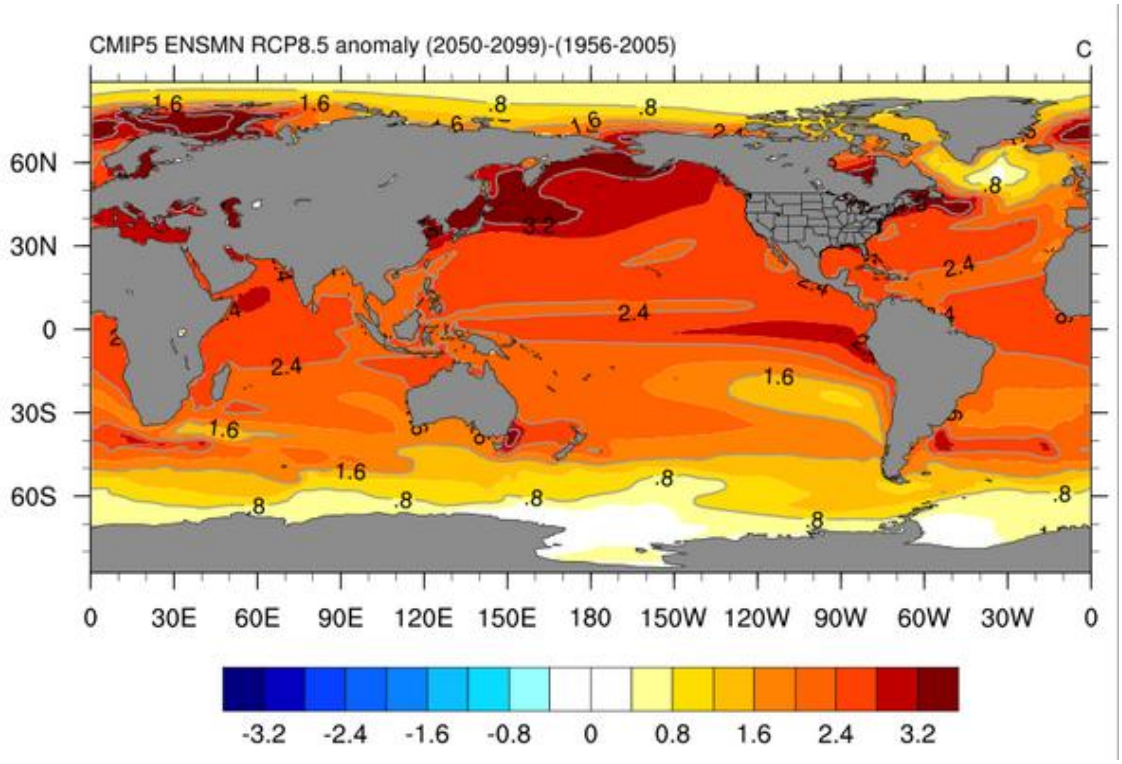
Modeling thermal tolerance of winter run Chinook salmon embryos

NOAA FISHERIES

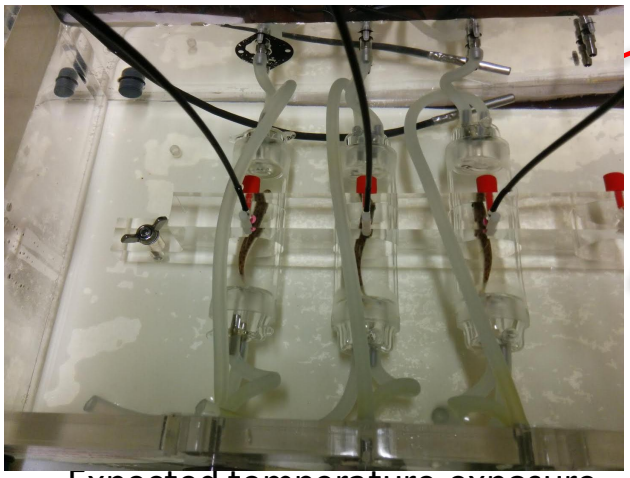
It’s getting warmer…



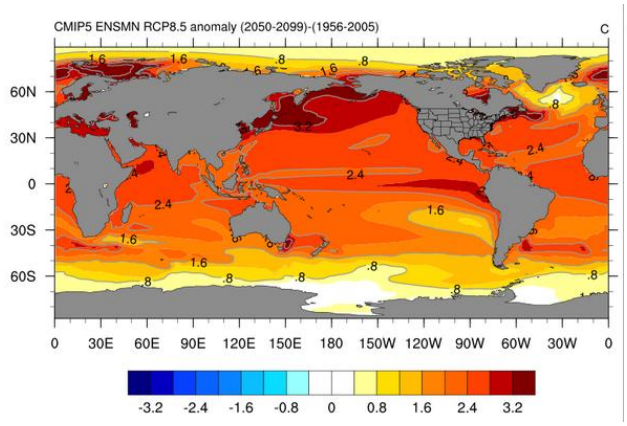
How will species respond?

Thermal response curves

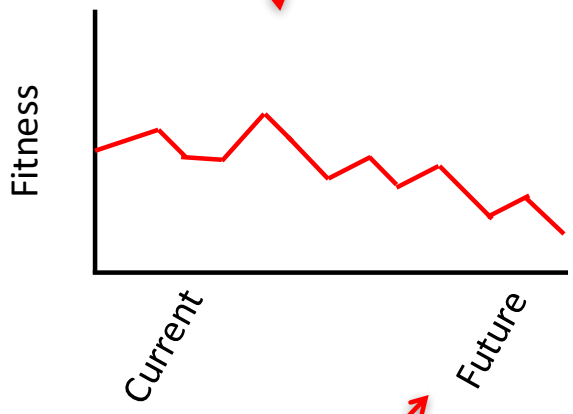
Lab experiment



Expected temperature exposure



Assumes relationship between temperature and performance in lab holds in nature



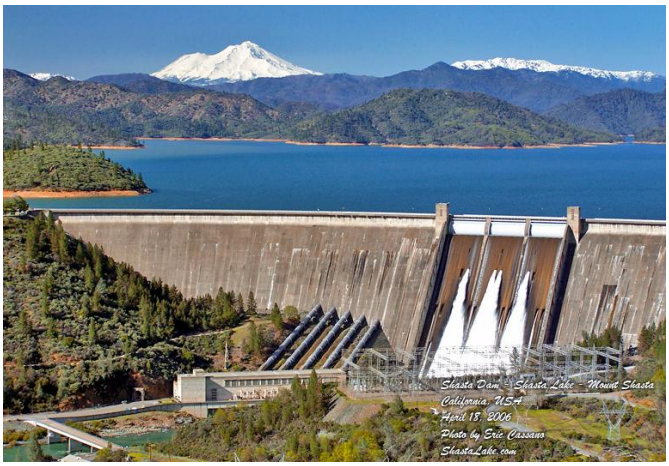
By the time we find out if that is true it's too late

Are statistical/descriptive lab derived models of thermal tolerance predictive in nature?

A case study with Sacramento Winter-run

- ESA listed population

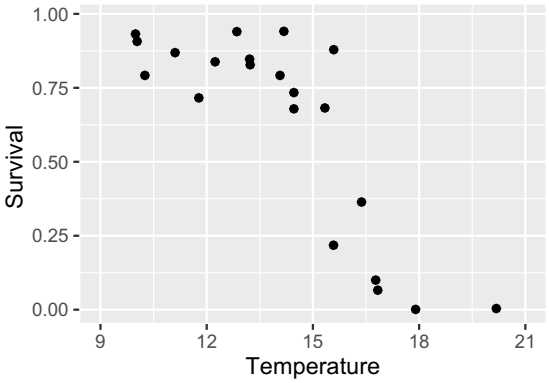
- Blocked from historic spawning grounds
- Embryos, most sensitive life stage to temperature



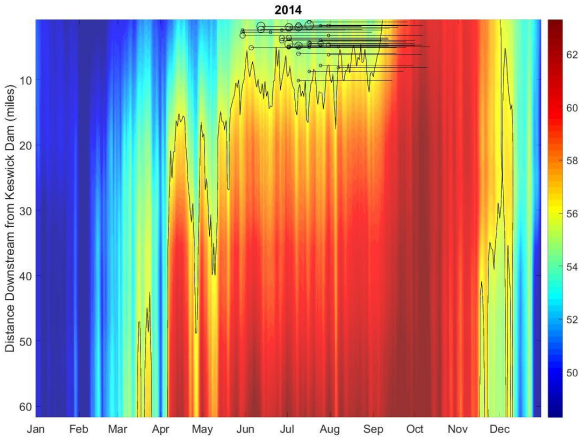
- Water release managed to avoid high embryo mortality
  - Temperature targets based on laboratory data

A case study with Sacramento Winter-run

Lab data



Exposure data



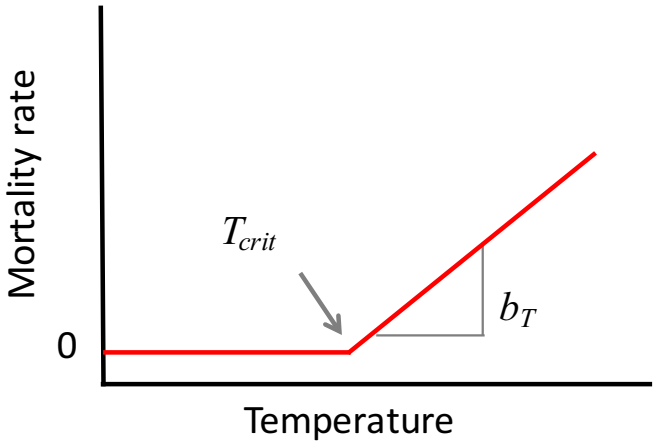
Red-bluff diversion dam survival data

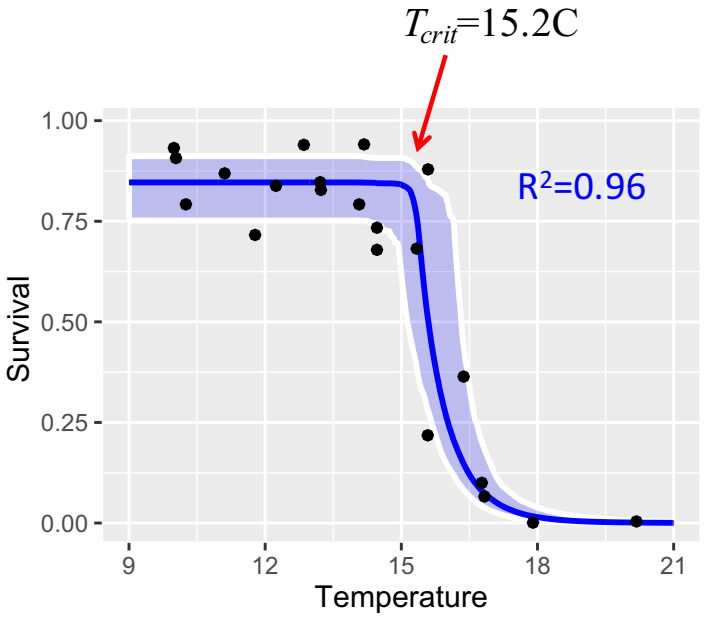
USFWS

Thermal tolerance model

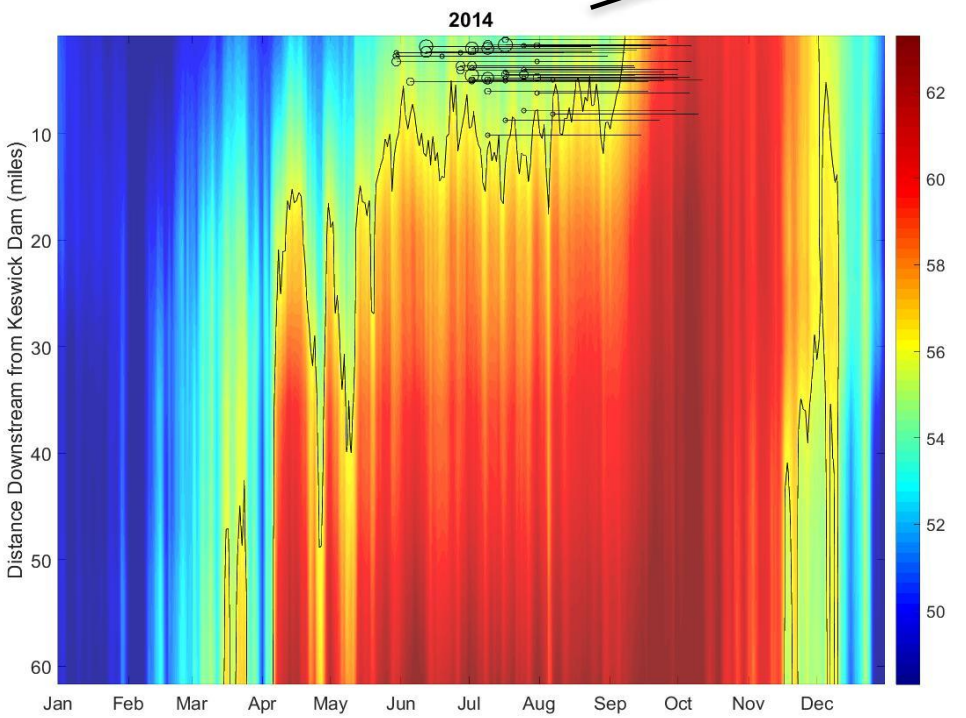
$$h_i = b_T \max(T_i - T_{\text{crit}}, 0)$$

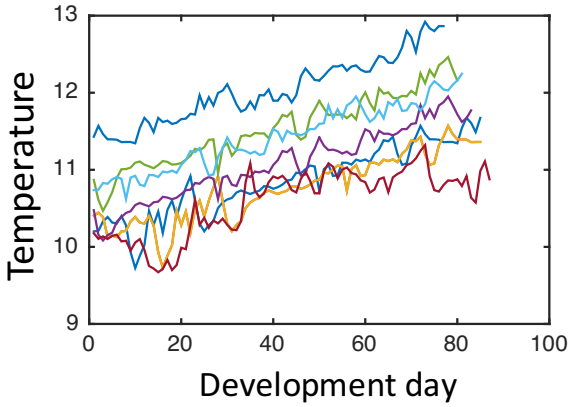
$$M_T = 1 - \prod_{i=1}^{n} \exp(-h_i)$$

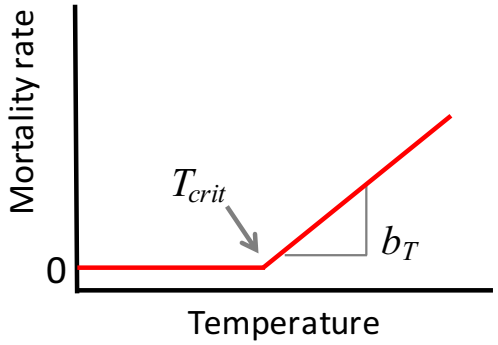




Data from: Combs and Burrows 1957, Jenson and Groot 1991, USFWS 1999







$$h_i = b_T \max(T_i - T_{\text{crit}}, 0)$$

$$M_T = 1 - \prod_{i=1}^{n} \exp(-h_i)$$

Assumptions

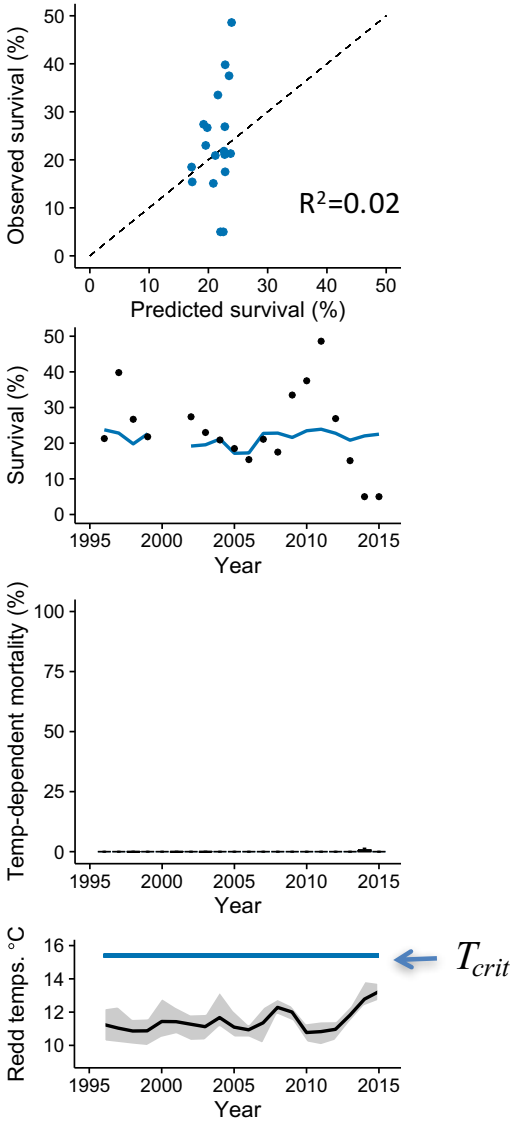
- Constant thermal tolerance parameters throughout embryonic stage
- Other sources of mortality grouped into background survival parameter
- Temp-dependent mortality occurs only during embryonic stage

Testing the lab model

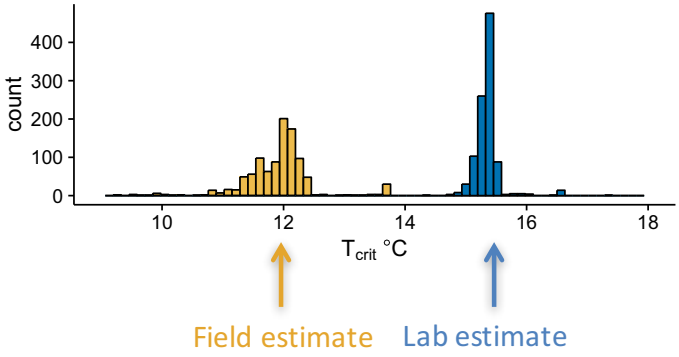
Why so bad?

- H1: Factors other then temperature drive annual variation in survival
- H2: Thermal tolerance in the field differs from the lab

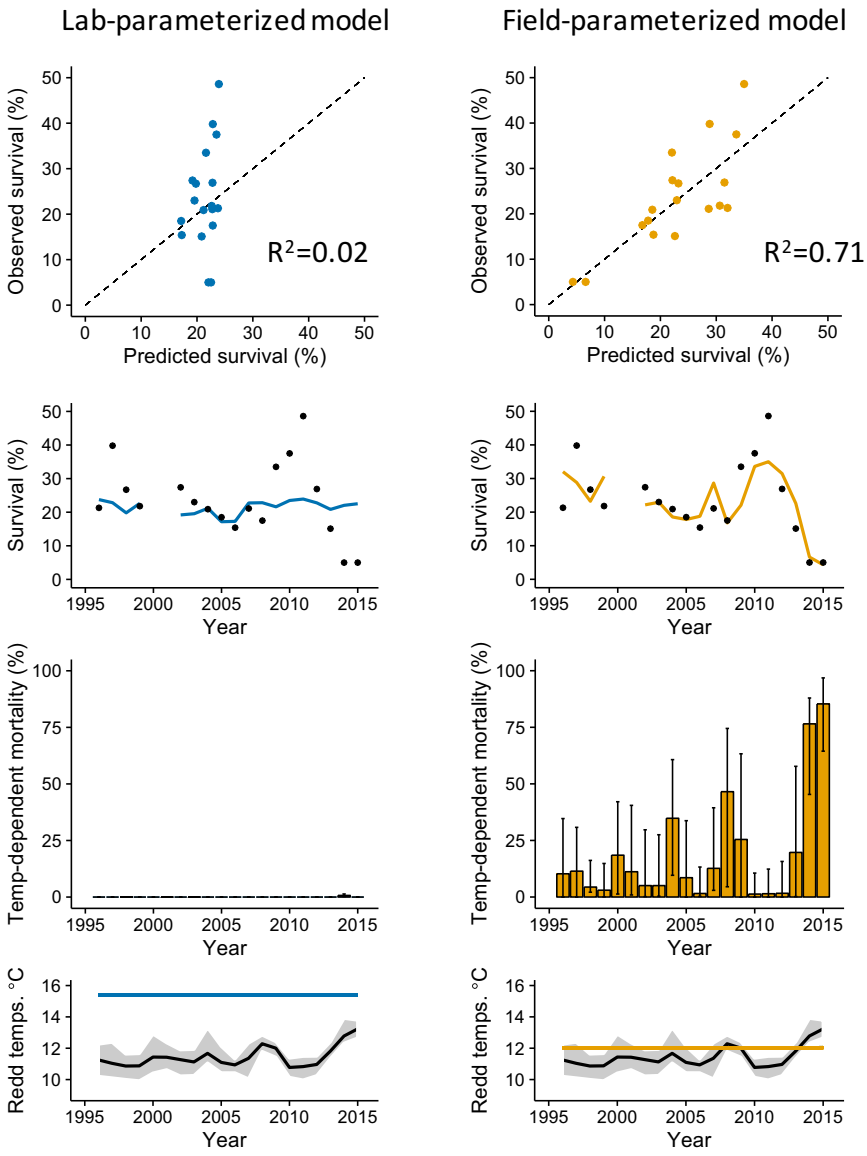
Test: rerun analysis, but estimate thermal tolerance parameters using field data



Lab vs. field



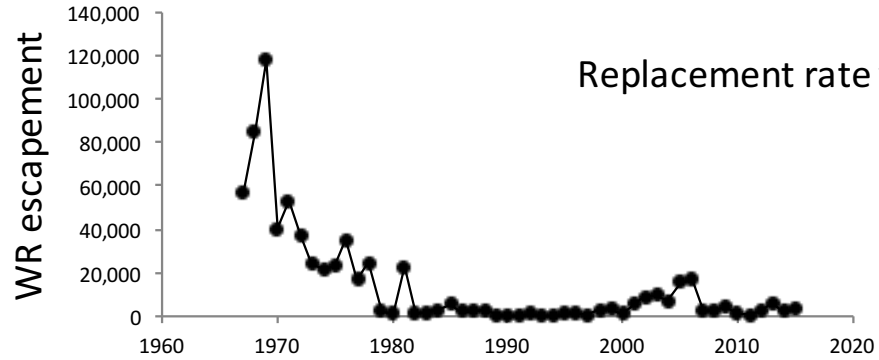
Thermal tolerance in the field
3C lower than in the lab!



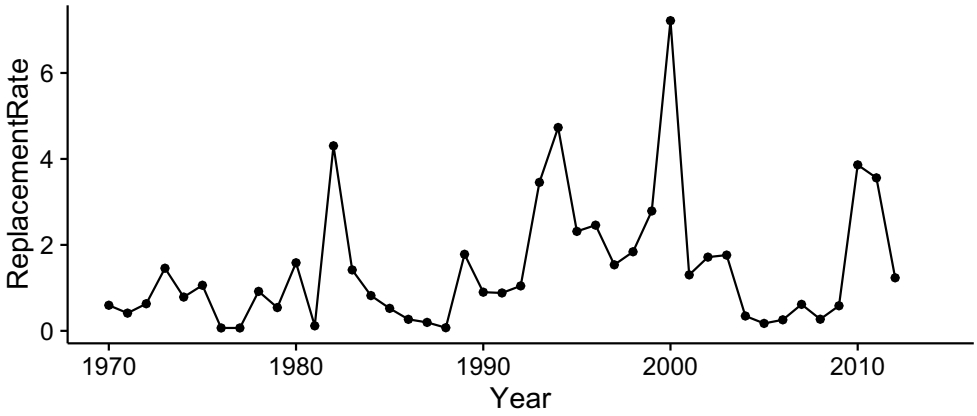
Validation

Does the model predict patterns that weren't used to fit the model?

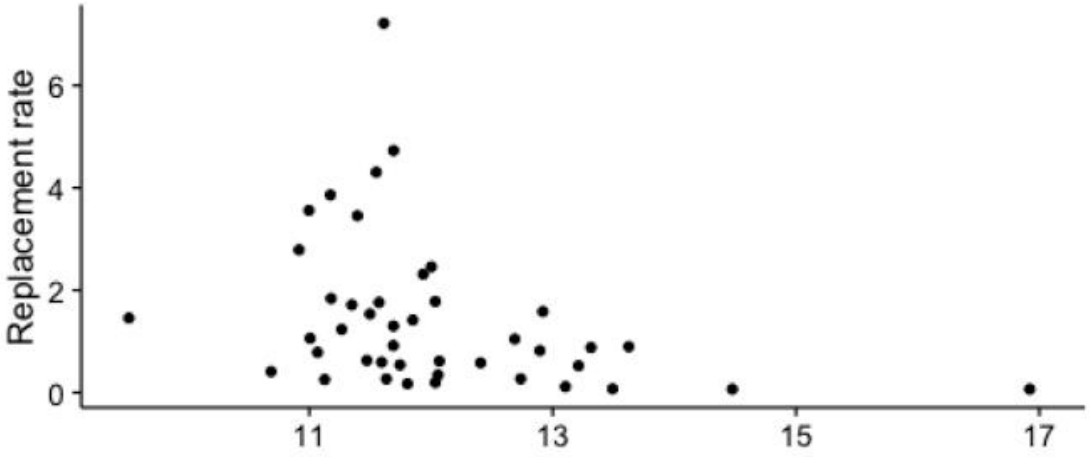
Can other data be used to test the extent of temperature-dependent mortality in embryos?

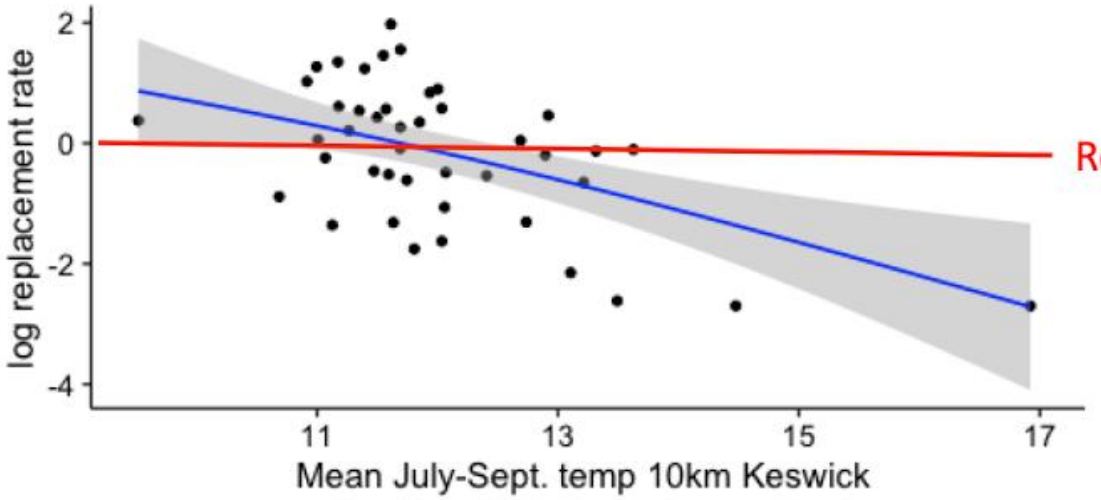


$$\text{Replacement rate year (t)} = \frac{\text{Escapement year (t+3)}}{\text{Escapement year (t)}}$$



Does temperature during embryonic period explain variation in relative escapement 3 years later?





Replacement rate = 1

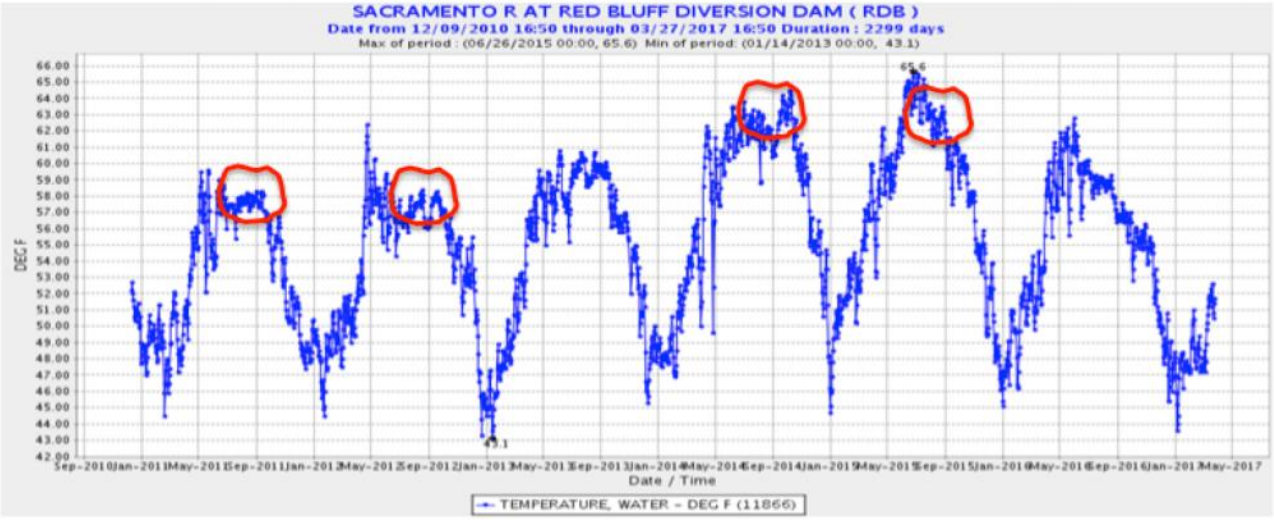
r^2= 0.30

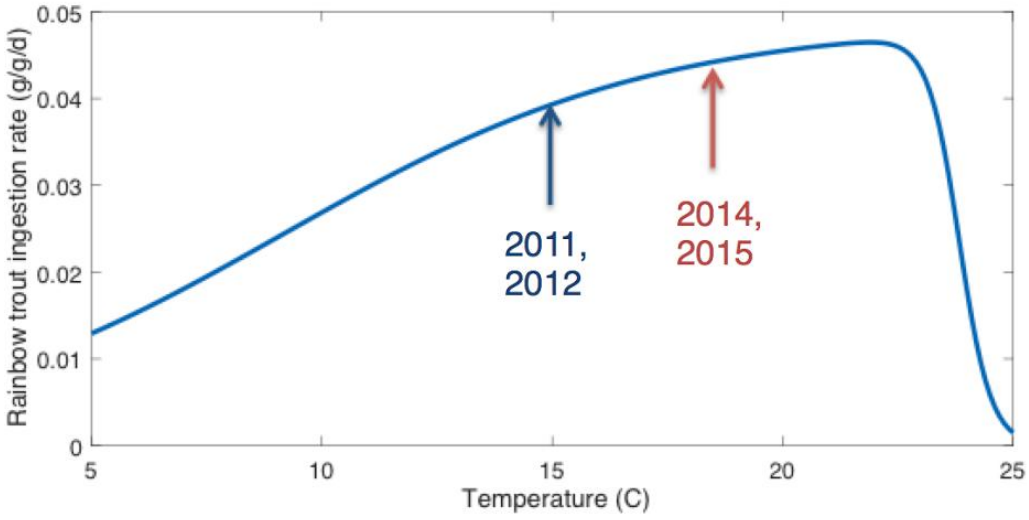
P-value = 0.0000881

Could other factors explain this pattern?

- Temperature-dependent predation
- Flow?

Rearing temperatures at RBDD 15°C (2011,2012) vs. 18-19°C (2014-2015)



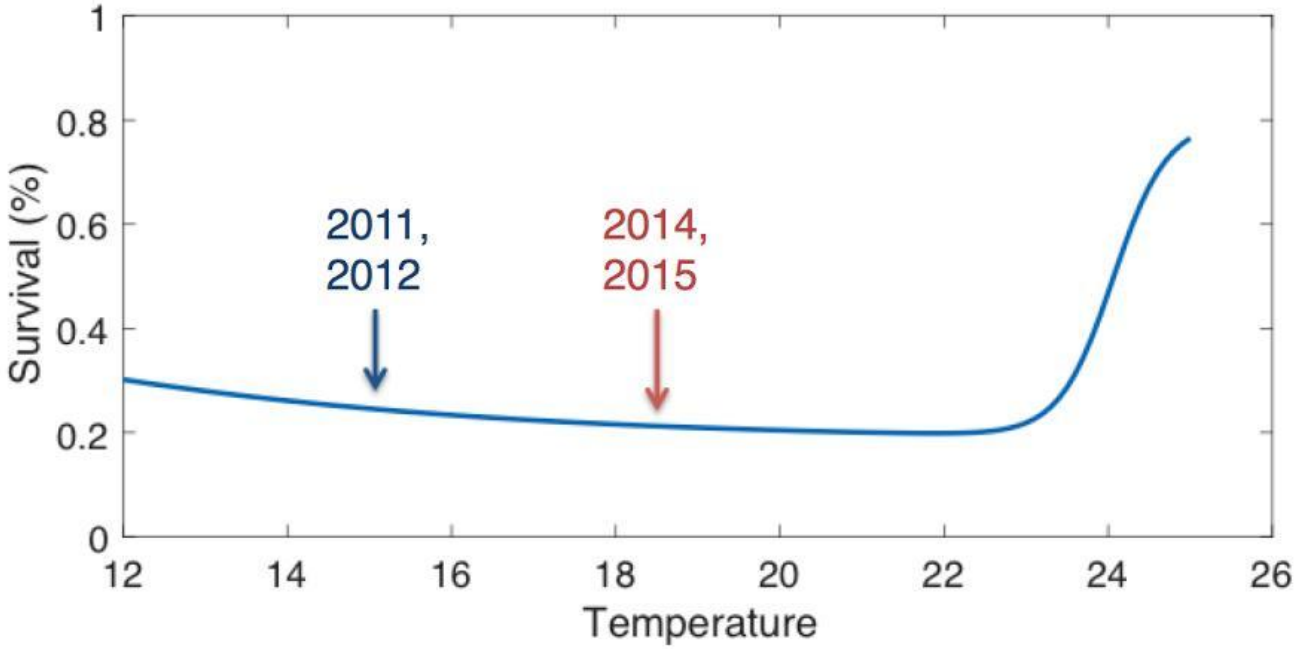


The Open Fish Science Journal, 2010, *3*, 69-79

Estimation of Bioenergetics Parameters for Rainbow Trout (*Oncorhynchus mykiss*) Using Capture-Recapture Data with Comparison to Estimates from a Laboratory-Based Model

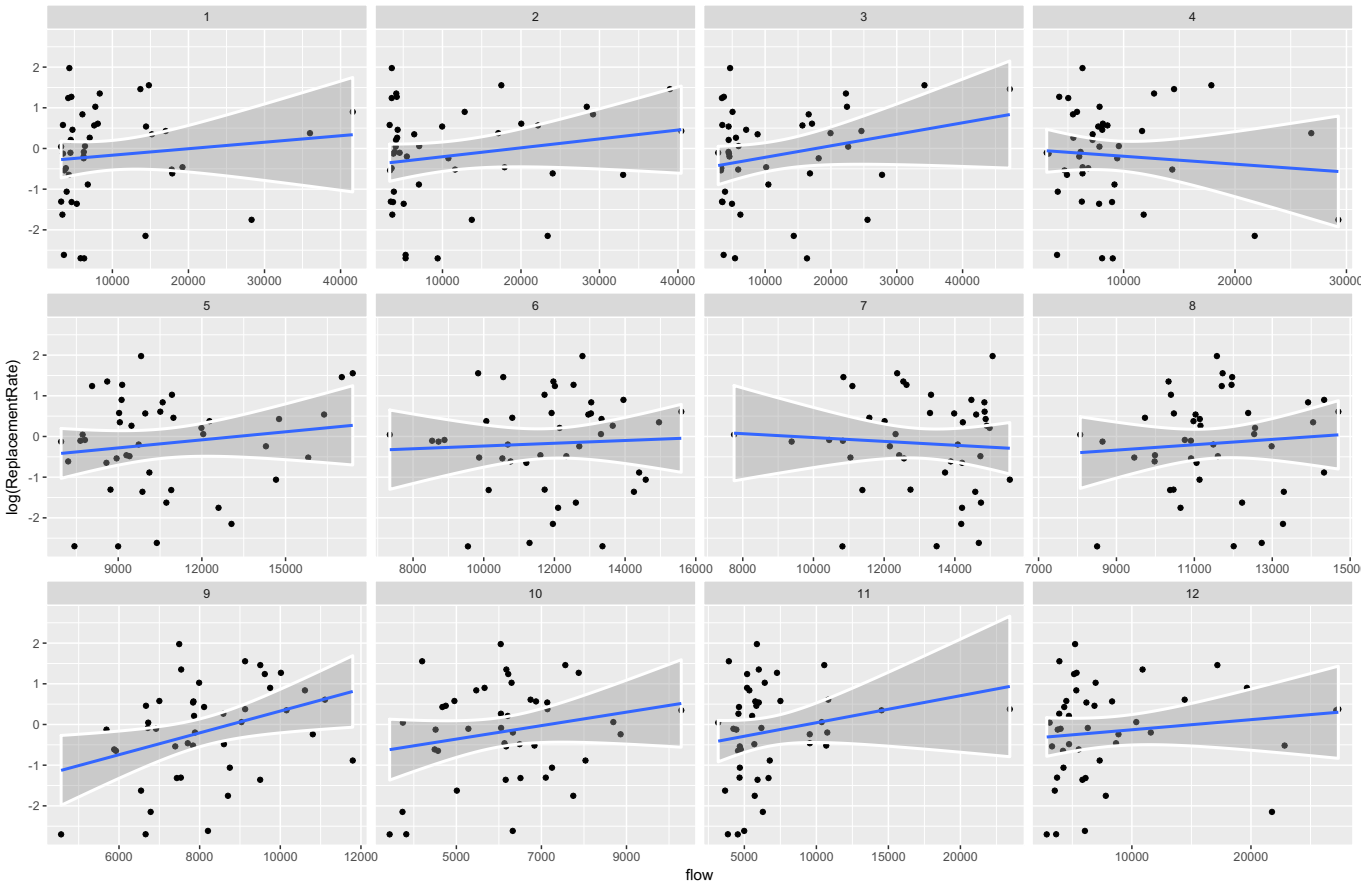
Brett T. van Poorten* and Carl J. Walters

Fisheries Centre, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada



Based on bioenergetics modeling 3-4°C difference in fry rearing temperatures in 2011 and 2012 vs. 2014 and 2015 would result in ~ 3% difference in ETF survival (compared to a roughly 30% observed difference)

Replacement rate vs. flow

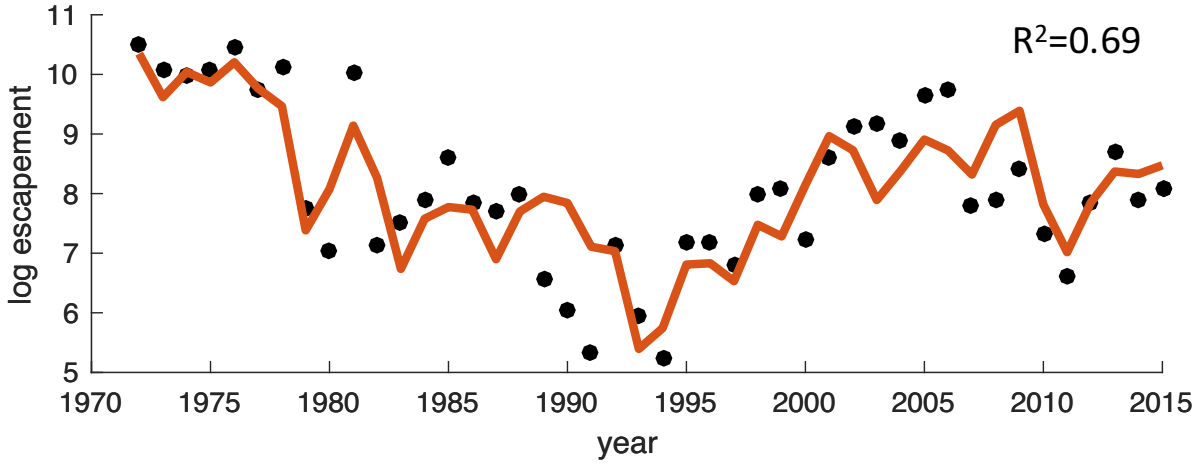


Marginally significant effect of keswick discharge in only one month (Sept)
P= 0.02 r-squared = 0.1

Log(replacement rate) = flow(month) + temperature(July-Sept)

	Flow		Temperature	
	t value	Pr(>|t|)	t value	Pr(>|t|)
Jan	-0.37	0.71	-4.28	0.000023
Feb	0.90	0.37	-4.19	0.000034
March	1.39	0.16	-4.17	0.000036
April	-1.85	0.07	-4.67	0.000004
May	-0.23	0.82	-4.20	0.000032
June	-1.12	0.26	-4.48	0.000009
July	-1.44	0.15	-4.55	0.000007
Aug	-0.76	0.45	-4.37	0.000015
Sept	0.02	0.99	-3.36	0.000830
Oct	-1.07	0.28	-4.18	0.000034
Nov	-0.50	0.62	-4.10	0.000049
Dec	-0.30	0.76	-4.23	0.000027

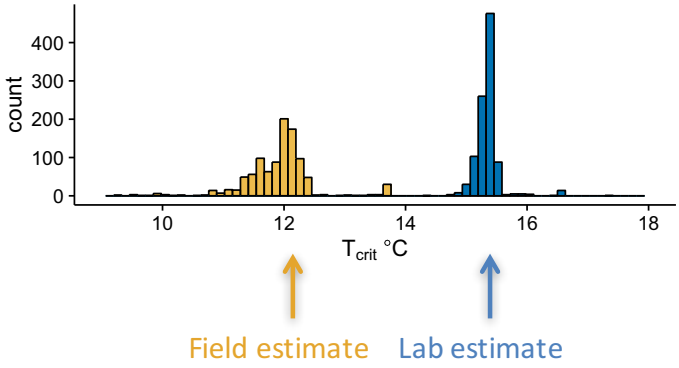
Can other data be used to test the extent of temperature-dependent mortality in embryos?



Temperature and density dependent embryonic survival alone explain ~70% of variation in winter run population dynamics from 1970-2015

The T_{crit} estimated from escapement data (11.5°C) not statistically different from estimate from egg-to-fry survival data (12.0°C)

Fortunately, field data available for winter-run to reality check lab-derived model



But for many species, such data does not exist

What mechanism can account for differences in thermal tolerance?

Why might lab and field thermal tolerance differ

- In redds
  - Eggs buried in gravel with low flows
  - Eggs surrounded by other eggs, compete for resources, exposed to waste products
    - Typical Chinook egg pocket has 900 eggs

Oxygen limitation?

Climate Change Affects Marine Fishes Through the Oxygen Limitation of Thermal Tolerance

Hans O. Pörtner* and Rainer Knust

Science 2007

Differences in Thermal Tolerance Among Sockeye Salmon Populations

Erika J. Eliason,[1]* Timothy D. Clark,[1,2,3] Merran J. Hague,[4] Linda M. Hanson,[2] Zoë S. Gallagher,[1] Ken M. Jeffries,[3] Marika K. Gale,[3] David A. Patterson,[4] Scott G. Hinch,[3] Anthony P. Farrell[1,2]

Science 2011

Climate change tightens a metabolic constraint on marine habitats

Curtis Deutsch,[1]* Aaron Ferrel,[2]† Brad Seibel,[3] Hans-Otto Pörtner,[4] Raymond B. Huey[5]

Science 2015

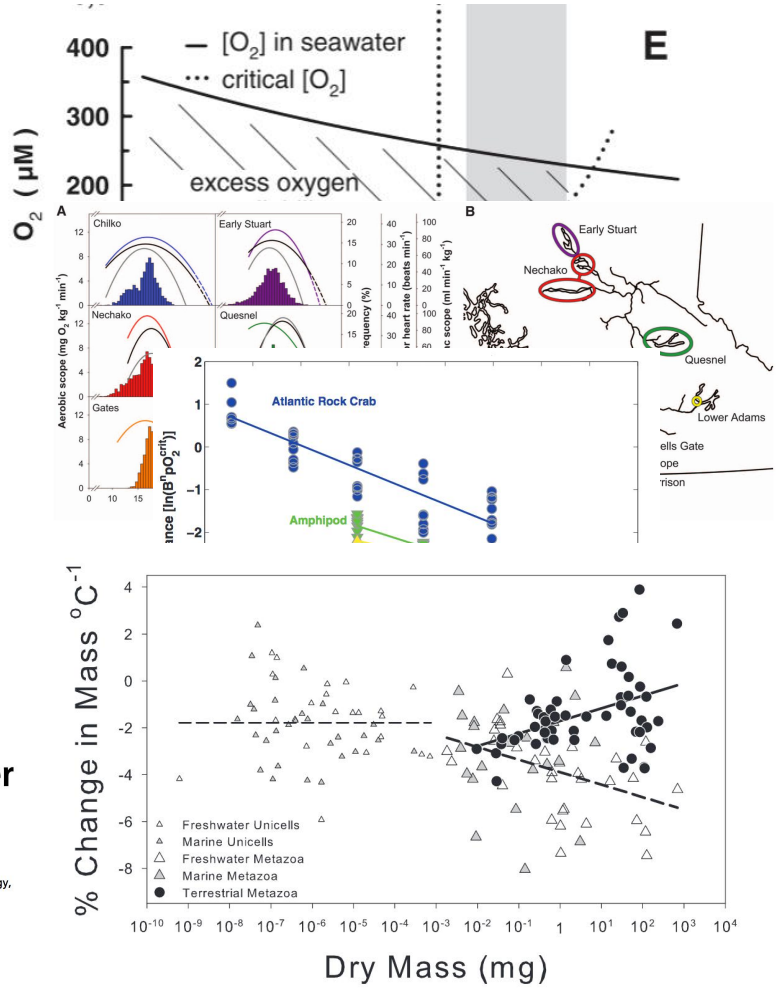
Warming-induced reductions in body size are greater in aquatic than terrestrial species

Jack Forster[a], Andrew G. Hirst[a,1], and David Atkinson[b]

[a]School of Biological and Chemical Sciences, Queen Mary University of London, London E1 4NS, United Kingdom; and [b]Institute of Integrative Biology, University of Liverpool, Liverpool L69 7ZB, United Kingdom

Edited by James H. Brown, University of New Mexico, Albuquerque, NM, and approved October 2, 2012 (received for review June 22, 2012)

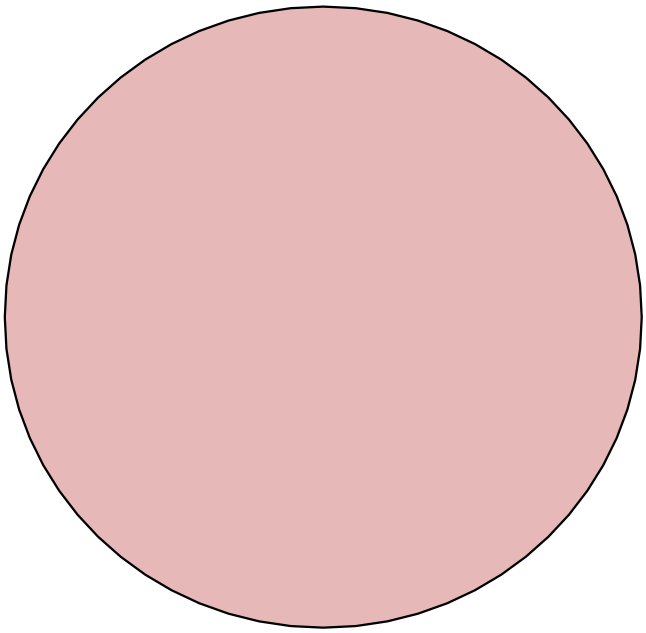
PNAS 2012



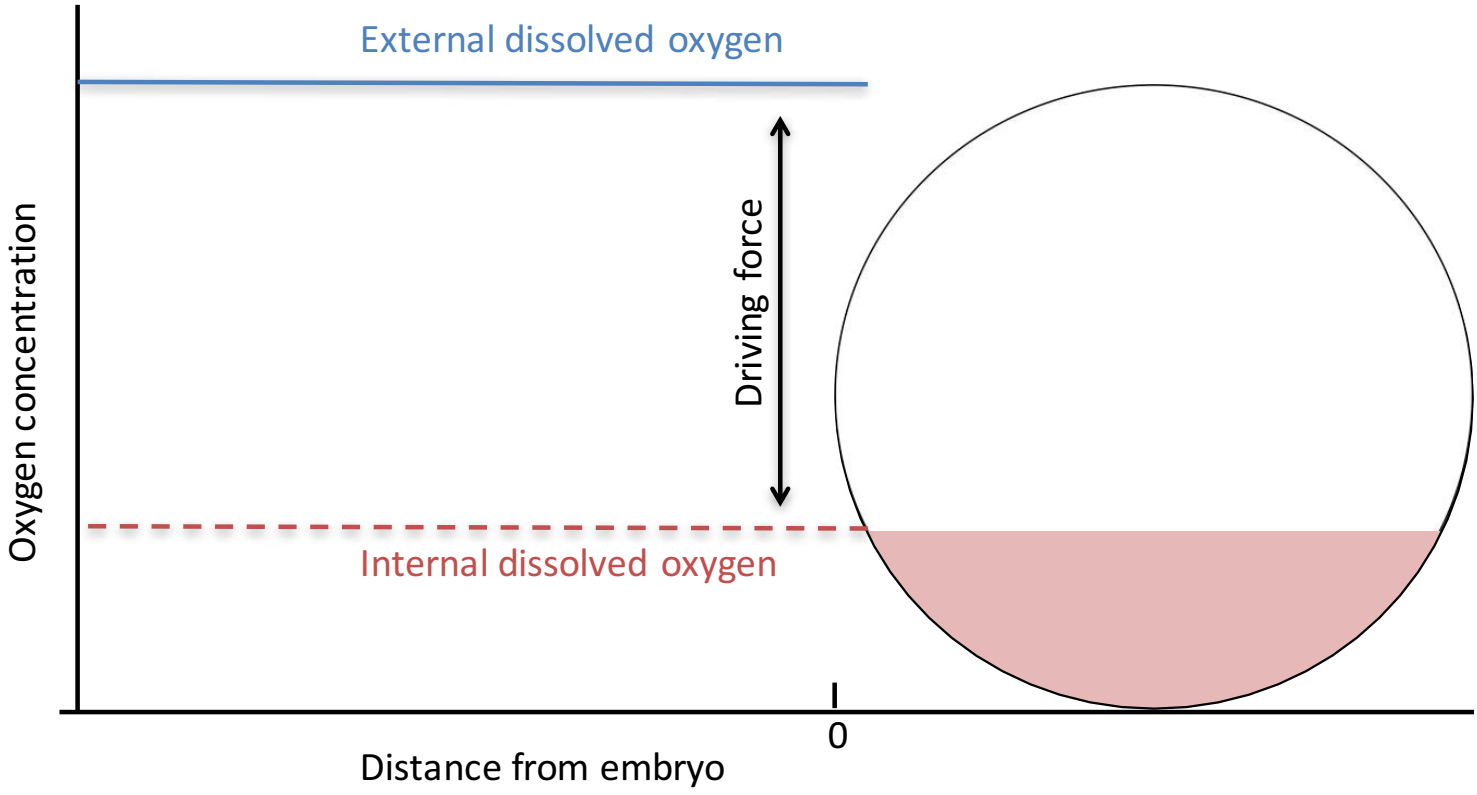
Oxygen limitation?

In embryos?

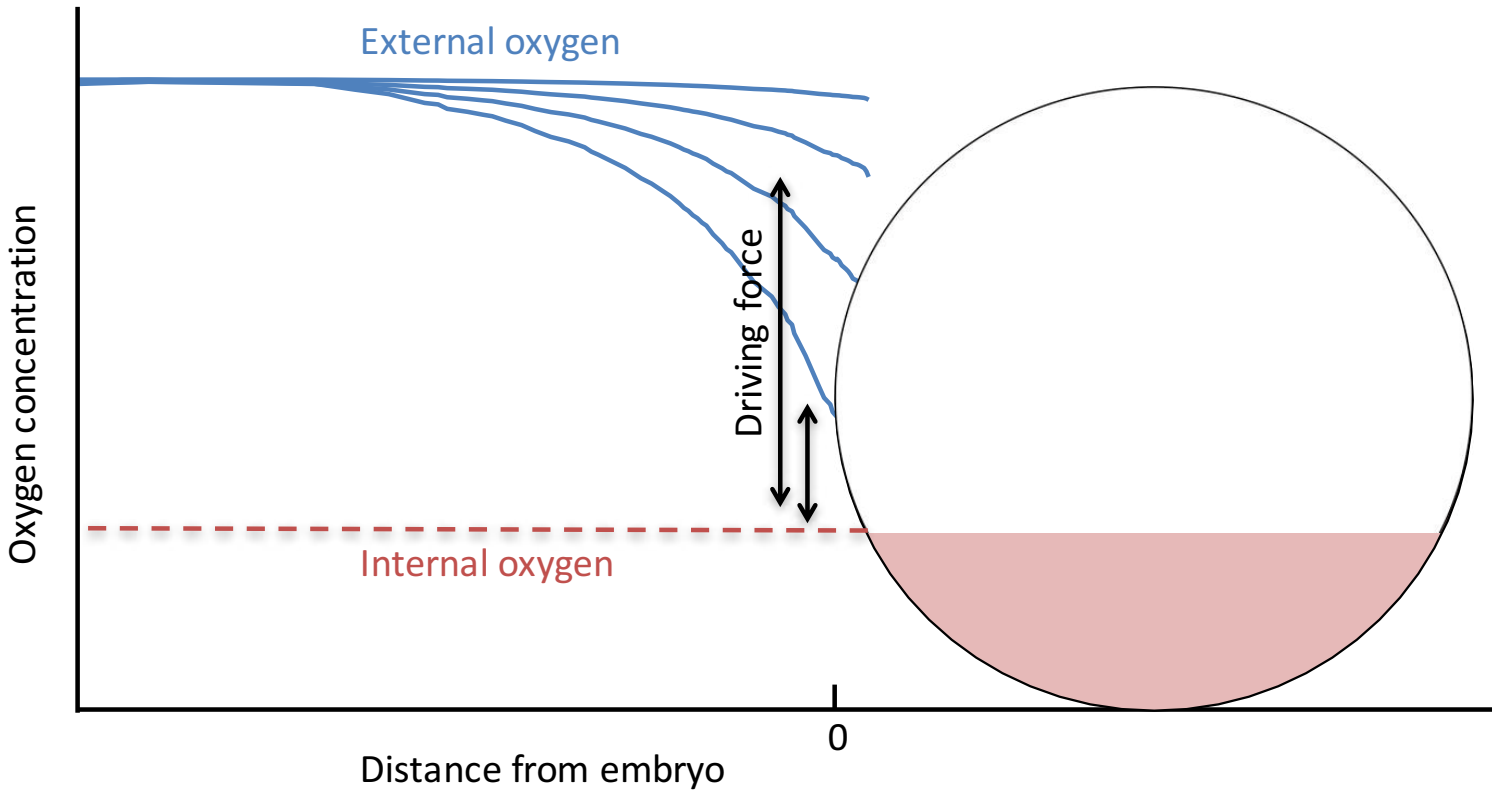
- Can't move
- High mass-specific oxygen demand
- Supply dependent on environment
  - DO
  - Flow



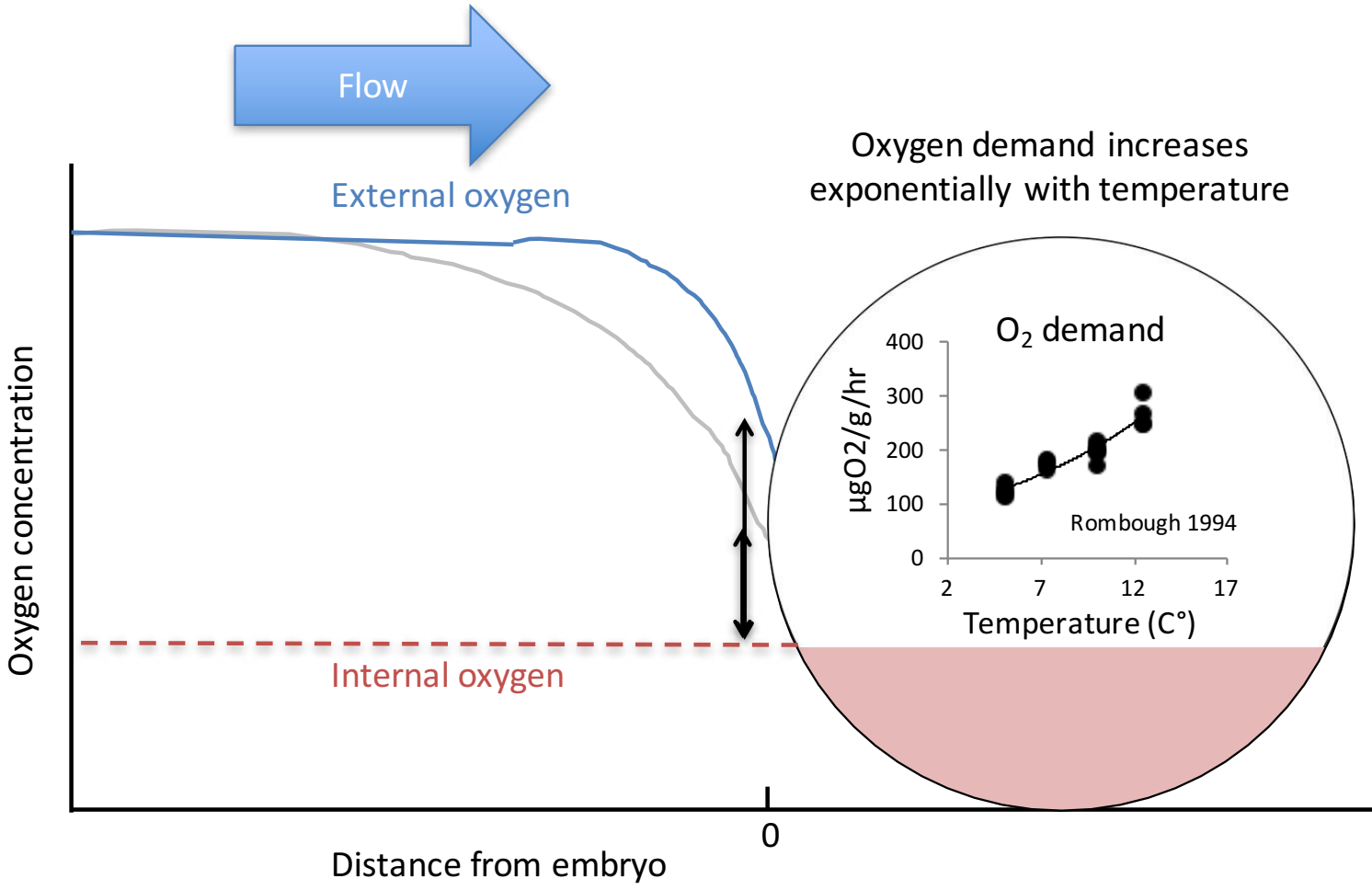
Oxygen limitation?



Oxygen limitation?

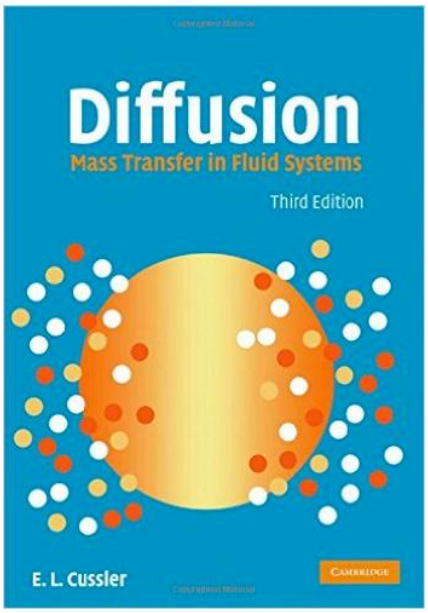


Oxygen limitation?

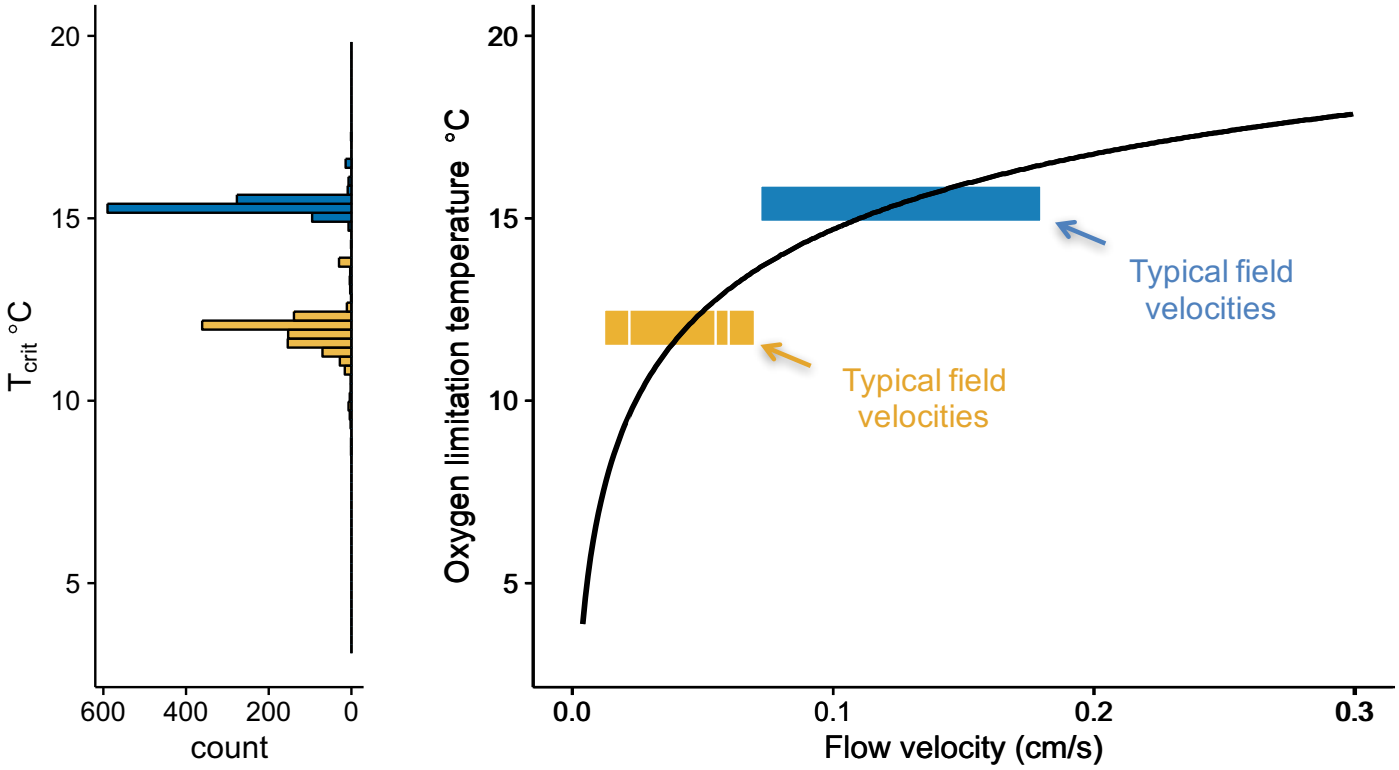


Mass-transfer theory

- Physics worked out long ago, but rarely applied
- Can calculate thermal tolerance function of flow, DO
- Few parameters needed
  - Biological (4)
    - Temp-dependent metabolic rate (2)
    - Critical oxygen tension and egg conductance (2)
  - Physical (2)
    - Look up in a textbook



$$U_{crit} = \frac{\mu\left(\frac{5N\delta Rk_e}{2D\left(4\pi R^2 k_e\left(P_e - P_i^*\right) - N\delta\right)} + \frac{5}{2}\right)^2}{2R\left(\frac{\mu}{D}\right)^{2/3}}$$


20
15
10
5
T_{crit} °C
600
400
200
0
count
Oxygen limitation temperature °C
0.0
0.1
0.2
0.3
Flow velocity (cm/s)
Typical field velocities
Typical field velocities

Bulk O2 depletion

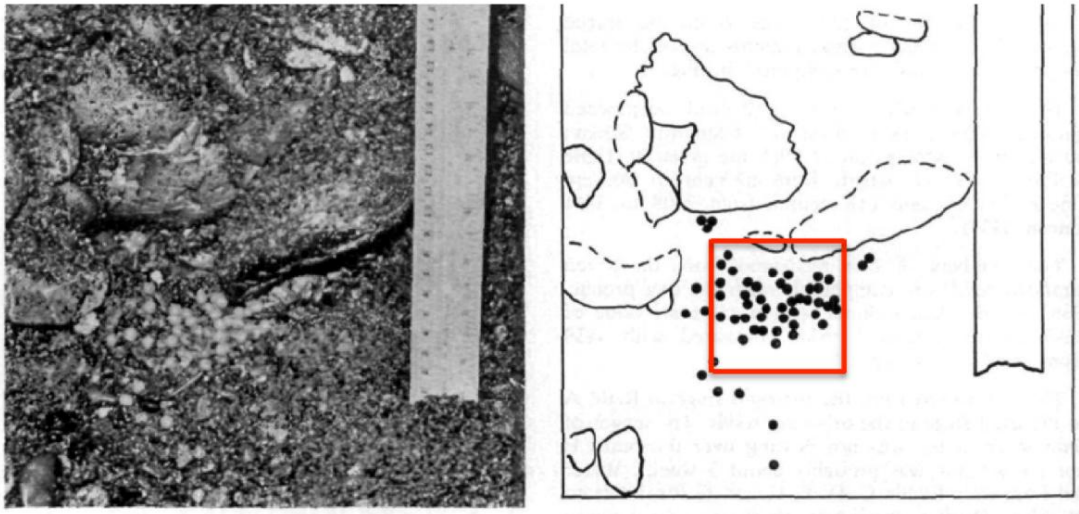
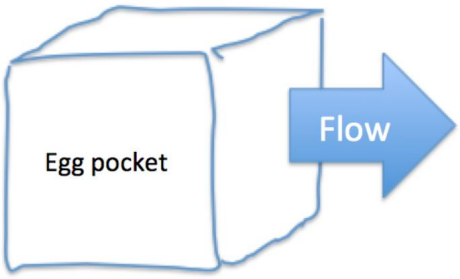
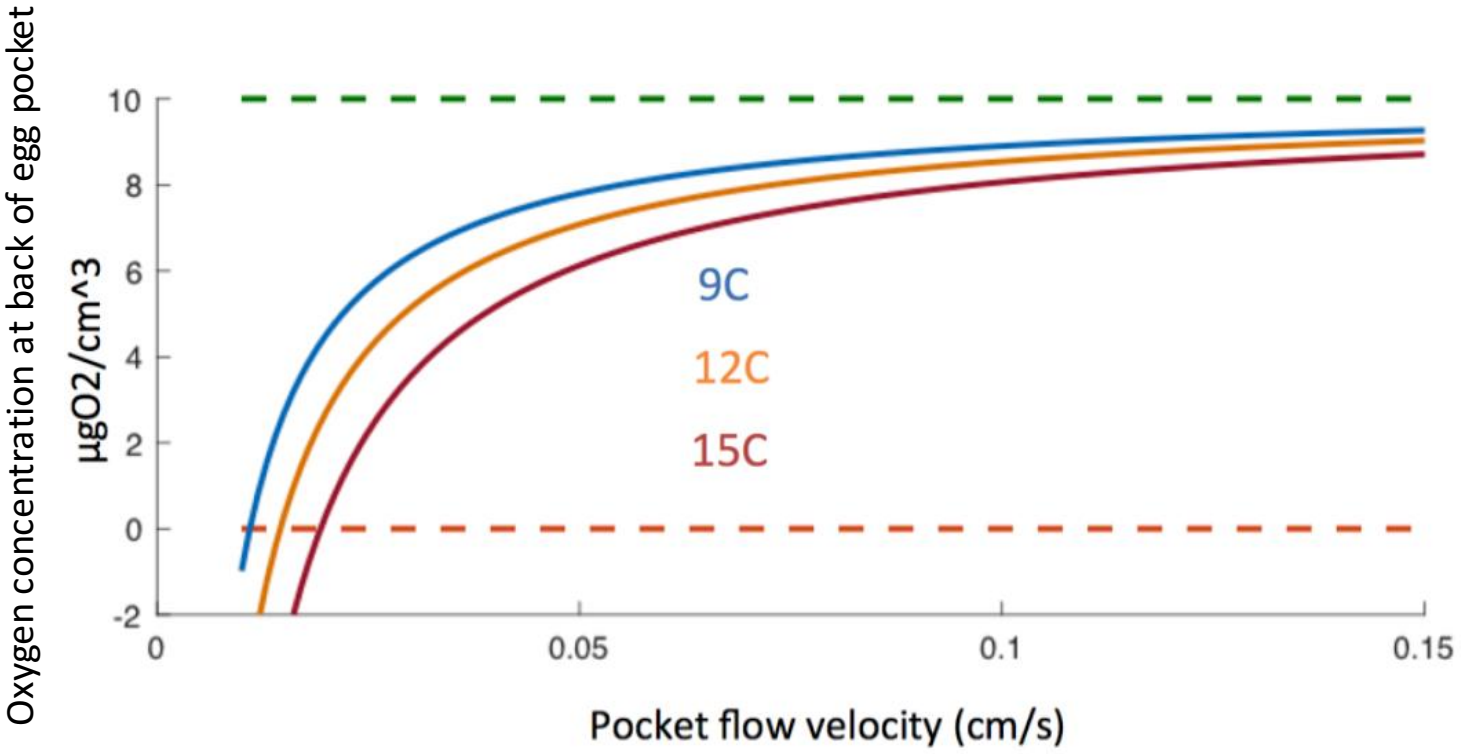


FIG. 2—Typical egg pocket in a redd of quinnat salmon *Onchorhynchus tshawytsha* during excavation, Mathias River, South Island, New Zealand, May-June 1974.

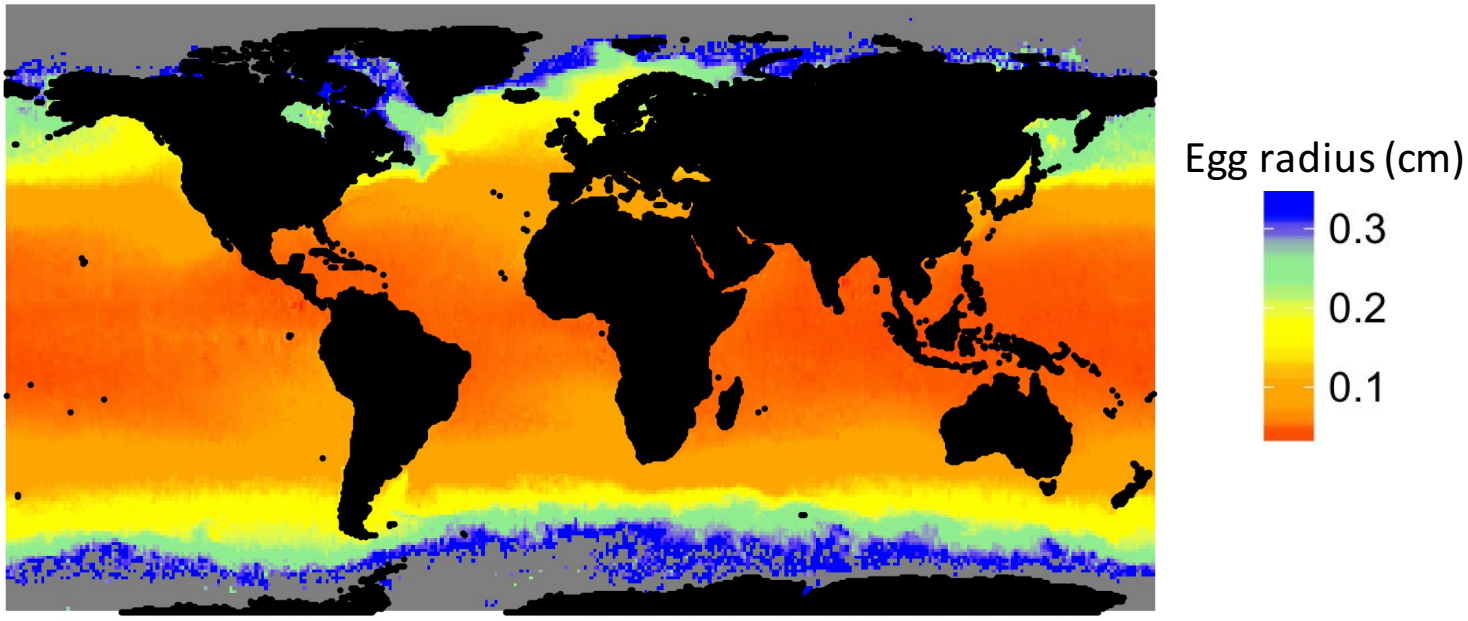


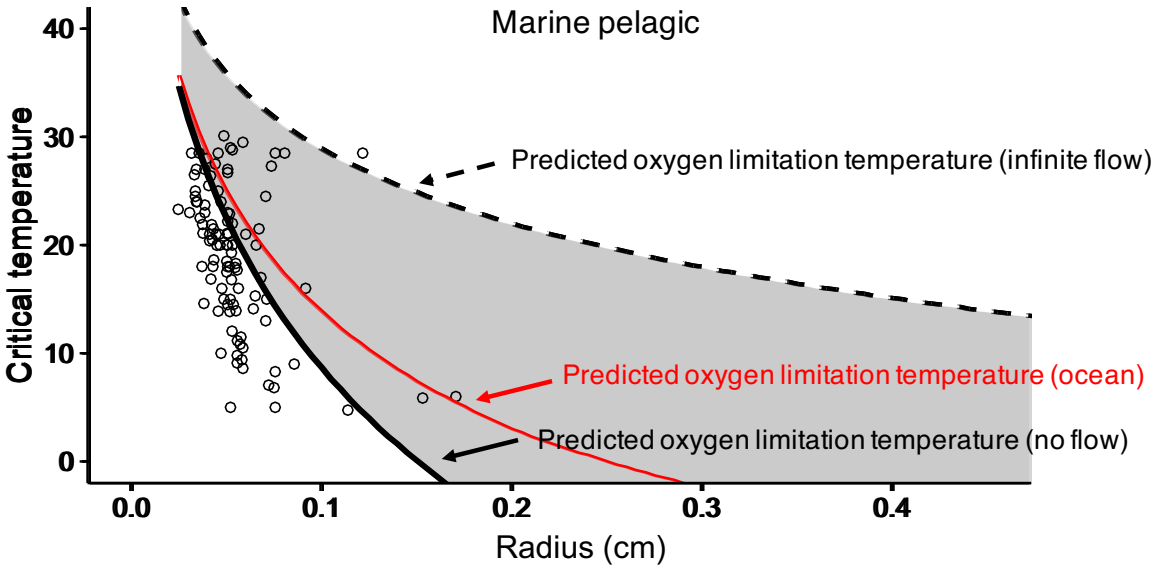
Bulk oxygen depletion in egg pocket

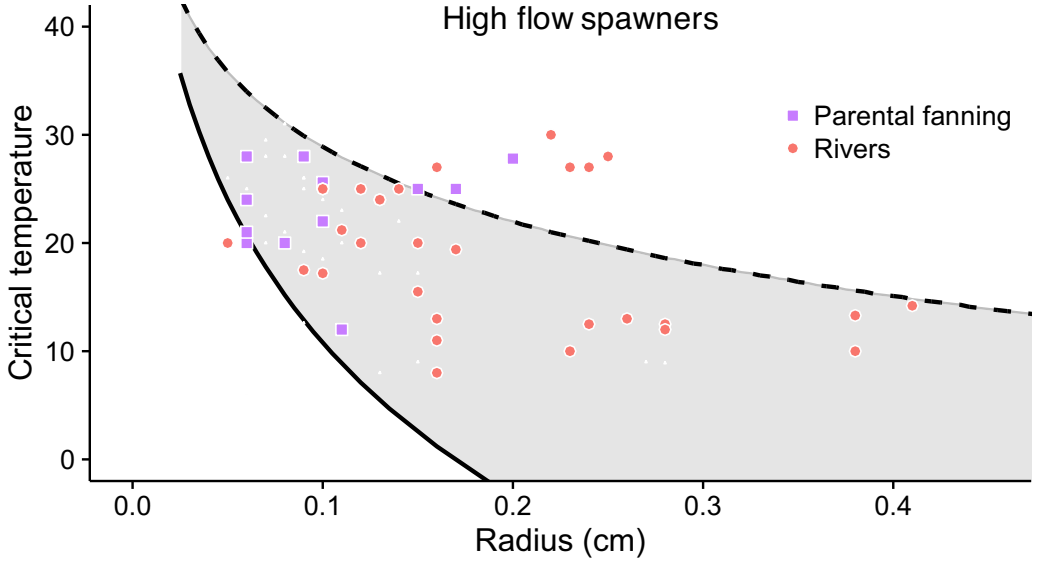


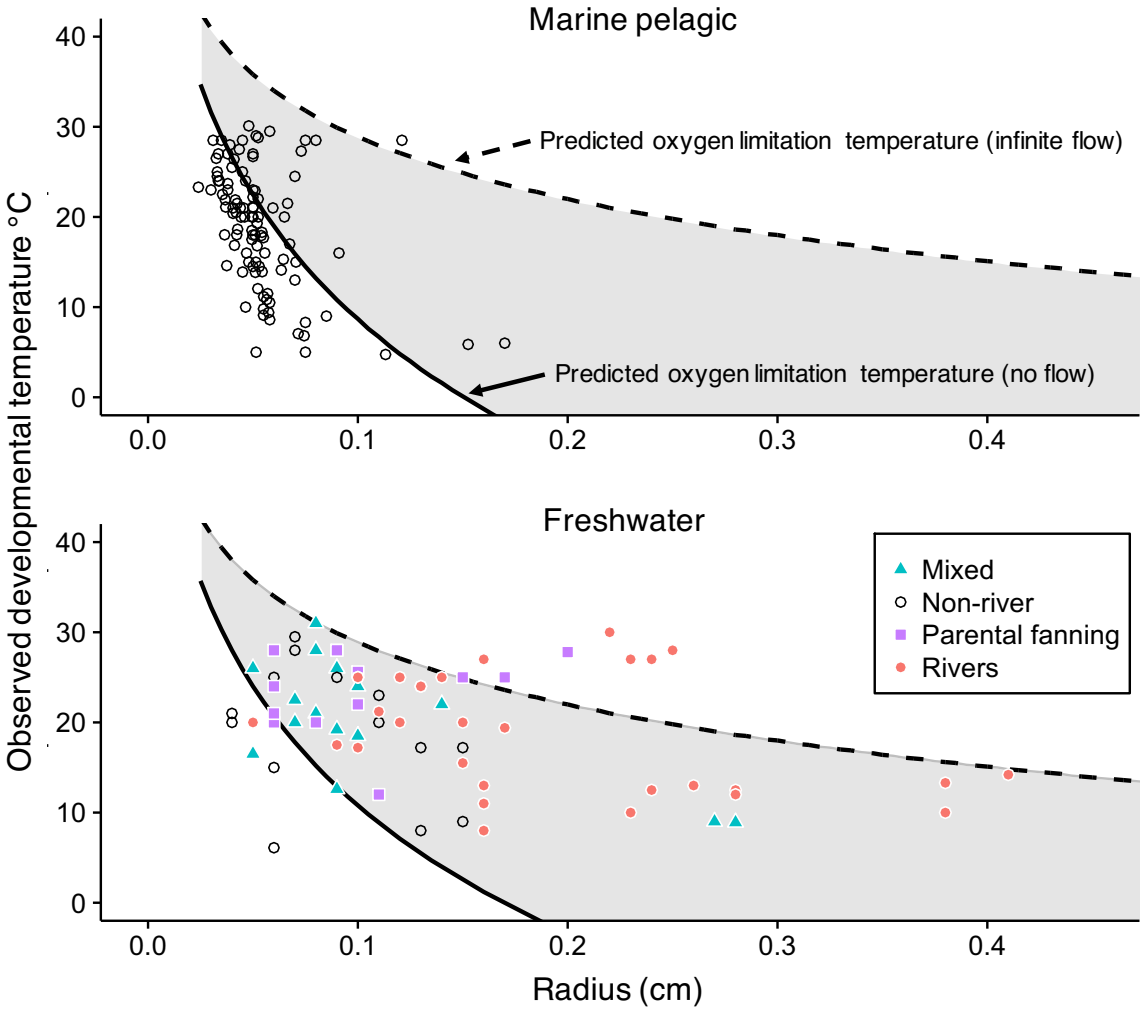
How general is O_2 limitation in fish embryos?

- Testable predictions
  - Maximum egg size decreases with temperature




Marine pelagic
Critical temperature
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
Radius (cm)
Predicted oxygen limitation temperature (infinite flow)
Predicted oxygen limitation temperature (ocean)
Predicted oxygen limitation temperature (no flow)


High flow spawners
Critical temperature
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
Radius (cm)
Parental fanning
Rivers


Marine pelagic
Predicted oxygen limitation temperature (infinite flow)
Predicted oxygen limitation temperature (no flow)
Freshwater
Mixed
Non-river
Parental fanning
Rivers
Observed developmental temperature °C
Radius (cm)
0
10
20
30
40
0.0
0.1
0.2
0.3
0.4

Summary

- Lab derived model of thermal tolerance not predictive in the field
- But, the same model with parameters fitted to field data explained most of the variation in egg-to-fry survival
- Suggest a reduction in thermal tolerance in the field compared to lab
  - Supported by escapement data
- Oxygen limitation hypothesis provides mechanistic explanation for why thermal tolerance may not be fixed, but is context dependnt