Toward empirical assessment of adaptive capacity in aquatic populations across scales: from genomes to landscapes in native rainbow trout populations in Idaho

Caudill, C.C., T. Seaborn, Z. Chen, J. Masingale, S. Narum, A. Ringelman, E. Keeley, L. Huang, K. Andrews, T. Link, E. Du, K. Griswold, B. Kline, P. Hohenlohe, L. Waits, D. Pradhan, A. Wooding and B. Small

Society for Freshwater Science, 2023

University of Idaho

GEM3
Genes by Environment
Modeling · Mechanisms · Mapping

NSF

IDAHO EPSCoR

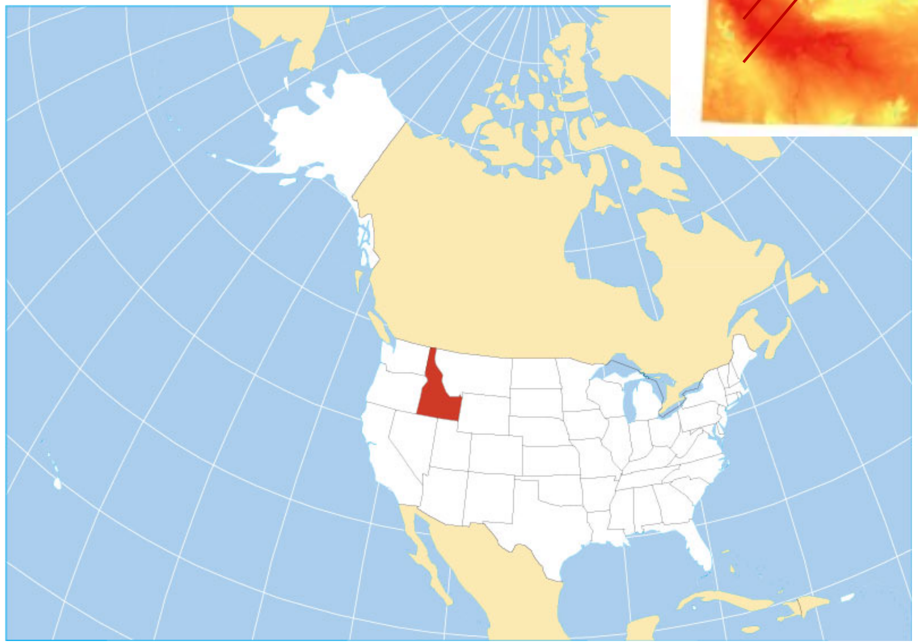
Idaho State University

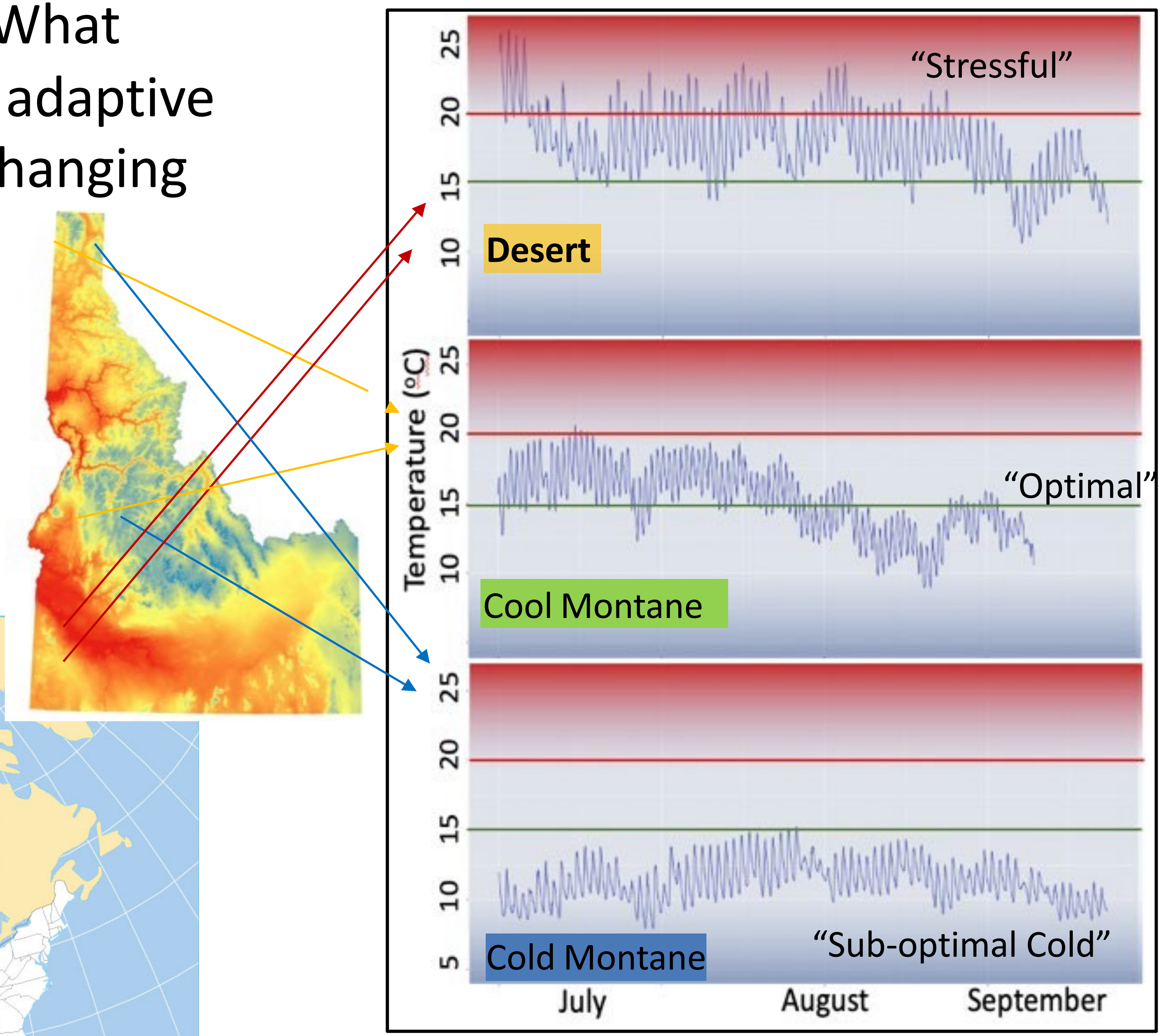
YAKAMA NEZ PERCE WARM SPRINGS UMATILLA

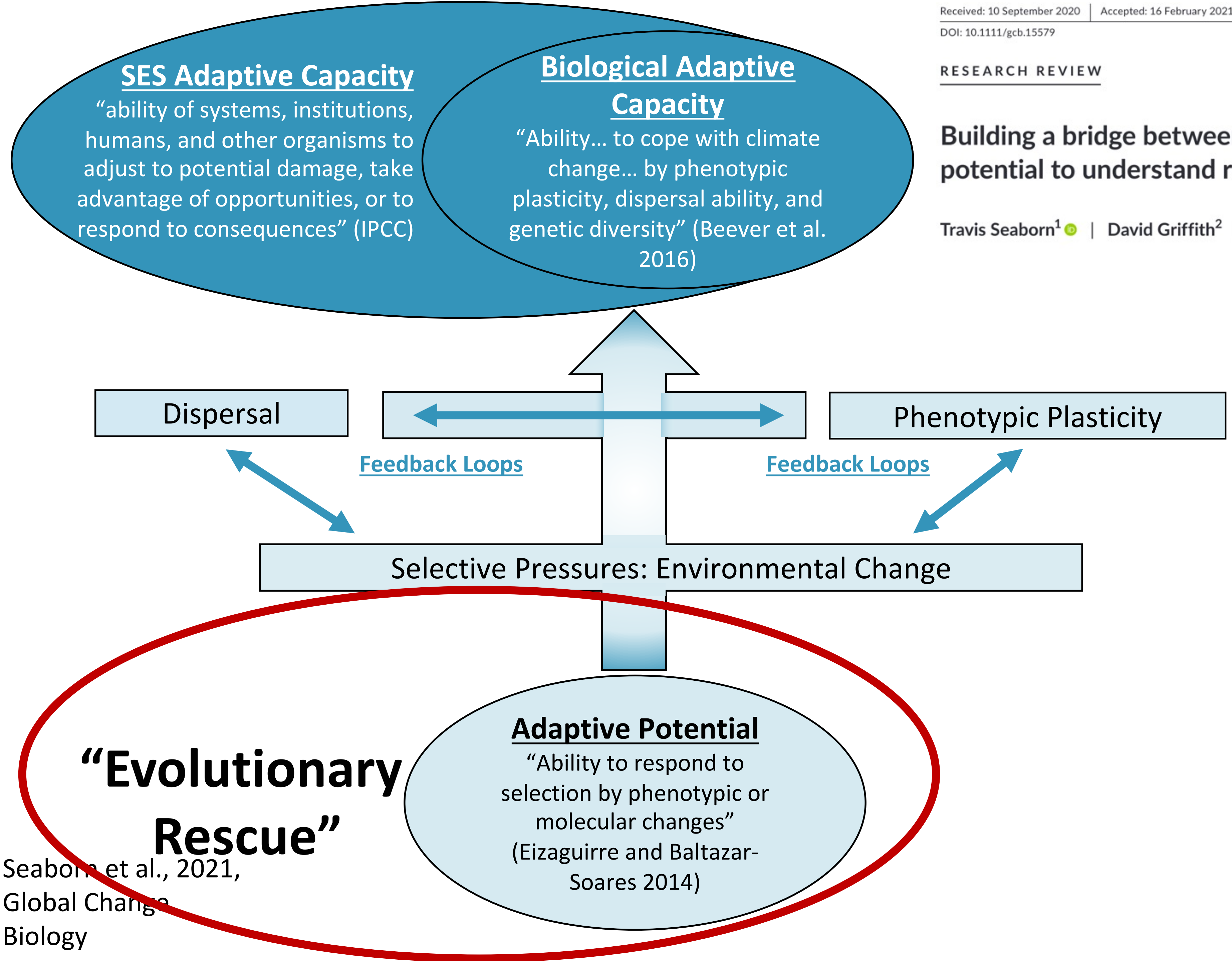
NDSU

This research is made possible by Idaho NSF-EPSCoR Program (award OIA-1757324).

<u>GEM3 Big Question</u>: What mechanisms provide adaptive capacity for trout in changing thermal regimes?







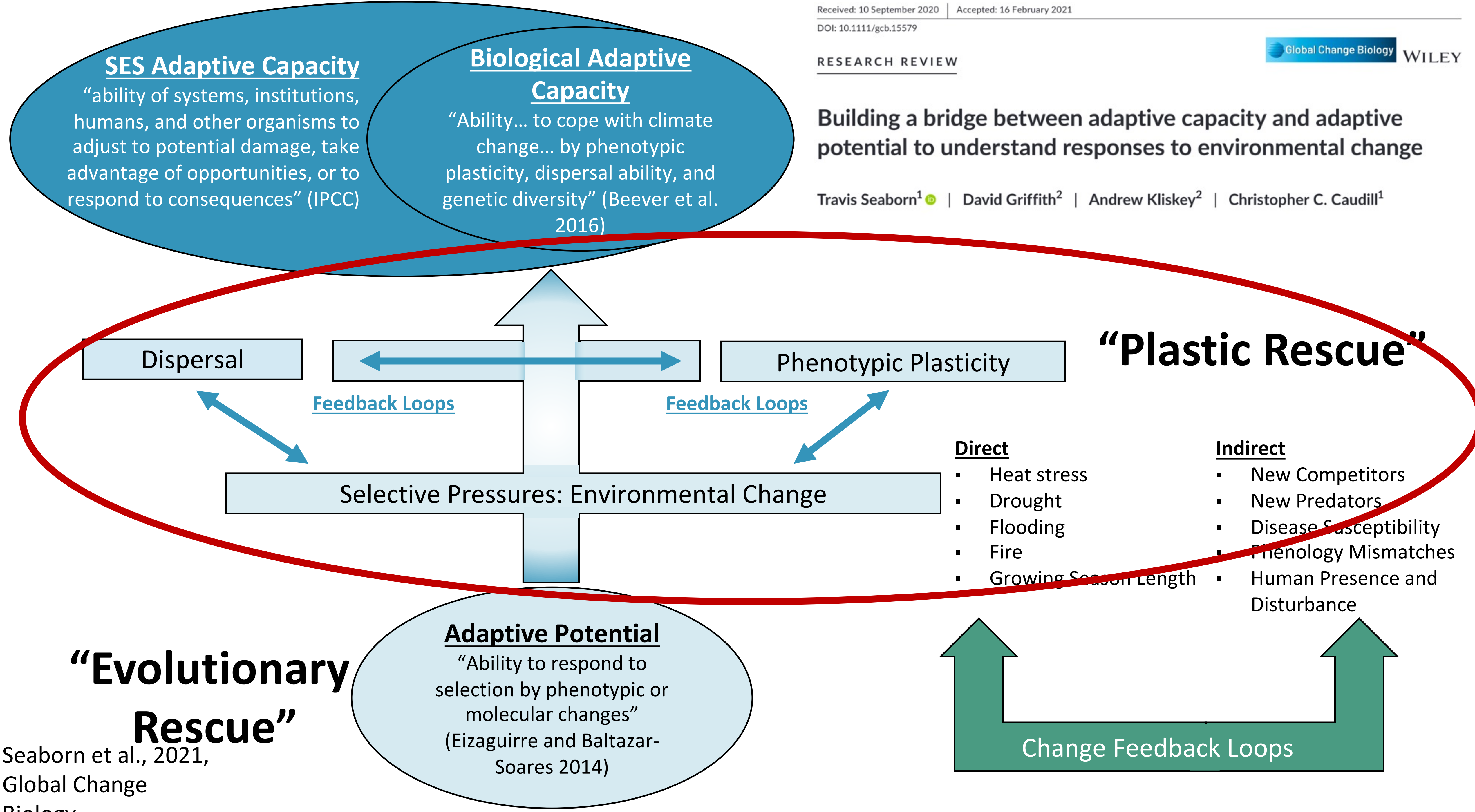
Received: 10 September 2020 | Accepted: 16 February 2021
DOI: 10.1111/gcb.15579
Global Change Biology WILEY

RESEARCH REVIEW

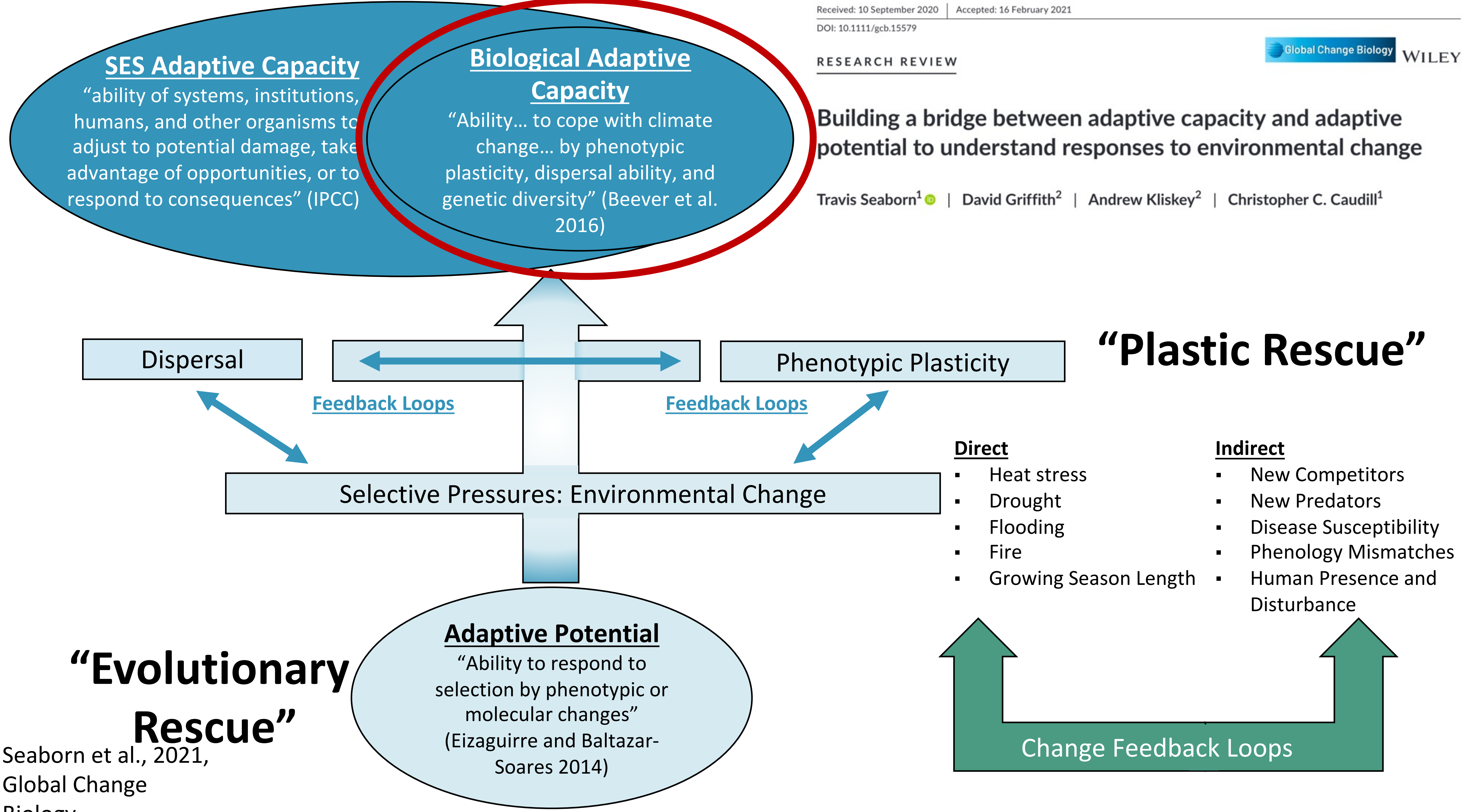
Building a bridge between adaptive capacity and adaptive potential to understand responses to environmental change

Travis Seaborn[1] | David Griffith[2] | Andrew Kliskey[2] | Christopher C. Caudill[1]

Seaborn et al., 2021, Global Change Biology



Seaborn et al., 2021, Global Change Biology



Seaborn et al., 2021, Global Change Biology

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RESEARCH REVIEW

Global Change Biology WILEY

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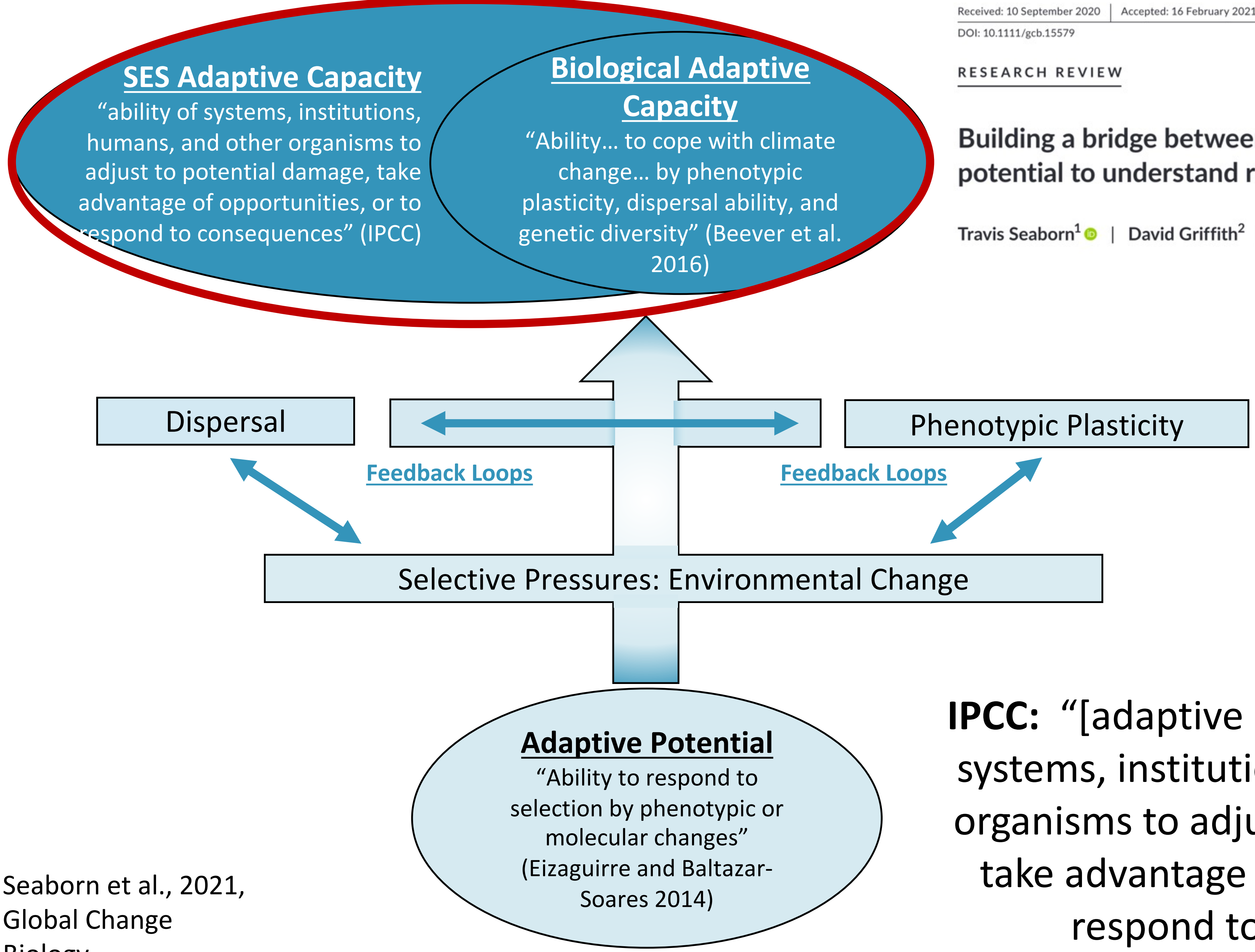


Seaborn et al., 2021, Global Change Biology

IPCC: "[adaptive capacity] is the ability of systems, institutions, humans, and other organisms to adjust to potential damage, take advantage of opportunities, or to respond to consequences."

GEM3 Trout Mechanisms Working Group

Some of the Trout Team, Hagerman, ID.
September 2019

<u>Genomics</u>

A. Patterns of genomic diversity

<u>Genotypes to phenotypes</u>

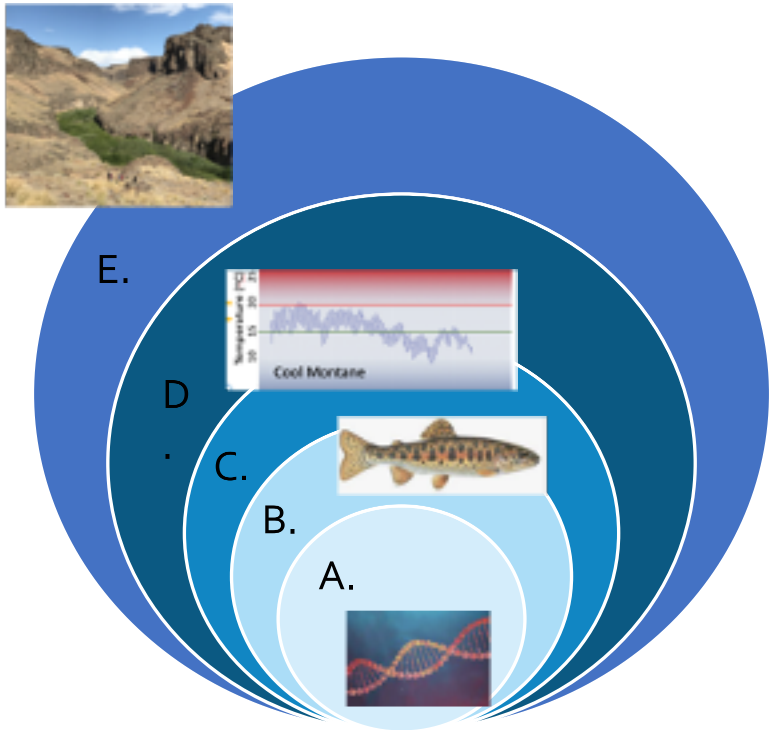
B,C. How does thermal regime affect the expression of genotypes and phenotypic performance? **(Common Garden)**

<u>Stream habitat and population dynamics</u>

C,D. How do population-specific traits and habitat quality affect fitness and population dynamics? (Habitat studies; ABM models)

<u>Watersheds and Socio-ecoloigcal Systems (SES)</u>

E. How do management, land-use, climate and other SES-related factors affect trout habitat and trout adaptive capacity? (Geospatial and ABM Modeling)

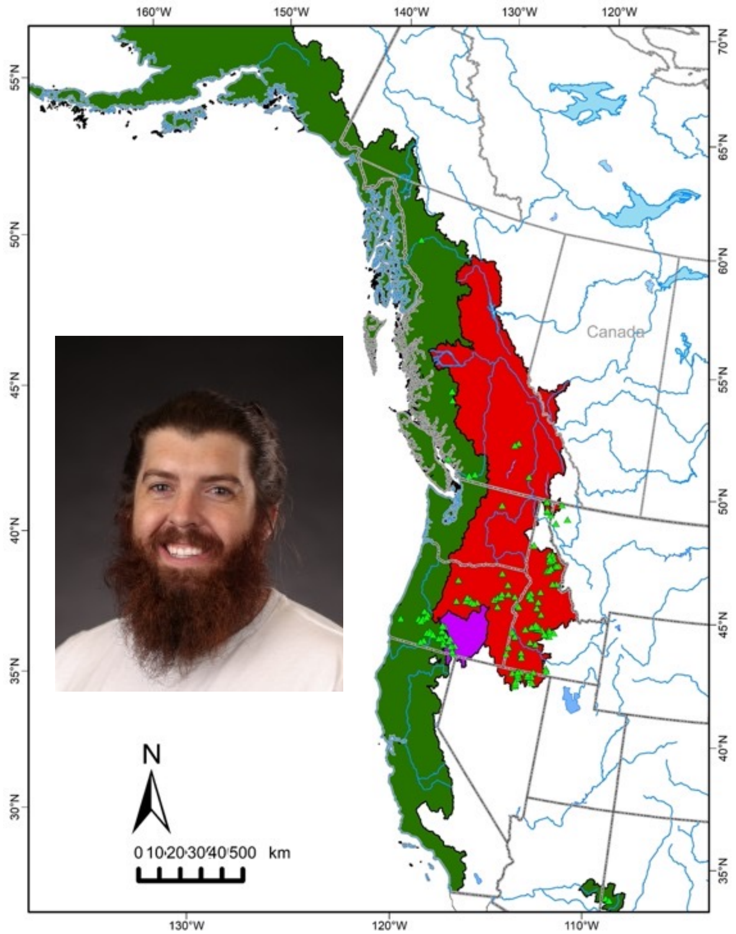


Genomics

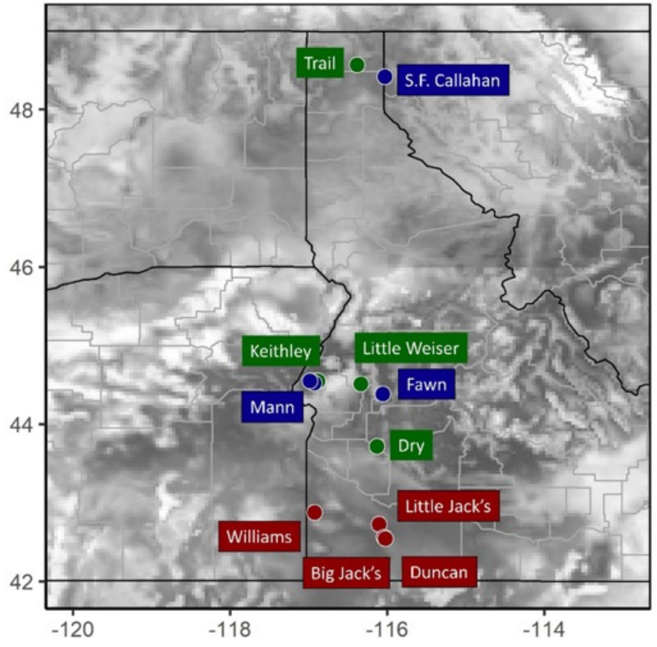
Phylogenomics of *O. mykiss* subspecies sampling underway-sequencing in 2022 – 2023: 170 populations

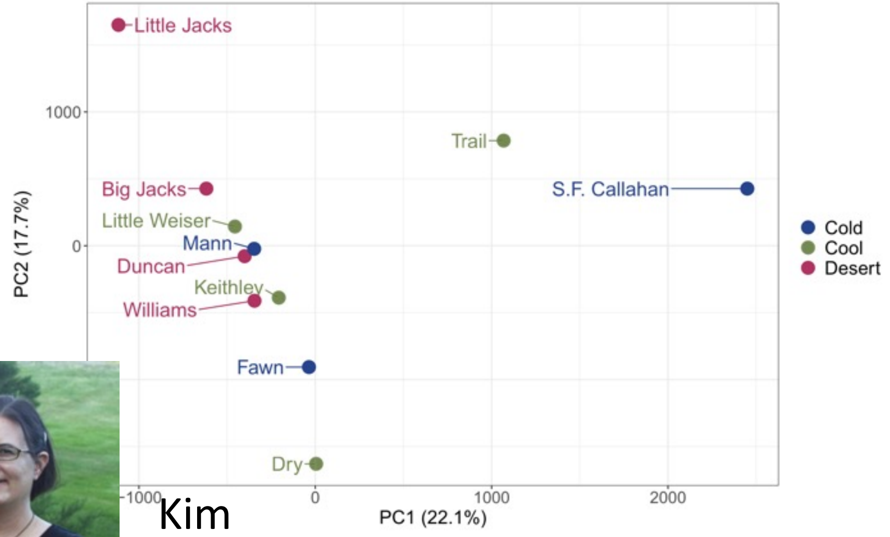
Legacy samples: 20 collections of redband trout across ecotypes (13 sites; n = 632)

Neutral genetic structure indicates connectivity and isolation is **largely related to geography** (Andrews et al. 2022)



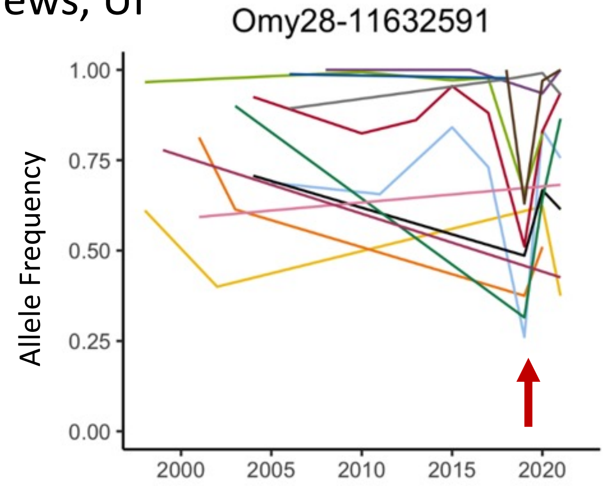
Tyler Breech, ISU





Kim Andrews, UI

Josh Egan, UI



Analysiss of legacy sample allele frequencies through time reveals correlated changes at some loci (Egan et al. on-going)

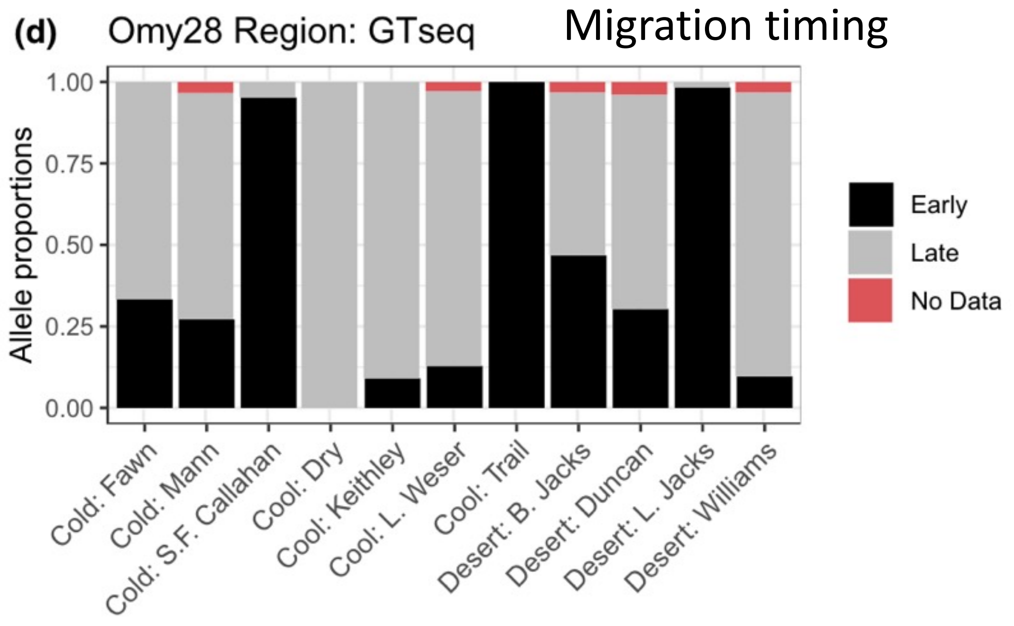
DOI: 10.1111/mec.16810

ORIGINAL ARTICLE

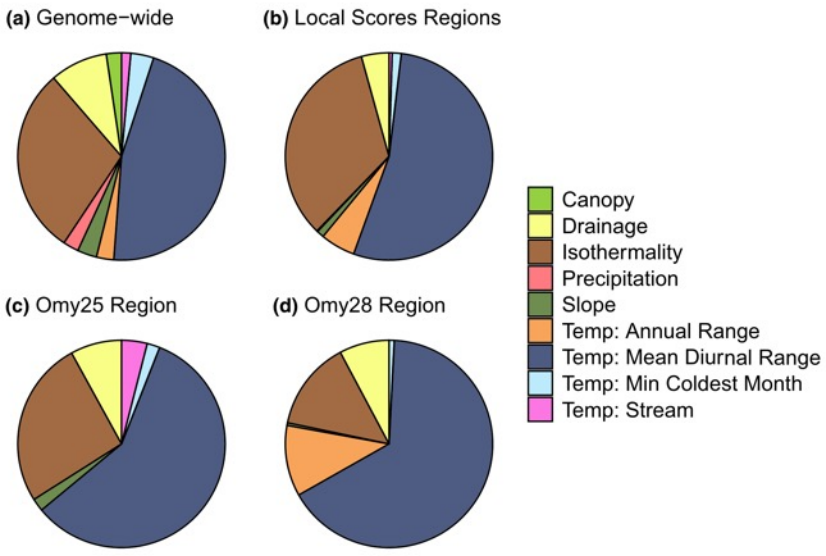
MOLECULAR ECOLOGY WILEY

Whole genome resequencing identifies local adaptation associated with environmental variation for redband trout

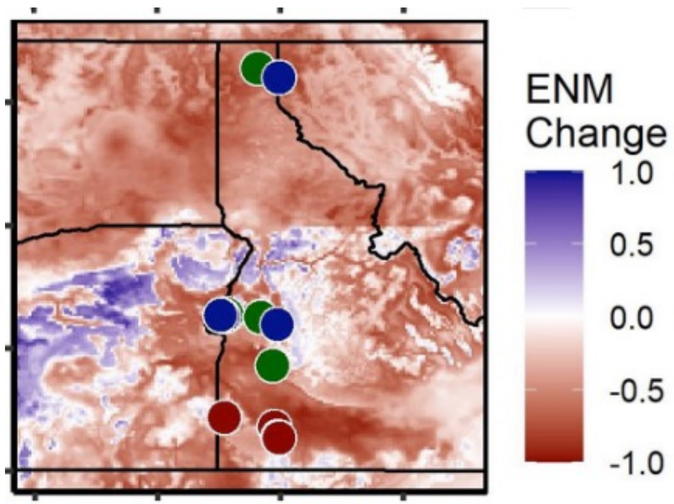
Kimberly R. Andrews[1] | Travis Seaborn[2] | Joshua P. Egan[3,4] | Matthew W. Fagnan[1] | Daniel D. New[1] | Zhongqi Chen[5] | Paul A. Hohenlohe[3] | Lisette P. Waits[2] | Christopher C. Caudill[2] | Shawn R. Narum[5,6]



- Evidence of local adaptation at 12 genomic regions incl.
  - Age at maturation
  - Migration timing
- GEA found strong signal of diurnal temperature variation
- Genetic offset analyses revealed strong genetic shifts required for persistence of desert populations under predicted warming



Mean Diurnal Temp Range



SSP 585

Genotypes to Phenotypes: Common Garden

Partition phenotypic variation into genetic and plastic components

Total Variation = Genetic (G) + Environment (E) + $G \times E$

Genetic Rescue **Plastic Rescue**

Source Genetics

Desert

Cool Montane

Cold Montane

Acclimation regimes

Rearing Environment

15°C

18°C

21°C

"Cohort 1"

Common Garden

Genotypes to Phenotypes: Common Garden

Partition phenotypic variation into genetic and plastic components

Total Variation = Genetic (G) + Environment (E) + G × E

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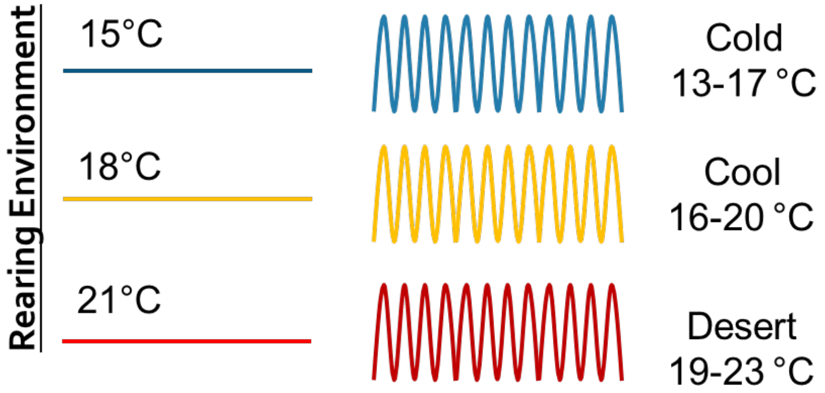


"Cohort 3"

Common Garden

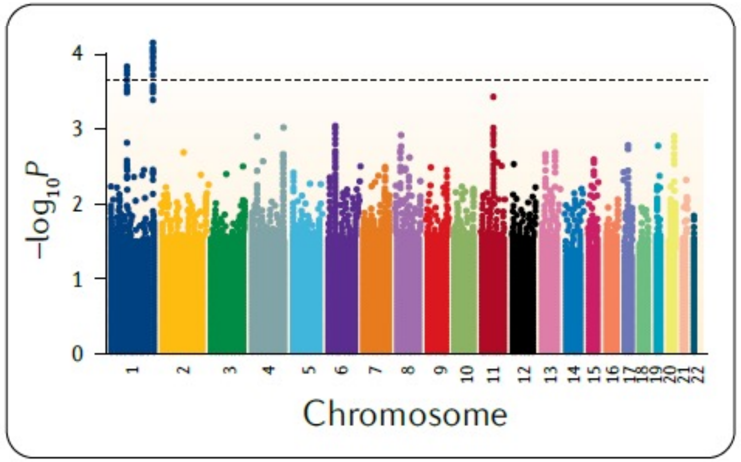
Genotypes to Phenotypes: Common Garden

Partition phenotypic variation into genetic and plastic components

Total Variation = Genetic (G) + Environment (E) + G × E

Genetic Rescue **Plastic Rescue**

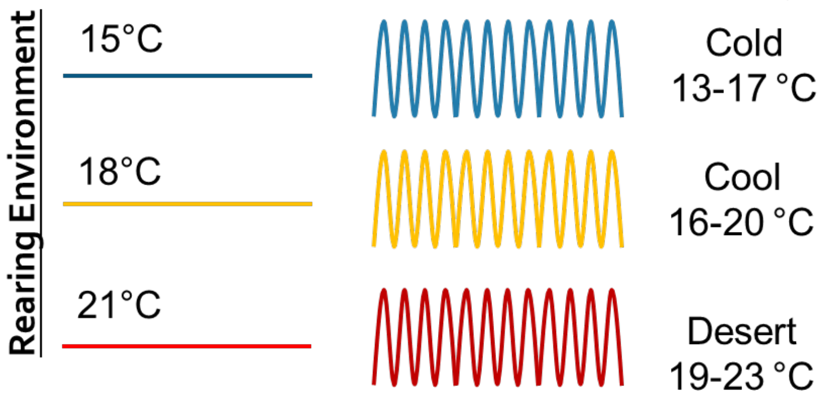
- **Thermal tolerance**
- **Hypoxia tolerance**
- **Growth**
- **Maturity**
- **Swimming**
- **Cardiorespiratory function**
- **Behavior, etc.**



Physiology

Genomics

Acclimation regimes

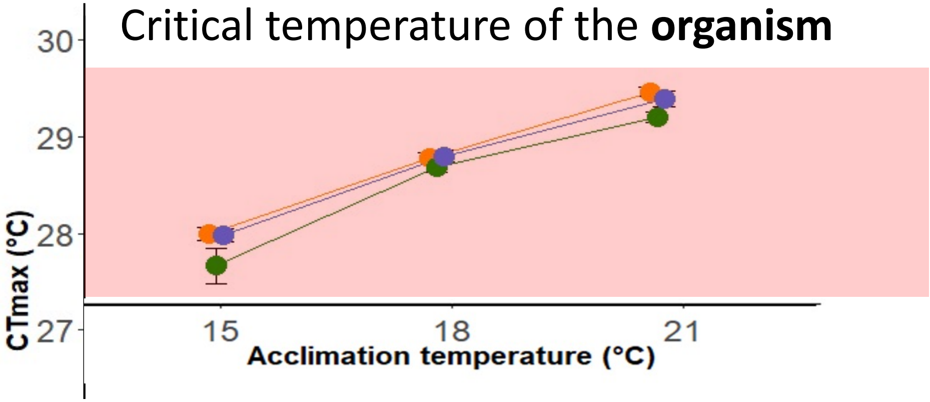


Common Garden

Thermal tolerance & performance

CTmax

Critical temperature of the **organism**

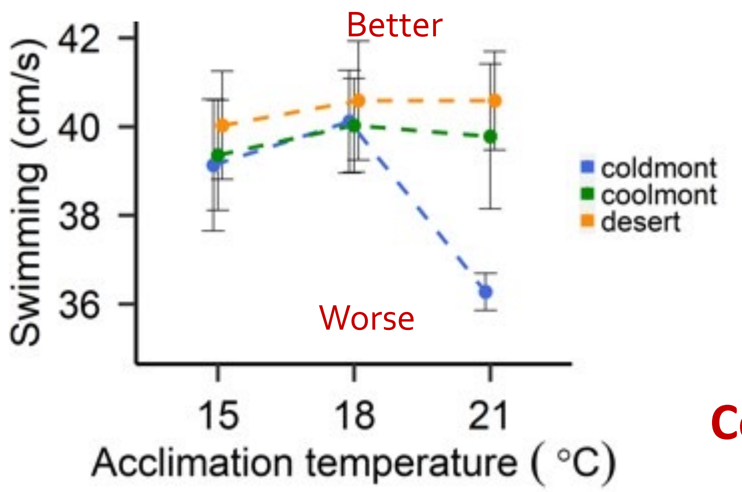


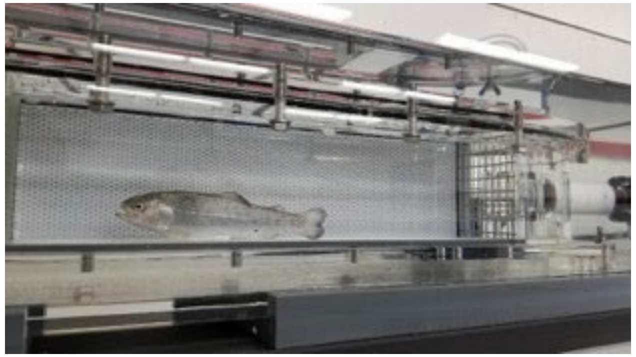
Strong E
Weak G

Zhongqi Chen, UI

Carlie Sharpes, UI

Swimming Performance

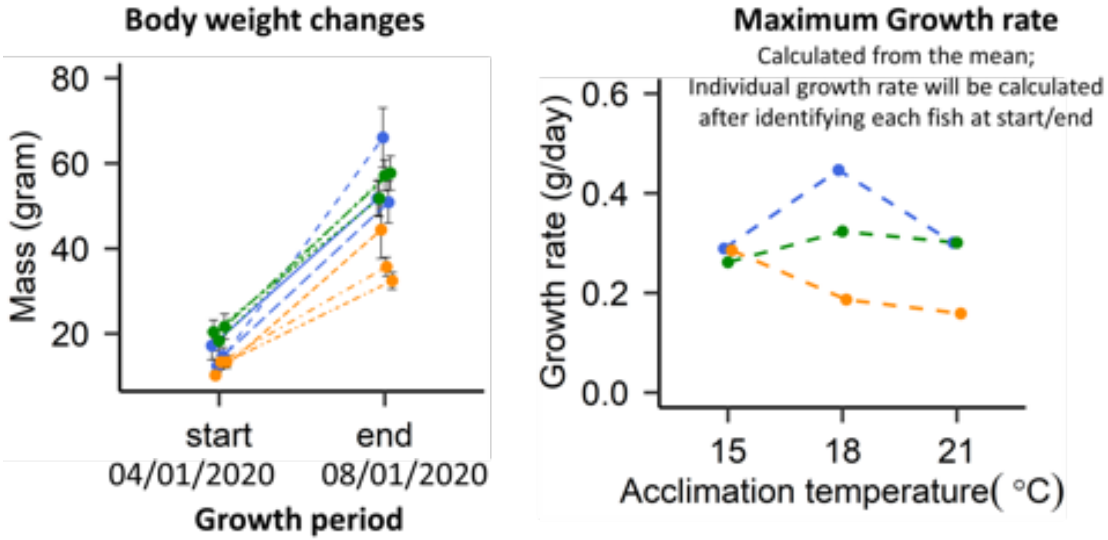




Complex GxE

Ph.D student: Jon Masingale

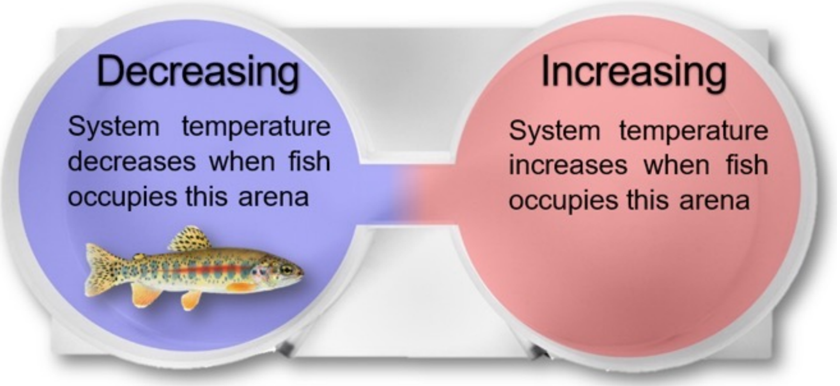
Growth Performance



Complex GxE

Fish Behavior

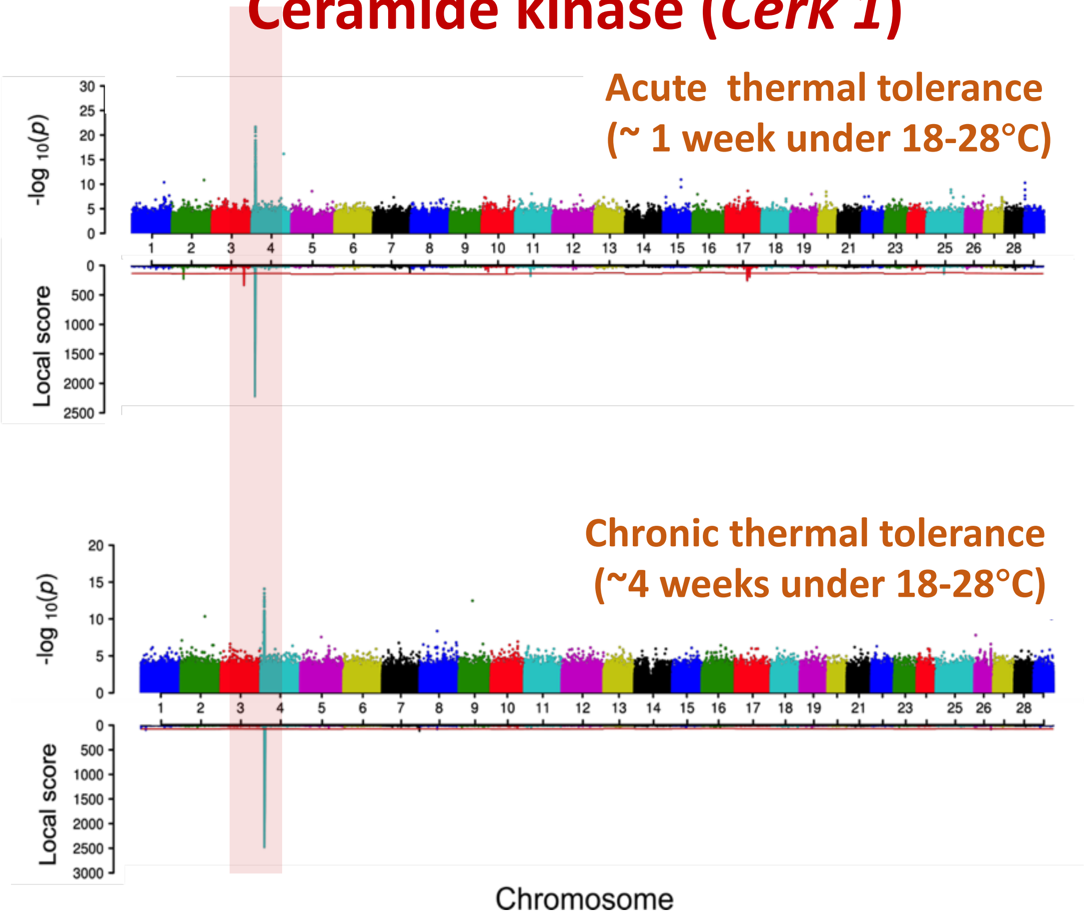
Thermal Preference

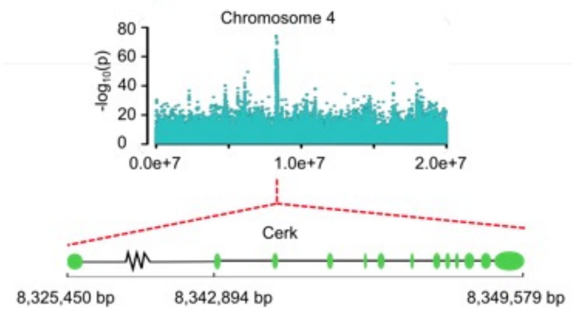


Selection on Cardiac Performance Ceramide kinase (*Cerk 1*)

Acute thermal tolerance (~ 1 week under 18-28°C)

Chronic thermal tolerance (~4 weeks under 18-28°C)





Received: 10 January 2020 | Revised: 14 October 2020 | Accepted: 19 October 2020

DOI: 10.1111/mec.15717

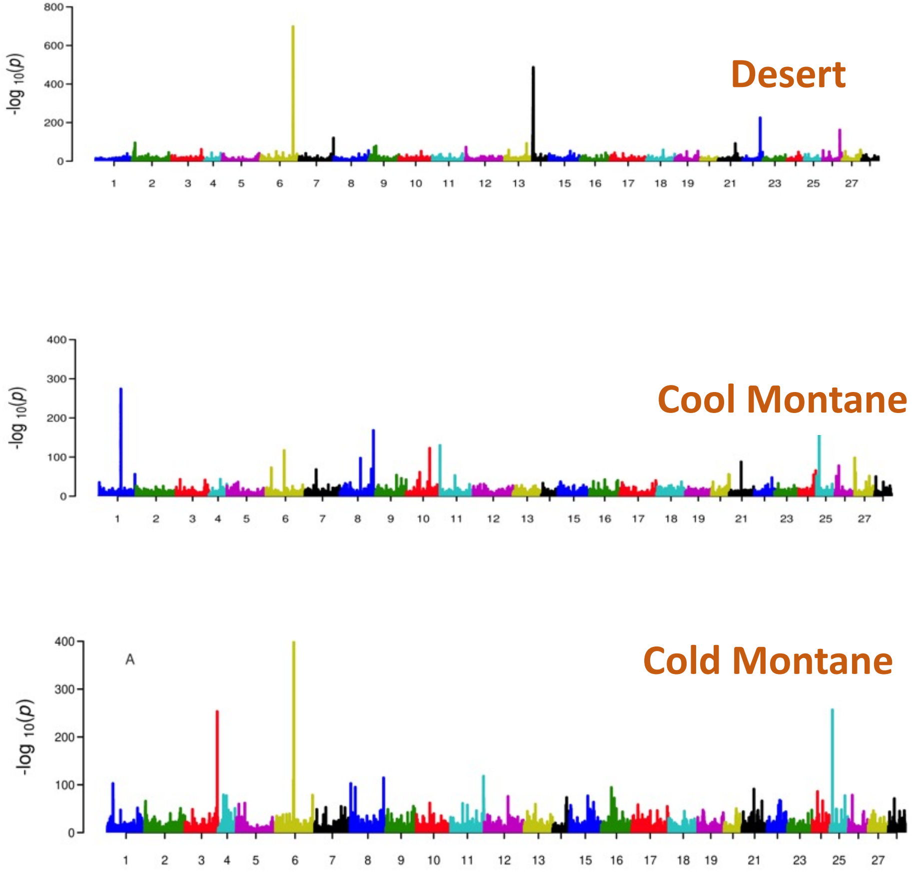
MOLECULAR EC

ORIGINAL ARTICLE

Whole genome resequencing reveals genomic regions associated with thermal adaptation in redband trout

Zhongqi Chen[1] | Shawn R. Narum[1,2]

Ongoing: ID of loci and putative functional basis associated with critical thermal maximum limit



Additional candidate genes

Habitat and Watersheds

How many trout can a stream reach support?

2 Desert vs. 2 Montane streams

Net Energy Intake (NEI) = energy gain – (energy costs + losses)

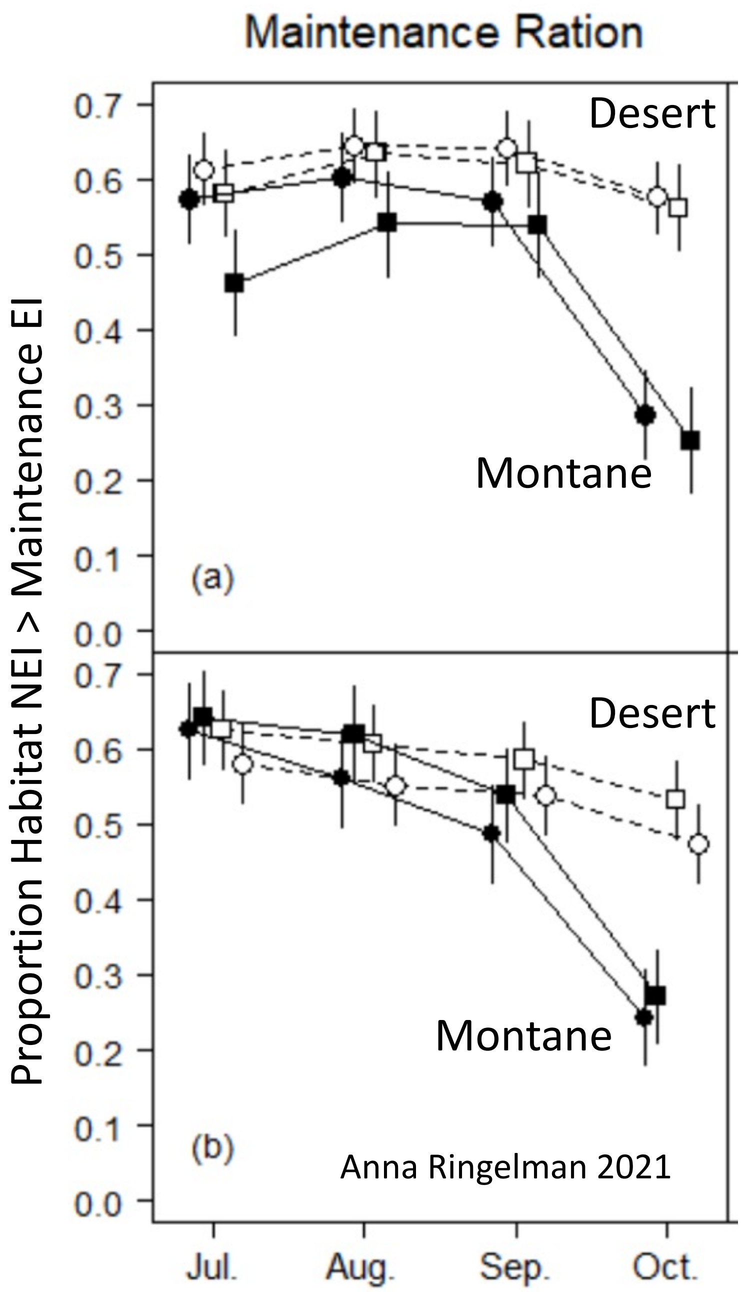
food intake

swimming costs (water velocity)
cost of capturing prey
metabolic costs (temp.)

- Desert streams:
  - Higher NEI
  - Higher trout biomass and size
  - Higher apparent survival

- Predicted habitat suitability declined with under warming, especially for larger trout

Anna Ringelman & Ernest Keeley, ISU



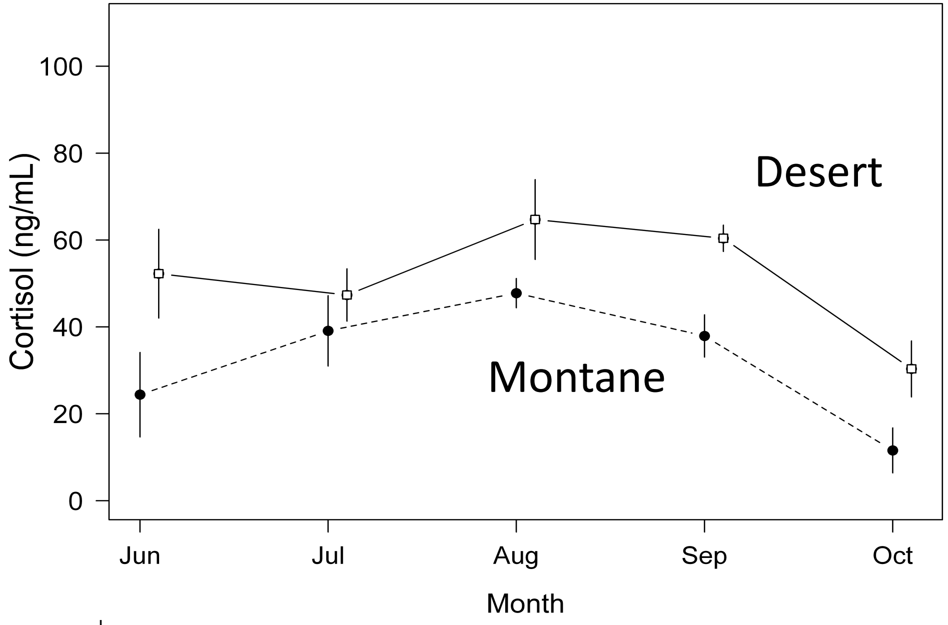
Habitat and Watersheds

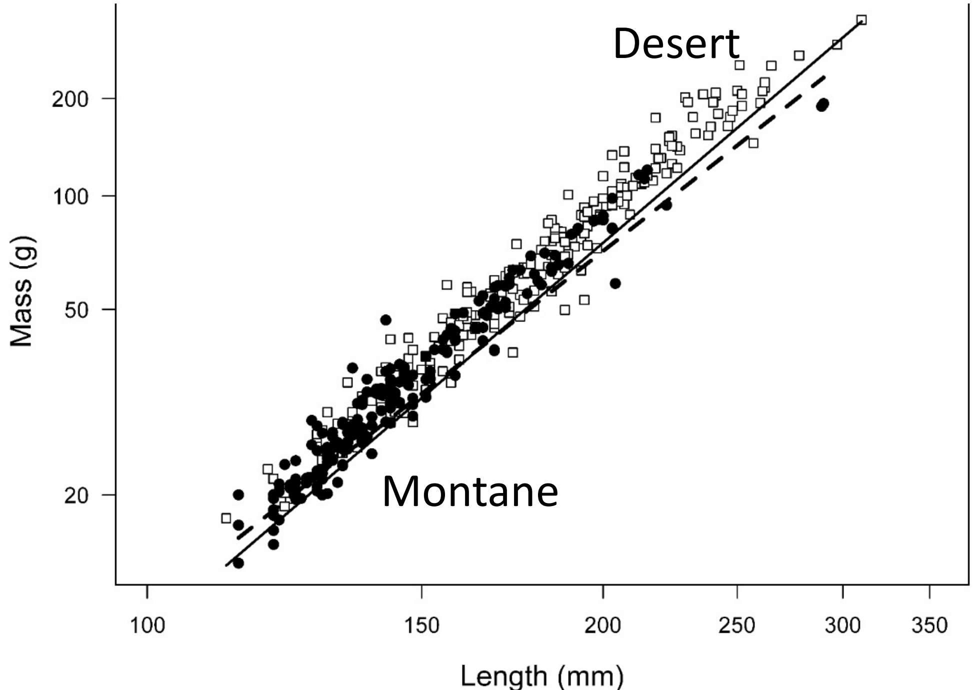
Stress physiology in field populations

2 Desert vs. 2 Montane streams

- Cortisol levels higher in desert
- *But not stressful concentrations*
- Body condition similar between stream types

- **Growth potential higher in desert stream despite higher temperatures**





Alex Wooding & Develeena Pradhan, ISU

Empirical Integration: Agent-based Modeling

CDMetaPOP

Dynamic Stream Environment:

100 m reach "Patches" each with:

-Temperature (NorWeST)

-"Habitat Quality" (growth, survival)

-Connectivity

2 "seasons" each year for multiple decades

Individual Trout:

Loci allow for Genetic Adaptation

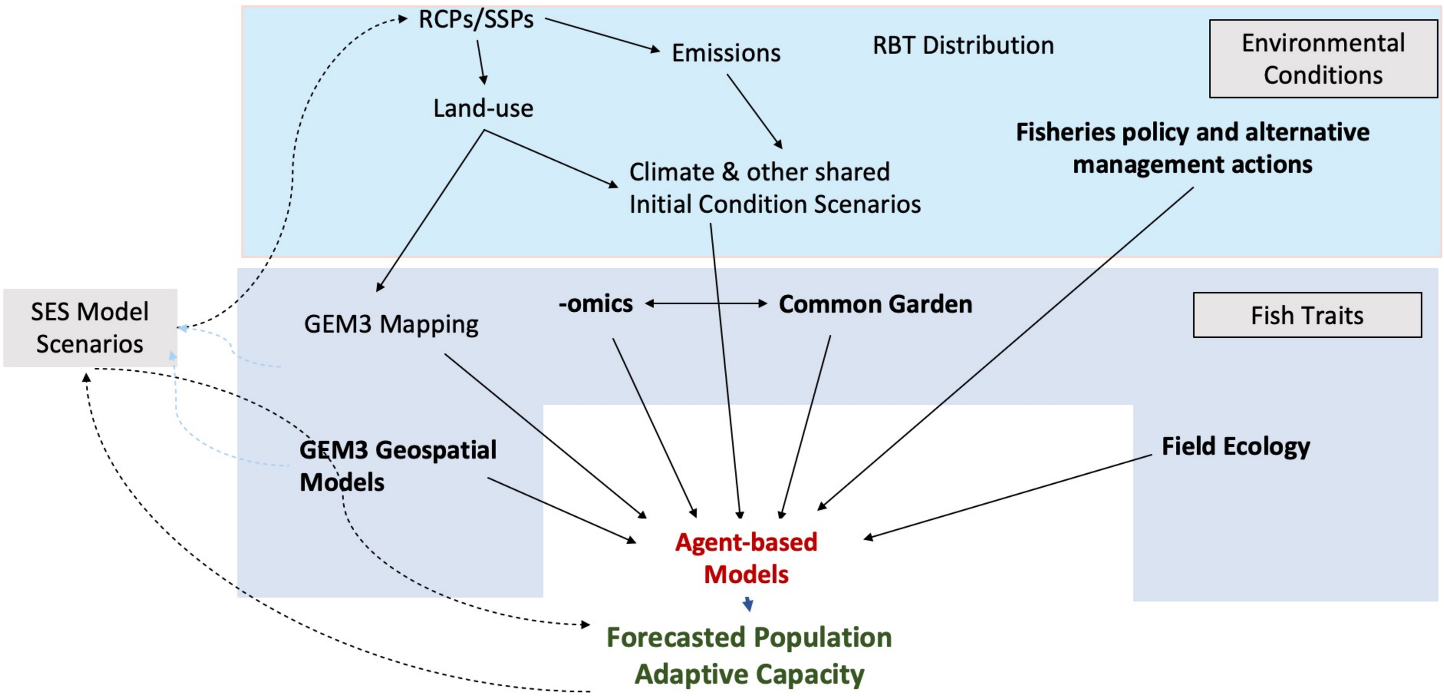
-Temperature-dependent growth & mortality

Behavior

-Straying among natal sites

Plasticity

-Habitat selection (temperature experience)



Travis Seaborn

NDSU

Received: 19 April 2021 | Revised: 29 March 2023 | Accepted: 31 March 2023
DOI: 10.1111/1755-0998.13799

RESOURCE ARTICLE

MOLECULAR ECOLOGY RESOURCES WILEY

Simulating plasticity as a framework for understanding habitat selection and its role in adaptive capacity and extinction risk through an expansion of CDMetaPOP

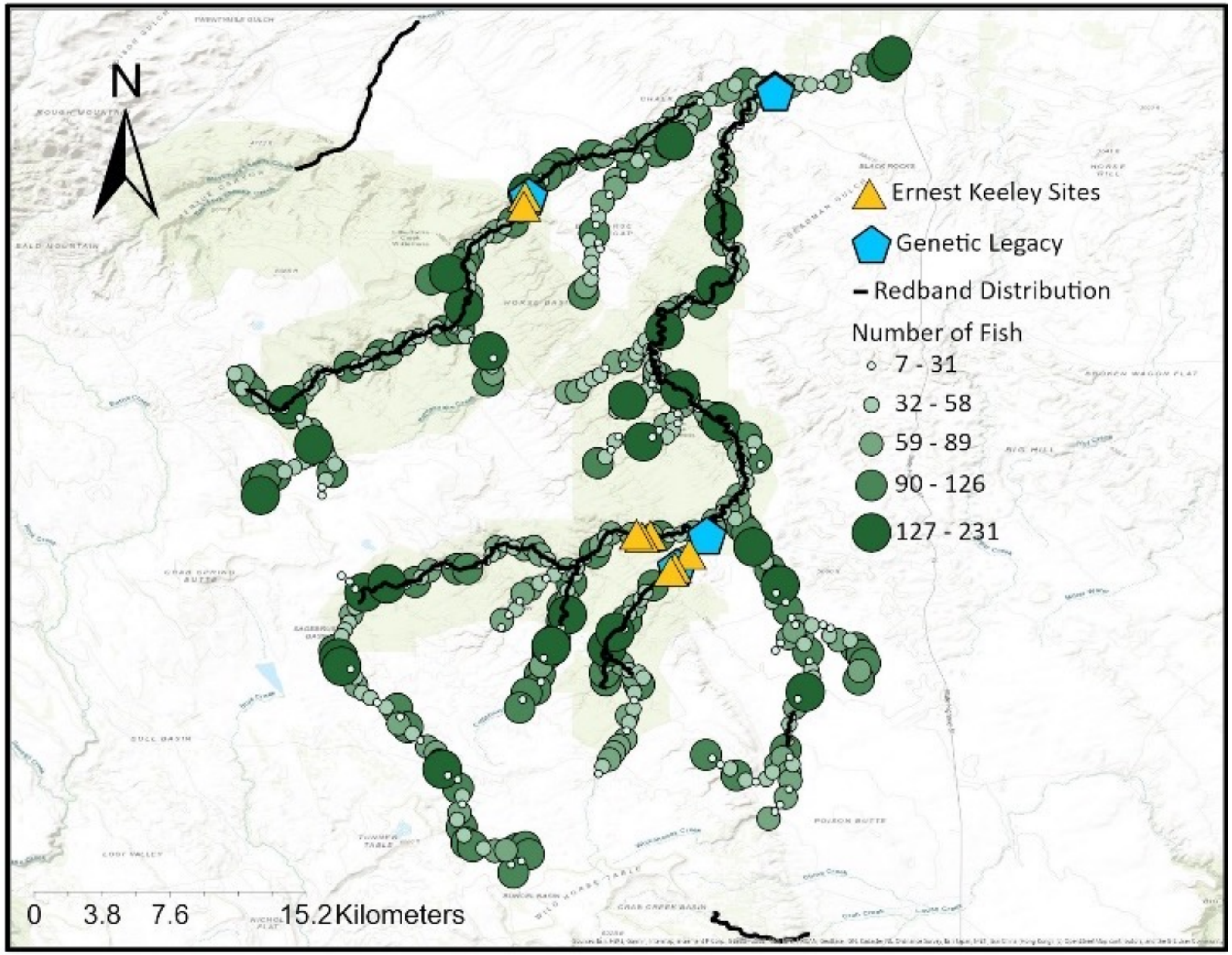
Travis Seaborn[1,2] | Erin L. Landguth[3] | Christopher C. Caudill[1]

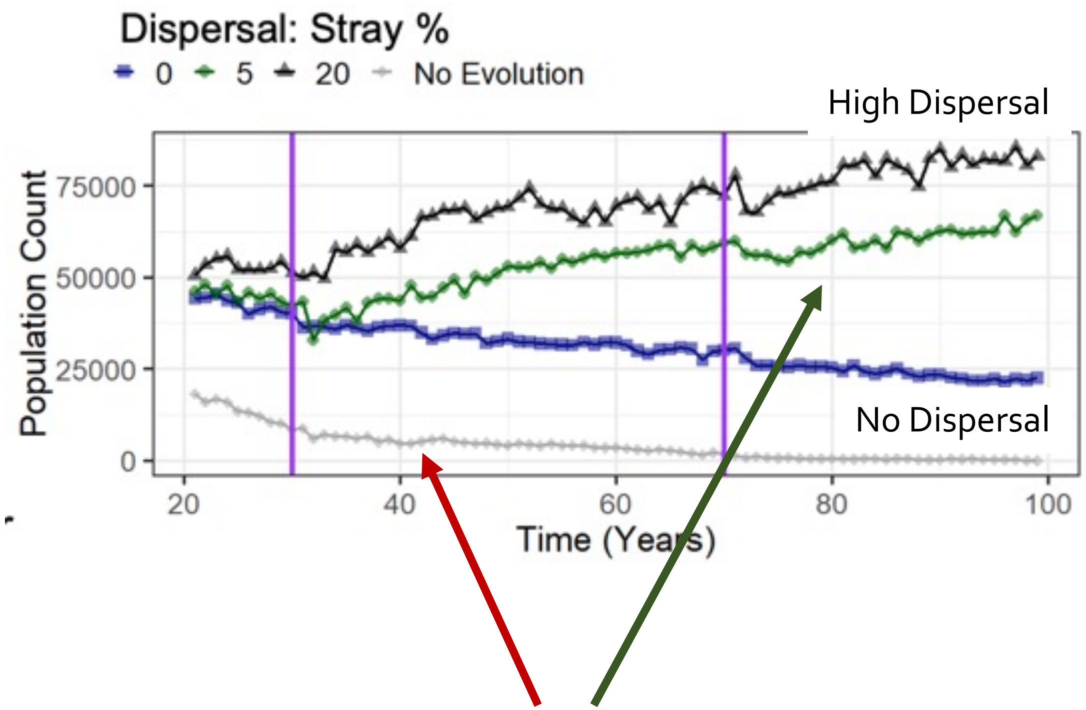
GEM3 Partner: Erin Landguth

Computational Ecology Lab

UNIVERSITY OF MONTANA

Agent-based Modeling: WIP





Extinction in absence of genetic trait; rate of evolution affected by dispersal rate

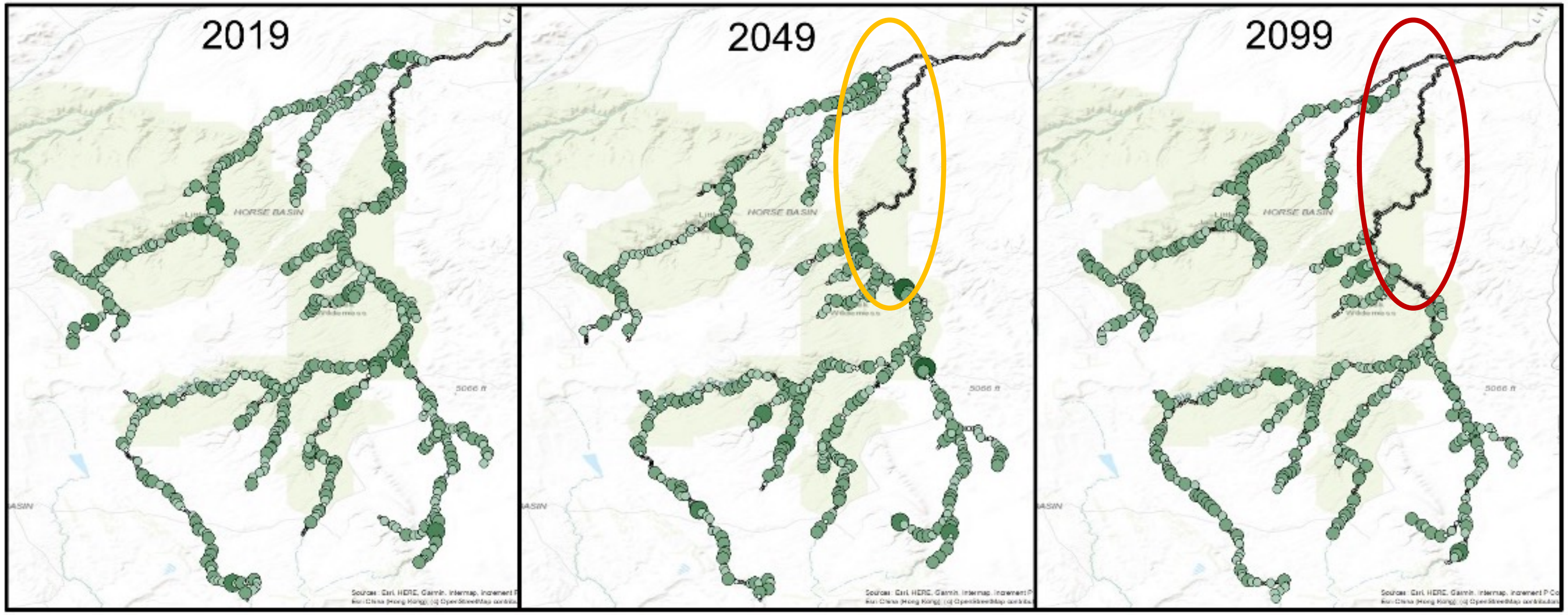
Agent-based Modeling: WIP

Next Step: Scenario Modeling

- Climate SSPs
- Riparian Condition (Grazing)
- Fire History
- Plasticity

Preliminary Stream temperature inputs from NorWeST Model for future stream temperatures

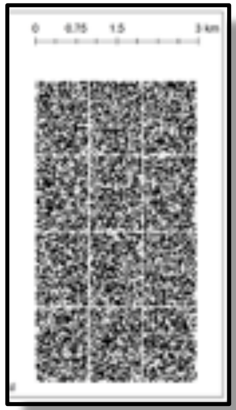
(Isaak, D. J., Wenger, S. J., Peterson, E. E., Ver Hoef, J. M., Nagel, D. E., Luce, C. H., ... & Chandler, G. L. (2017). The NorWeST summer stream temperature model and scenarios for the western US: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research, 53(11), 9181-9205)



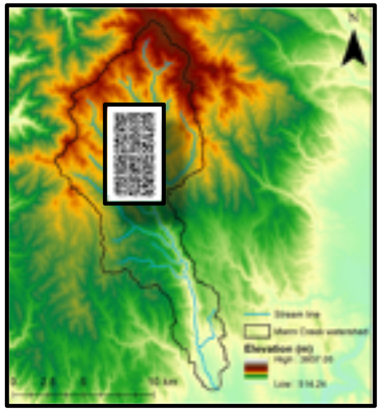
Adaptive potential < rate of environmental change

Watersheds: Modeling thermal and flow regimes

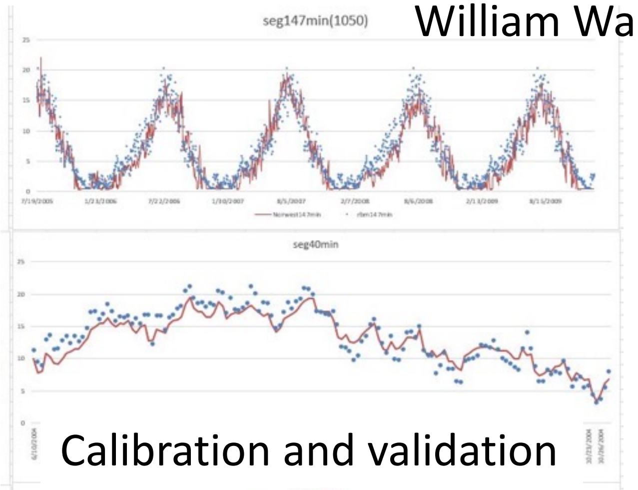
William Wang, Li Huang, Travis Seaborn, Enhao Du, Tim Link



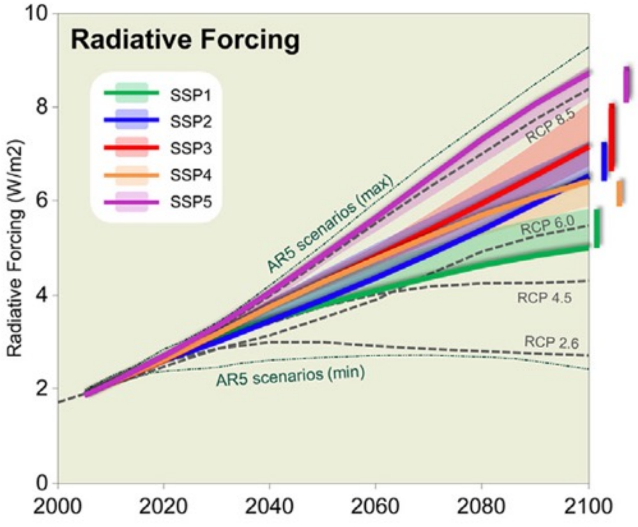
LiDAR
+
Landsat



Geographically Weighted Random Forest

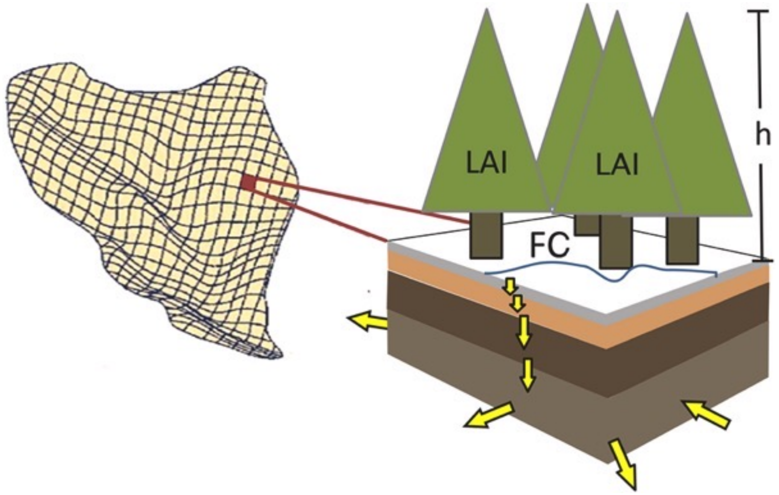


Calibration and validation

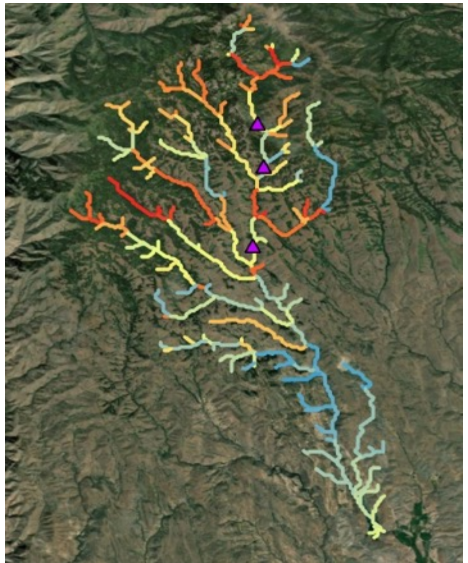


Future SSP Climate Scenarios

DHSVM-RBM Process-based Hydrologic Model



Predicted
Flow
Temperature



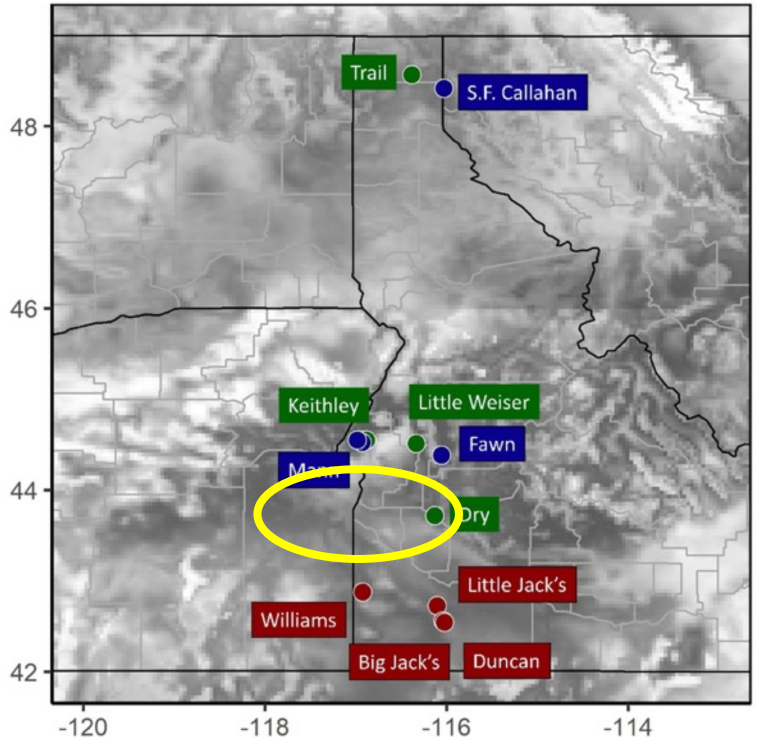
ABM Modeling Input

Baseline Mann Creek Hydro-climate model

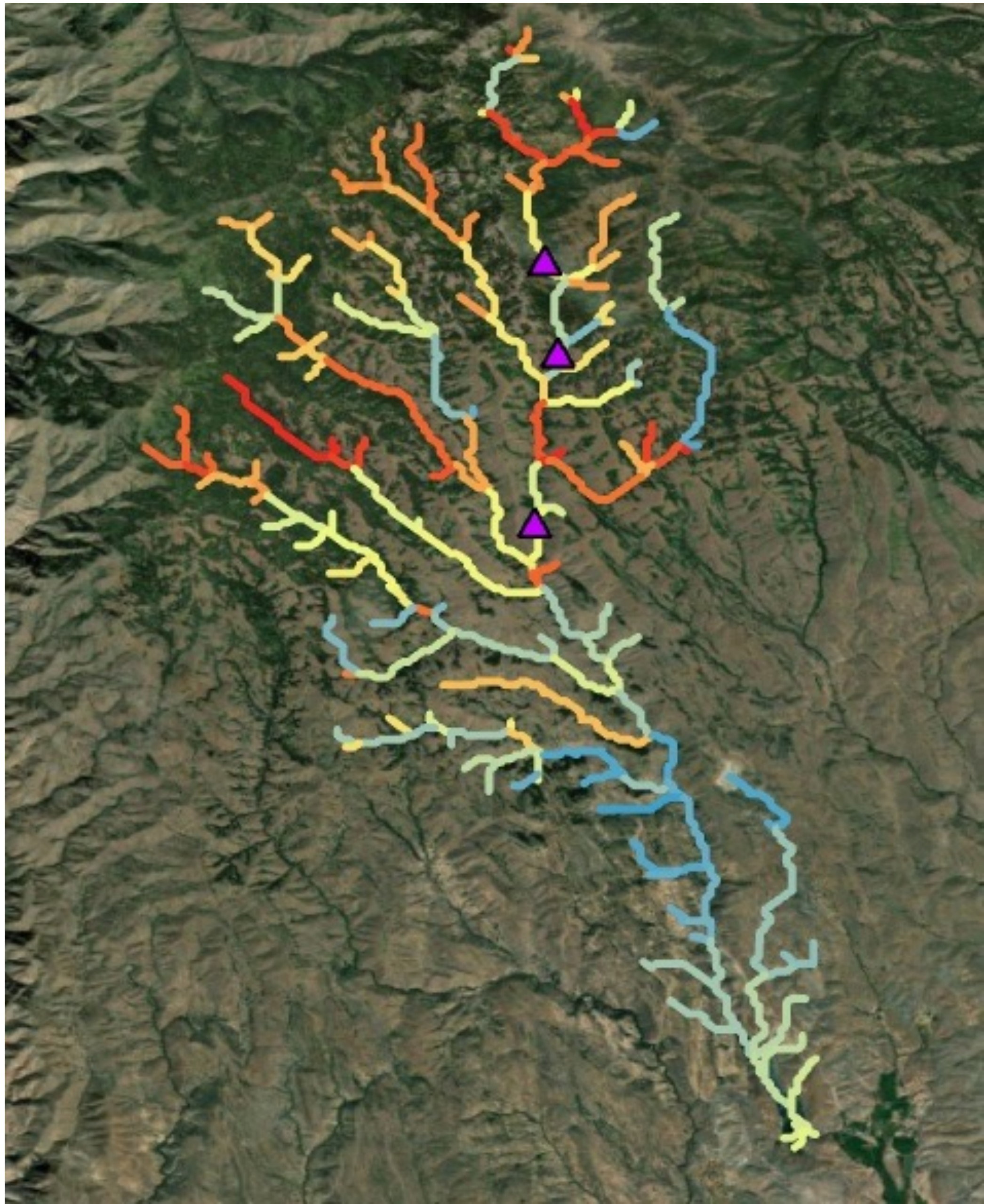
- Stream size, riparian vegetation and groundwater interact
- Warmest reaches are small and at **higher** elevations





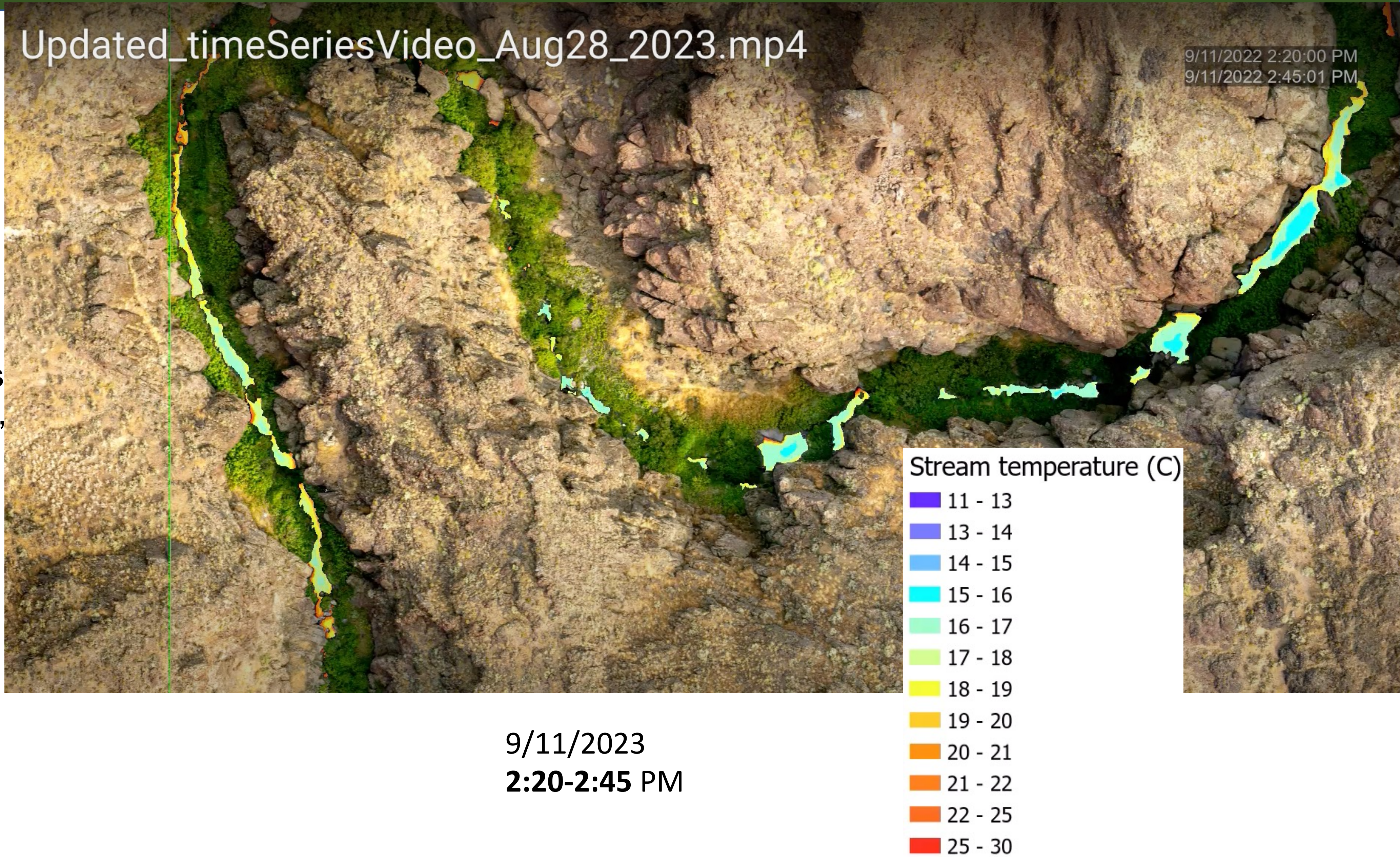
William Wang, Li Huang, Travis Seaborn, Enhao Du, Tim Link



Watersheds: Modeling thermal and flow regimes

UAS mapping of seasonal thermal refugia: integration of the 3Ms

Team: Mel Campbell, Donna Delparte, Chris Caudill, Ernest Keeley, Zhongqi Chen, Jonathan Masingale, Anna Ringleman, Youngwoo Cho



9/11/2023
2:20-2:45 PM

Watersheds: Modeling thermal and flow regimes

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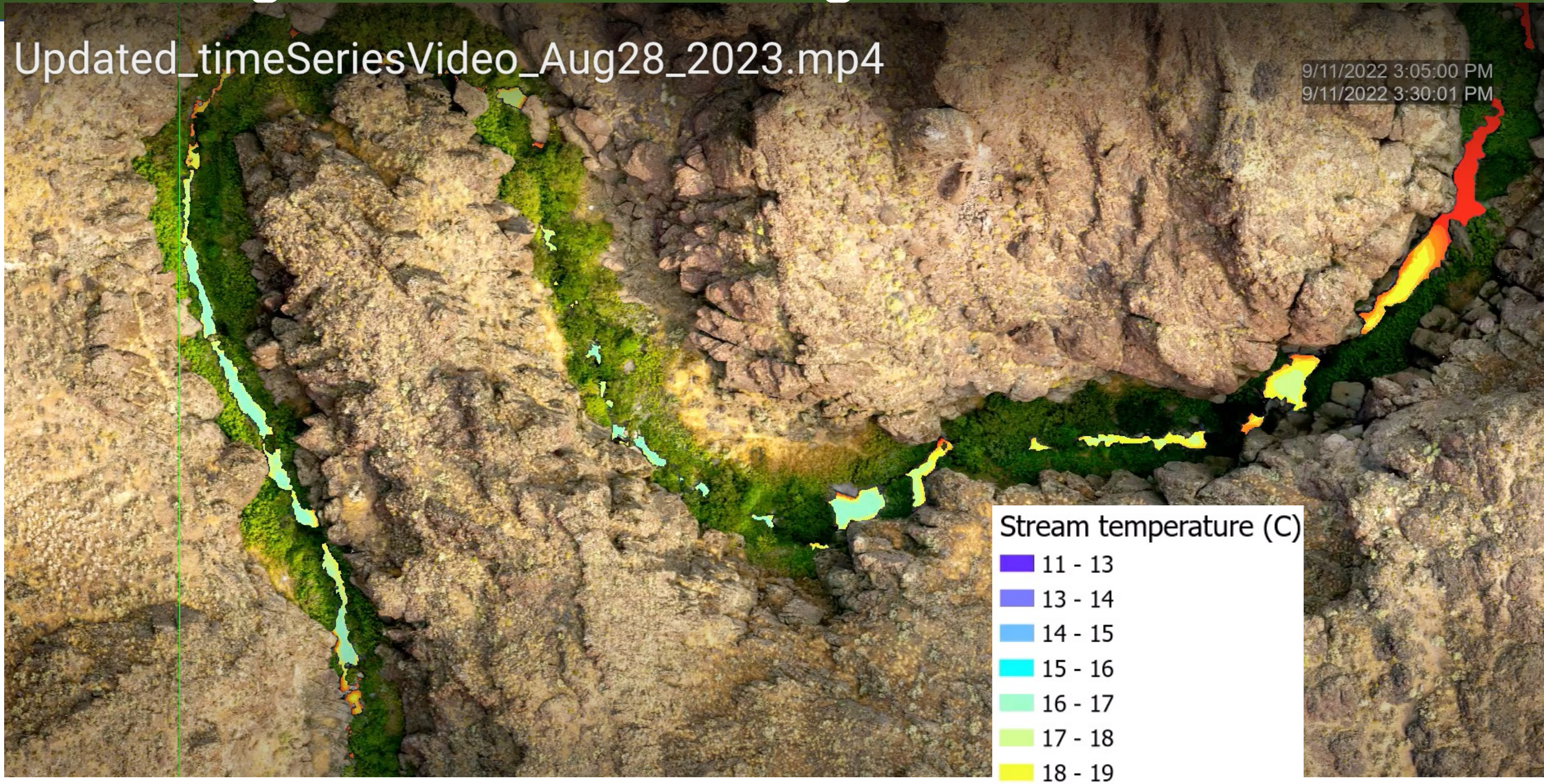
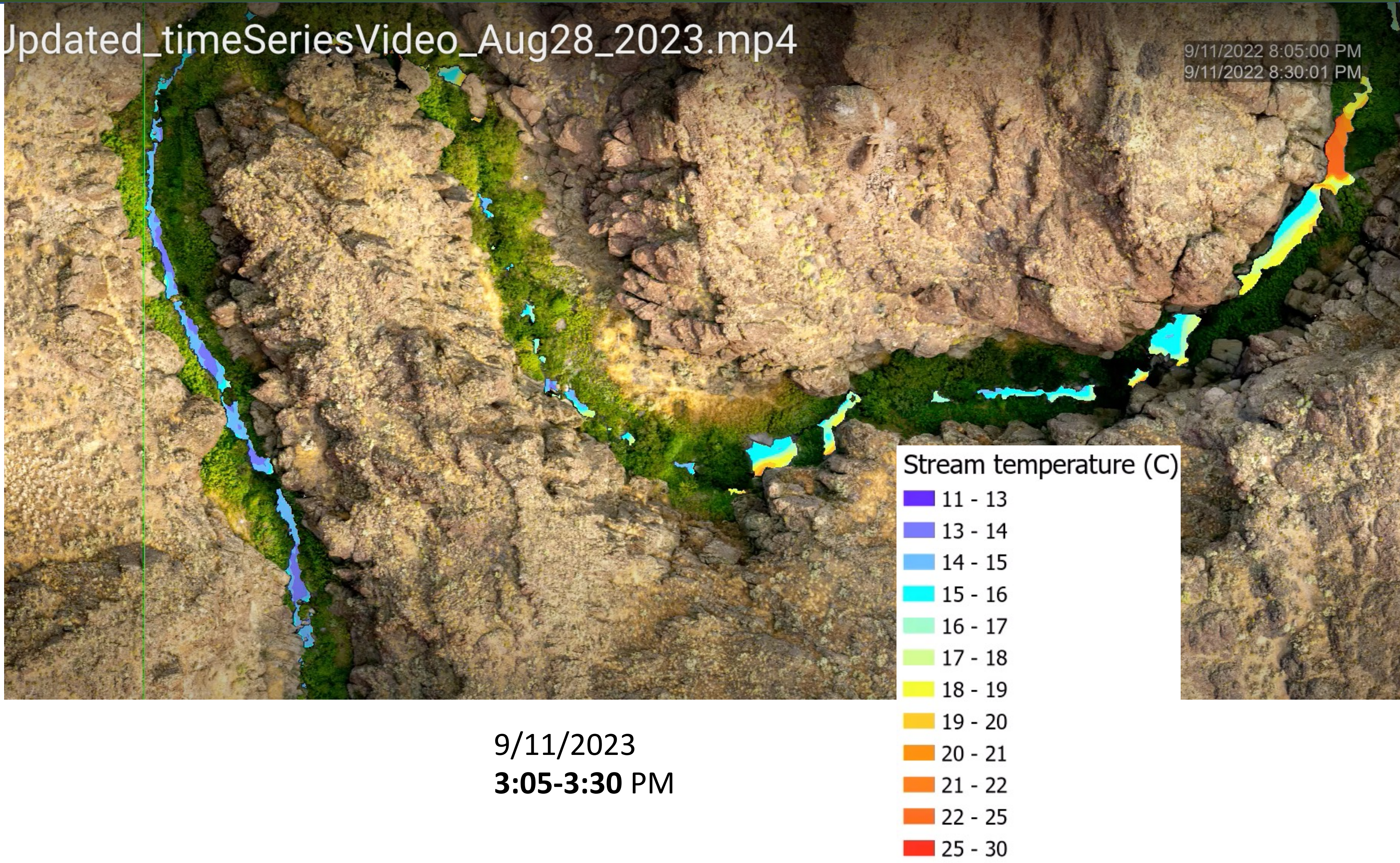


9/11/2023
3:05-3:30 PM

Watersheds: Modeling thermal and flow regimes

UAS mapping of seasonal thermal refugia: integration of the 3Ms

Team: Mel Campbell, Donna Delparte, Chris Caudill, Ernest Keeley, Zhongqi Chen, Jonathan Masingale, Anna Ringleman, Youngwoo Cho



9/11/2023
3:05-3:30 PM

Watersheds: Modeling thermal and flow regimes

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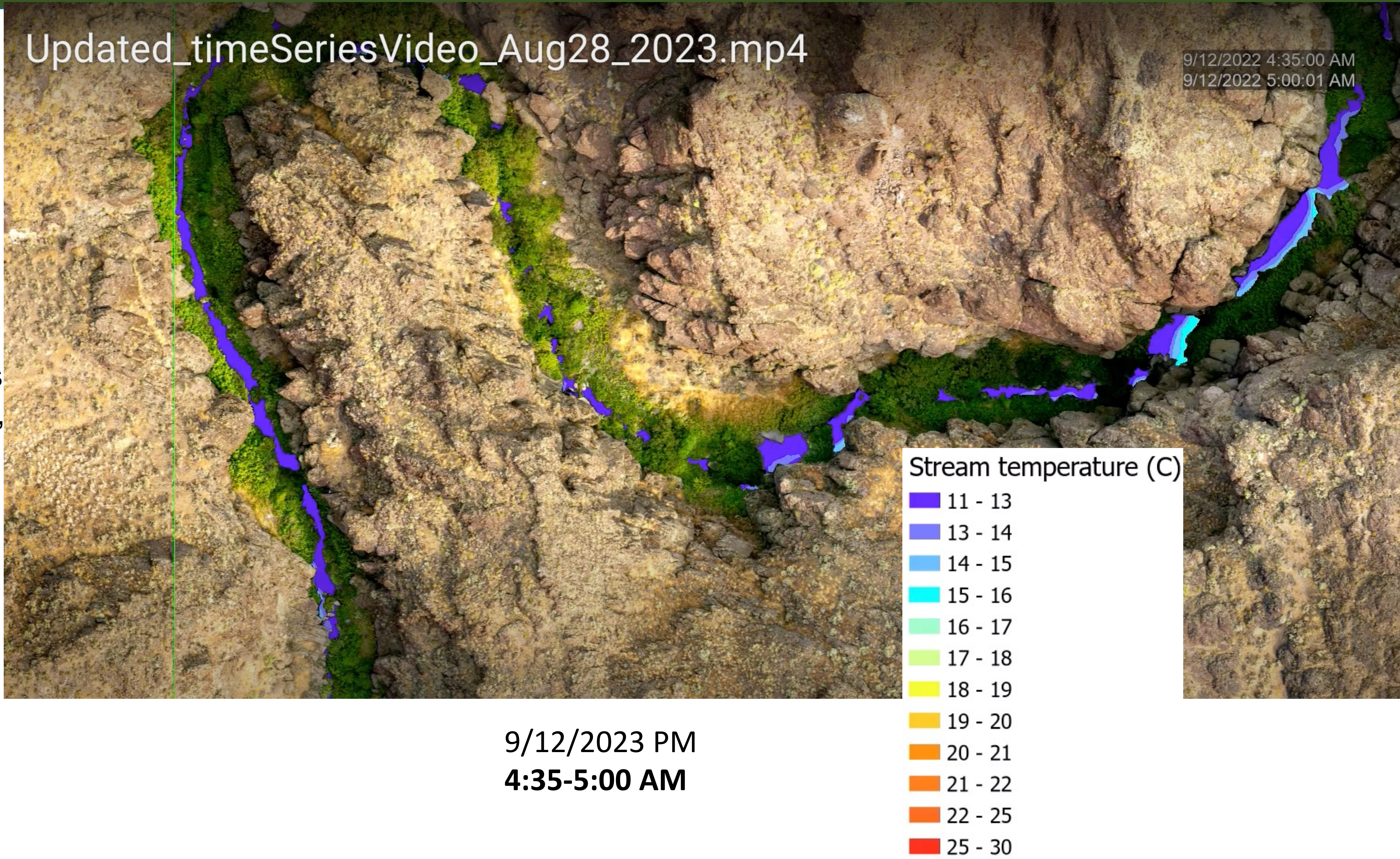
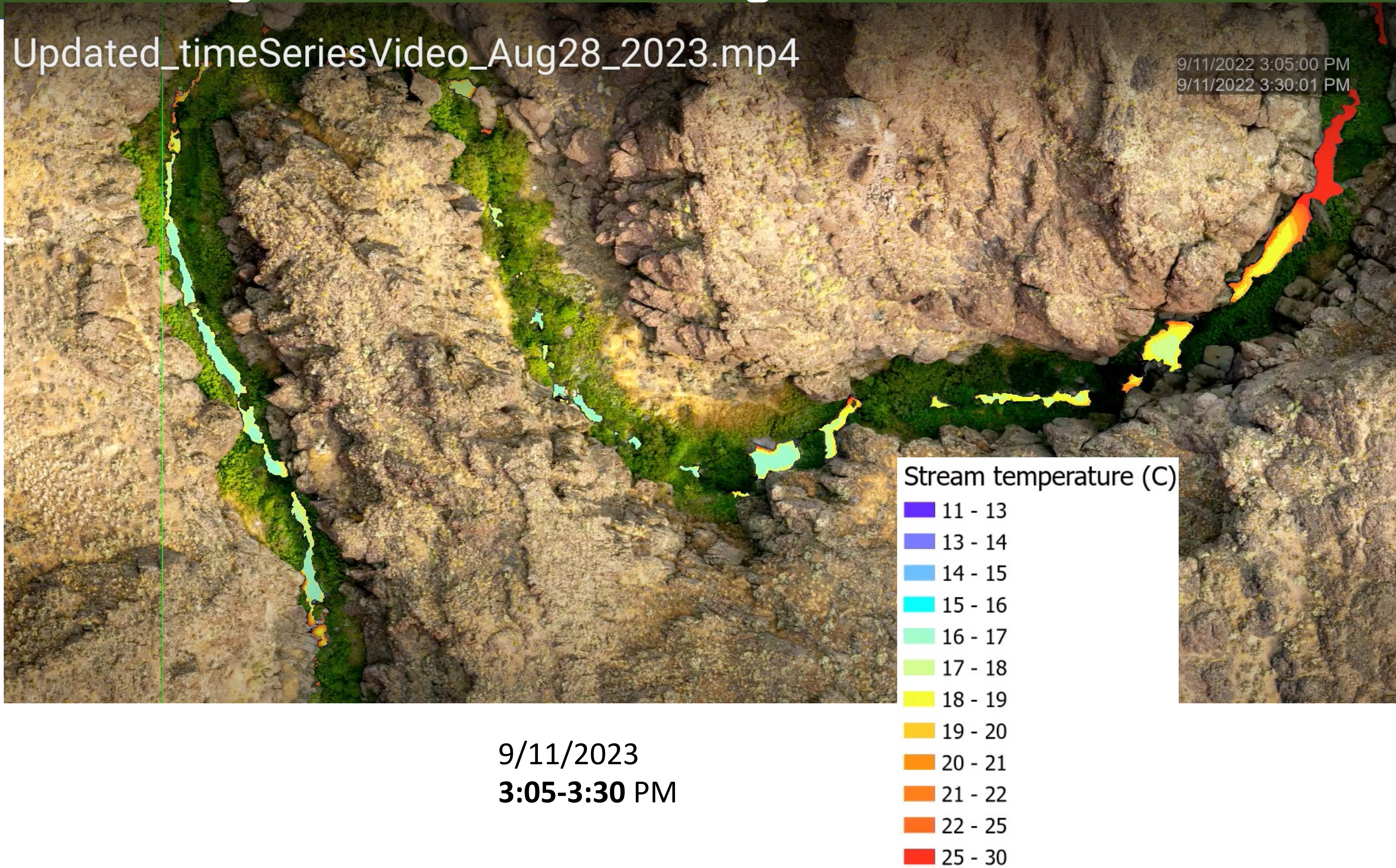


9/12/2023 PM
4:35-5:00 AM

Watersheds: Modeling thermal and flow regimes

UAS mapping of seasonal thermal refugia: integration of the 3Ms

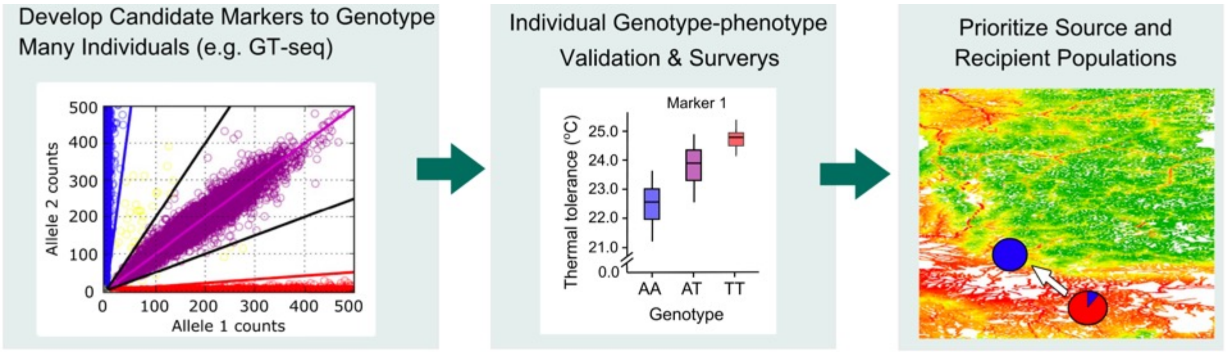
Team: Mel Campbell, Donna Delparte, Chris Caudill, Ernest Keeley, Zhongqi Chen, Jonathan Masingale, Anna Ringleman, Youngwoo Cho



9/11/2023
3:05-3:30 PM

SES and redband trout

- Applying genomics to assisted migration (Chen et al. 2022)



Received: 13 April 2021 | Revised: 18 November 2021 | Accepted: 1 December 2021
DOI: 10.1111/eva.13335

Evolutionary Applications Open Access WILEY

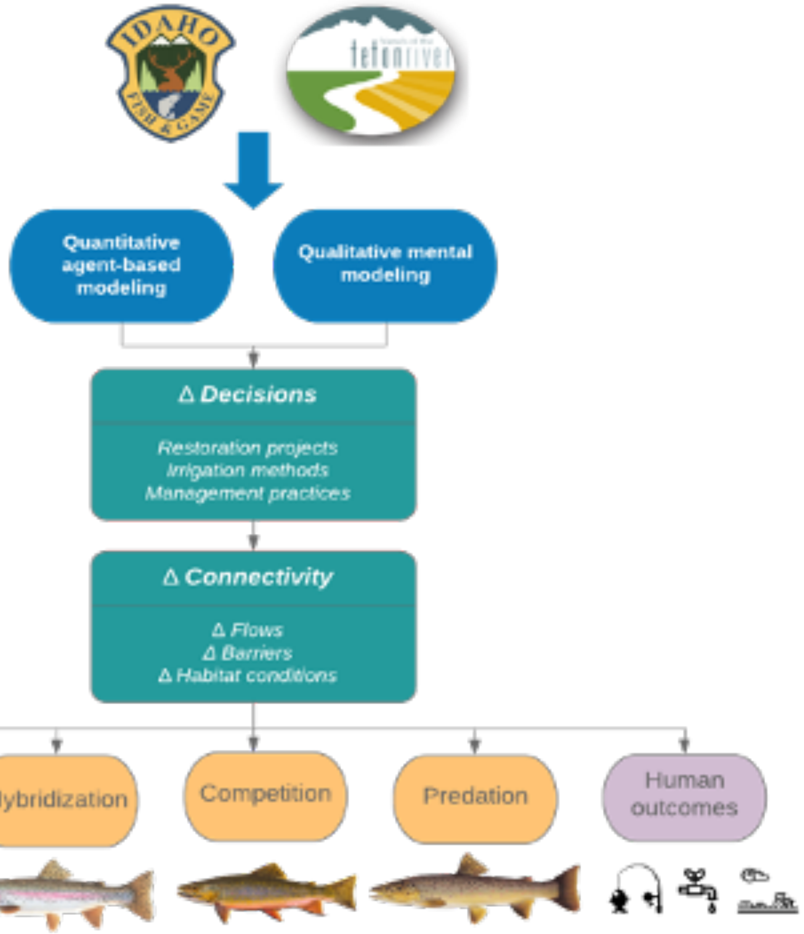
REVIEW

Applying genomics in assisted migration under climate change: Framework, empirical applications, and case studies

Zhongqi Chen[1] | Lukas Grossfurthner[2] | Janet L. Loxterman[3] | Jonathan Masingale[1] | Bryce A. Richardson[4] | Travis Seaborn[5] | Brandy Smith[3] | Lisette P. Waits[5] | Shawn R. Narum[6]

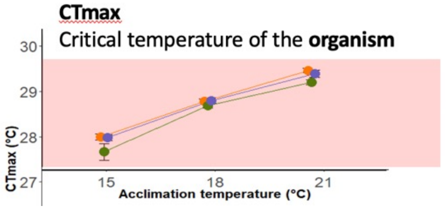
- Using social-ecological models to explore stream connectivity outcomes for stakeholders and Yellowstone cutthroat trout (Jossie et al 2023)

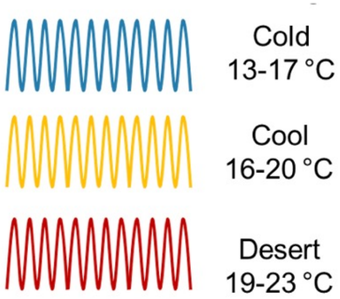
Elizabeth Jossie, ISU

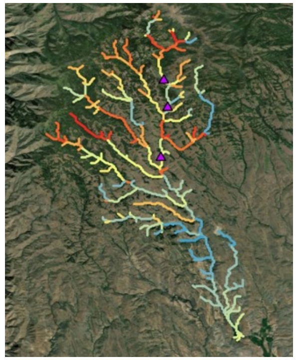


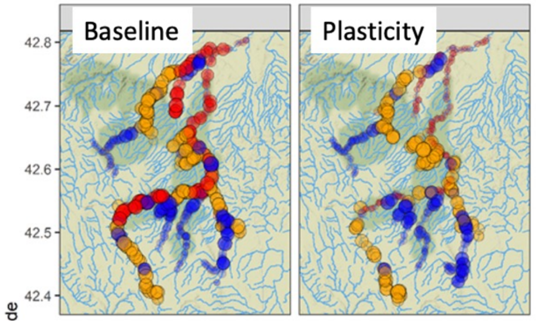
Summary and Emerging Patterns

- **What factors are most sensitive to changing environments**?
  - Plastic traits will be important in core habitat
  - Genetic adaptation allows persistence at edge of thermal limit
  - Desert populations may be at "hard ceiling"
- **Where are the 'surprises**'?
  - Strong signal of selection from **thermal variability** as well as maximum temperature-key test of common garden 'cohort 3'
  - Desert streams productive but periodically lethal
  - Future thermal conditions not always intuitive at local scale
- **What are key unknowns?**
  - Effects and costs of plasticity?
  - G, GxE of movement and dispersal
  - Temperature, GxE, microbiomes and pathogens (Egan et al.; Bledsoe et al.)
  - Scope of inference: Do these patterns hold in other species and systems?
- Genetic, **plastic**, and **habitat** factors contribute to local adaptive capacity



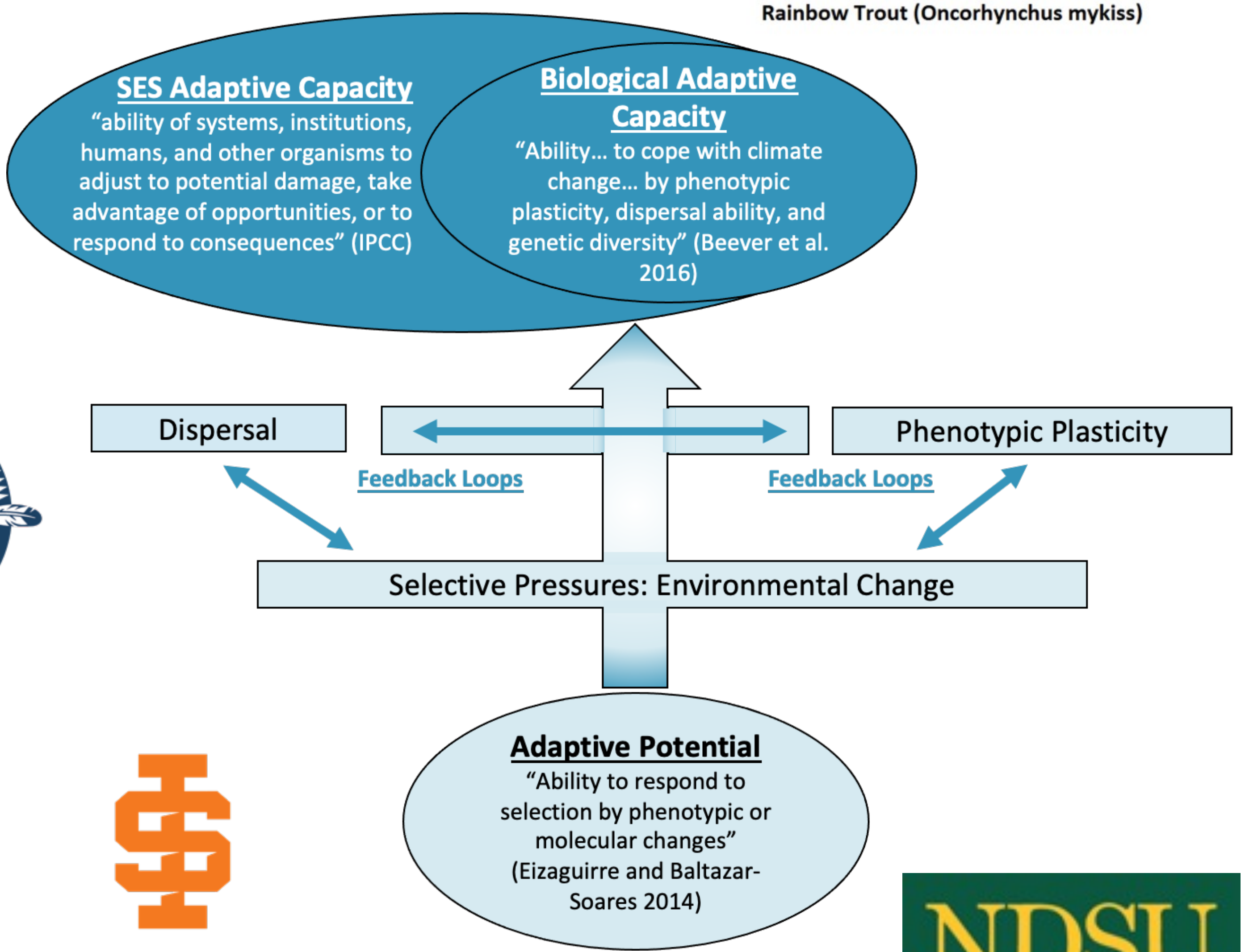






Thanks!

Rainbow Trout (Oncorhynchus mykiss)



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GEM3 Genes by Environment Modeling · Mechanisms · Mapping

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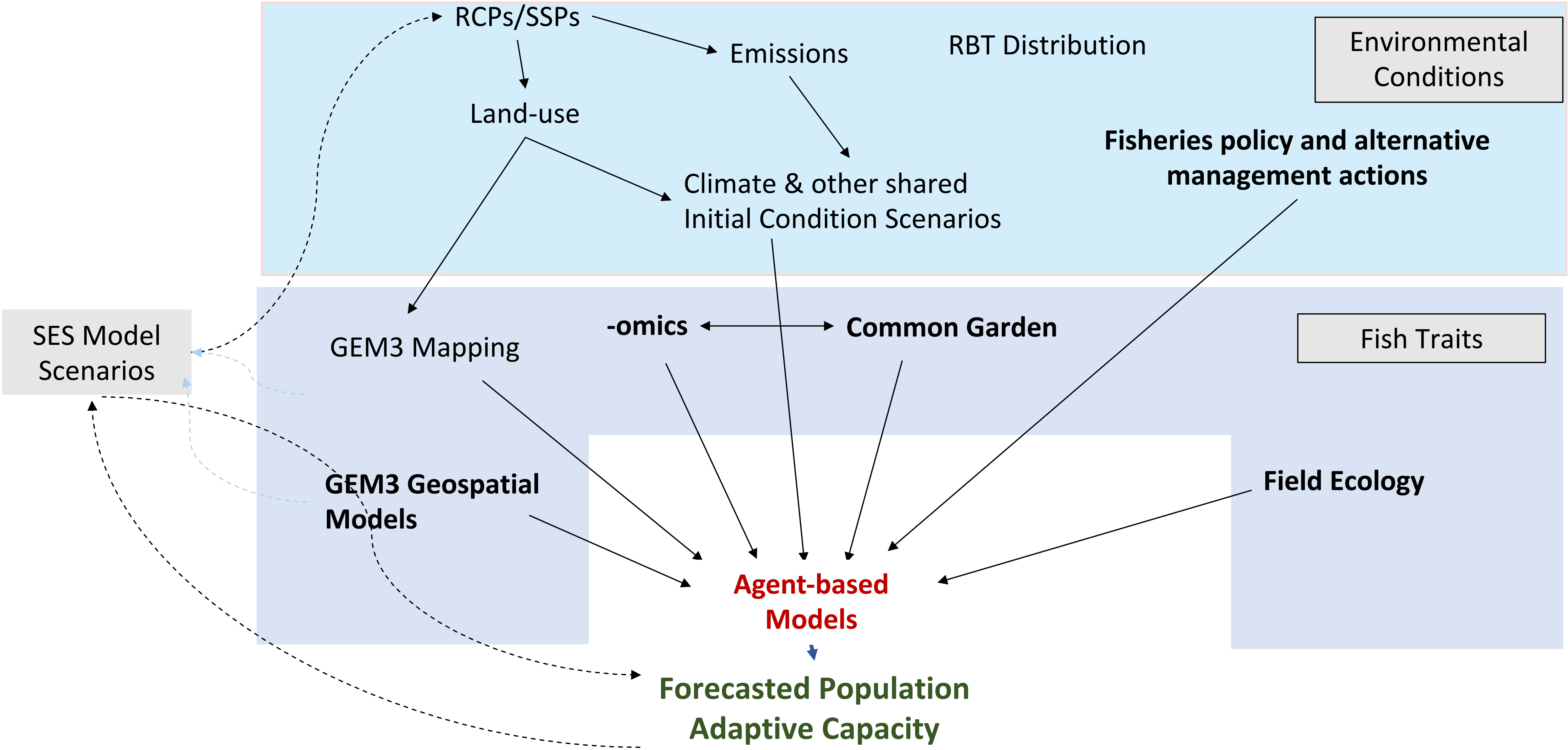
GEM3 Trout Mechanisms Working Group Workflow



Agent-based Modeling: WIP

Habitat Selection can increase individual survival but decrease abundance (Perfect thermal selection, no cost to plasticity)