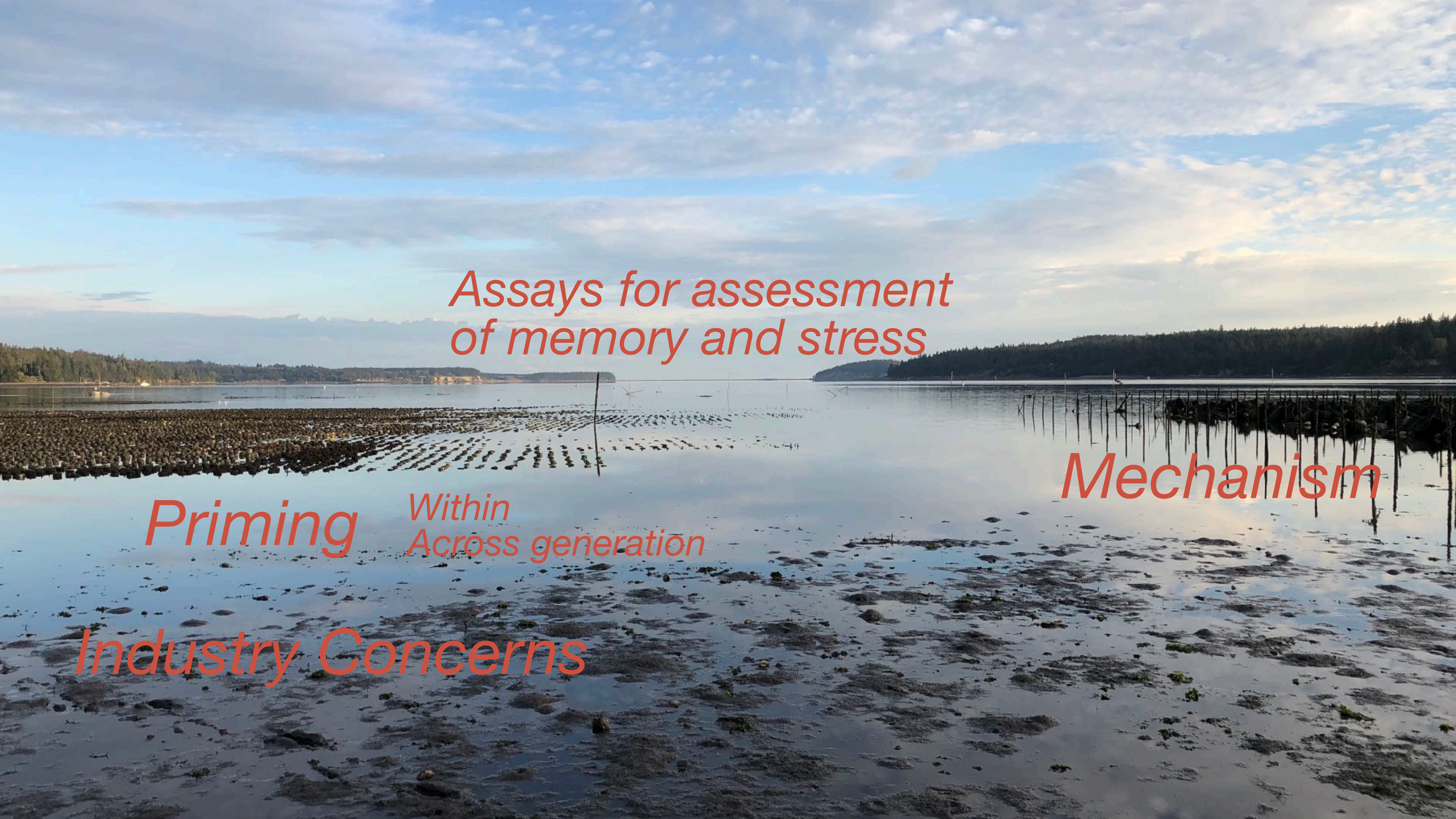
Shellfish Environmental Memory

Beyond Epigenetics

Steven Roberts

github.com/sr320/talk-EpiAqua-2026


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

Industry Concerns

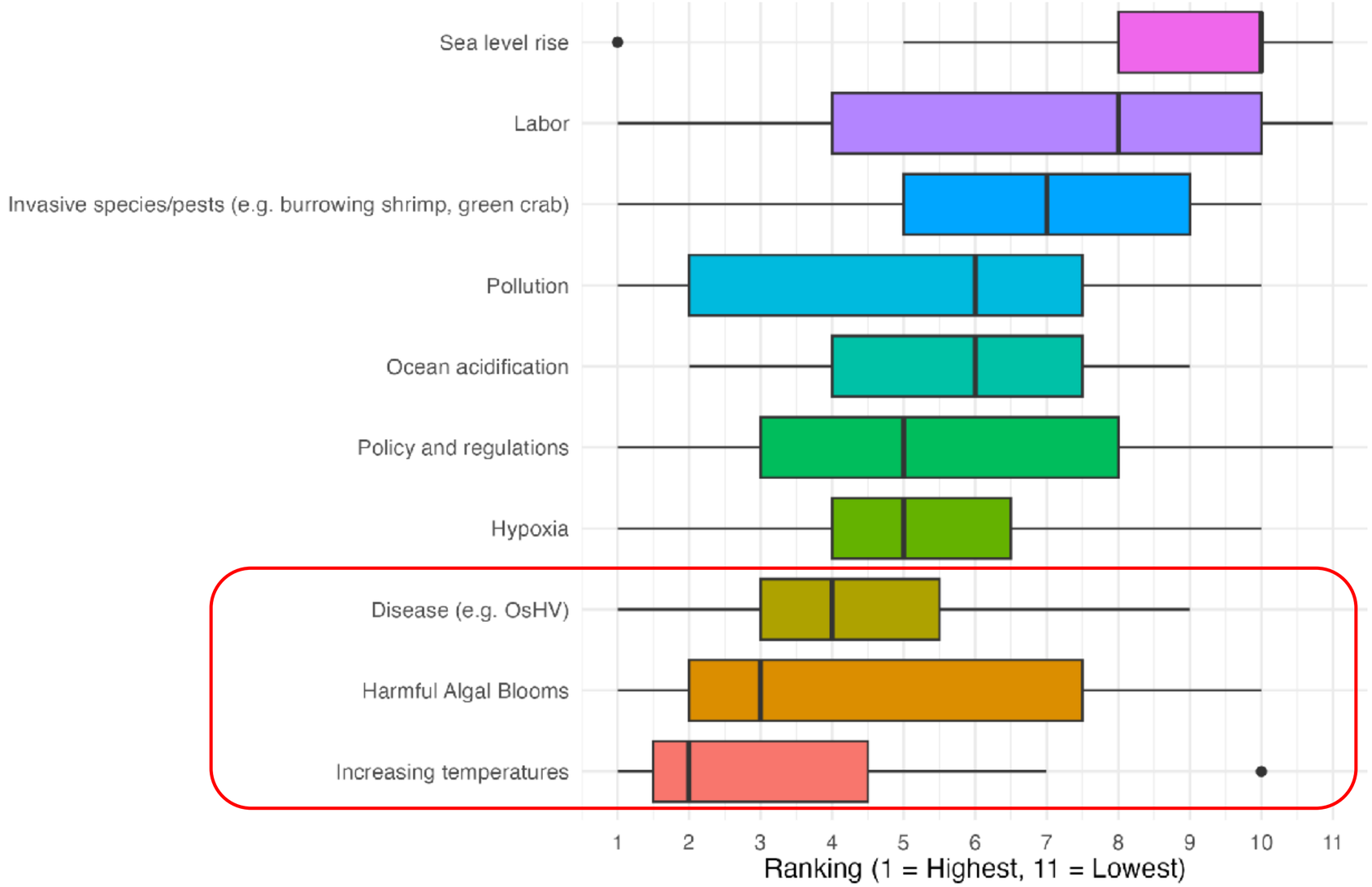
Grower Survey:
Perceptions of threats and proposed adaptation strategies

- 20-30 min interview:
  - Ranking threats
  - Input on leveraging environmental memory as an adaptation strategy

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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No	21%

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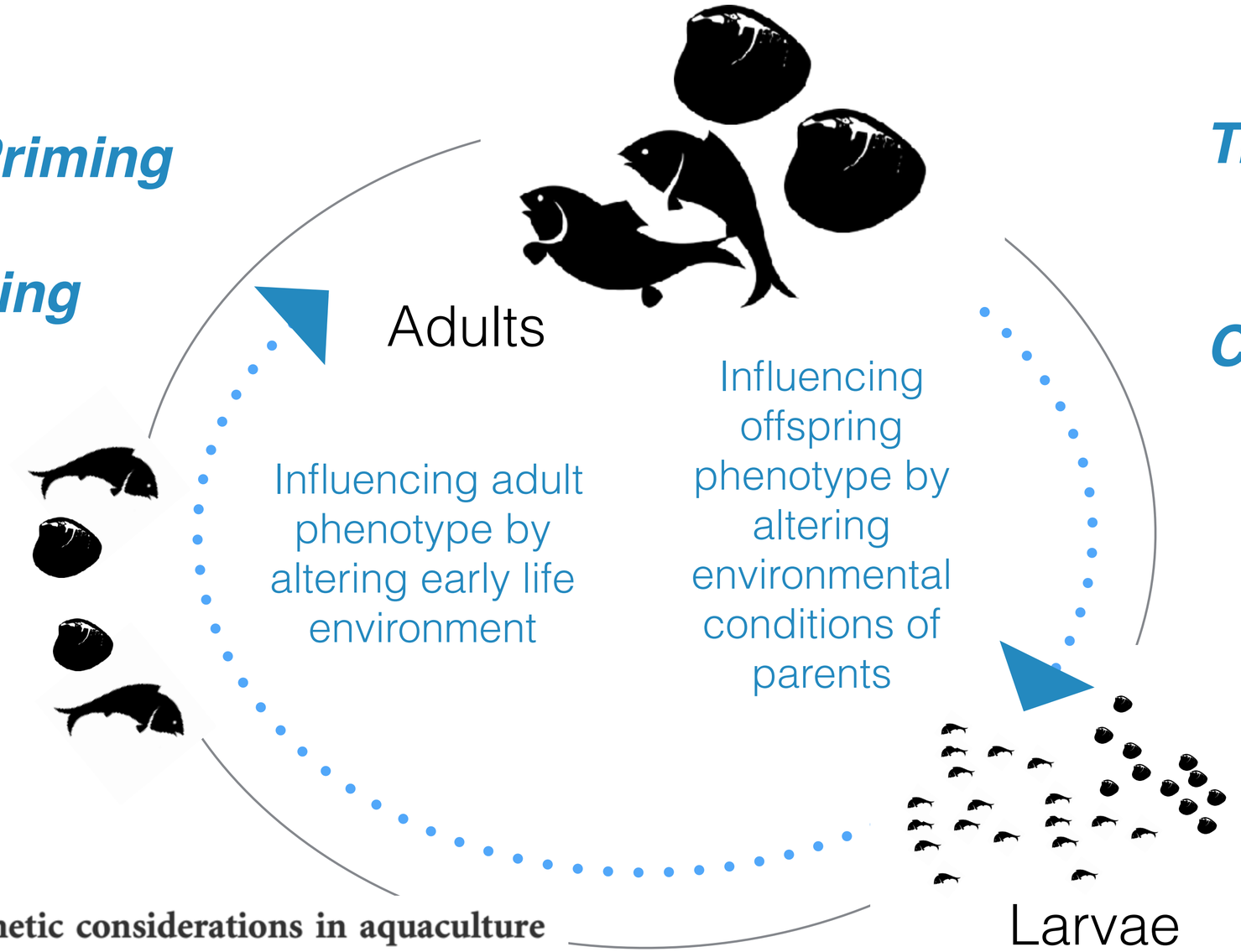
Priming
Industry Concerns

Early-life Priming

Hardening

Transgenerational Plasticity

Carry-over effects



PeerJ

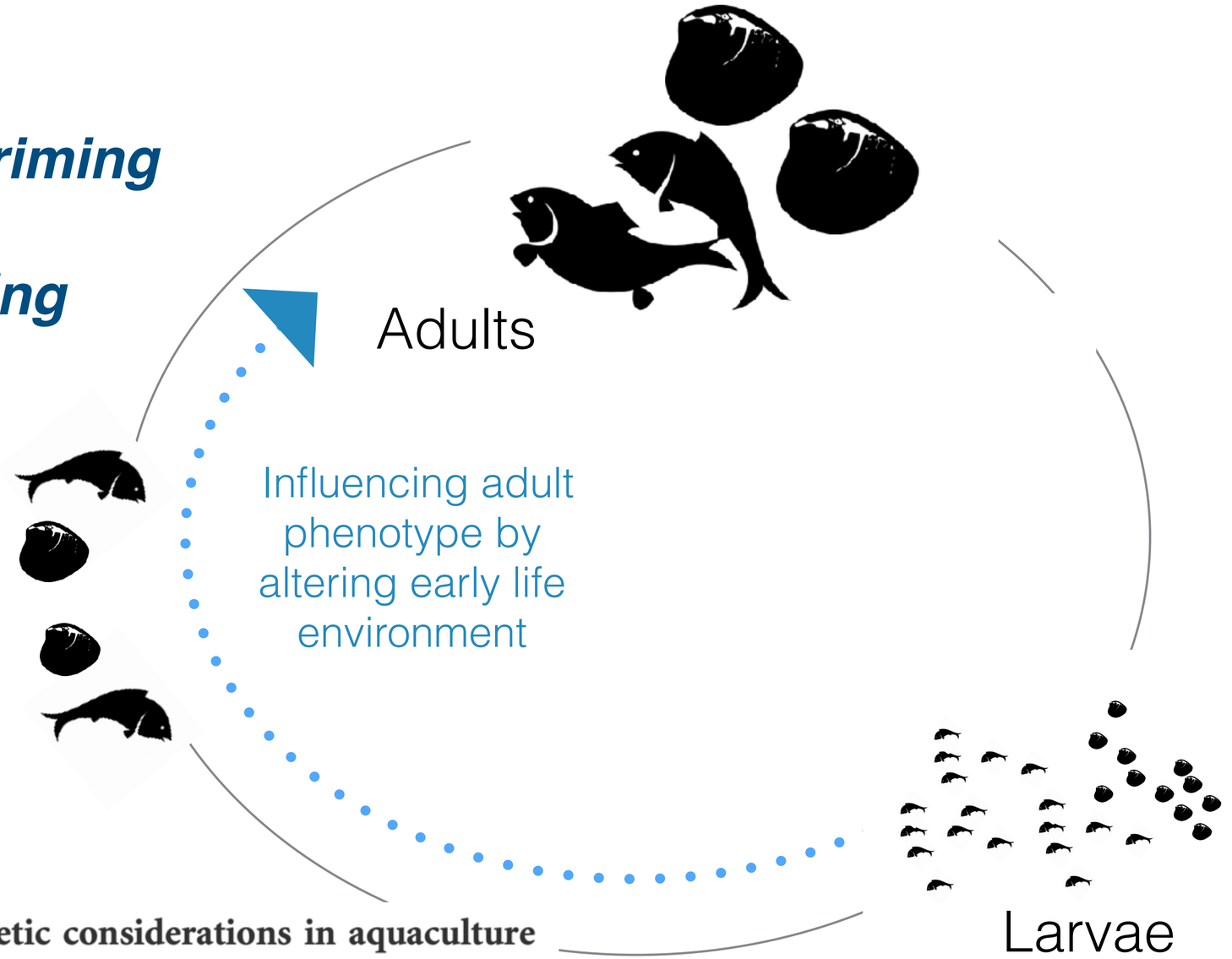
Epigenetic considerations in aquaculture

Mackenzie R. Gavery and Steven B. Roberts

School of Aquatic & Fishery Sciences, University of Washington, Seattle, WA, USA

Early-life Priming

Hardening



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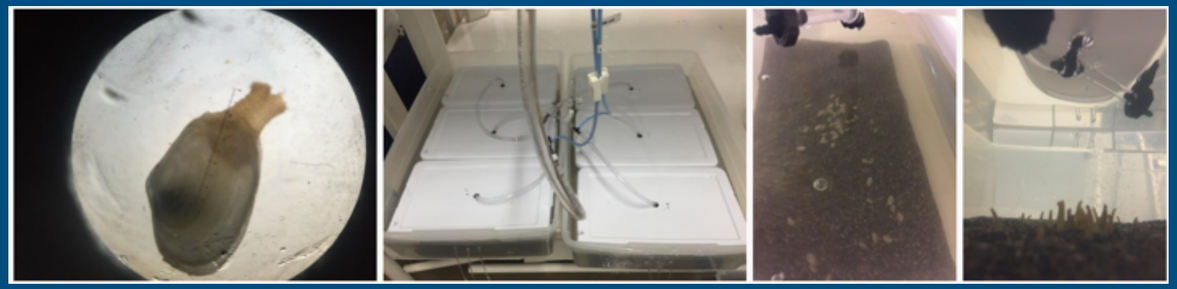
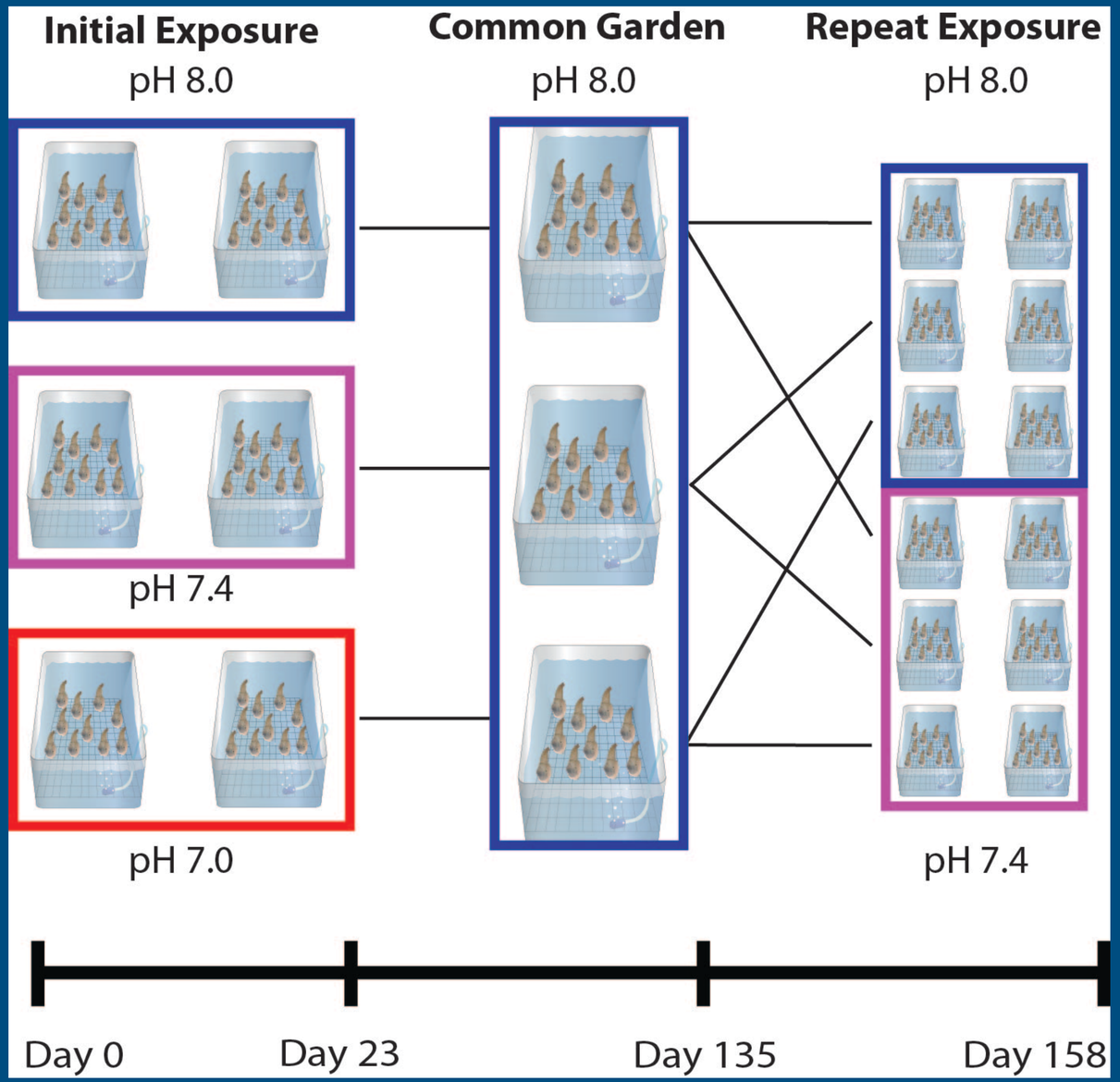
GEODUCKS CLAMS

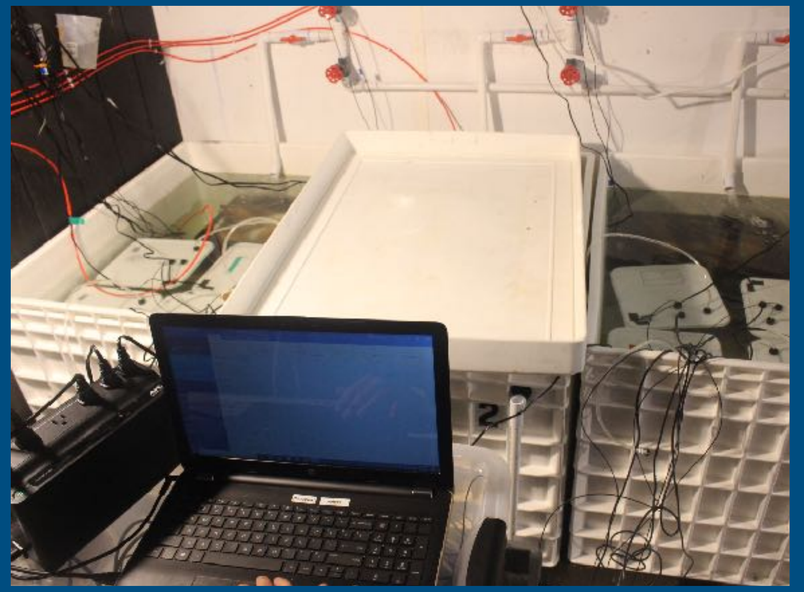


- Does conditioning to low pH confer tolerance within a generation?



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

GEODUCKS CLAMS



GEODUCKS CLAMS

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

Heat-Priming Pacific Oysters: Field Performance vs. Lab Stress Tolerance

Results from an 18-month Sea Grant experiment at Westcott Bay Shellfish

Project Leads: Emily Carrington & Steven Roberts

Research Team: Grace Leuchtenberger & Ariana Huffmyer

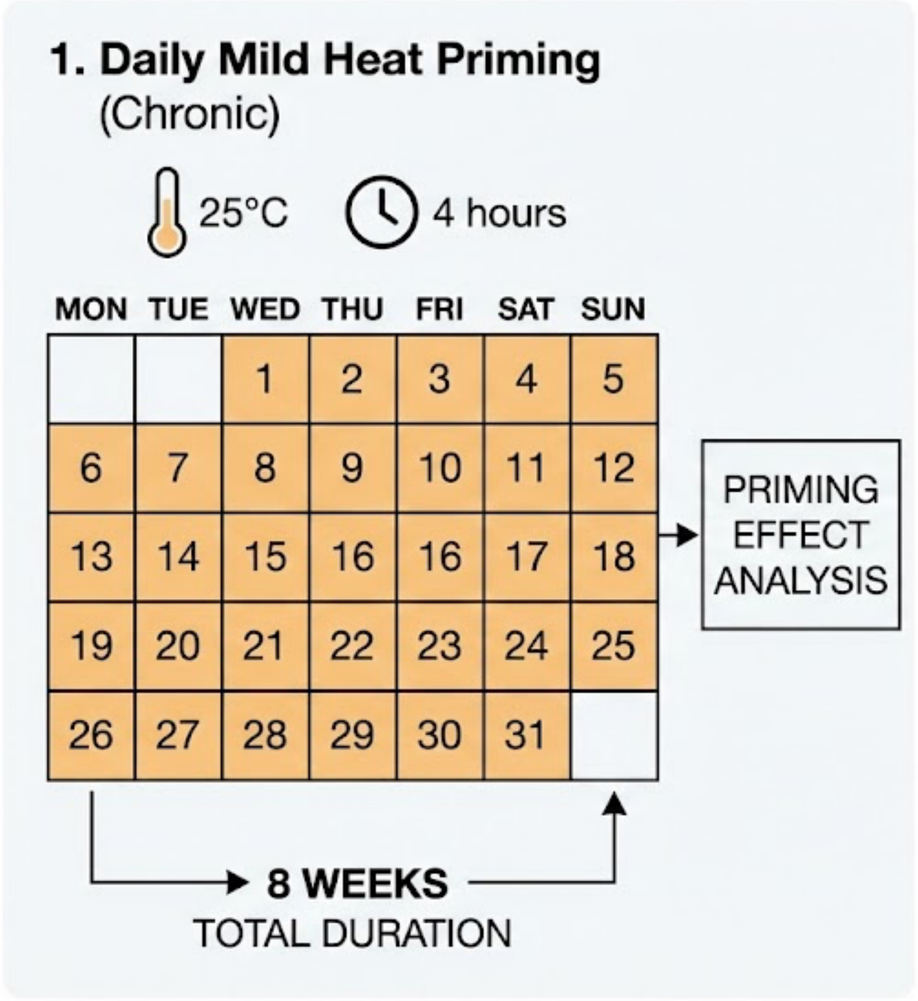
UNIVERSITY of WASHINGTON

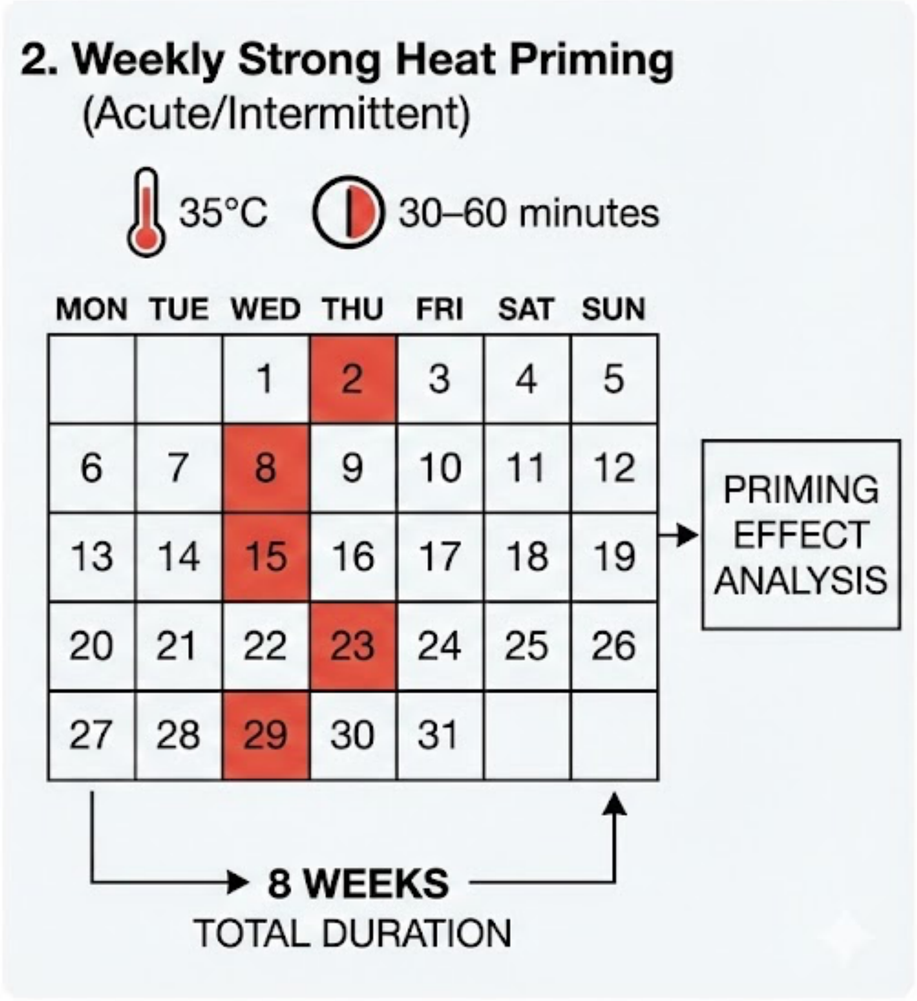
Sea Grant

WESTCOTT BAY SHELLFISH

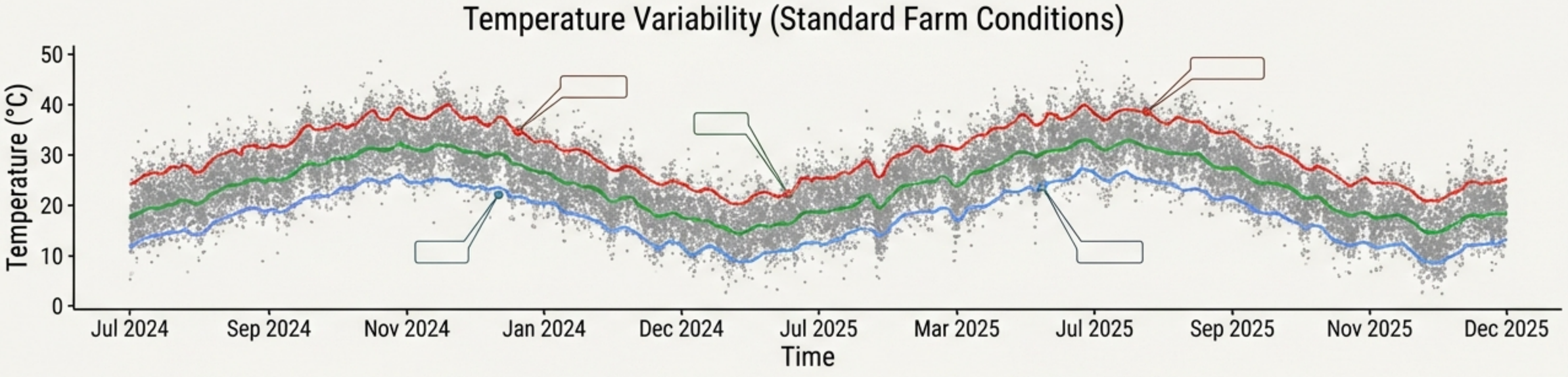
Pacific Oyster

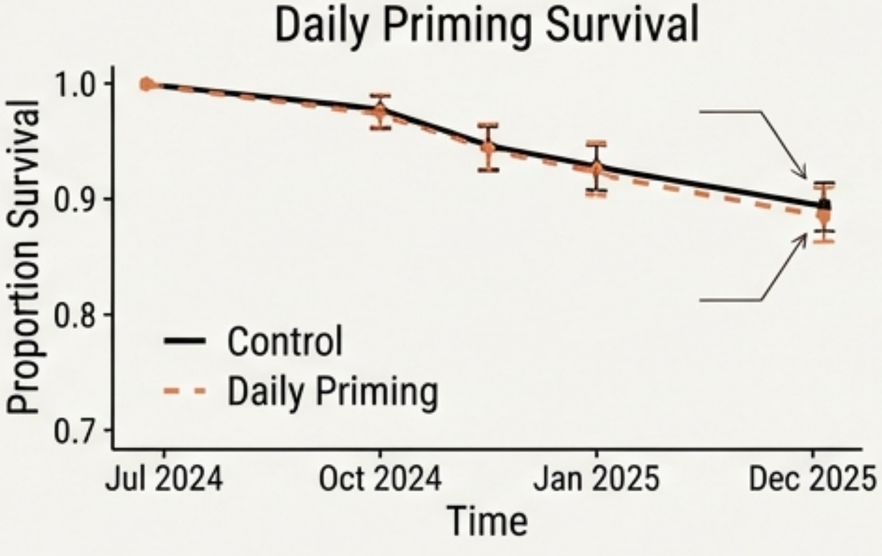
- Priming
  - Temperature
- Performance
  - Survival
  - Growth
  - Metabolism*

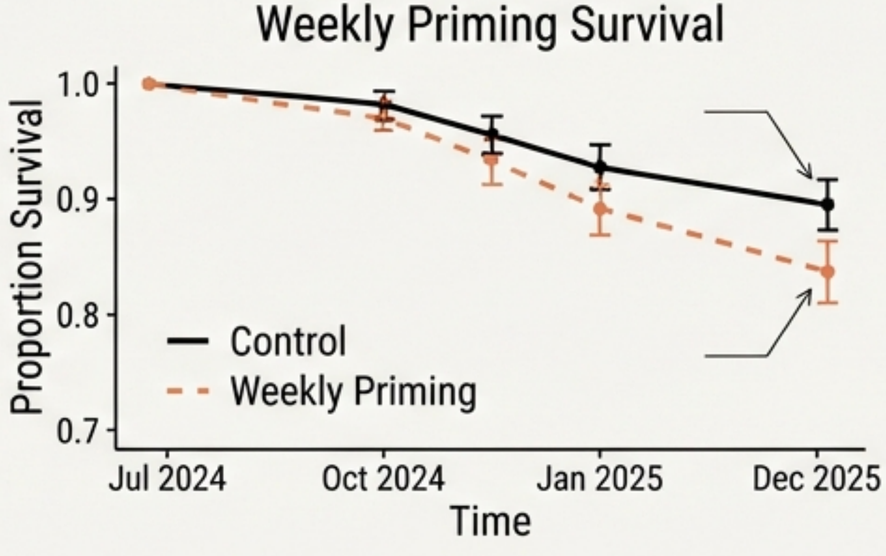




Heat hardening did not improve survival under standard farm conditions.





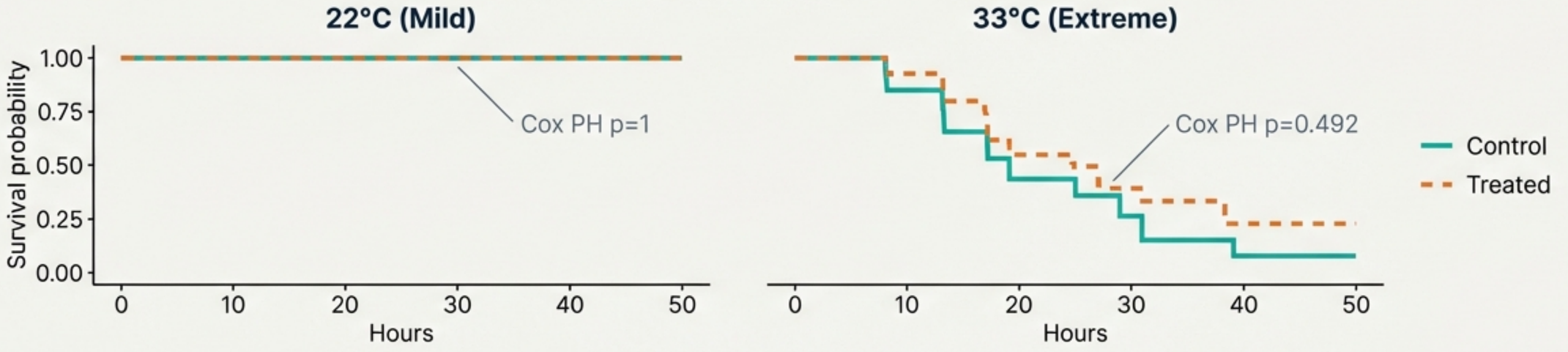


RESULT:

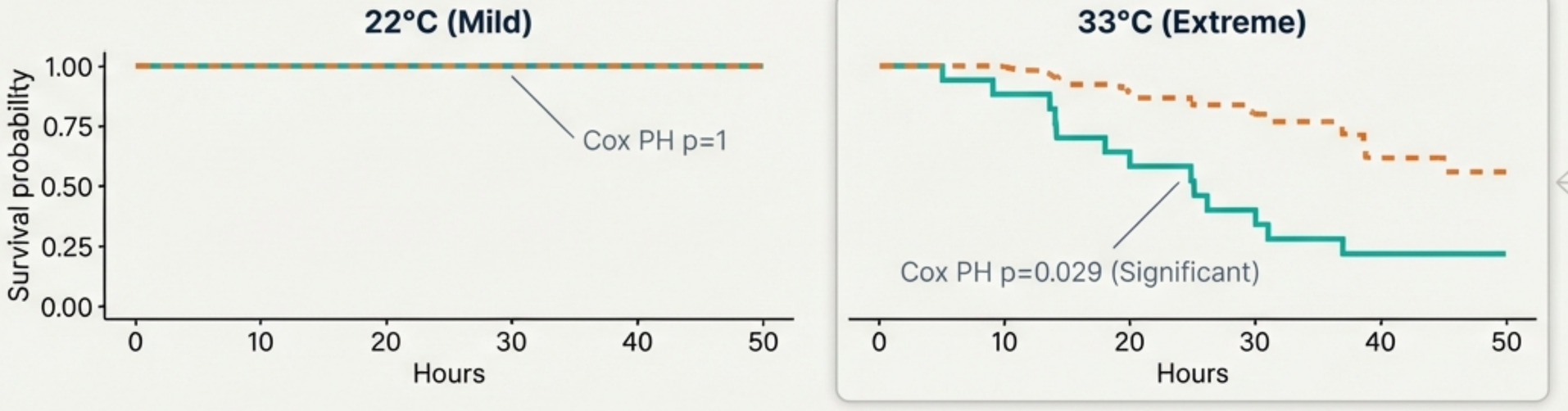
Weekly heat-hardened oysters survived slightly worse (~5% lower) than controls. The energetic cost of priming may have been a disadvantage.

Hardening worked—but only revealed itself under extreme acute stress.

Daily Hardening

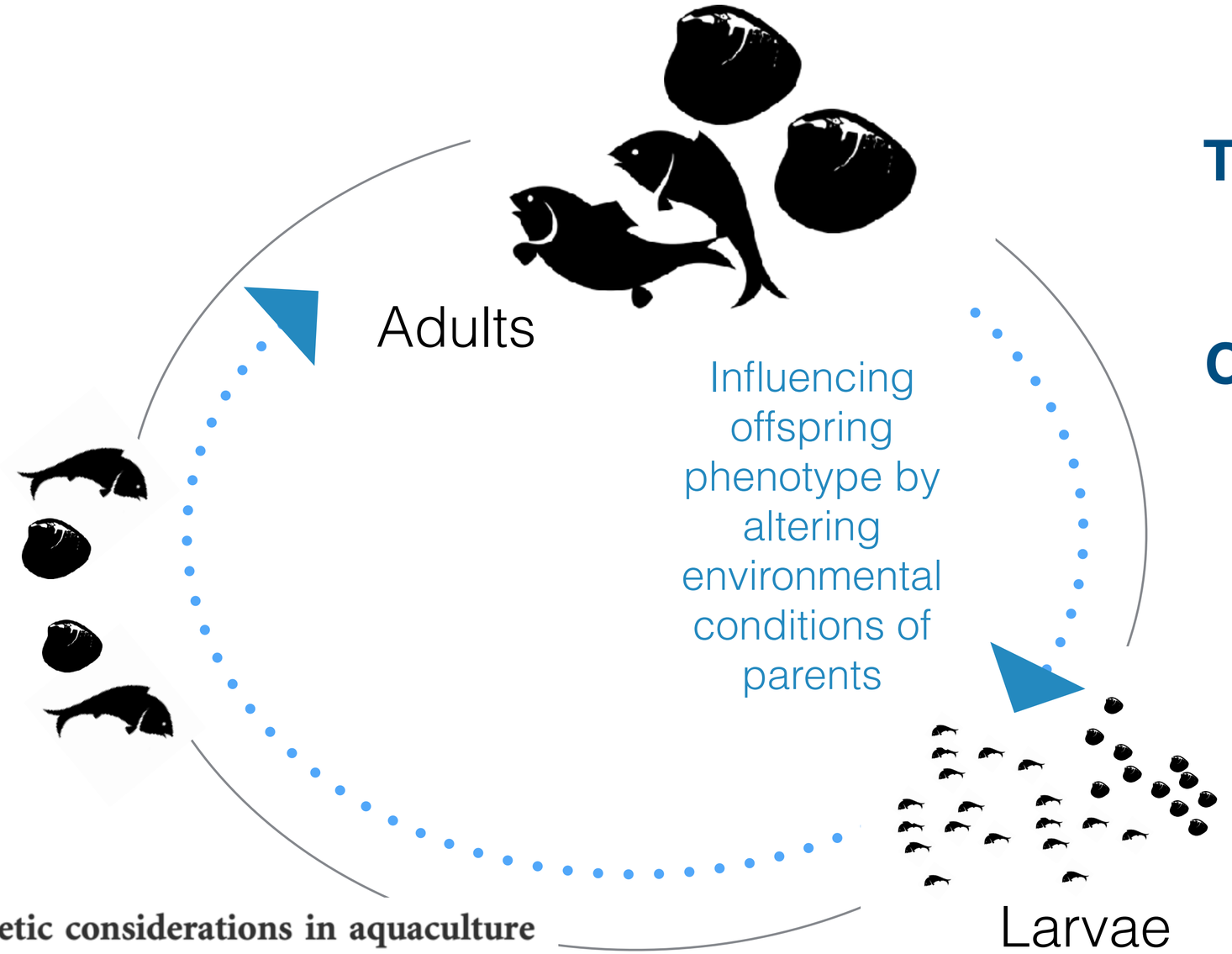


Weekly Hardening



SUCCESS:
Weekly primed oysters showed significantly higher survival during a simulated heat wave.


Priming
Across generation
Industry Concerns



Transgenerational Plasticity

Carry-over effects

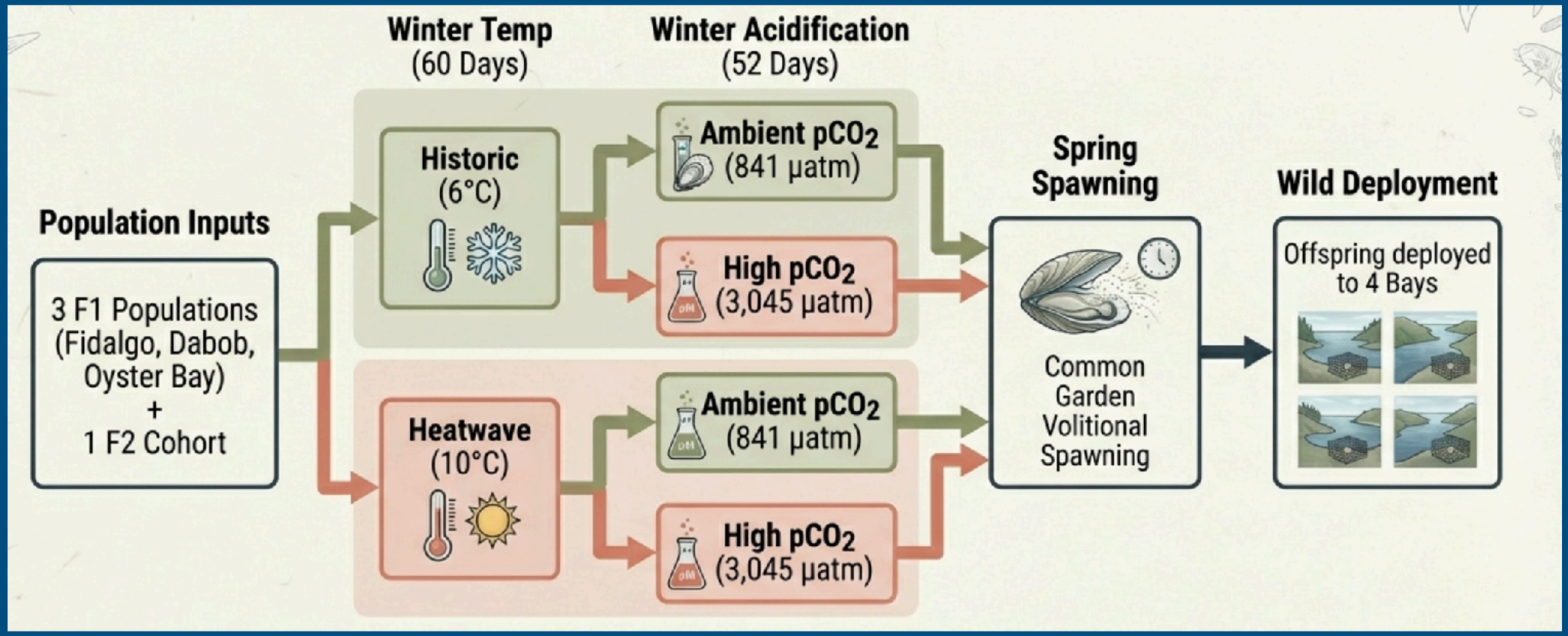
Epigenetic considerations in aquaculture

Mackenzie R. Gavery and Steven B. Roberts

School of Aquatic & Fishery Sciences, University of Washington, Seattle, WA, USA

PeerJ

EFFECTS OF TEMPERATURE AND OA IN OLYMPIA OYSTER POPULATIONS



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]

LAURA SPENCER

EFFECTS OF TEMPERATURE AND OA IN OLYMPIA OYSTER POPULATIONS

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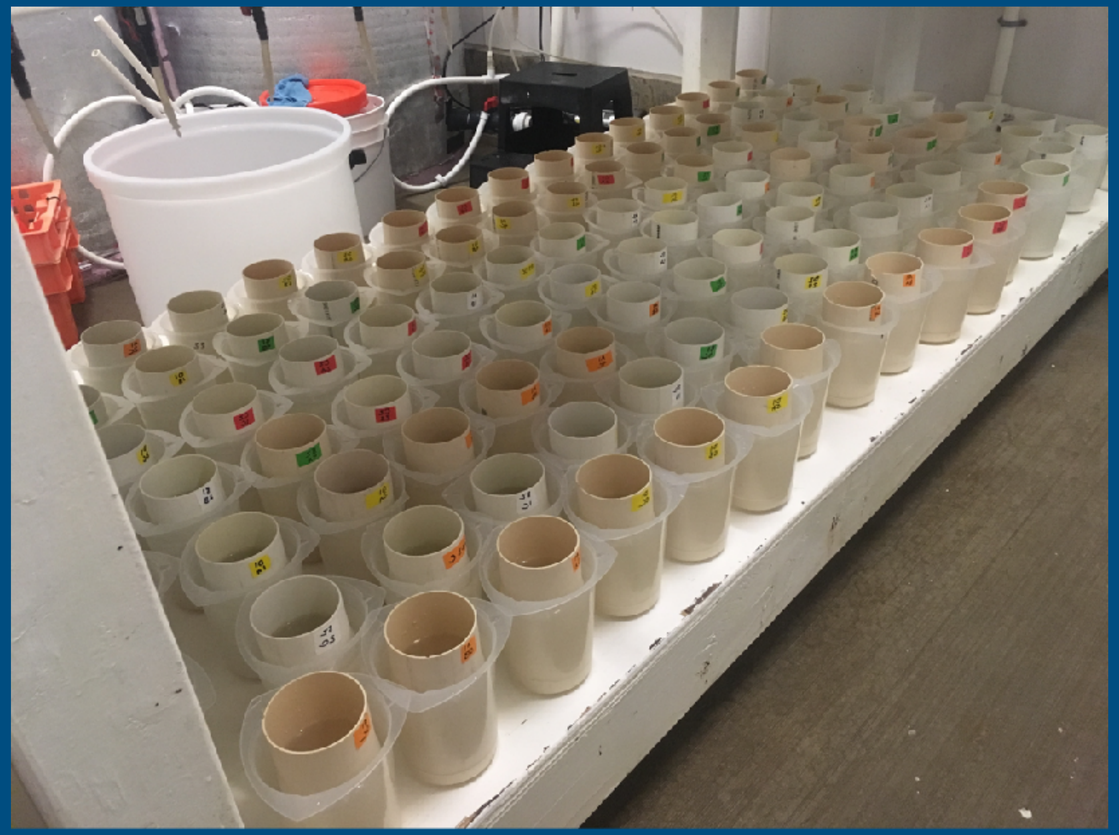
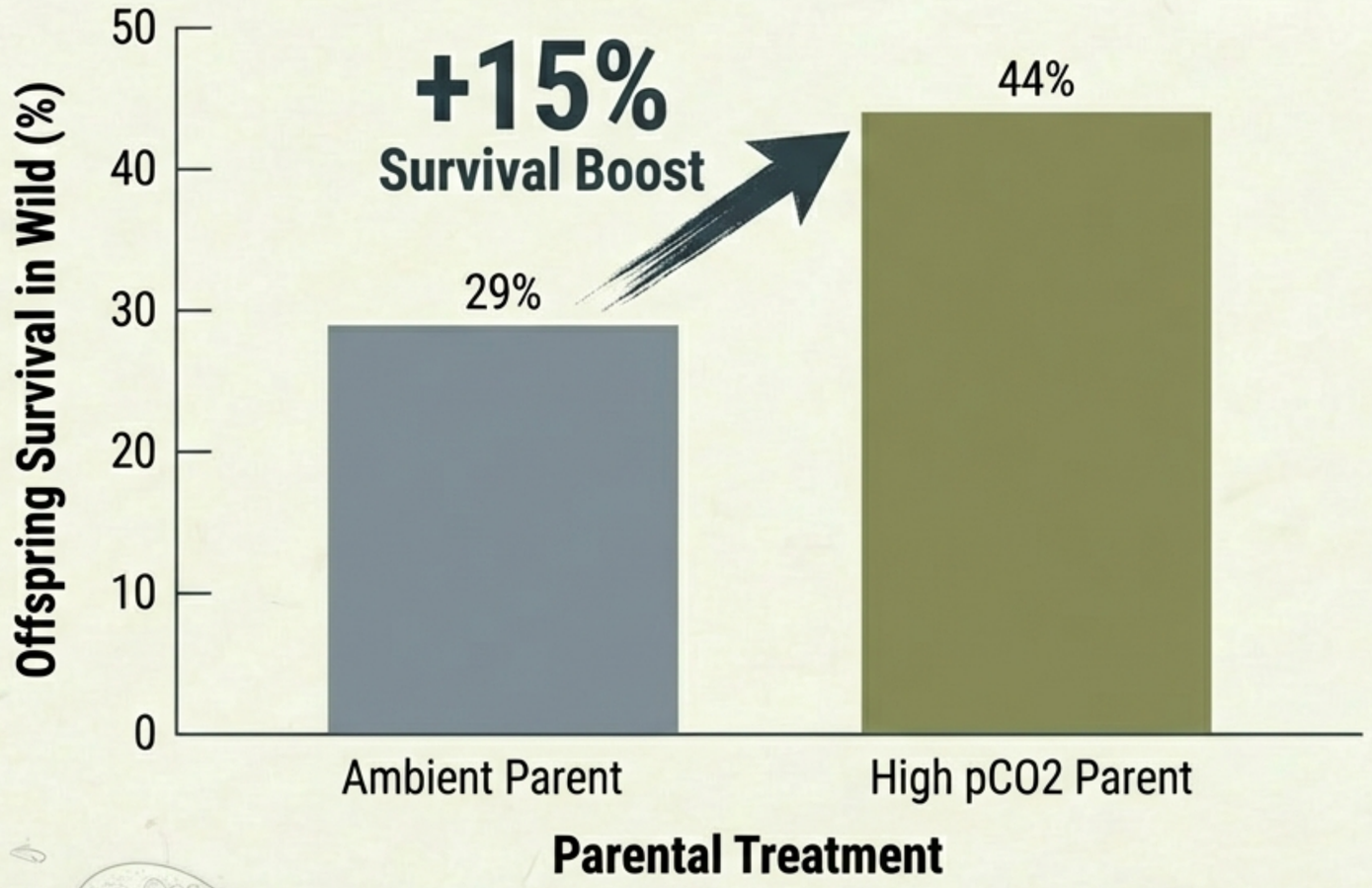


- Larval release occurred earlier in warm-exposed oysters
- Winter warming conditions increased larval production
- No effects on larval survival were detected
- **Juveniles of parents exposed to elevated pCO_2 had higher survival rates in the natural environment**

Stress as Preparation: The Beneficial Carryover



- **Finding:** Offspring of parents exposed to High pCO2 had significantly higher survival rates.
- **Interpretation:** Intergenerational Plasticity. The parents "primed" the offspring for a tough environment.

Resilience is Context-Dependent

Significant Survival Boost.
(Low pH / High Salinity Bays)

Significant Survival Boost.

Matching Stressful Environment

No Significant Benefit.

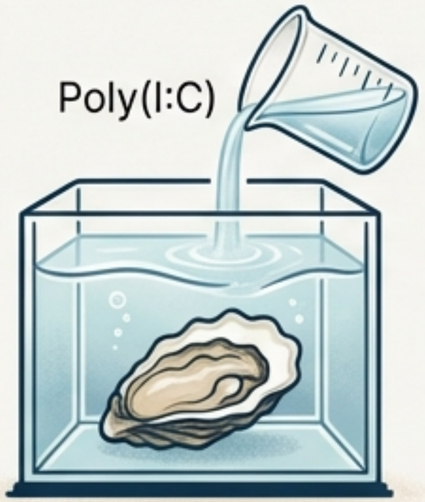
Mismatch

The benefit wasn't universal. The "preparation" provided by parents is most useful when offspring face a matching stressful environment.

The Experiment: Engineering Resilience

Broodstock Exposure

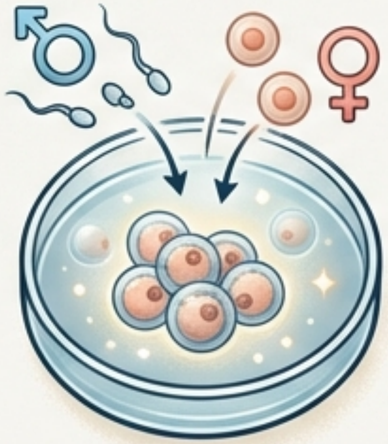
Oct 2024



Adults immersed in Poly(I:C) vs. Control.

Spawning

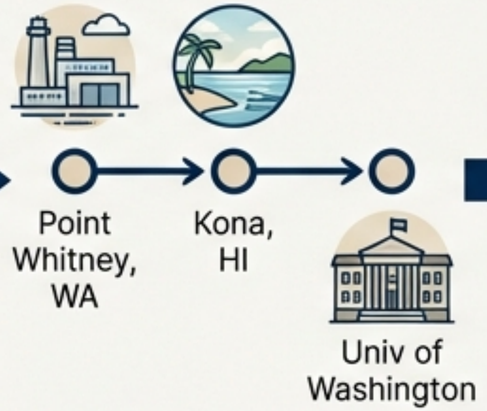
Immediate



Strip spawning following exposure.

Larval Rearing

Oct - Feb



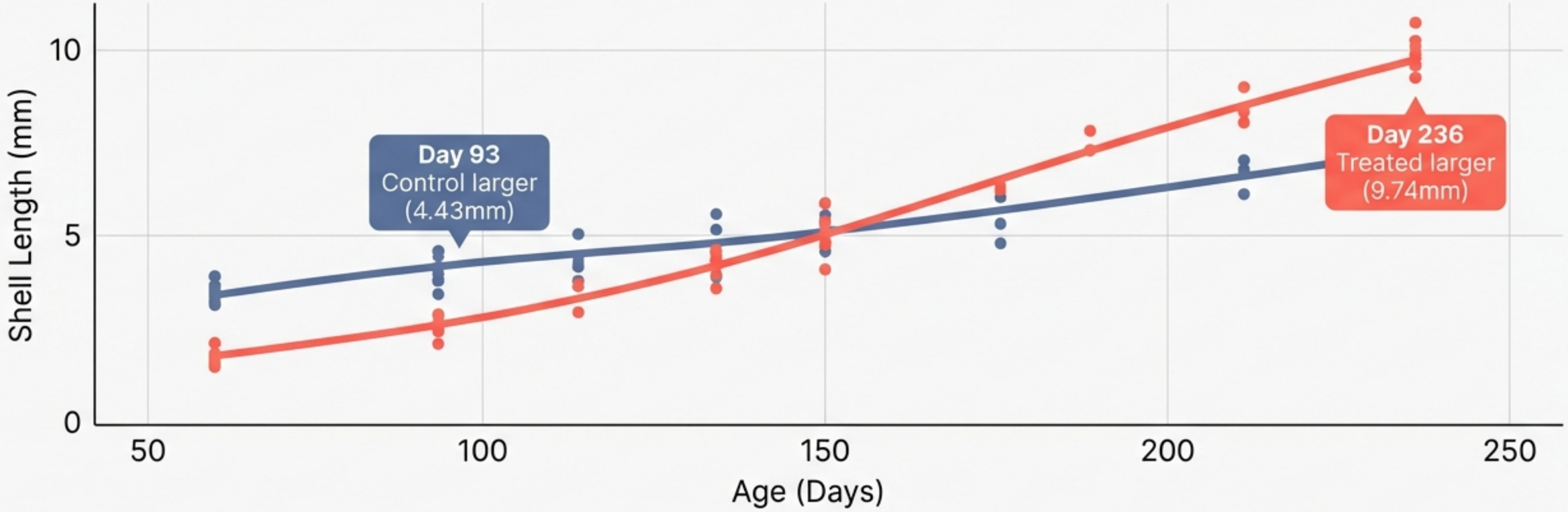
7+ months of development tracked.

The Stress Test

Feb - Mar 2025

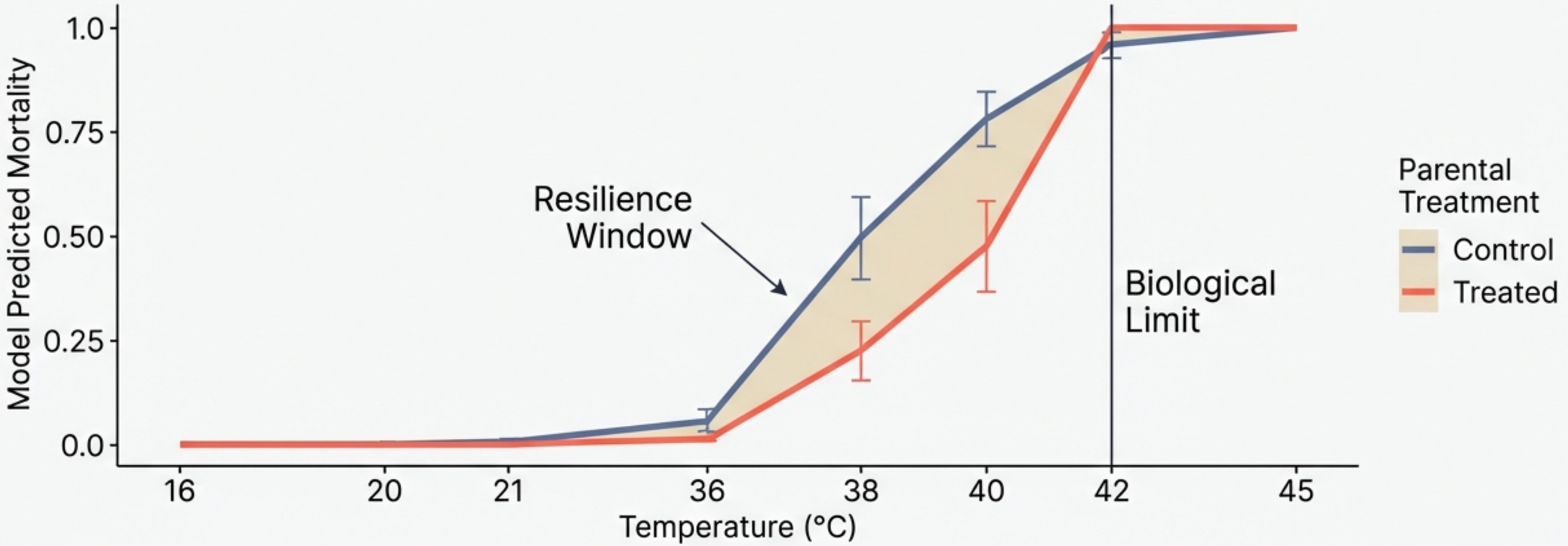
Offspring subjected to extreme thermal stress.

Growth Dynamics: The ‘Catch-Up’ Phenomenon



Insight: Treated offspring started slower—likely investing energy in immune defense—but **accelerated later** to become significantly larger.

Thermal Tolerance: The Resilience Window

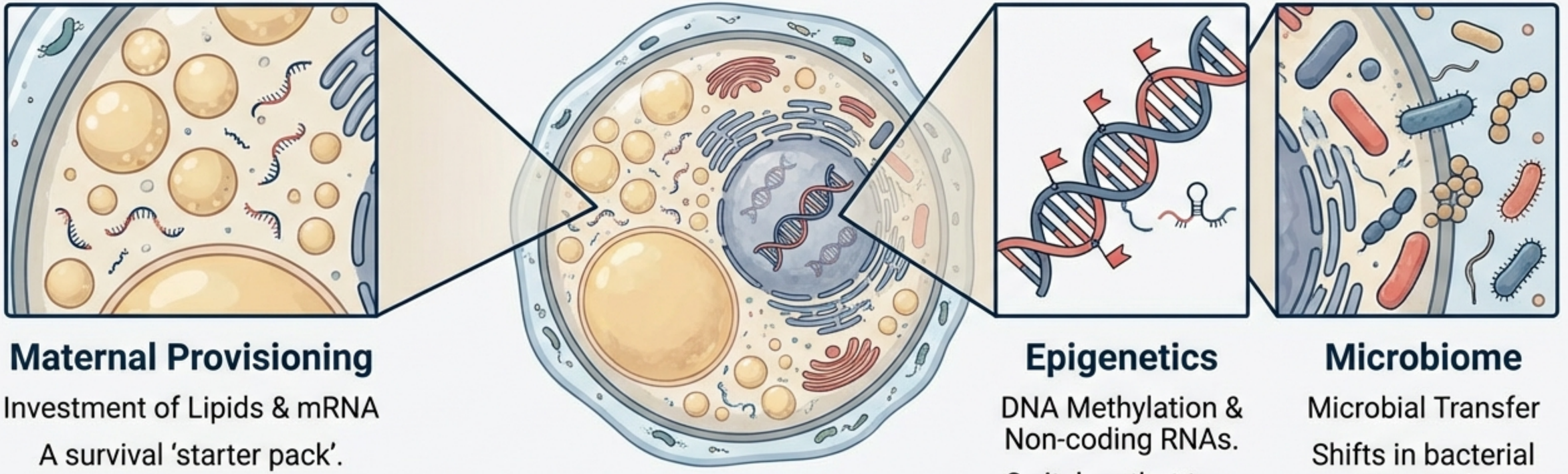


Insight: Priming widens the survival window up to 40°C, creating a ‘buffer zone’ for heatwaves. However, this defense mechanism has a biological breaking point at 42°C.

Cross-Protection: Immune Inputs, Thermal Outputs

The Surprise: Parents were treated with a viral mimic, yet offspring showed heat tolerance. Why? The ‘fire drill’ prepared the cellular machinery for both fire (heat) and intruders (virus).

How is the Message Passed?



Maternal Provisioning

Investment of Lipids & mRNA

A survival ‘starter pack’.

Oyster Egg Cell

Epigenetics

DNA Methylation & Non-coding RNAs.

Switches that turn stress genes On/Off.

Microbiome

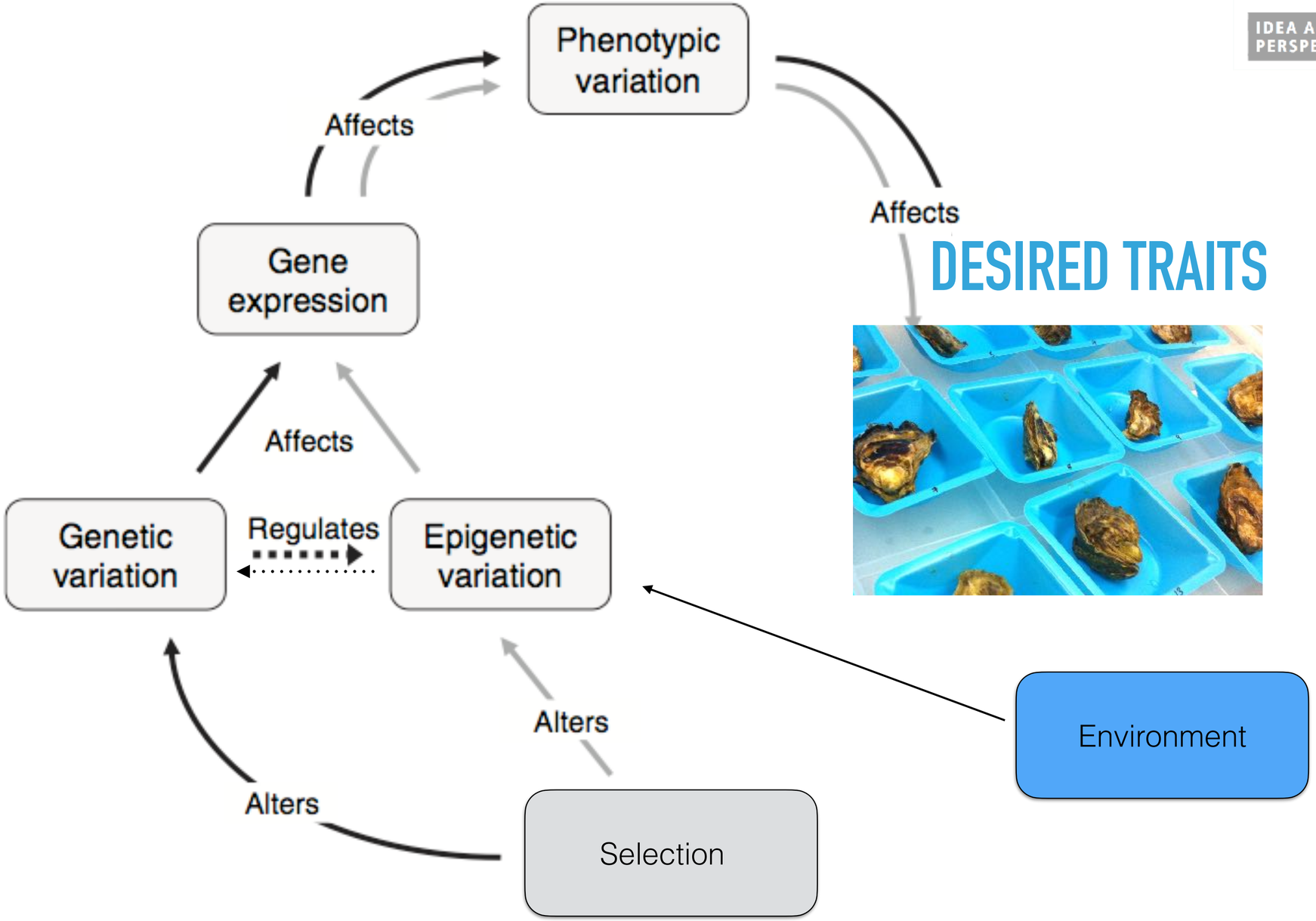
Microbial Transfer

Shifts in bacterial community passed to seed.

Status: Observed effects persisted >7 months, strongly suggesting epigenetic mechanisms beyond simple energy provisioning.


Mechanism
Priming
Within
Across generation
Industry Concerns

ECOLOGICAL EPIGENETICS



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

IDEA AND PERSPECTIVE

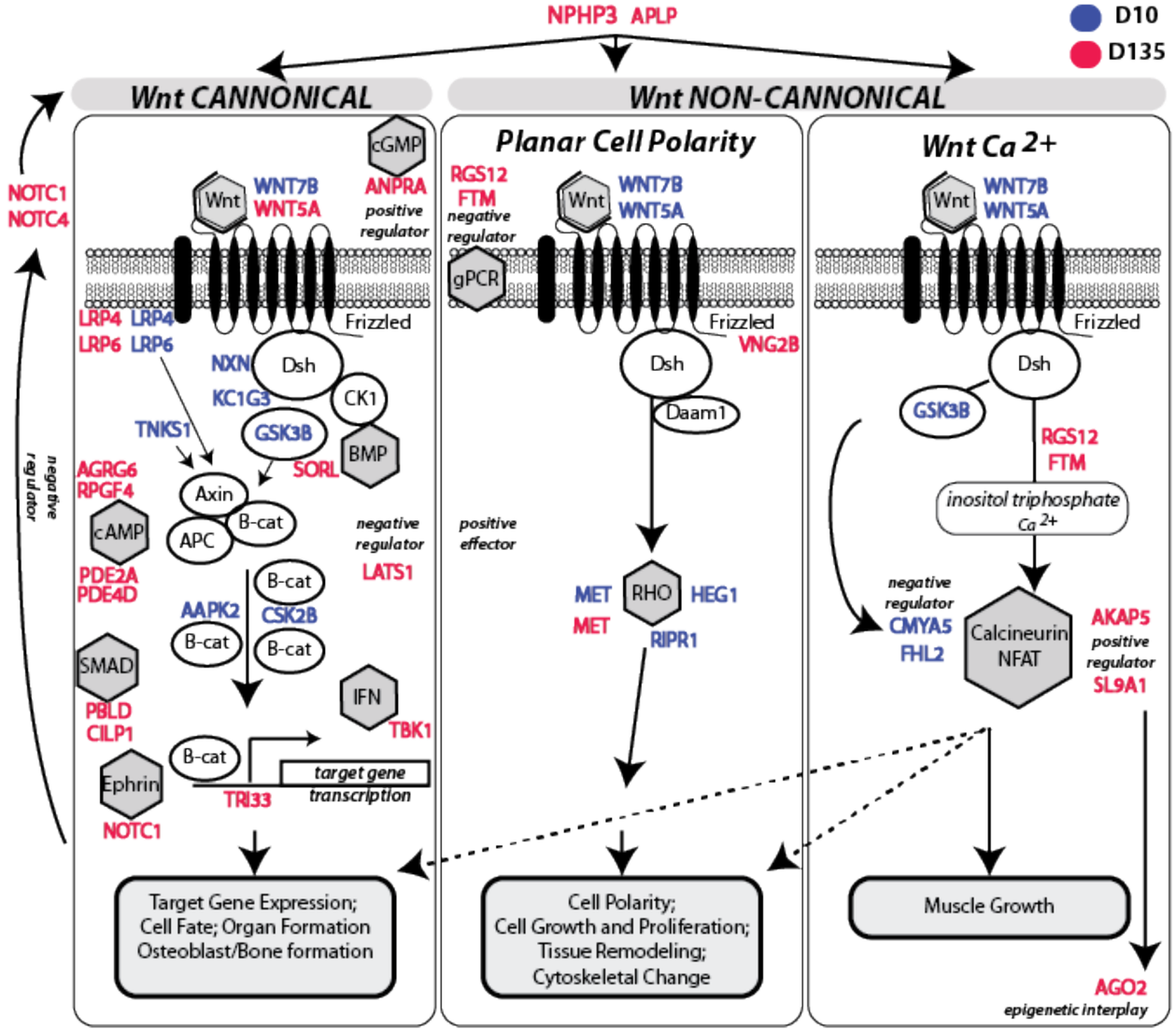
Epigenetics for ecologists

DESIRED TRAITS

GEODUCKS CLAMS

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

GEODUCKS AND OA



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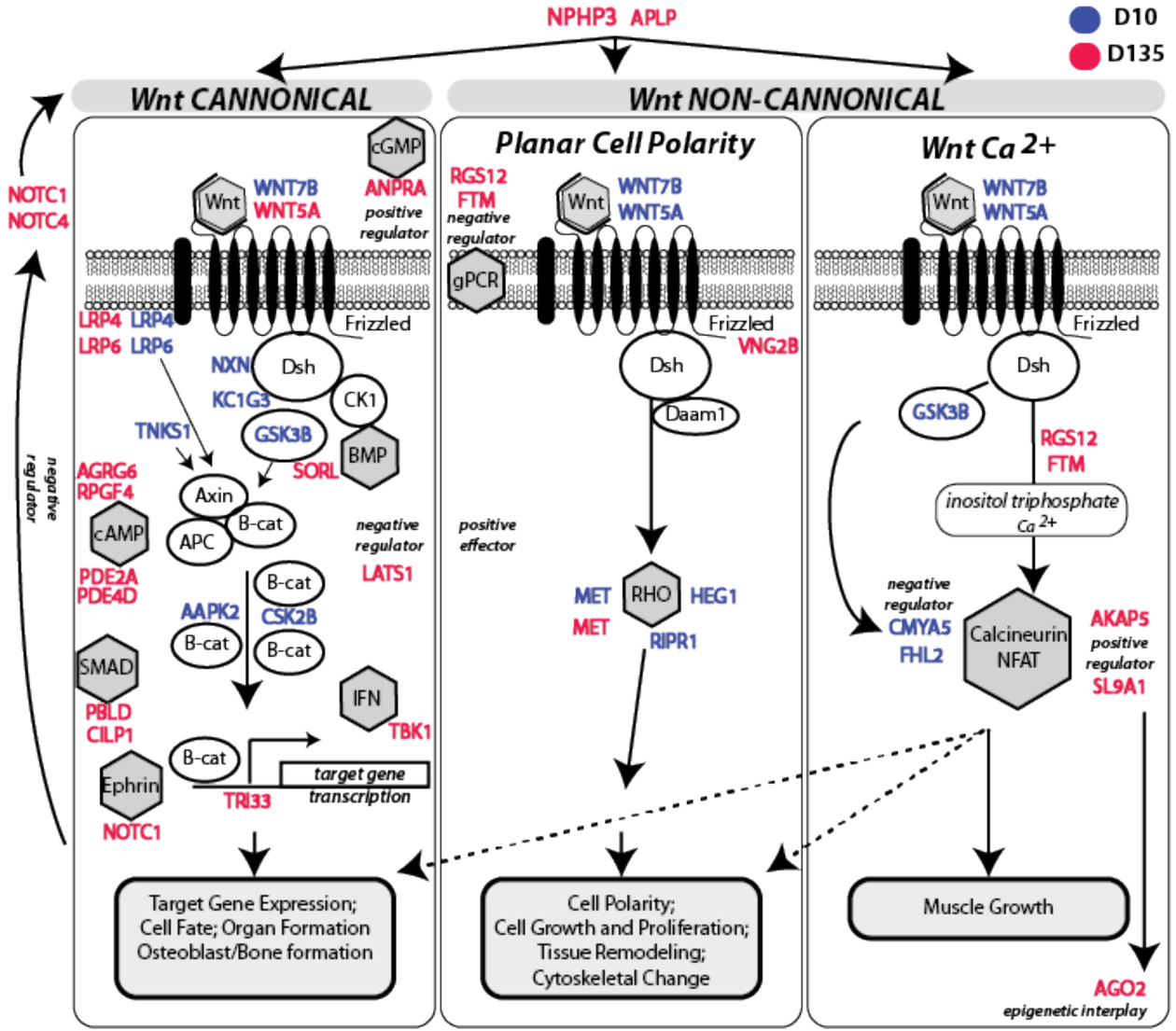


New Results

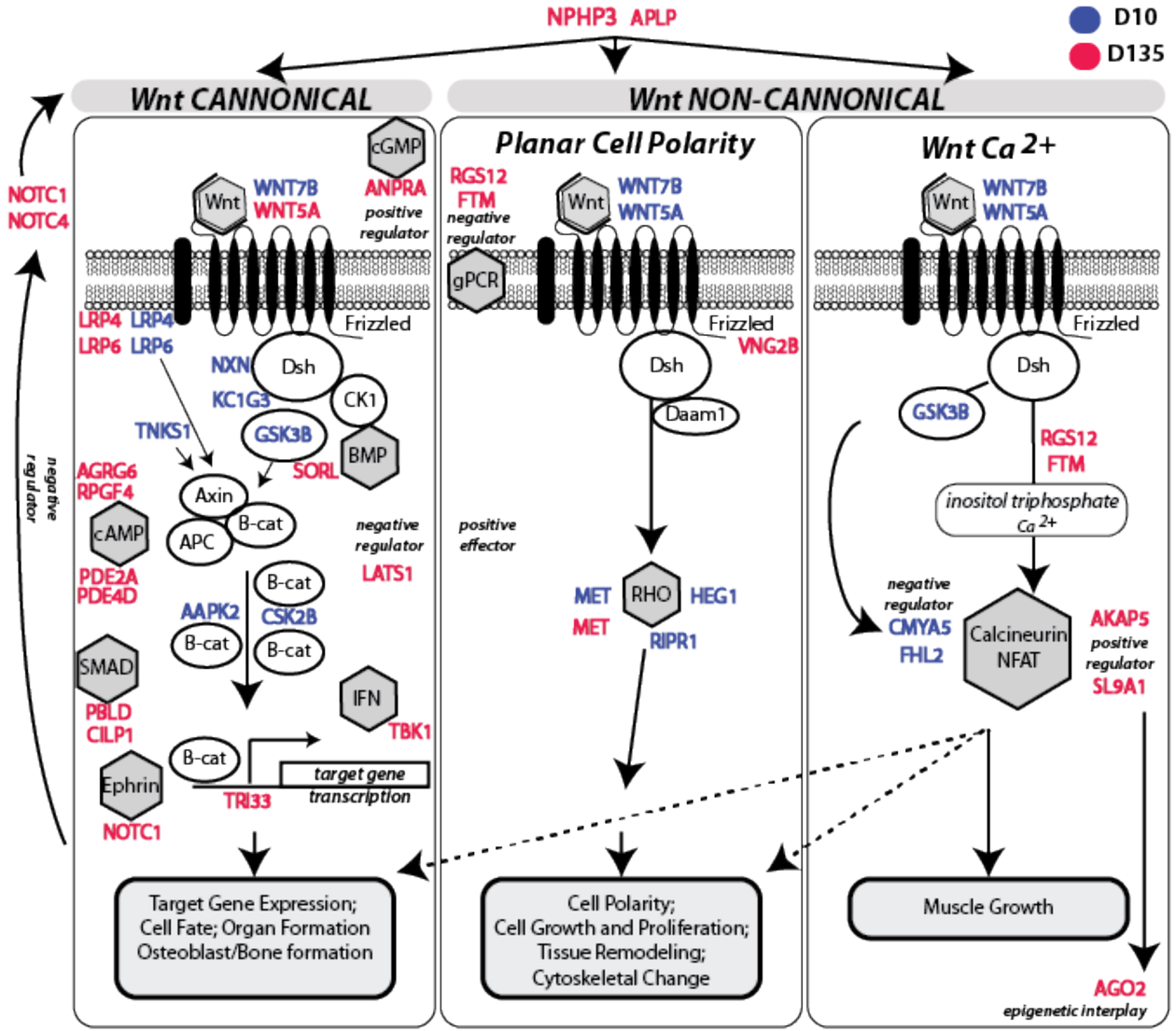
Follow this preprint

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.

EXCITING?
COMPLEX
‘LAYER’ OF RESILIENCE

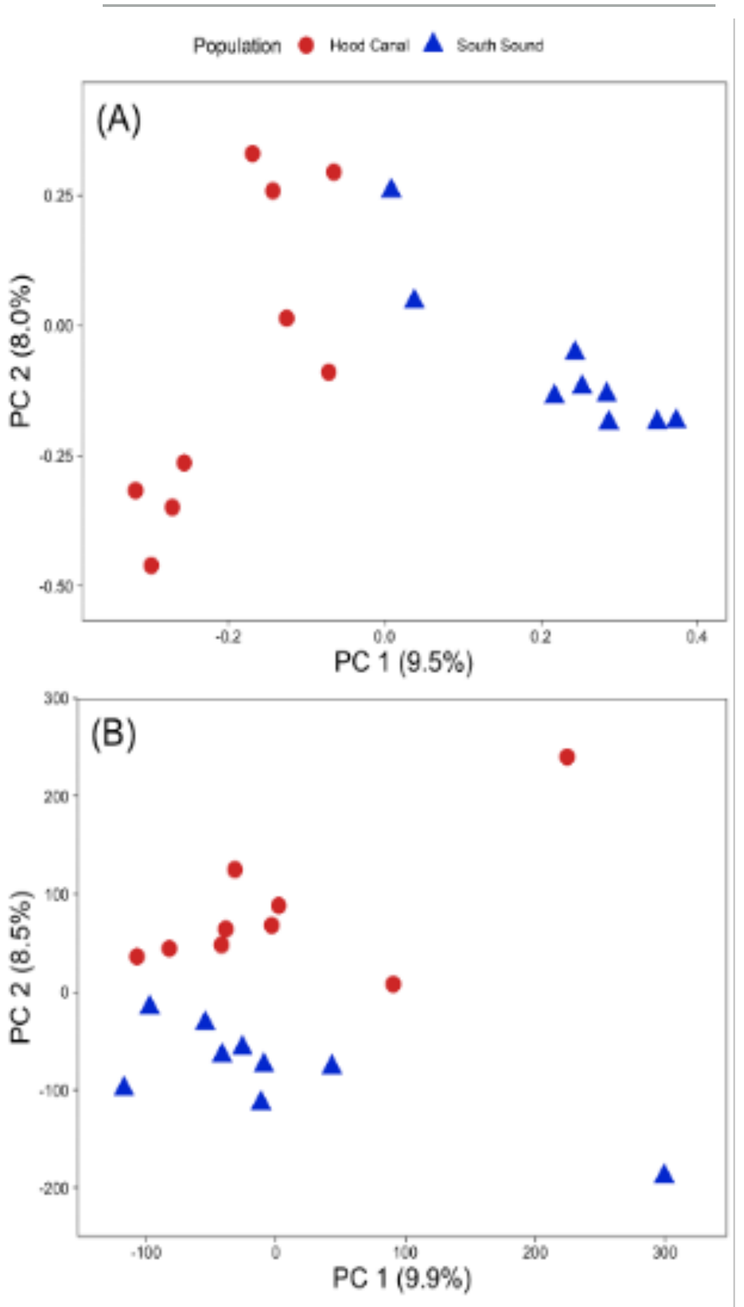
Epigenetic and Genetic Population Structure is Coupled in a Marine Invertebrate

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

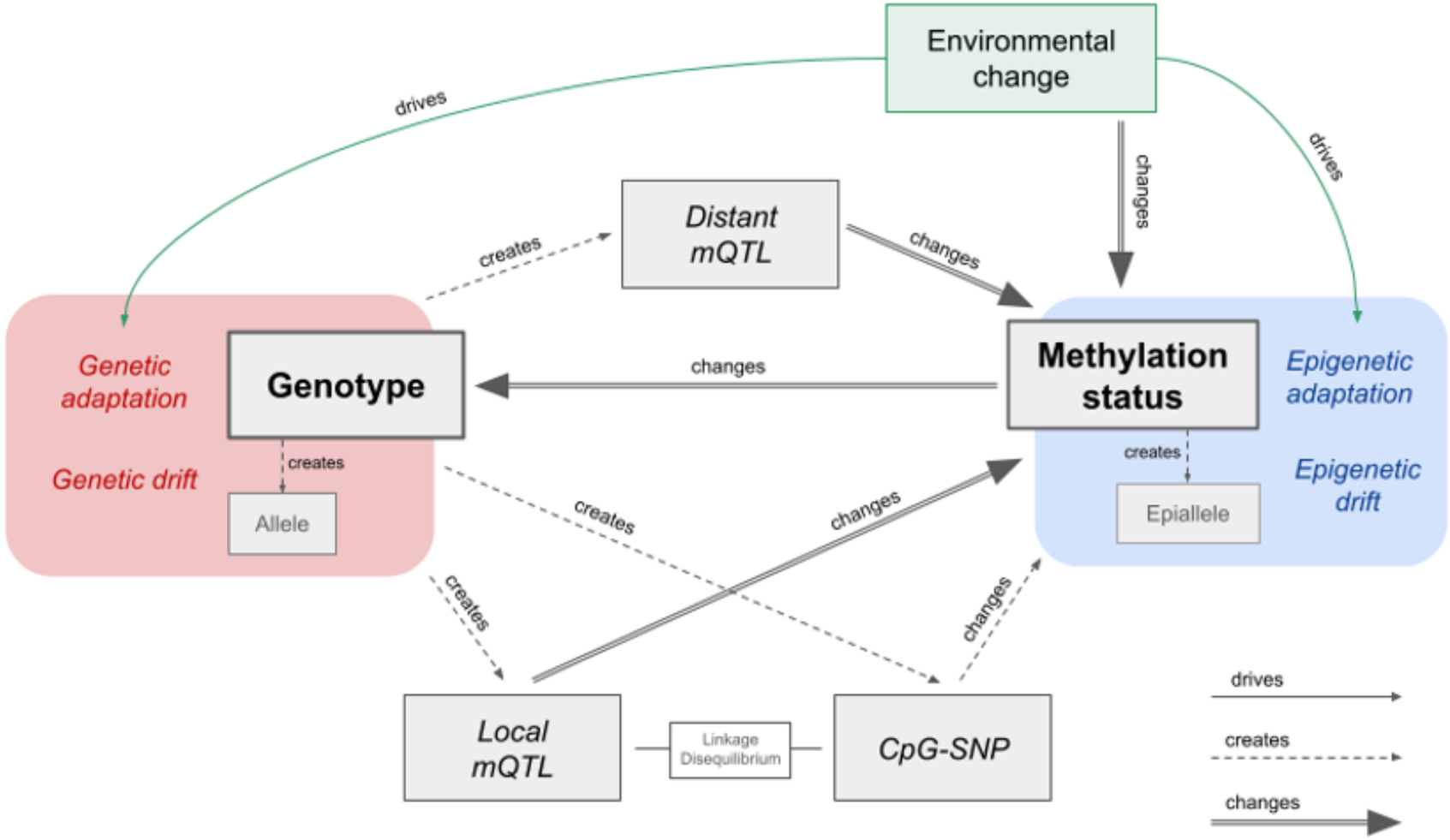
First characterization of genome-wide DNA methylation patterns in the oyster genus *Ostrea*

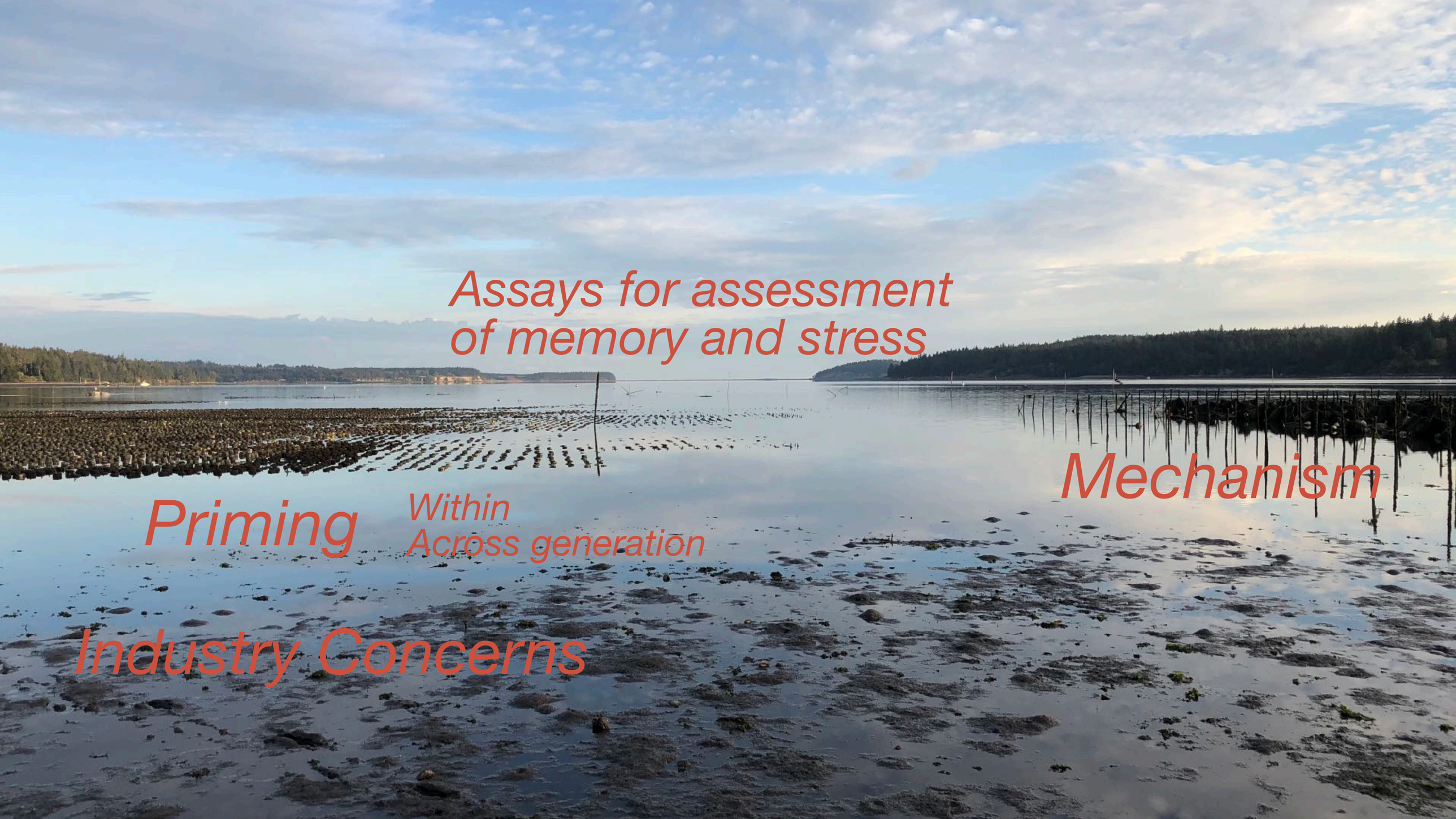
Identified 3,963 differentially methylated loci between populations. Clear coupling between genetic and epigenetic patterns of variation, **with 27% of variation in inter-individual methylation differences explained by genotype**.

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

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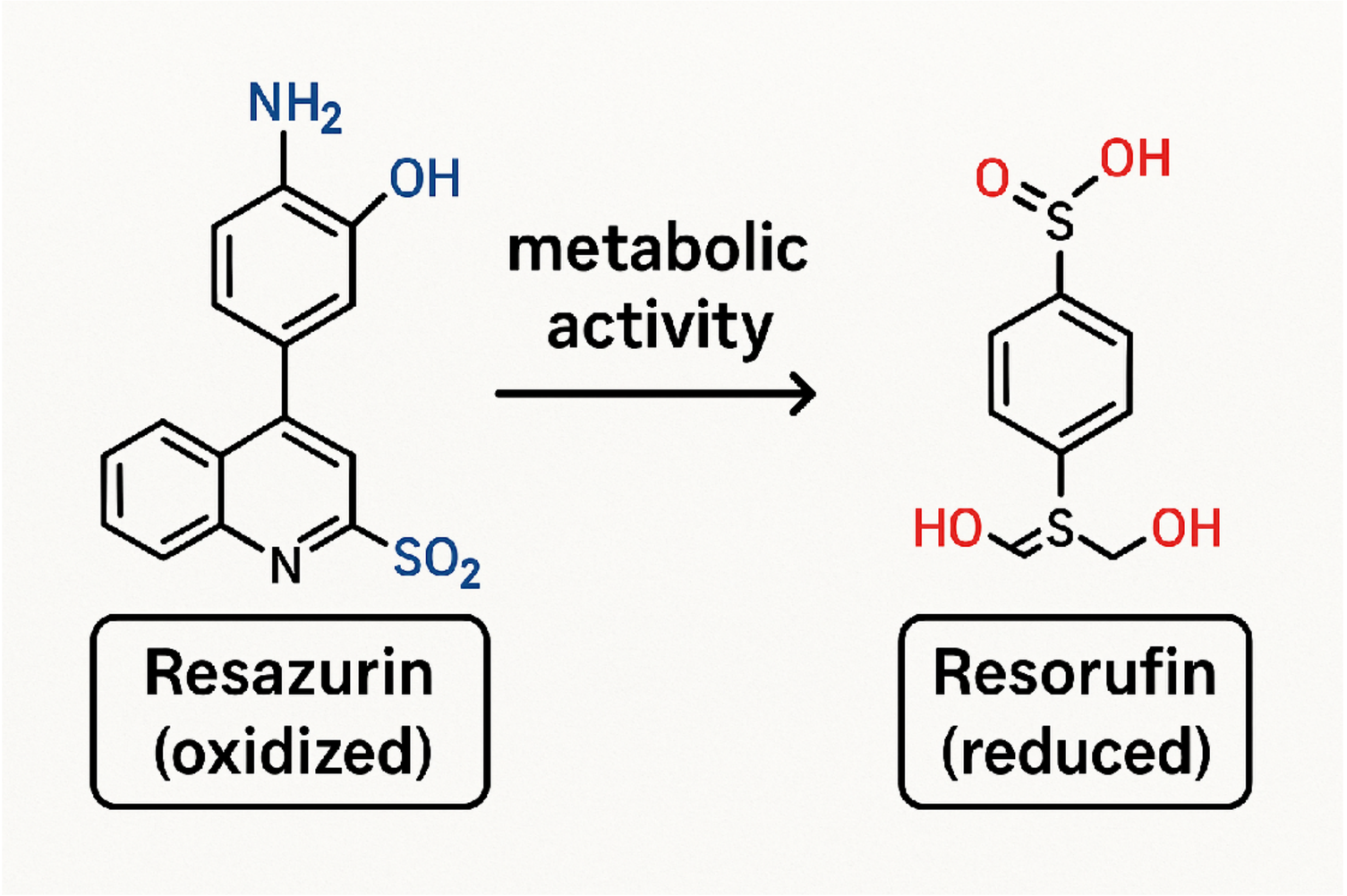
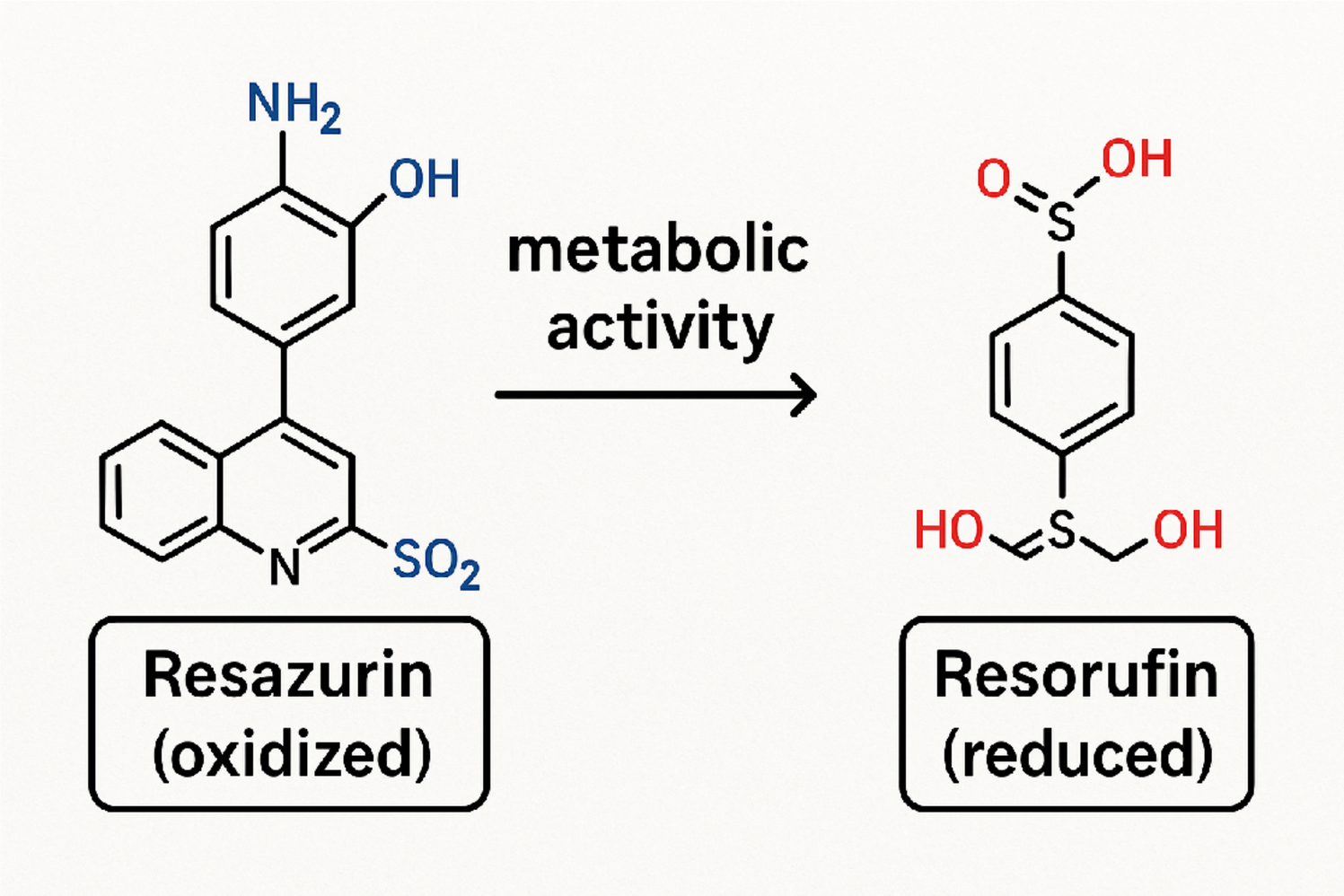
Resazurin


NH2
OH
N
SO2
metabolic activity
O
S
OH
HO
S
OH
Resazurin (oxidized)
Resorufin (reduced)

Resazurin

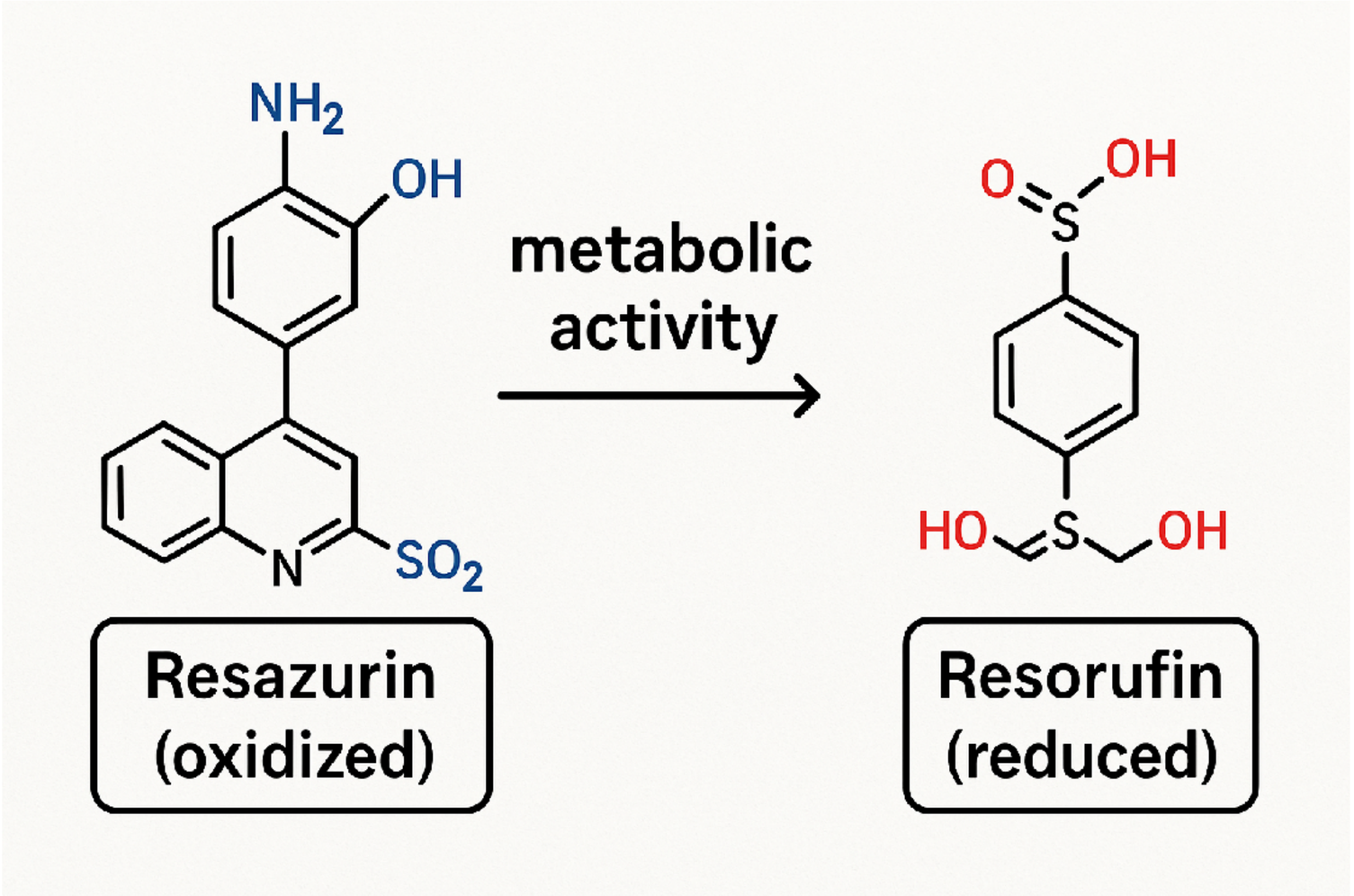


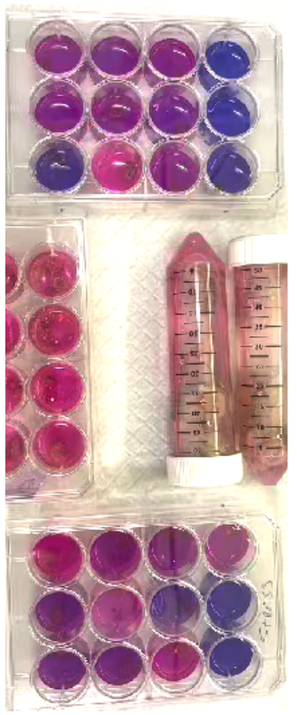
Highly fluorescent (excitation ~570 nm, emission ~585 nm)

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

Applications

Resazurin





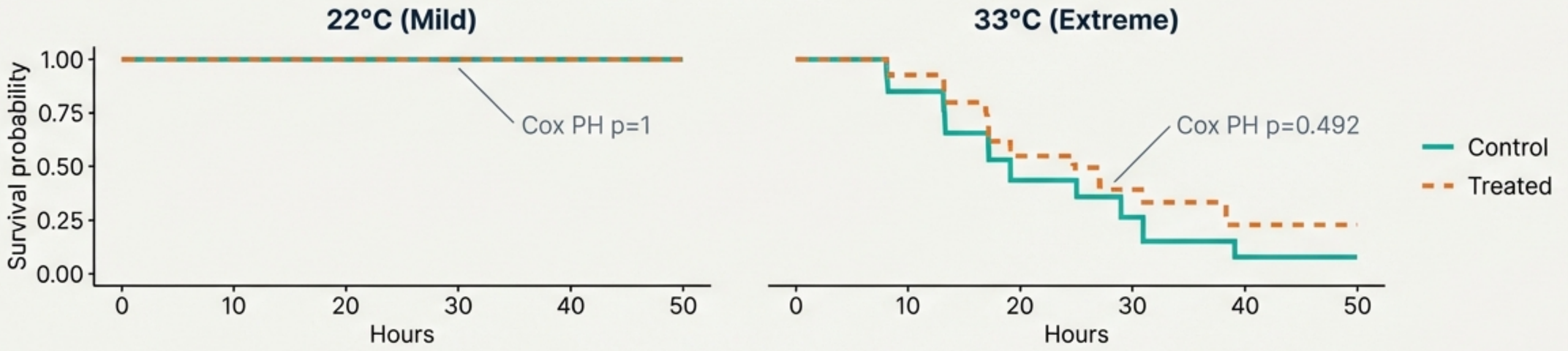
Is metabolic activity associated with a stress event different when oyster had previously experienced a stress? (Is there evidence for functional priming?)

Applications

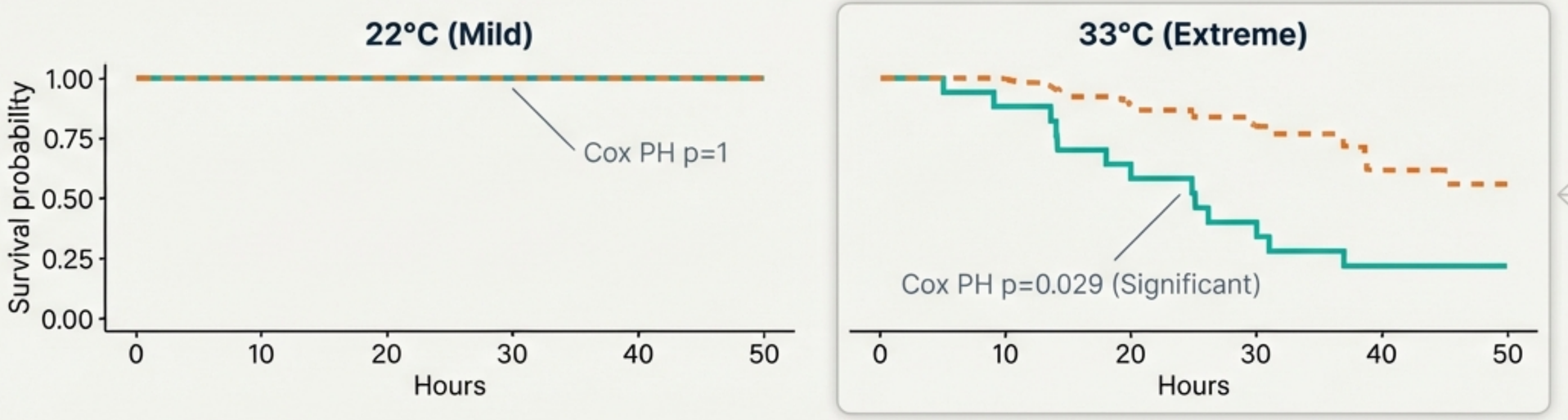
Ariana Huffmyer - UW

Hardening worked—but only revealed itself under extreme acute stress.

Daily Hardening



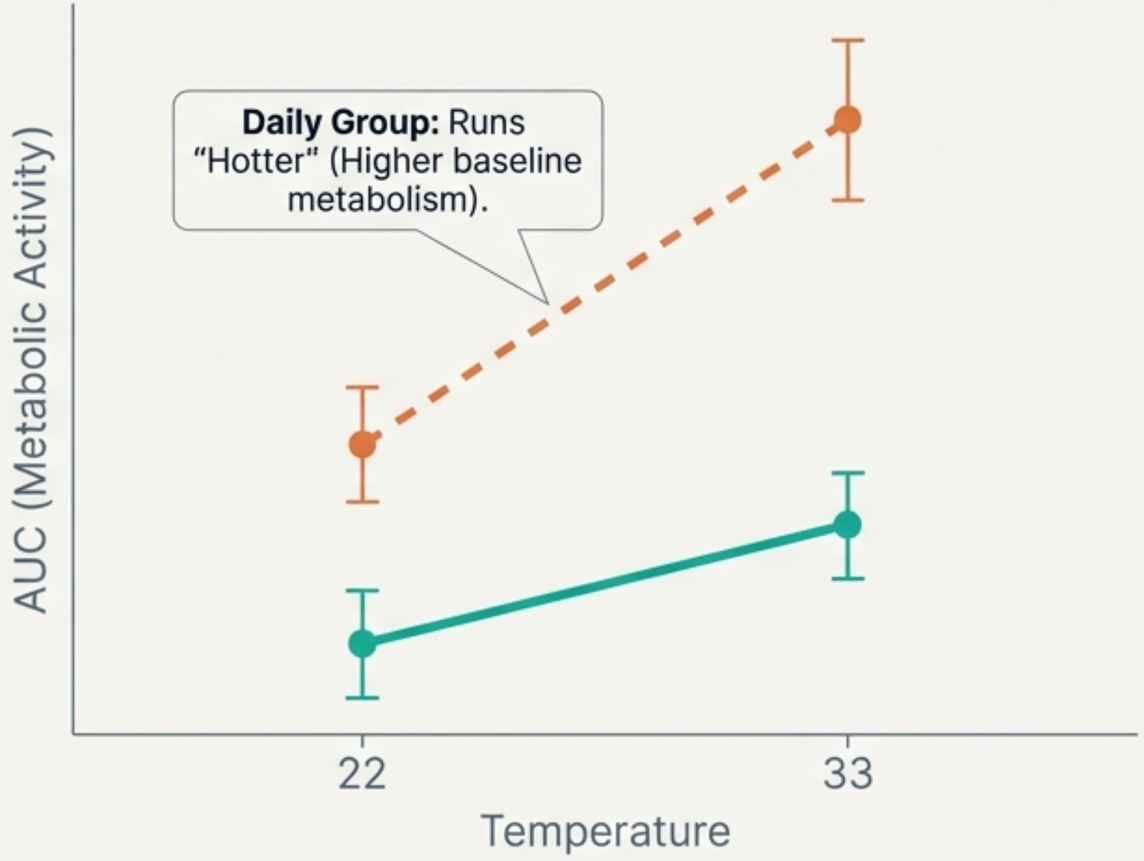
Weekly Hardening



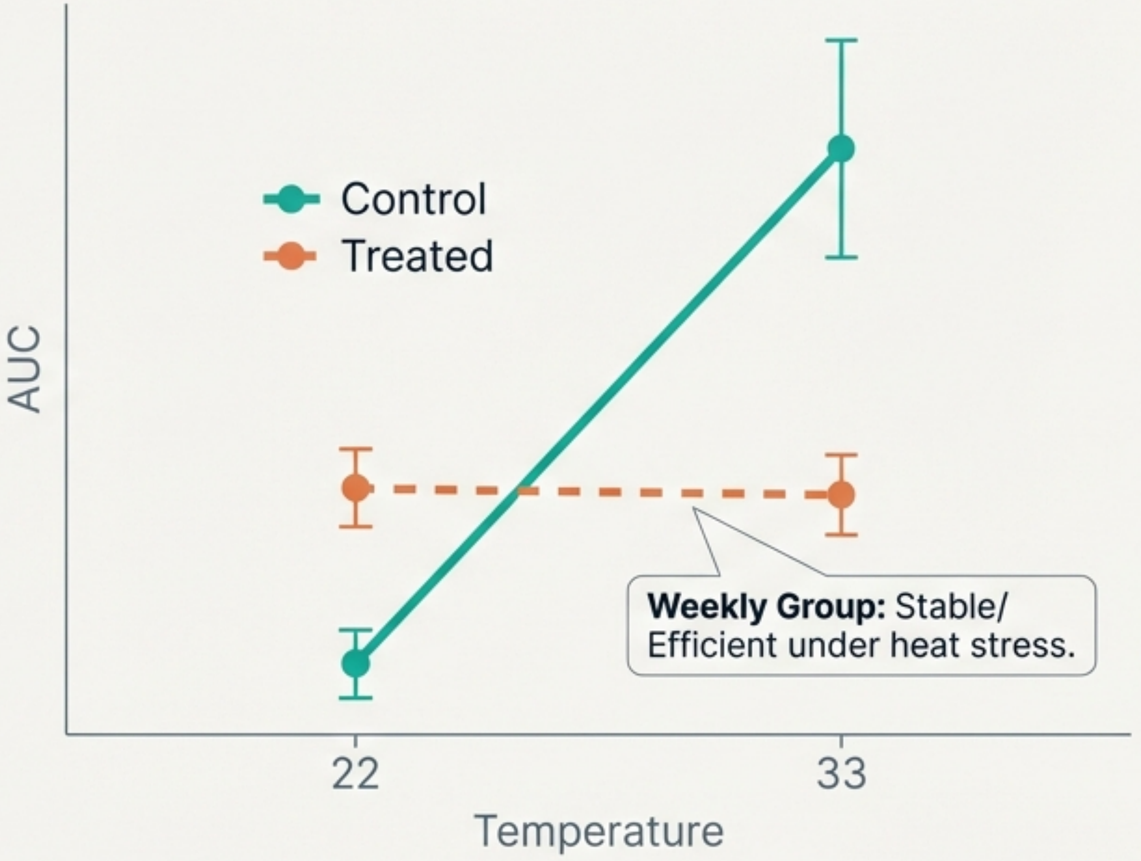
SUCCESS:
Weekly primed oysters showed significantly higher survival during a simulated heat wave.

Priming fundamentally altered oyster metabolic strategies.

Daily Hardening Metabolism



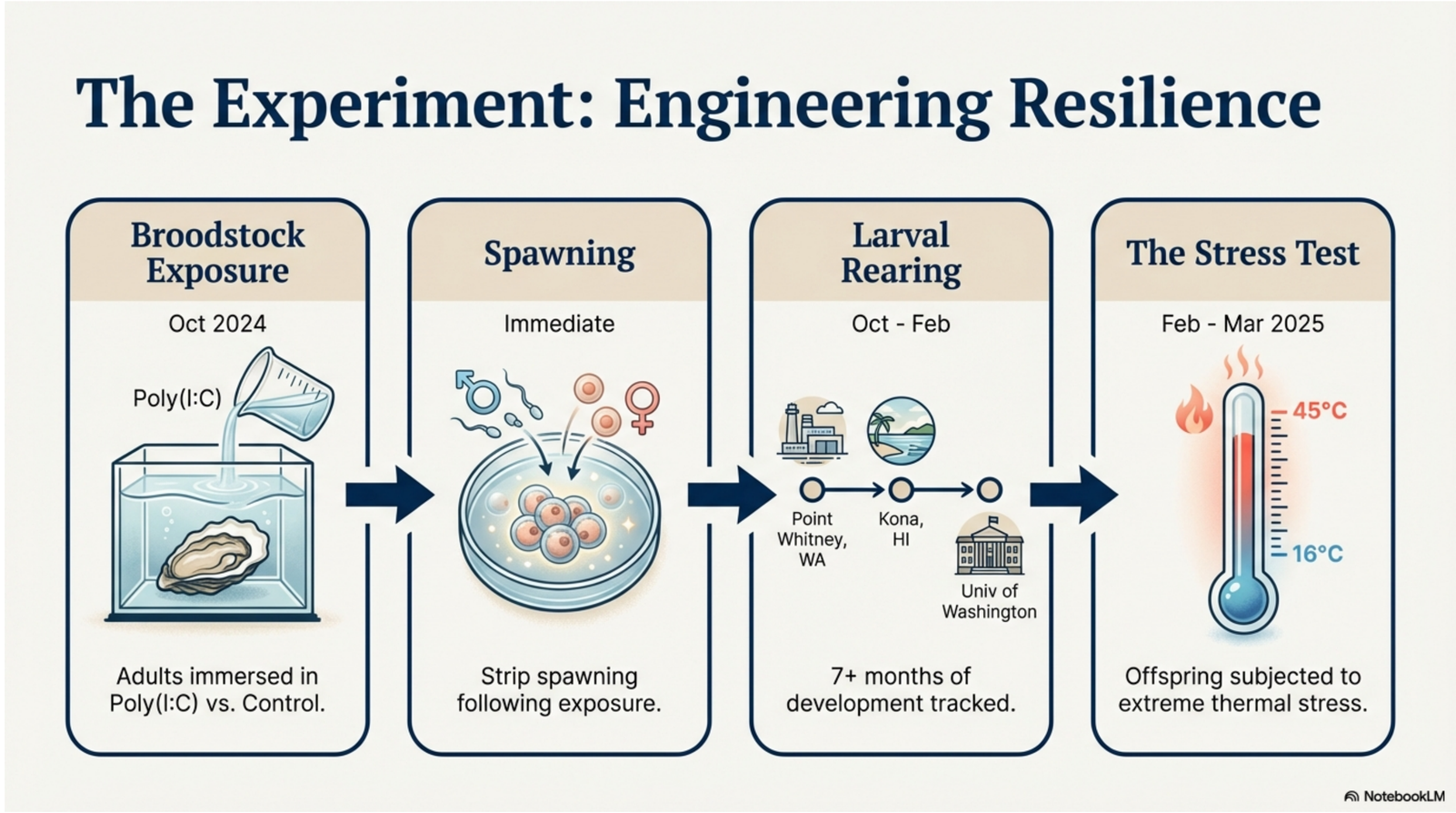
Weekly Hardening Metabolism

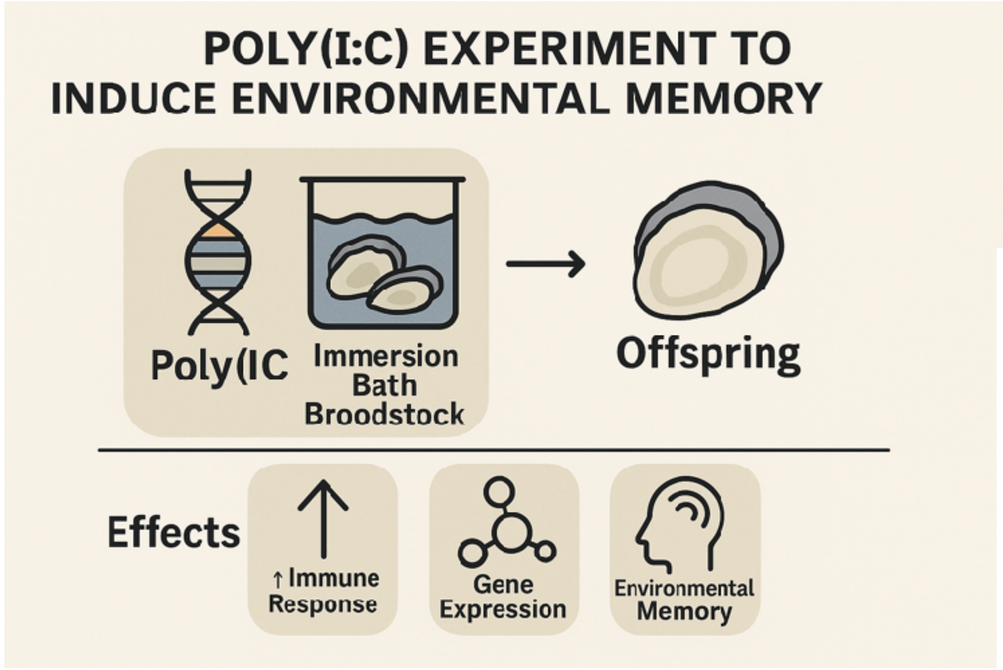


Conclusion: The hatchery treatments successfully programmed long-term changes in energy management.

Applications

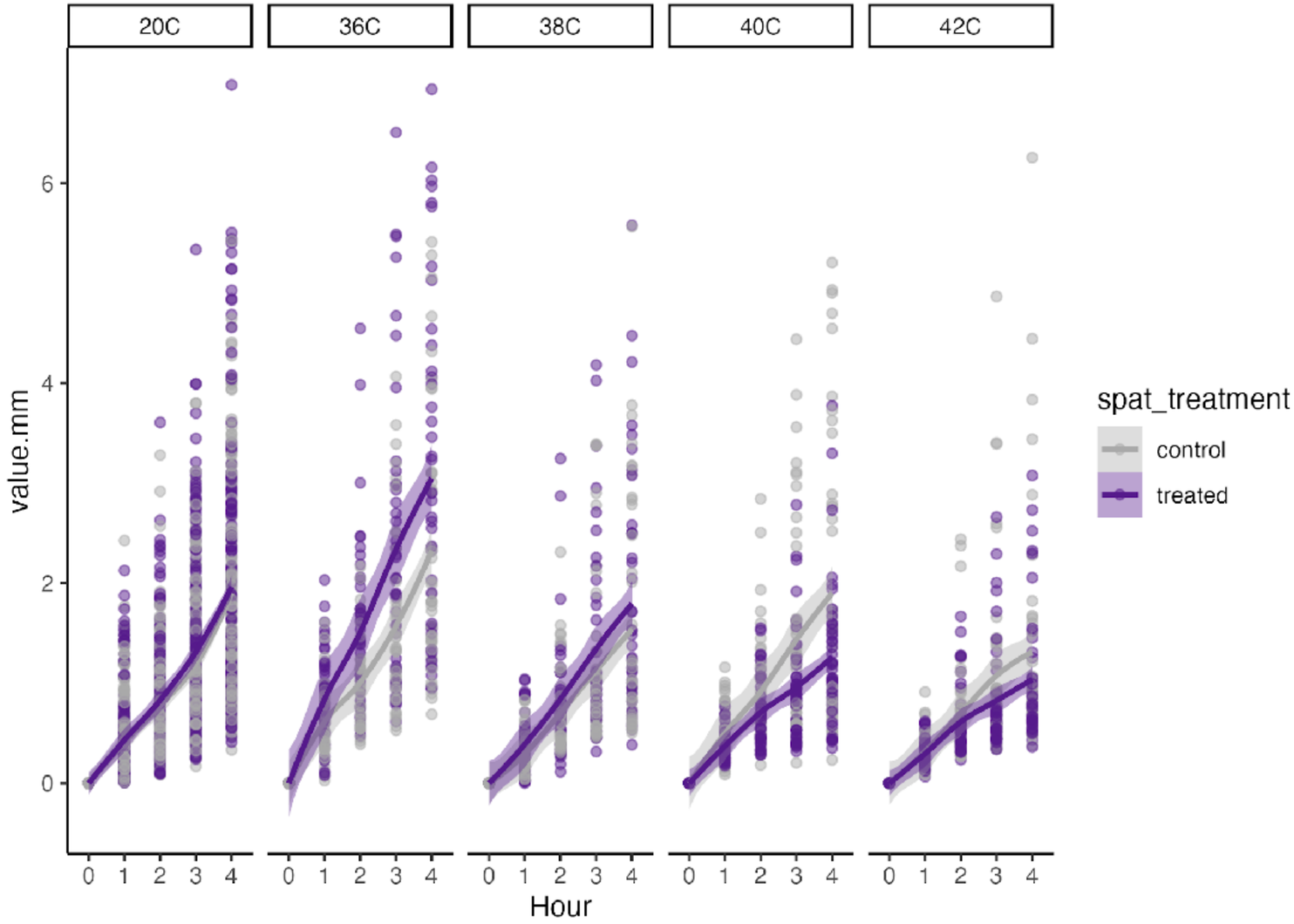
Ariana Huffmyer - UW



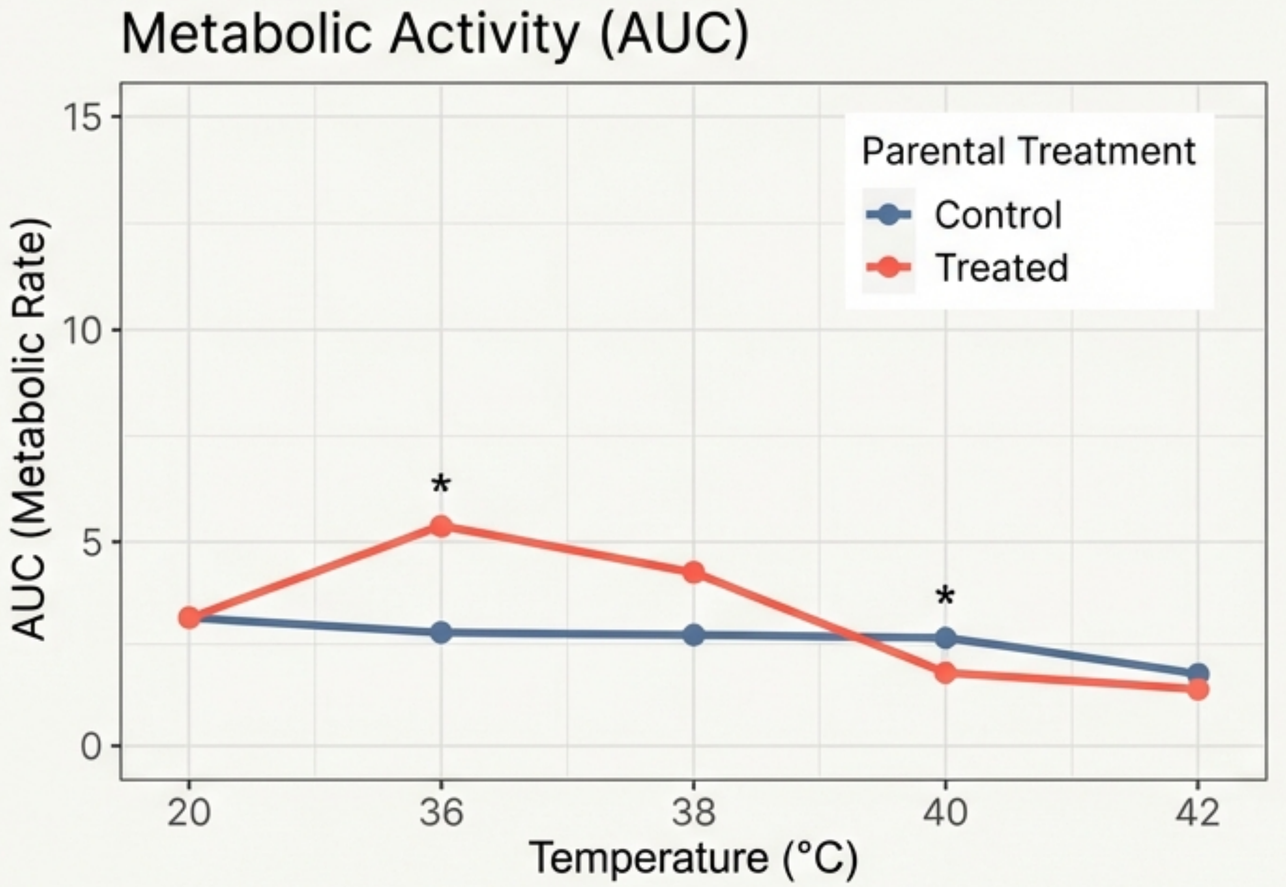


Ariana Huffmyer - UW

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



The Hidden Mechanism: Metabolic Flexibility

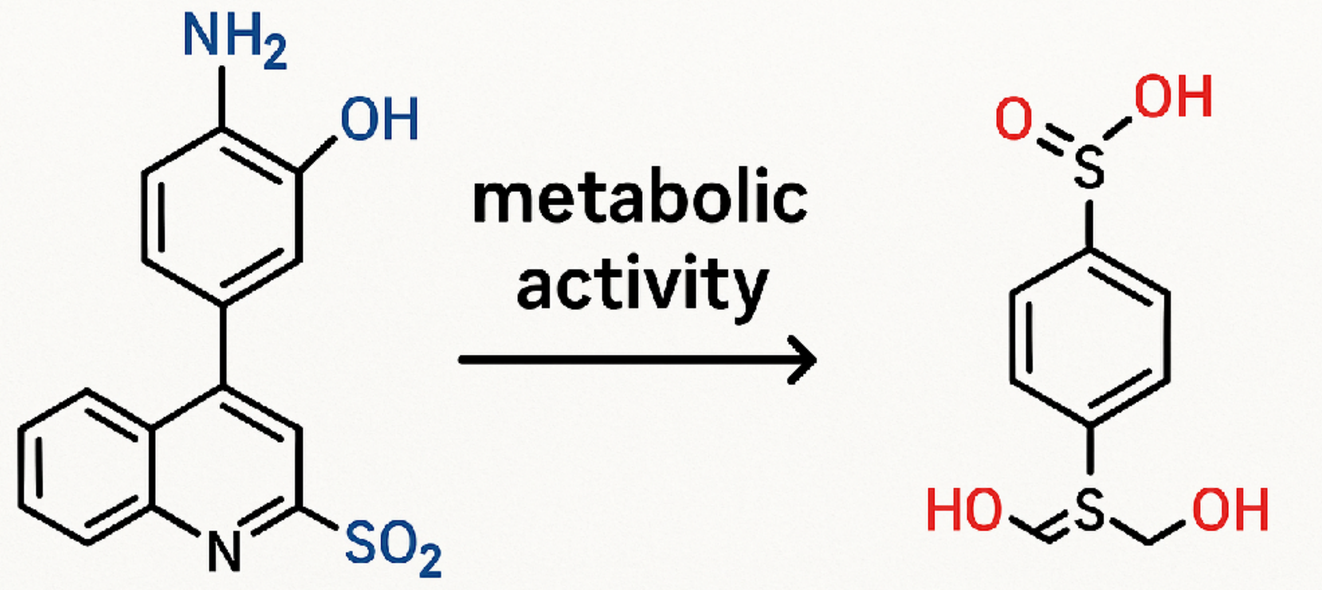


36°C: Ramping Up Defenses

40°C: Metabolic Depression (Conservation Mode)

Insight: Treated offspring were not just ‘tougher’; they were metabolically flexible. They revved up early to prepare, then idled down to survive the peak heat.

More Applications



Resazurin (oxidized)

Resorufin (reduced)

Using Resazurin Assay to Study Oysters and Improve Aquaculture

Screening for Stress-Resilient Oyster Lines

Test metabolic activity under thermal, salinity, or pH stress

Assessing the Effects of Microbiome Manipulation

Measure host metabolic health changes from microbiome modifications

Monitoring Larval and Juvenile Health in Hatcheries

Rapid assessment of viability and metabolic status

Evaluating Impact of Environmental Exposures

Measure metabolic response to pollutants, harmful algal blooms, etc.

Testing the Efficacy of Diets or Nutritional Supplements

Compare metabolic output of oysters fed different diets

Conclusions and Next Steps

Environmental Memory (*Epigenetics*) can be useful for aquaculture

- Environmental conditions can influence later phenotypes without genetic selection.
- In many cases a protective phenotype is prevalent under extreme conditions.
- Cross-protection makes priming practice amenable in aquaculture.
- There is a complex genetic - epigenetic relationship
- Inexpensive physiological assays can be used to assess how priming can improve performance.

Conclusions and Next Steps

More Questions

- What stress, intensity, timing, developmental stage is best for priming?
- How does DNA methylation, non-coding RNA, histone modification work together to imprint a memory?
- What is the role of the microbiome?
- Can epigenotype selection be useful tool in aquaculture industry?

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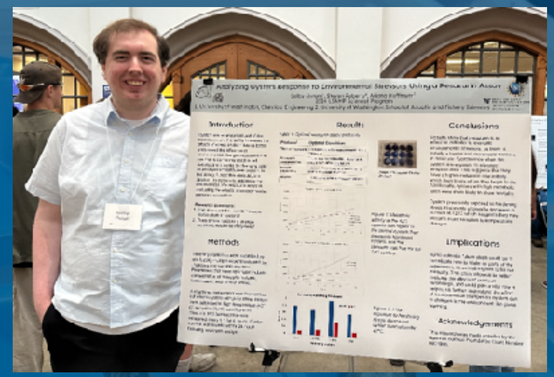

github.com/sr320/talk-EpiAqua-2026