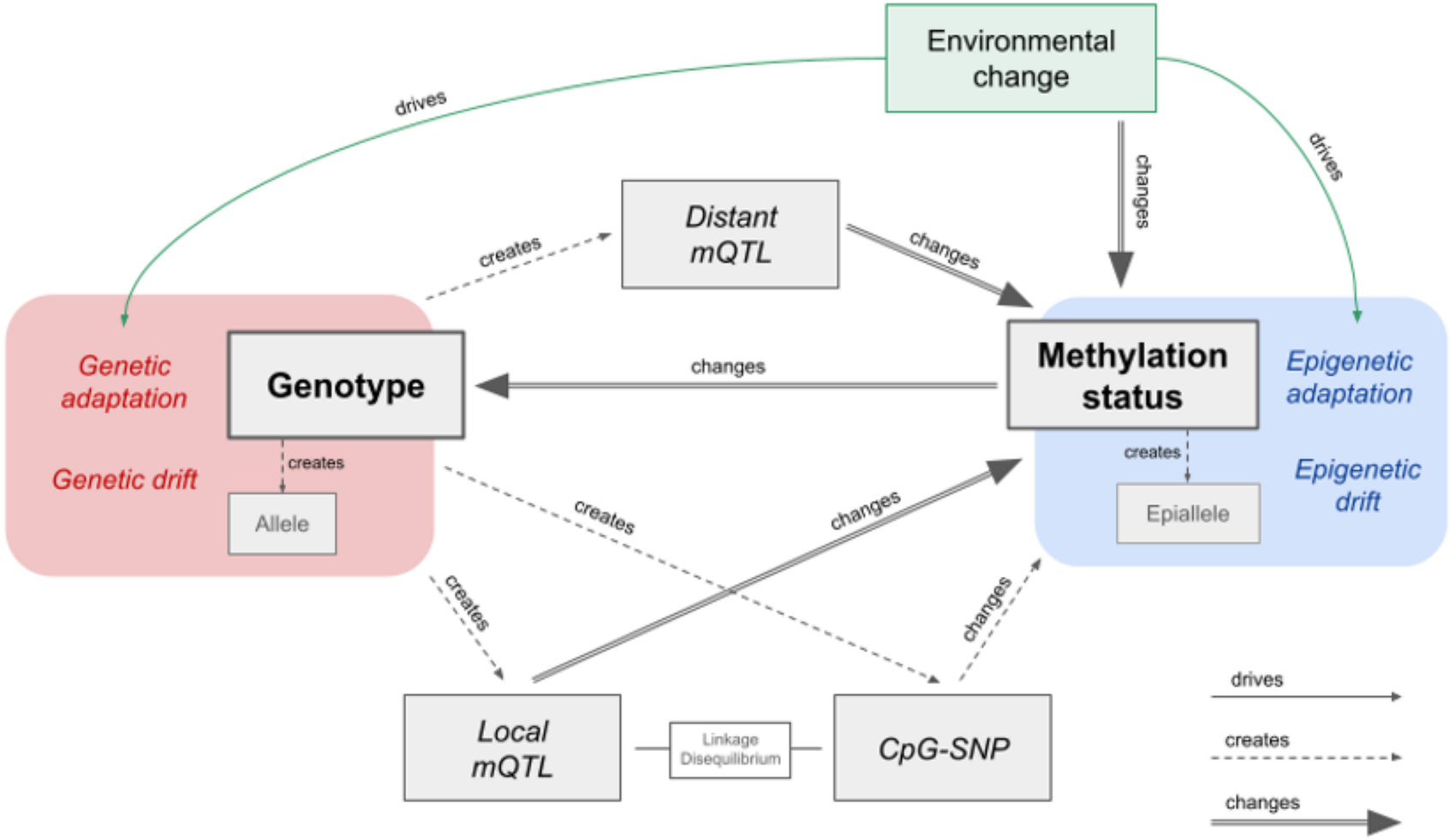
First characterization of genome-wide DNA methylation patterns in the oyster genus *Ostrea*

Identified 3,963 differentially methylated loci between populations. Clear coupling between genetic and epigenetic patterns of variation, **with 27% of variation in inter-individual methylation differences explained by genotype**.

Underlying this association are both direct genetic changes in CpGs (CpG-SNPs) and genetic variation with indirect influence on methylation (mQTLs).



EPIGENETIC AND GENETIC POPULATION STRUCTURE




Current work
Priming
Within
Across generation
Mechanism
Industry Concerns

Pacific Oyster

Ongoing Efforts

Emily Carrington - UW Biology

Pacific Oyster

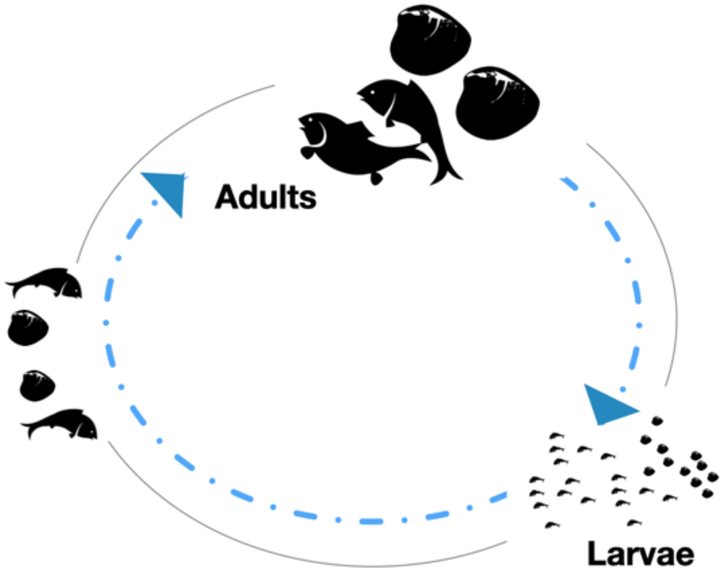
Ongoing Efforts

Emily Carrington - UW Biology

- Priming
  - Immune Challenge
  - Temperature
  - Salinity
  - Multiple
- Performance Testing
  - Survival
  - Growth
  - Metabolism*

Pacific Oyster

Ongoing Efforts

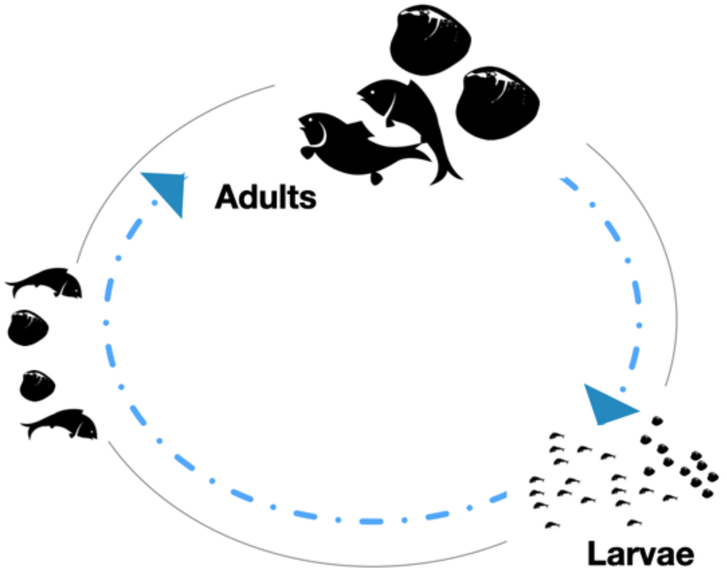


- Priming
  - Immune Challenge
  - Temperature
  - Salinity
  - Multiple

- Performance Testing
  - Survival
  - Growth
  - Metabolism*

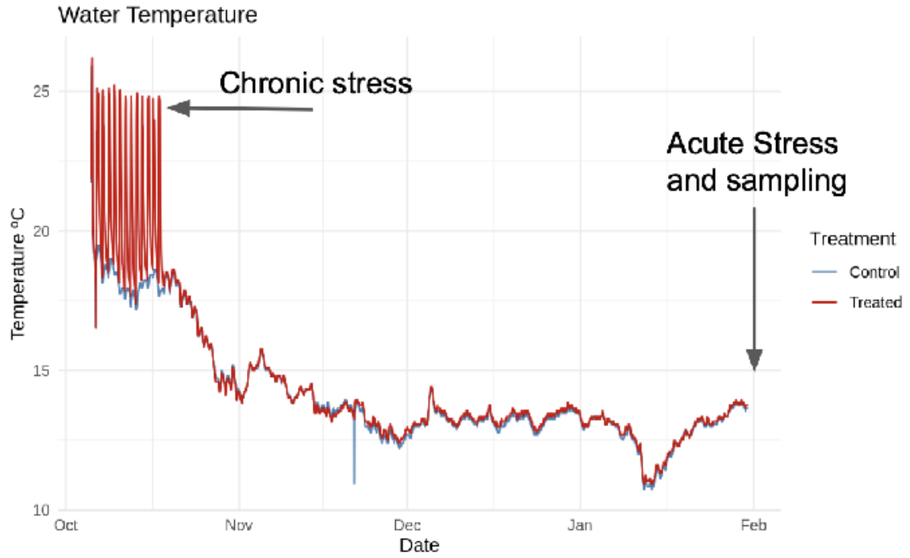
Pacific Oyster

Ongoing Efforts



- Priming
  - Immune Challenge
  - Temperature
  - Salinity
  - Multiple

- Performance Testing
  - Survival
  - Growth
  - Metabolism*



Pacific Oyster

Ongoing Efforts

- Priming
  - Immune Challenge
  - Temperature
  - Salinity
  - Multiple
- Performance Testing
  - Survival
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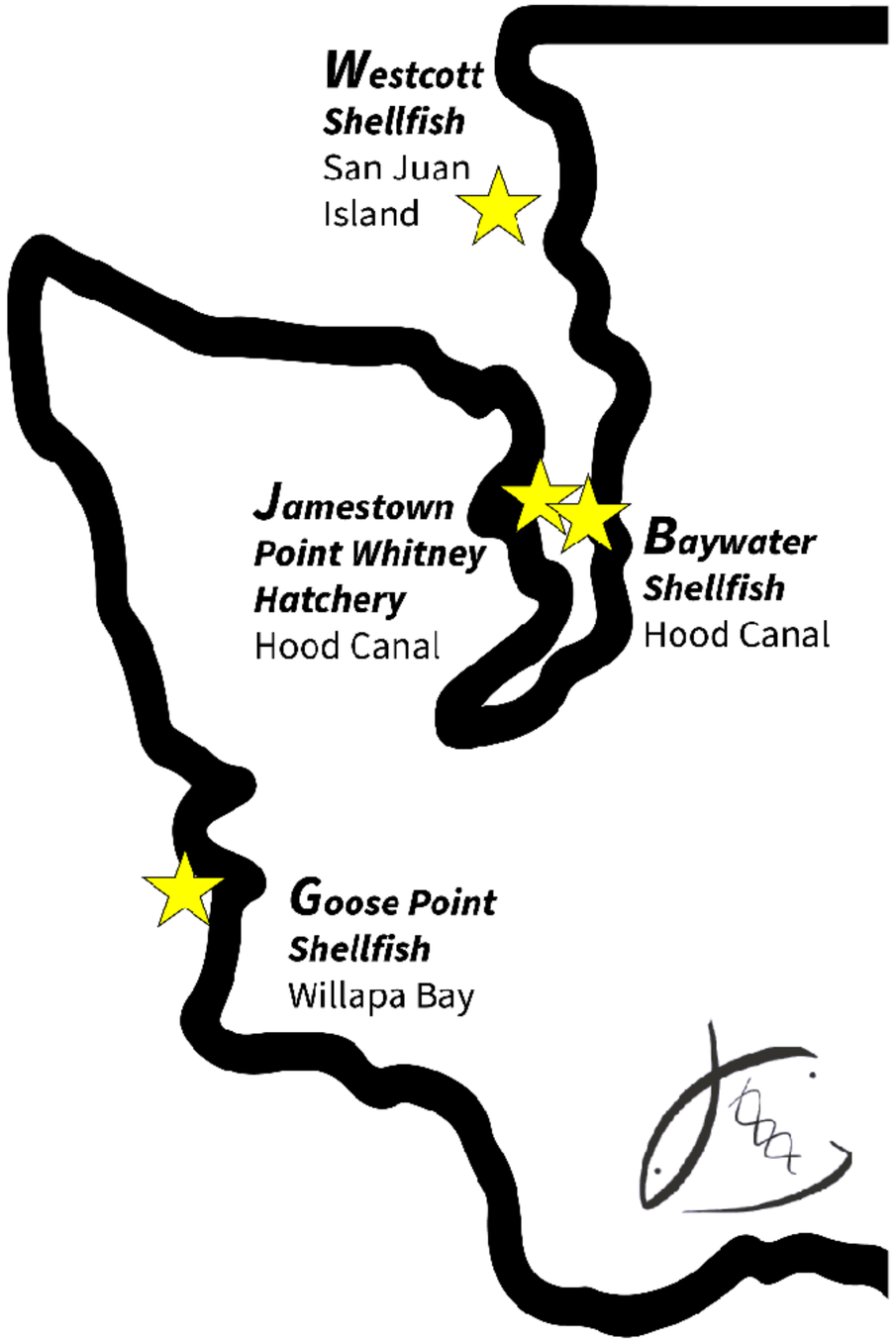


Sea Grant Washington

Pacific Oyster

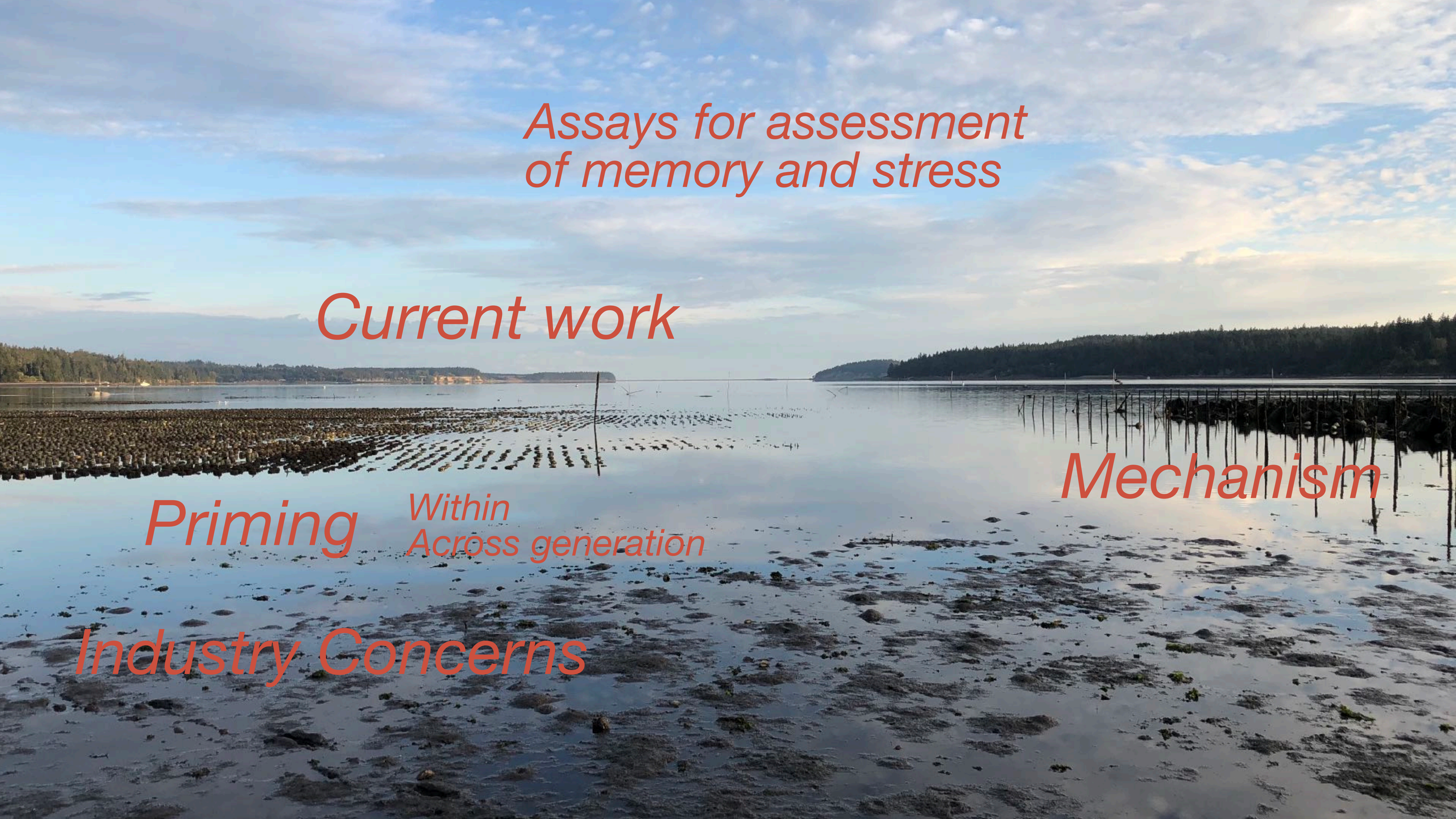
Ongoing Efforts

Core Partner:
Jamestown S'Klallam

Sea Grant Washington

- Priming
  - Immune Challenge
  - Temperature
  - Salinity
  - Multiple
- Performance Testing
  - Survival
  - Growth
  - Metabolism*

Jamestown Point Whitney Hatchery Hood Canal


Assays for assessment
of memory and stress
Current work
Priming
Within
Across generation
Mechanism
Industry Concerns

Pacific Oyster

Ongoing Efforts

- Priming
  - Immune Challenge
  - Temperature
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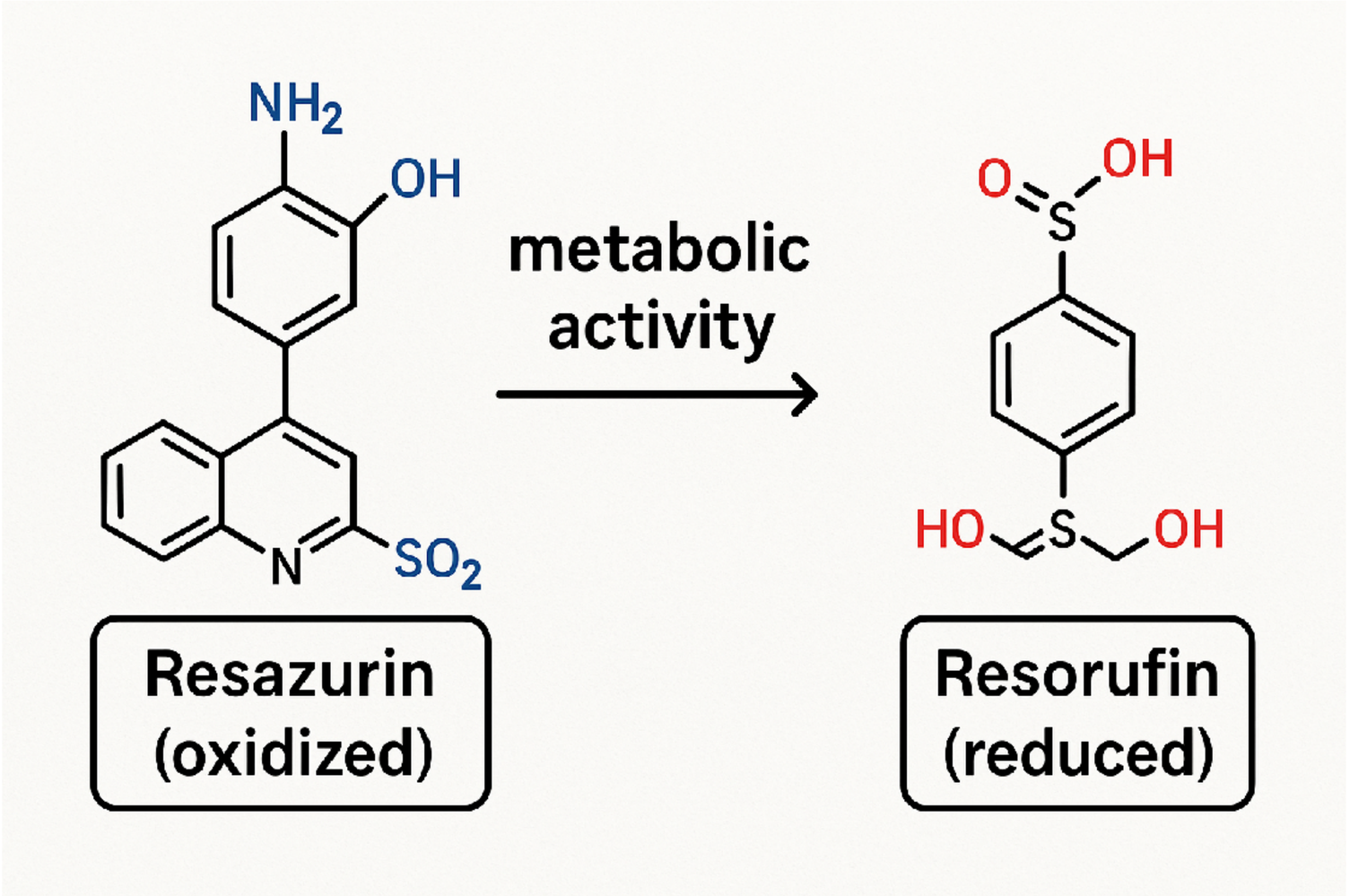
  - Growth
  - Metabolism*

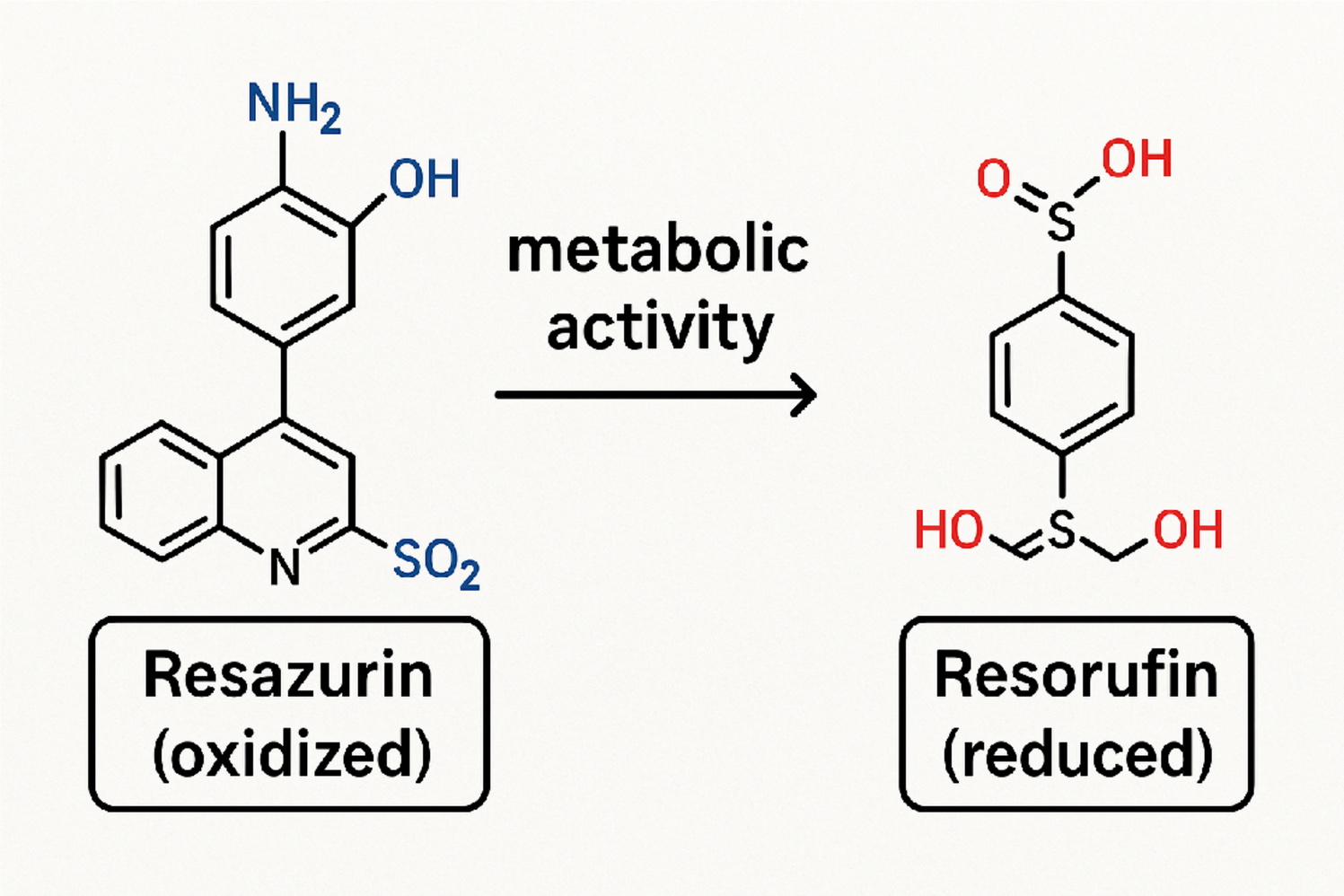
Predicting Performance

Pacific Oyster *Resazurin*

Louis Plough - USDA ARS



Pacific Oyster *Resazurin*

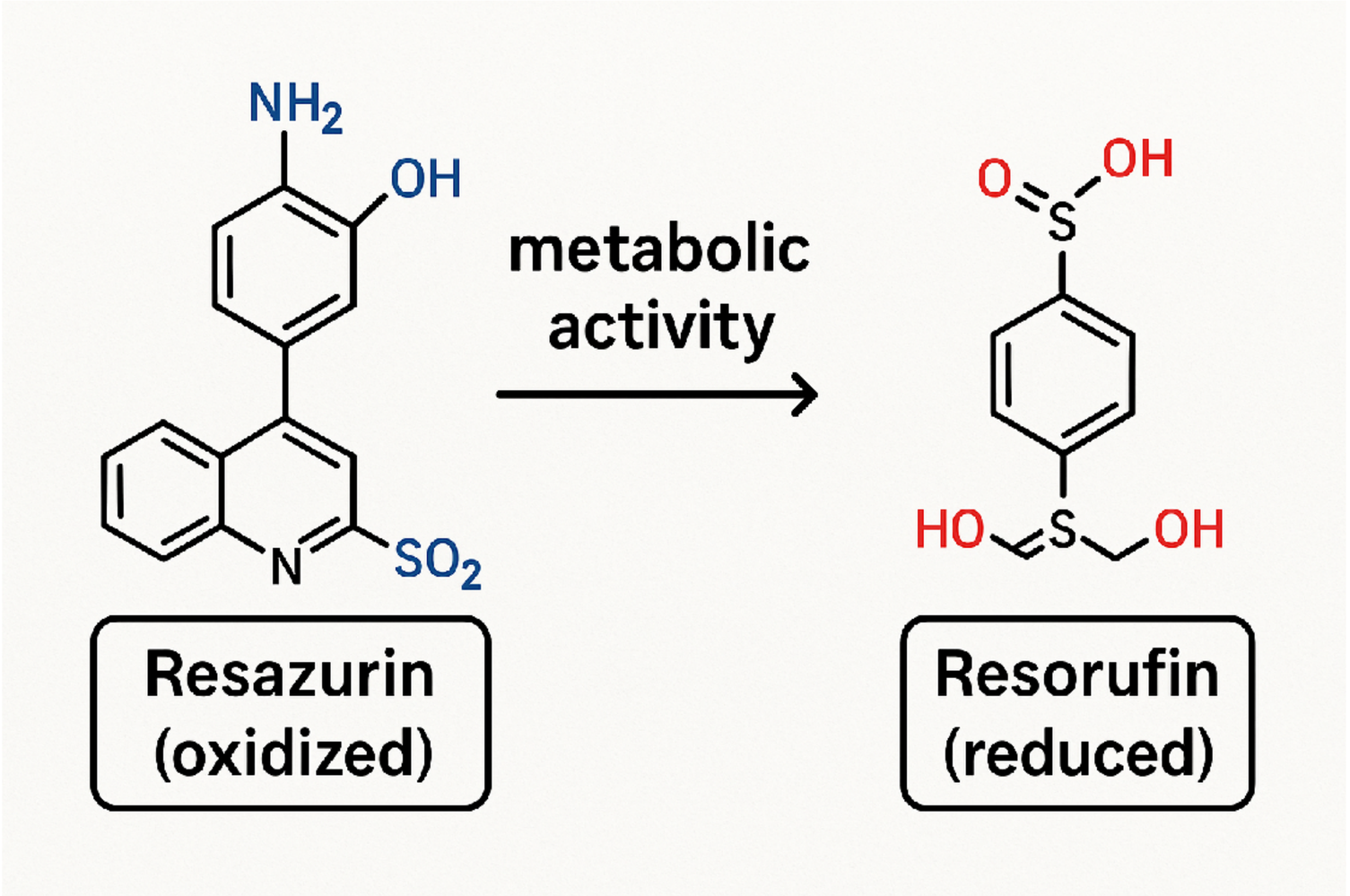


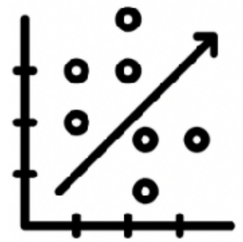
Highly fluorescent (excitation ~570 nm, emission ~585 nm)

The amount of resorufin produced is directly proportional to the metabolic activity of the cells.

Pacific Oyster

Resazurin





Correlated with oxygen consumption

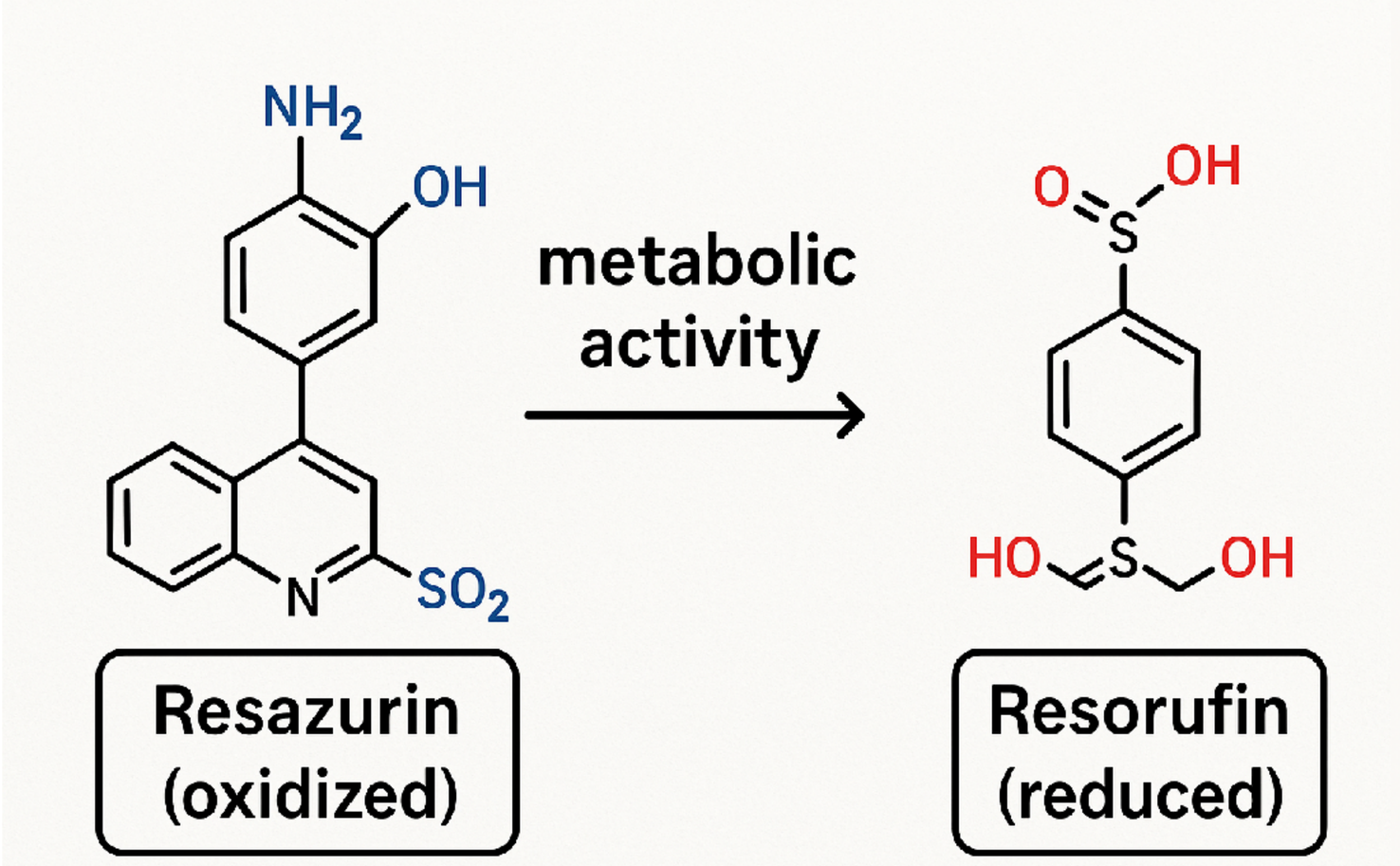
E.g., González-Pinzón et al. 2012, Ricciardi et al. 2014

Correlation with respiration in oysters (L. Plough, USDA, data analysis in progress)

Highly fluorescent (excitation ~570 nm, emission ~585 nm)

The amount of resorufin produced is directly proportional to the metabolic activity of the cells.

Pacific Oyster



Using Resazurin Assay to Study Oysters and Improve Aquaculture

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Test metabolic activity under thermal, salinity, or pH stress

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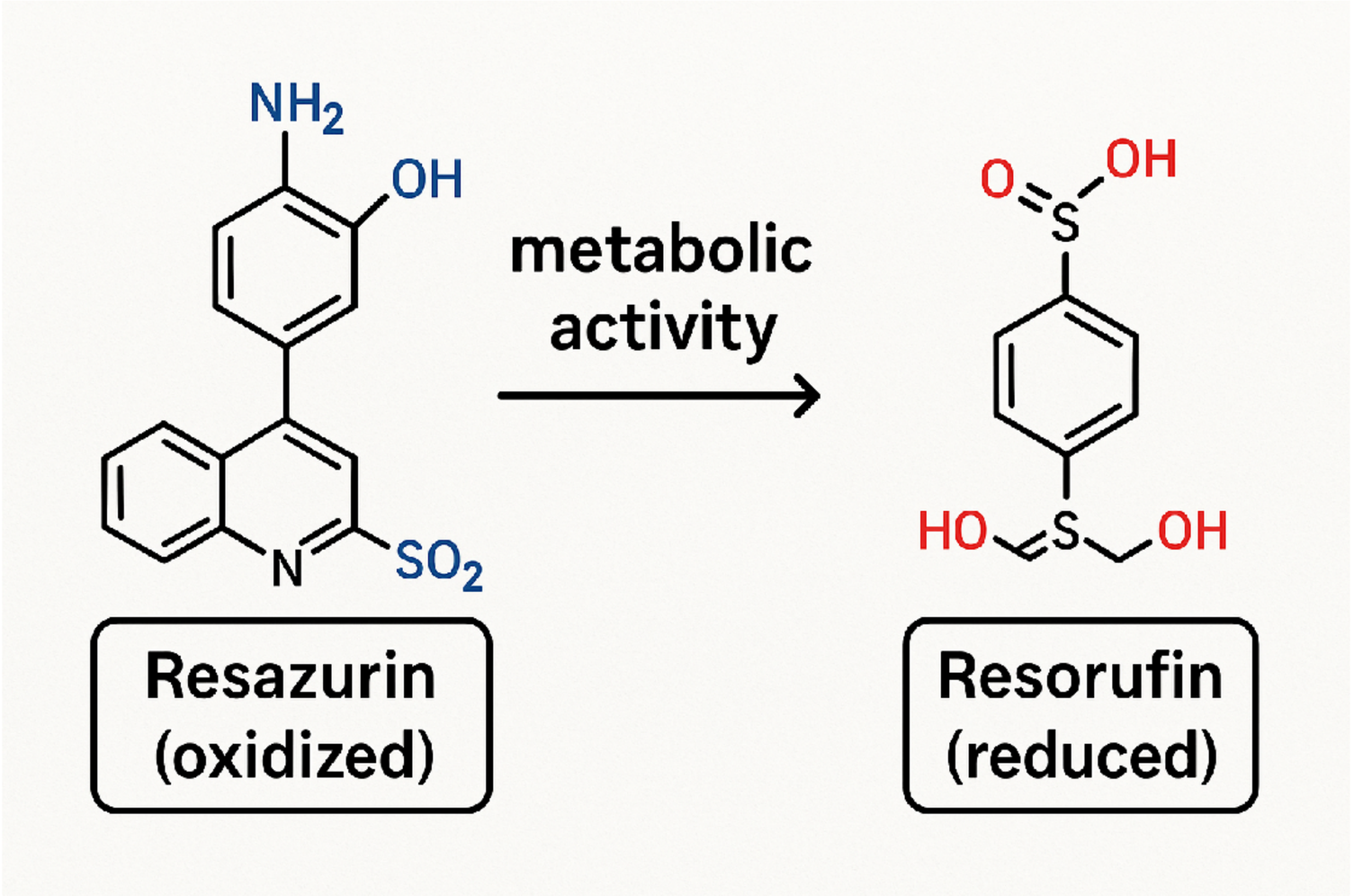
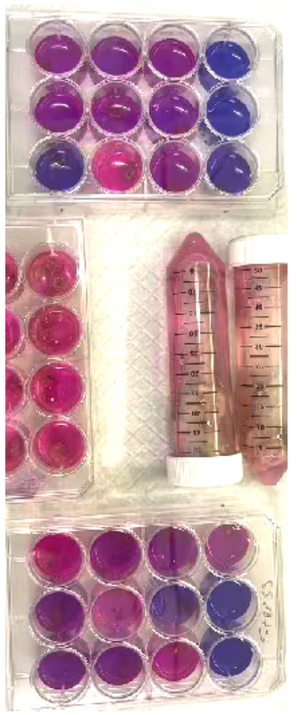
Applications

Resazurin

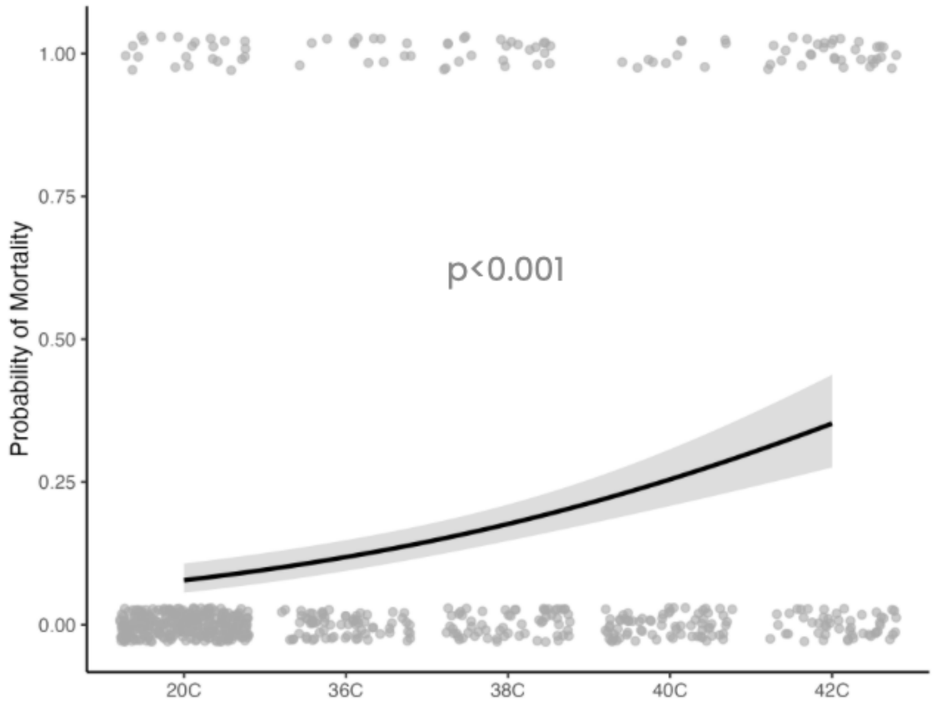




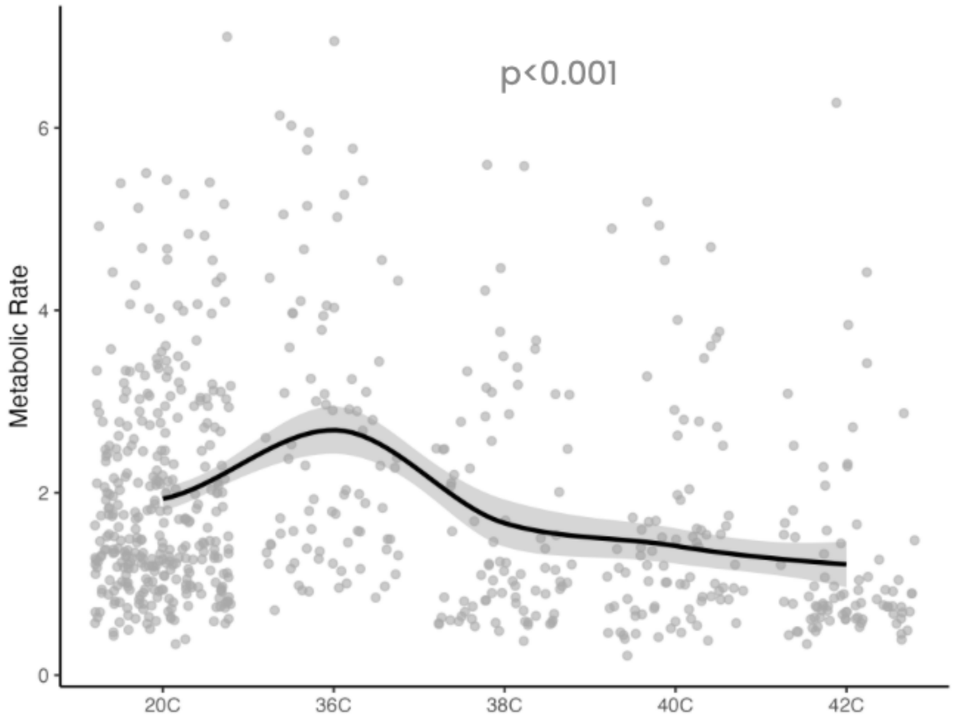
Is metabolic activity associated with a stress event different when oyster had previously experienced a stress? (Is there evidence for functional priming?)

Applications

Ariana Huffmyer - UW



Mortality ***increases*** with temperature



Metabolic rates ***decrease*** at high temperatures

N=768 oysters
Format: 96-well plates

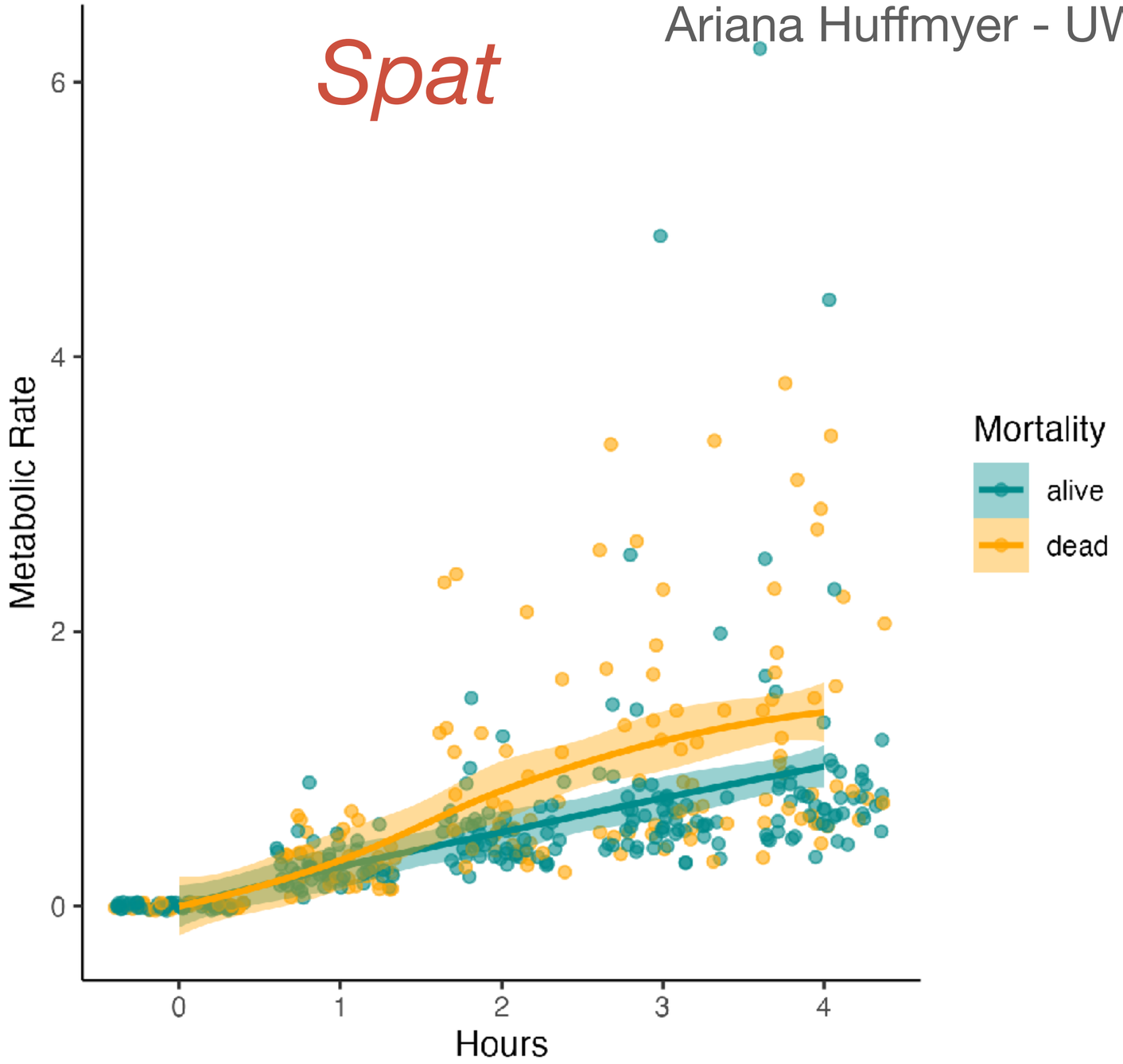
4-6 mm *C. gigas* seed
4 h exposure to 20-42°C

Applications

Ariana Huffmyer - UW

Spat

Oysters that ***survived stress trials*** had a greater capacity for metabolic depression



Applications

Ariana Huffmyer - UW

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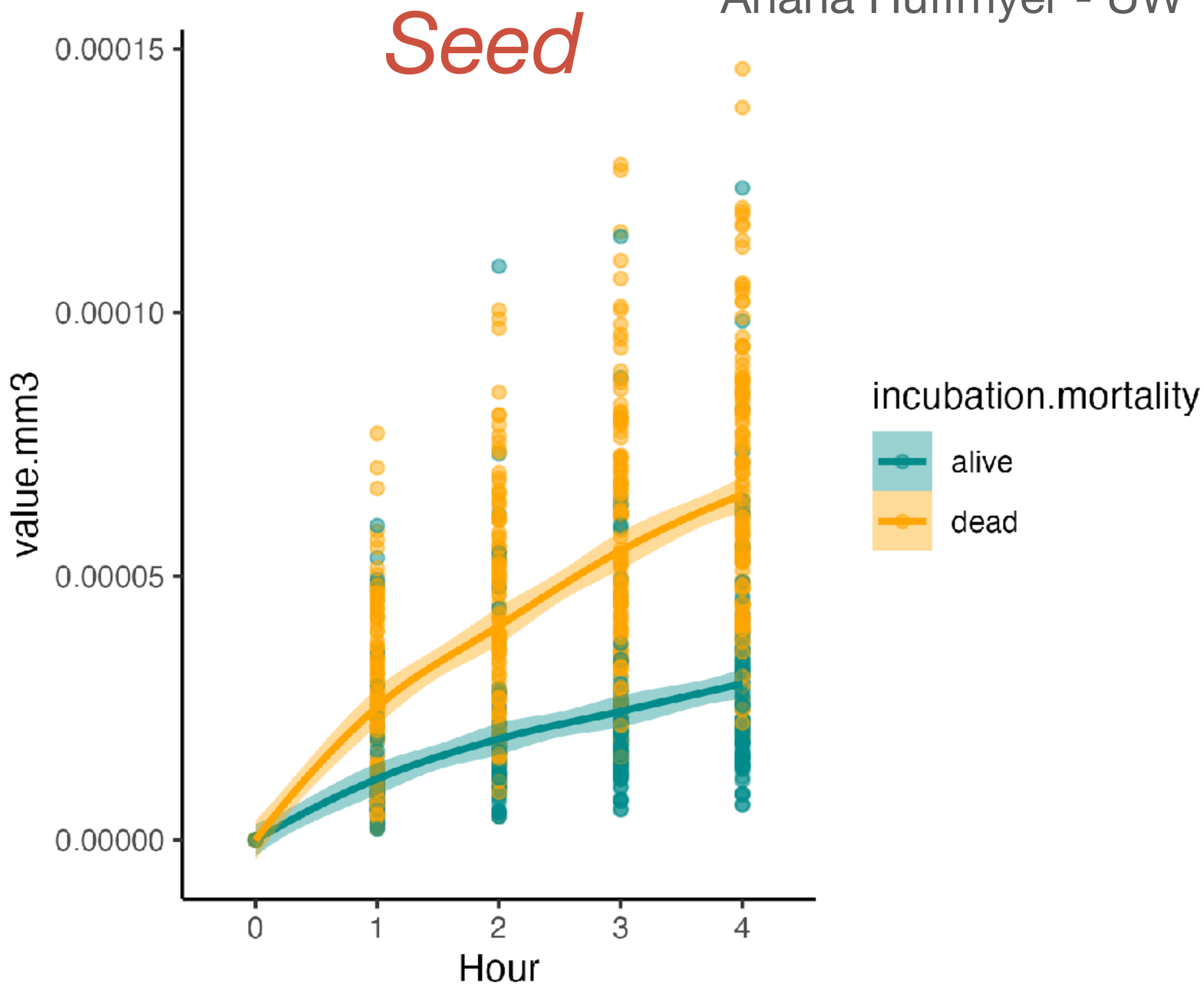
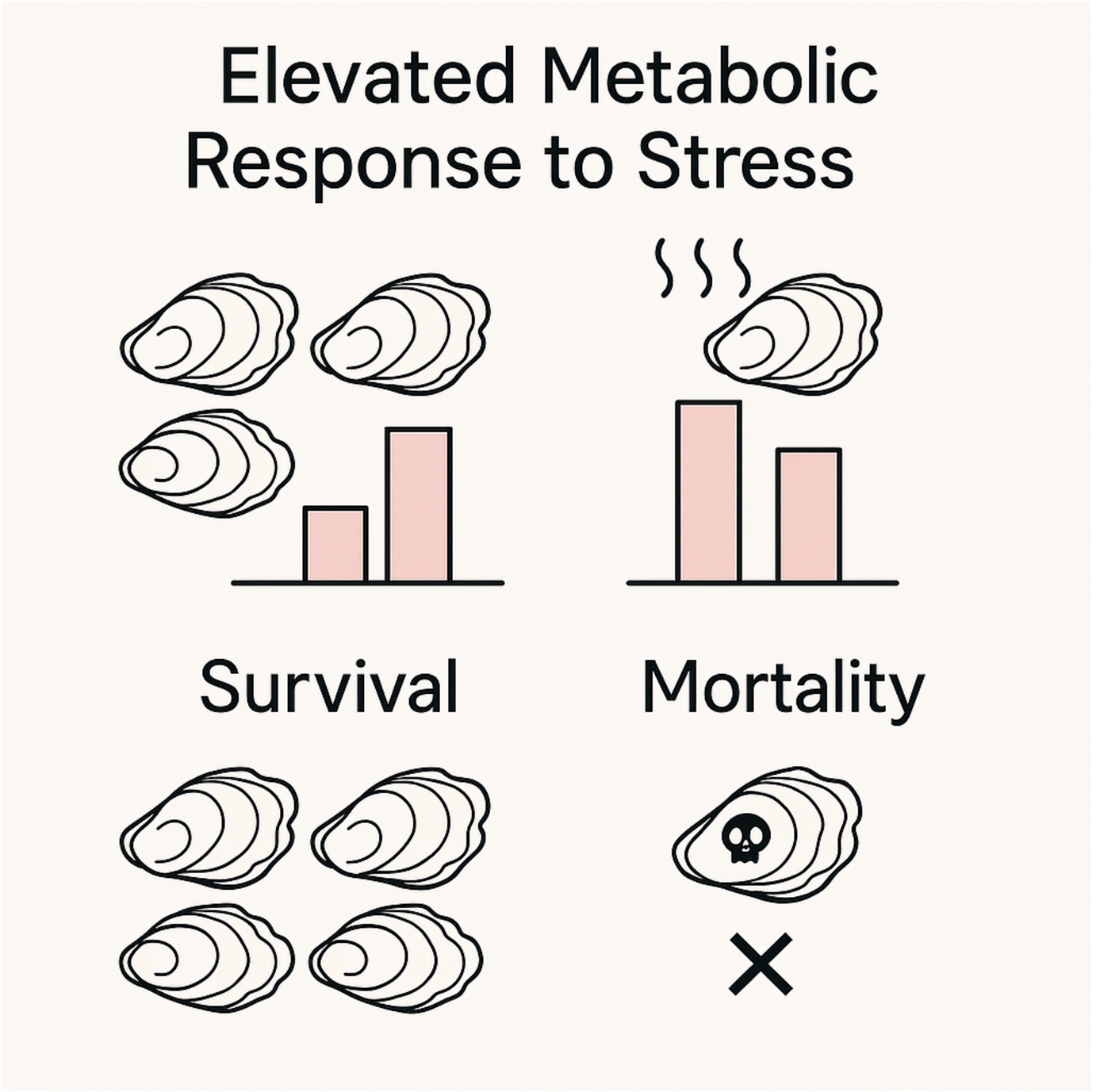
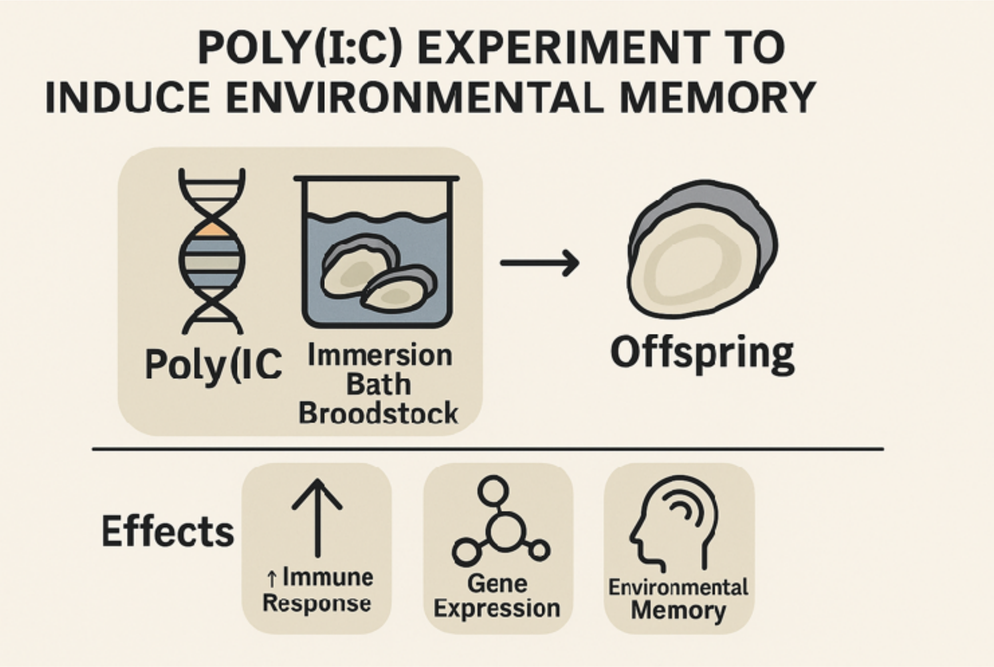


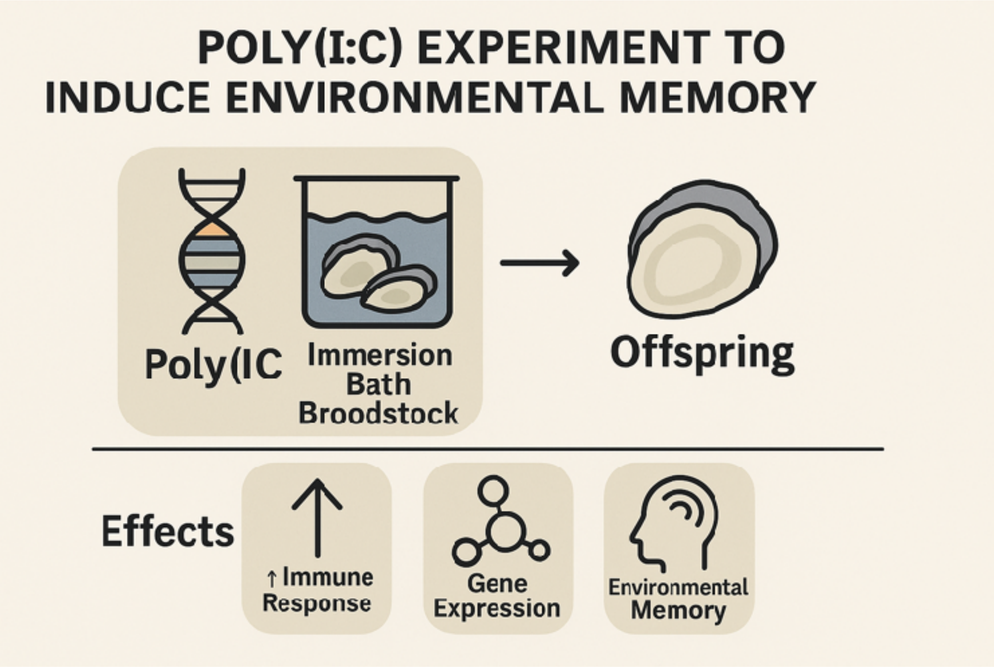
Applications

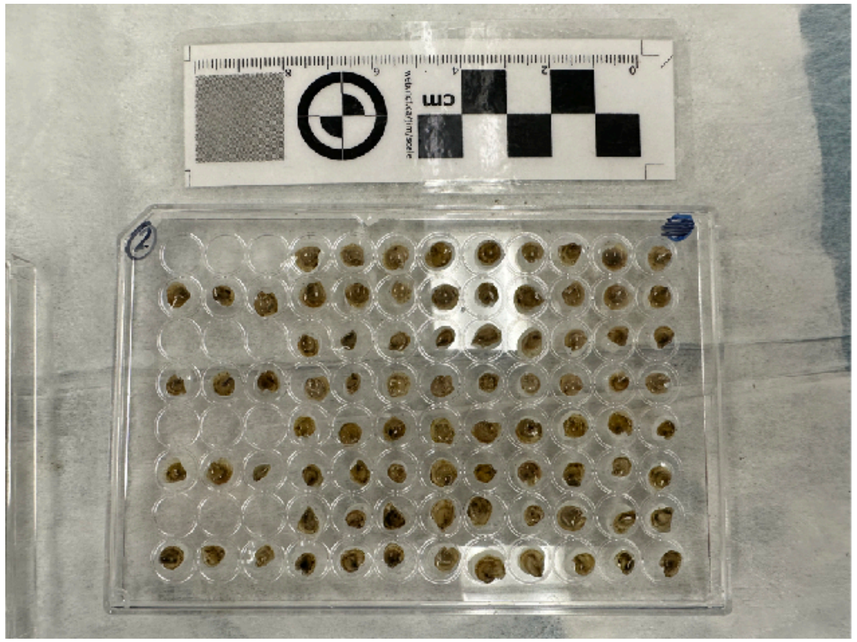


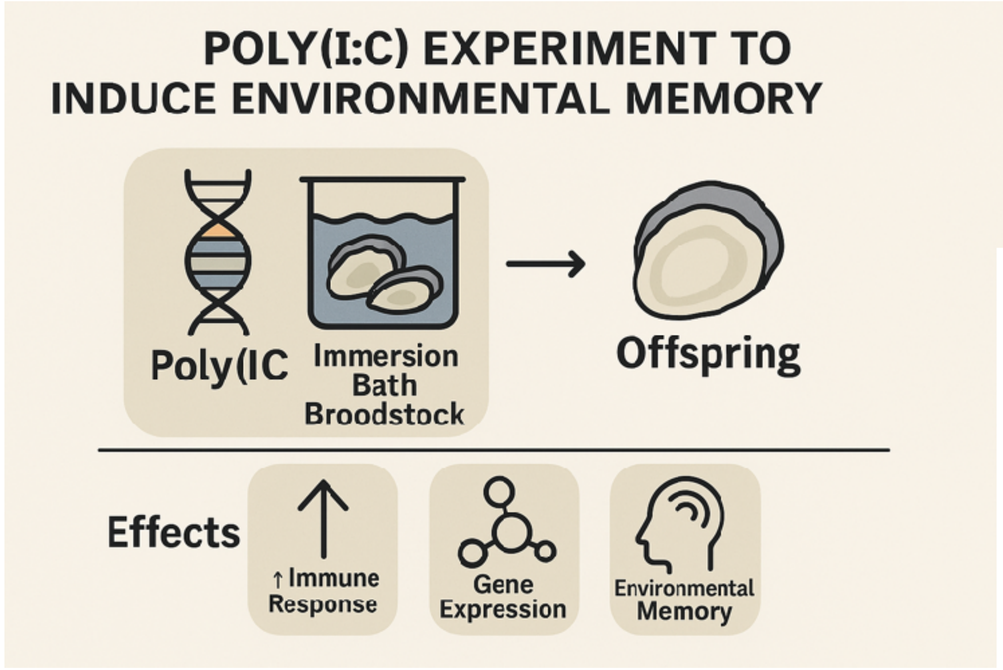


Ariana Huffmyer - UW

Ariana Huffmyer - UW

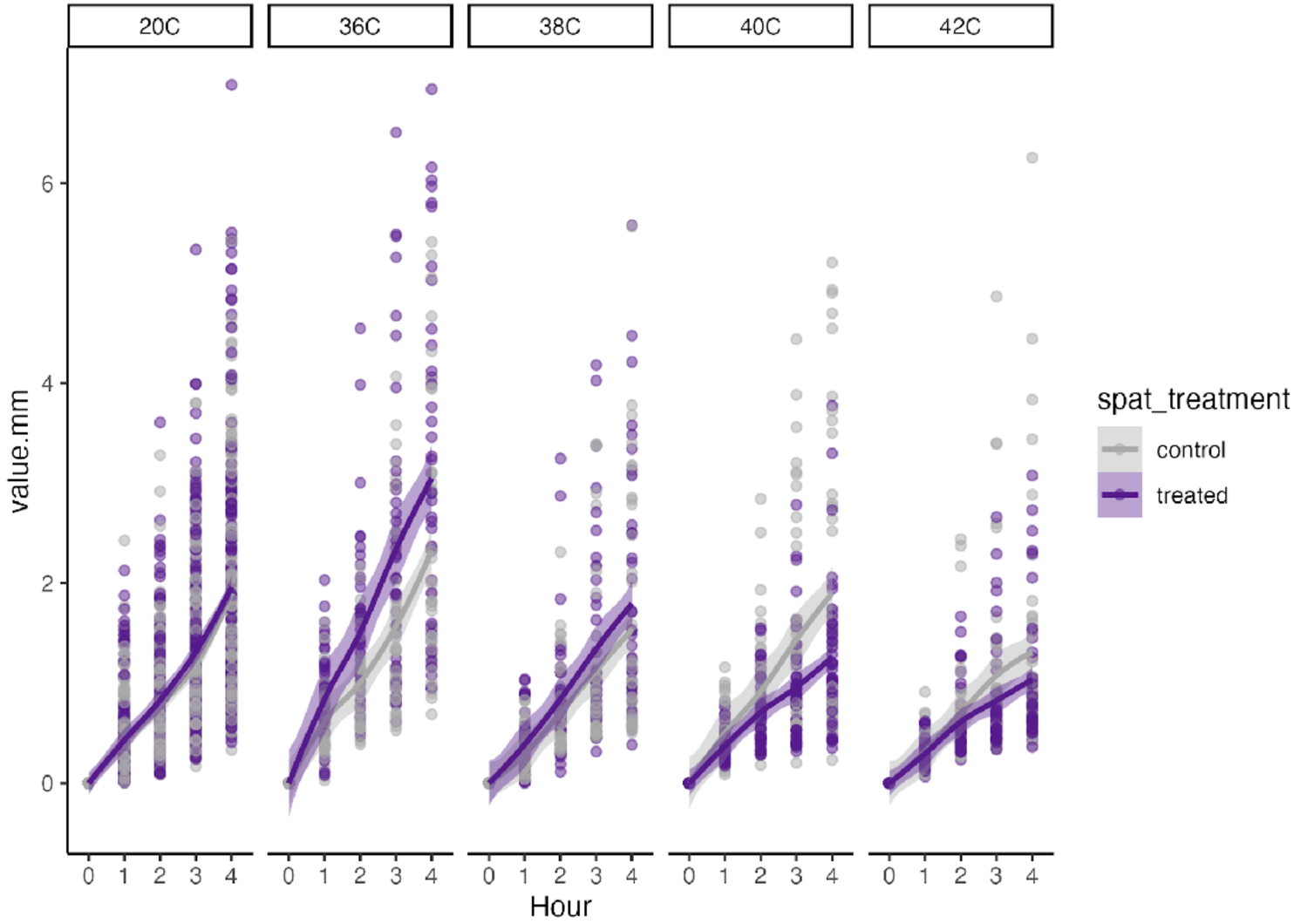




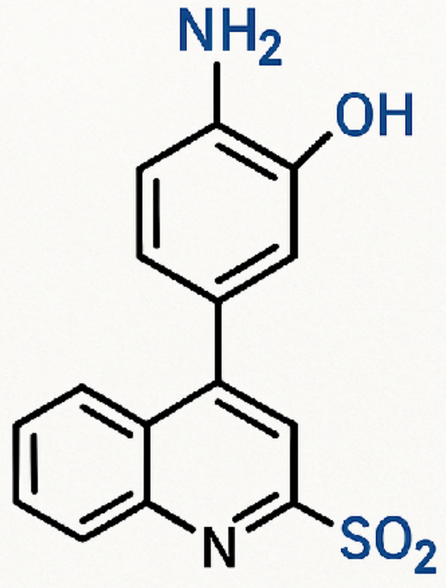


Ariana Huffmyer - UW

Offspring from immune-challenged parents exhibited ***greater metabolic flexibility***

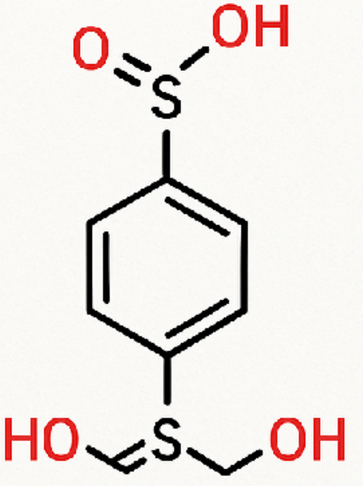


Using Resazurin Assay to Study Oysters and Improve Aquaculture



Resazurin (oxidized)

metabolic activity →



Resorufin (reduced)

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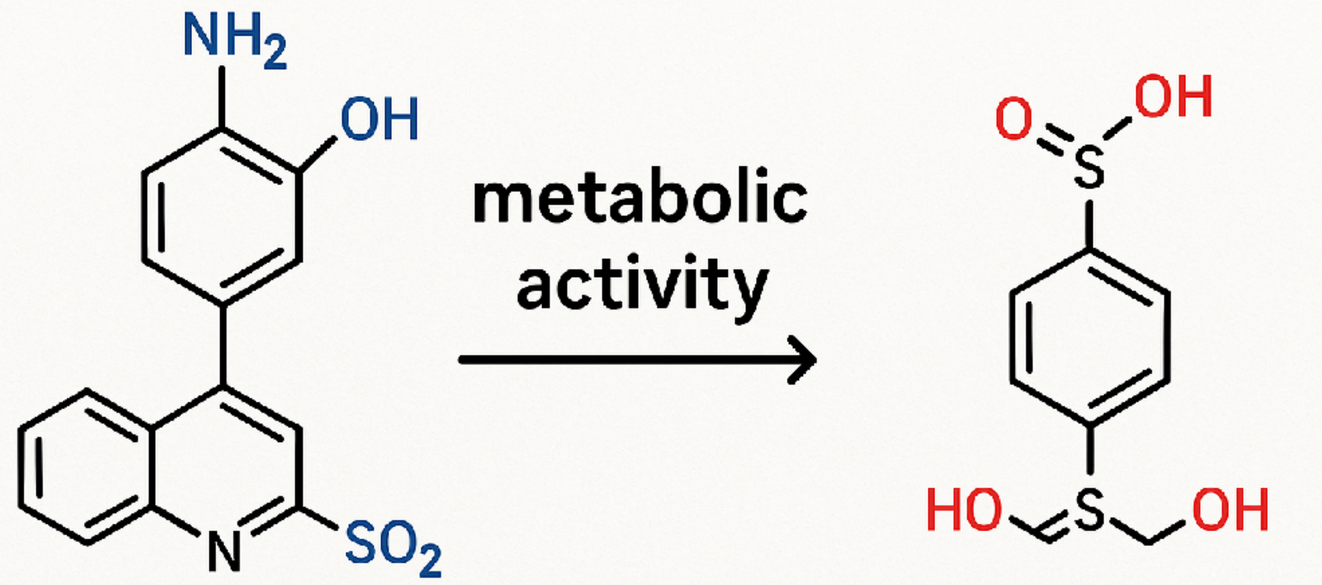

Resazurin (oxidized)

Resorufin (reduced)

Next Step

Using Resazurin Assay to Study Oysters and Improve Aquaculture

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Performance Testing

Development of SORMI (Summer Oyster Resilience and Mortality Index)
A quantitative tool for improving field survival

Bobbi Hudson - Pacific Shellfish Institute (Lead)
Neil Thompson - USDA-ARS Pacific Shellfish Breeding Center
Mackenzie Gavery - NOAA Northwest Fisheries Science Center
Kevin Marquez Johnson - California Polytechnic State University and California Sea Grant

- Performance Testing
  - Survival
  - Growth
  - Metabolism*

Predicting Performance

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Development of SORMI (Summer Oyster Resilience and Mortality Index)
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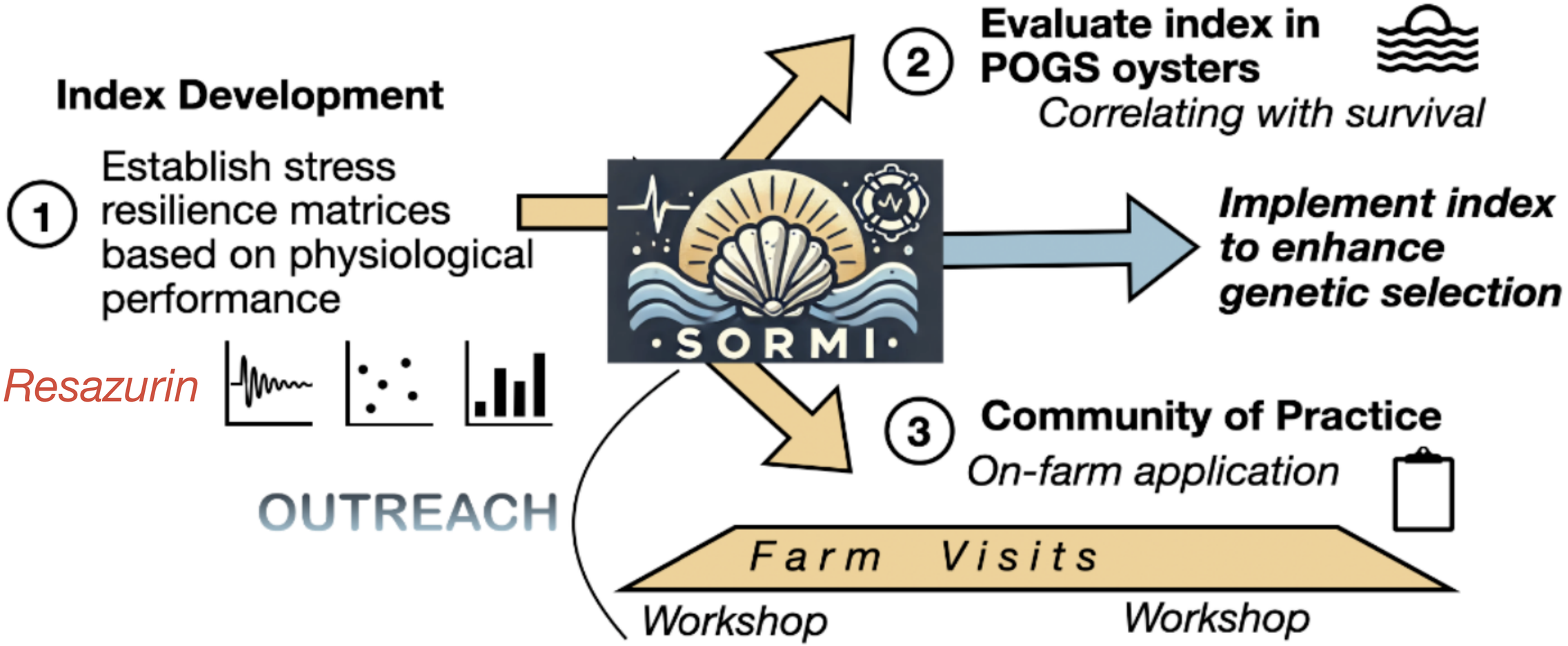

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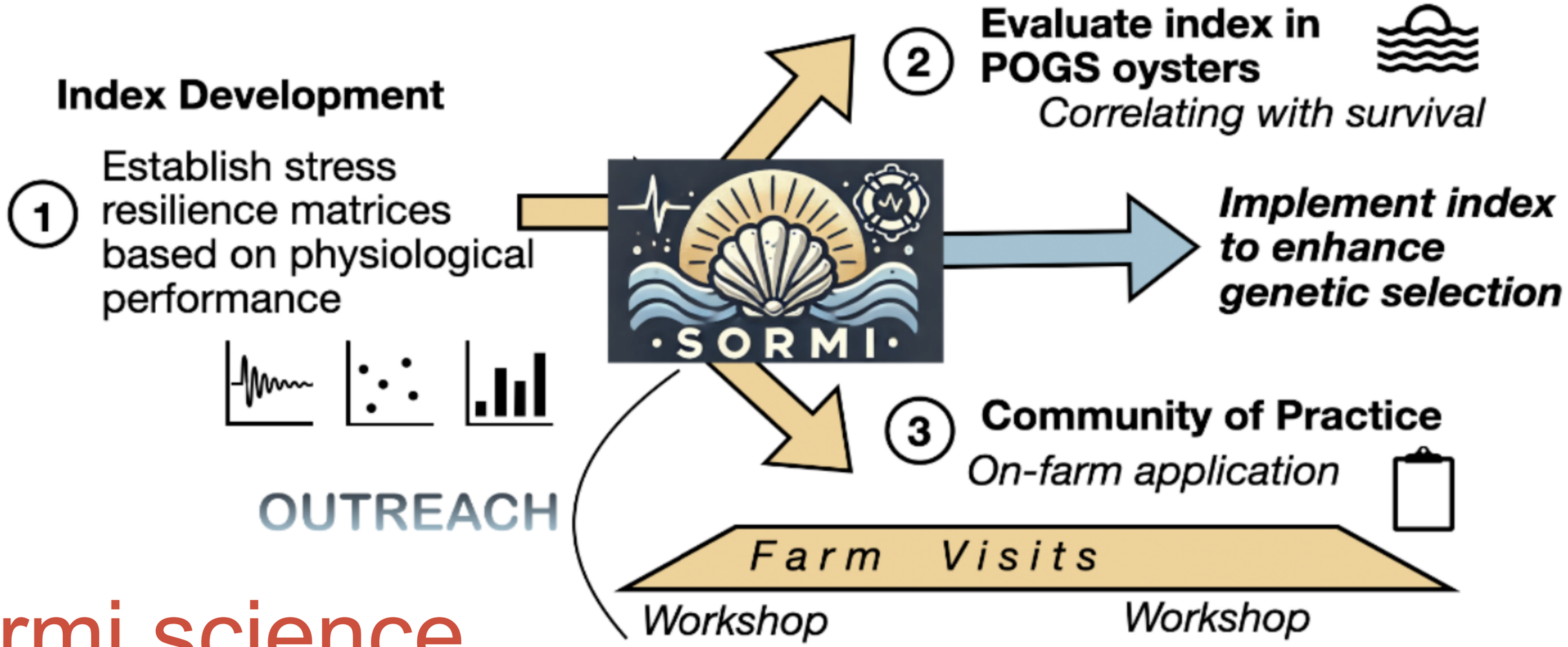

sormi.science

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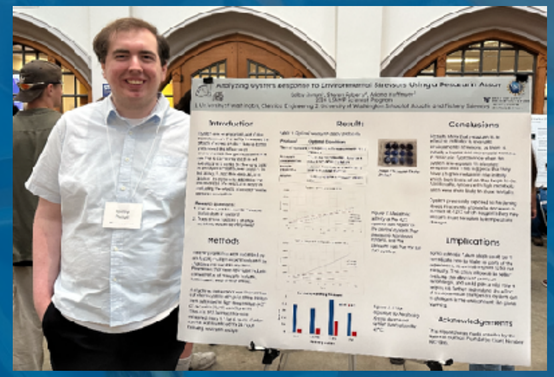

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