Energetic Costs of Multiple Stressors: Challenges in Quantifying the Impact of Silent Stressors on a Warming Planet

Marjorie Brooks
Southern Illinois University at Carbondale

BIOMARKERS WORKSHOP
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UC DAVIS – WALTER BUEHLER ALUMNI CENTER

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  - Interagency Ecological Program
  - Illinois EPA
  - Southern Illinois University

Challenges

1. Intellectual: Identify a universal approach for relating biomarkers to fitness (as growth and reproduction)
2. Experimental: Pair new environmentally realistic experiments with mensurative and manipulative field studies
3. Statistical: Directly relate those dynamic biologic signals to dynamic environmental stressors
4. Geospatial: Develop testable geospatial models of dynamic relationships
5. Management: Develop and test mitigation strategies

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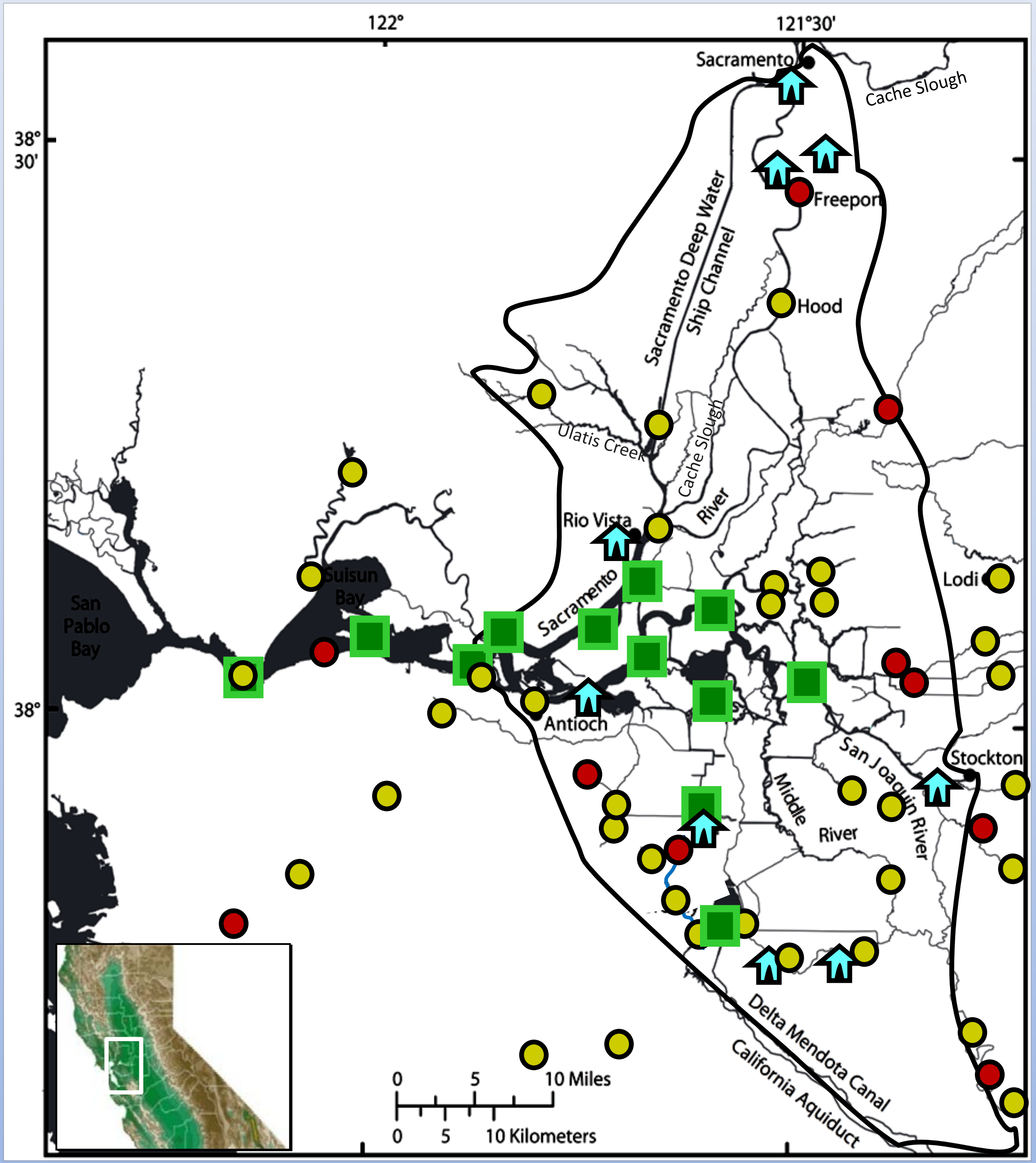
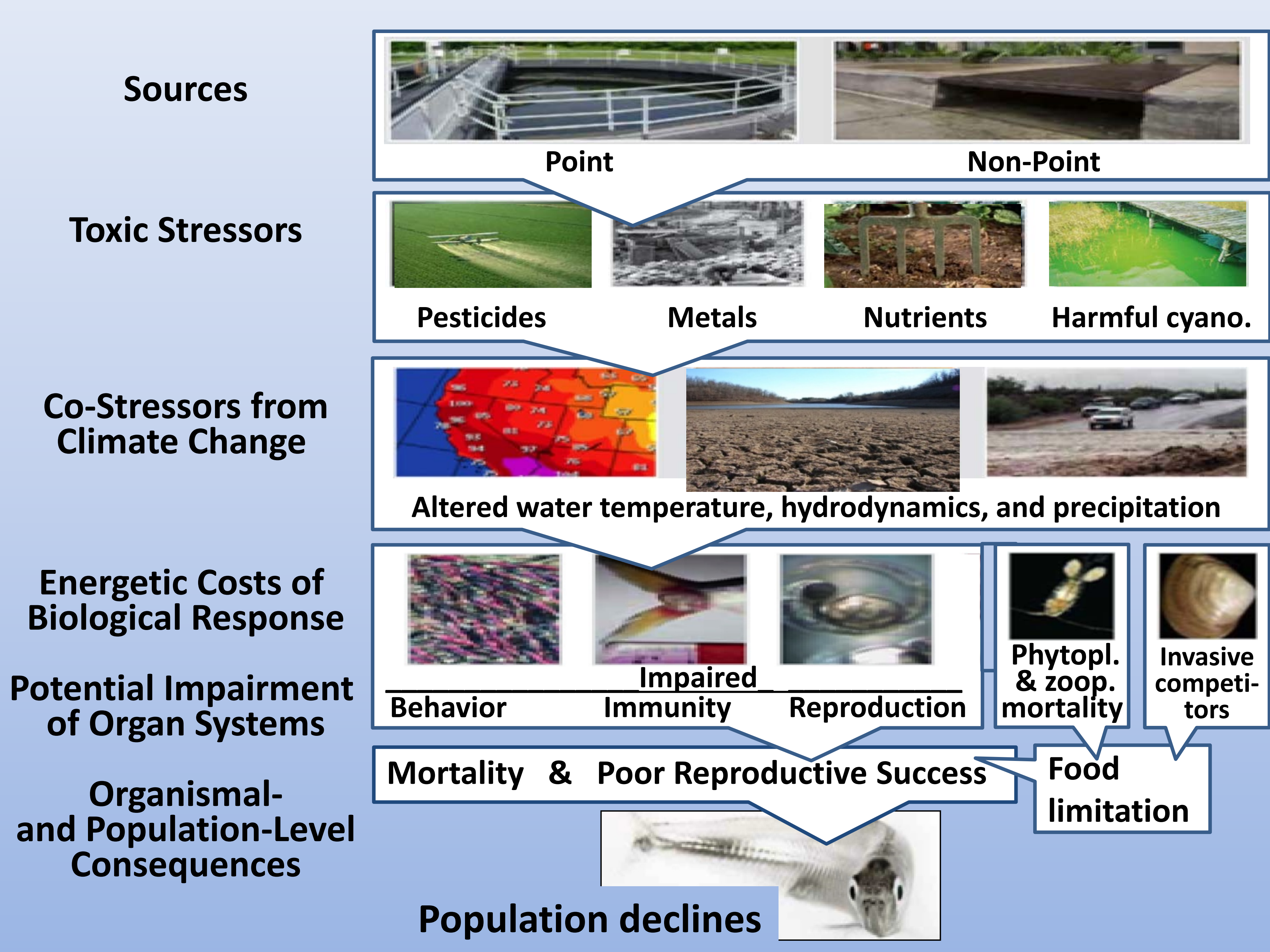
Widespread impacts

- Waters toxic to fish
- Waters toxic to prey
- Wastewater plant
- *Microcystis* bloom



Brooks et al. (2012)



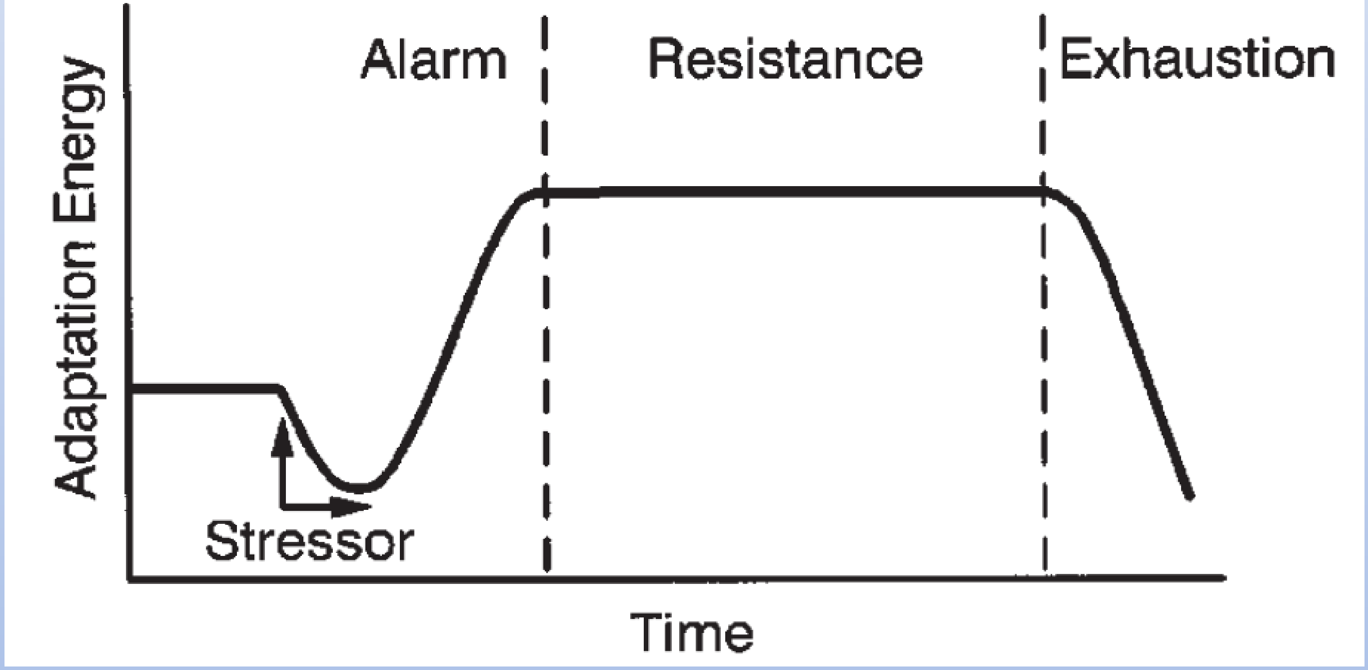
Sources
Point
Non-Point
Toxic Stressors
Pesticides
Metals
Nutrients
Harmful cyano.
Co-Stressors from Climate Change
Altered water temperature, hydrodynamics, and precipitation
Energetic Costs of Biological Response
Potential Impairment of Organ Systems
Impaired
Behavior
Immunity
Reproduction
Phytopl. & zoop. mortality
Invasive competi-tors
Mortality & Poor Reproductive Success
Food limitation
Organismal- and Population-Level Consequences
Population declines

General principles and predictions

- Habitats are highly impacted, yet available studies cannot assess impacts
- An obvious prediction is that stressors will be associated with poor body condition
- Organisms mitigate the effects of stressors in mainly four ways:
  1. Behavioral avoidance
  2. Sequestration
  3. Detoxification
  4. Elimination

…all of which require energy redirected from growth and reproduction.

Old Tool: General Adaptation Syndrome



Nonspecific response of biota to any demand:
alarm, **resistance** and **exhaustion**

(Selye 1956)

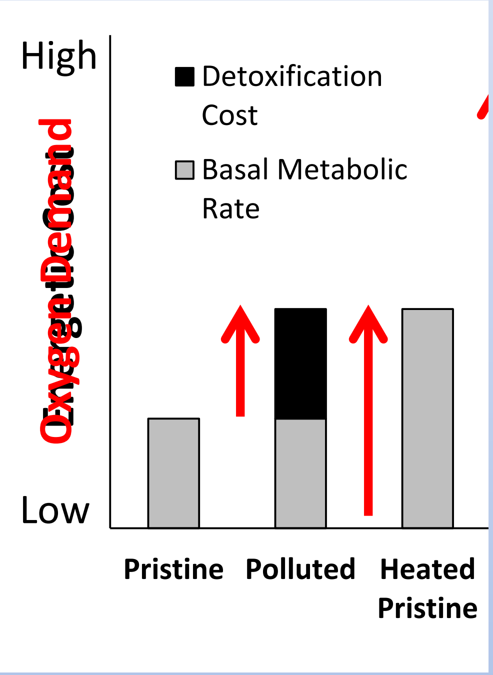
Sublethal Energetic Interactions

Example: Energetic Costs of Metals

- Cellular repair
- Detoxification and excretion
  - Metallothionein
  - Glutathione and other antioxidants

Energetic Costs of Temperature

- Metals can disproportionately elevate the metabolic response to temperature



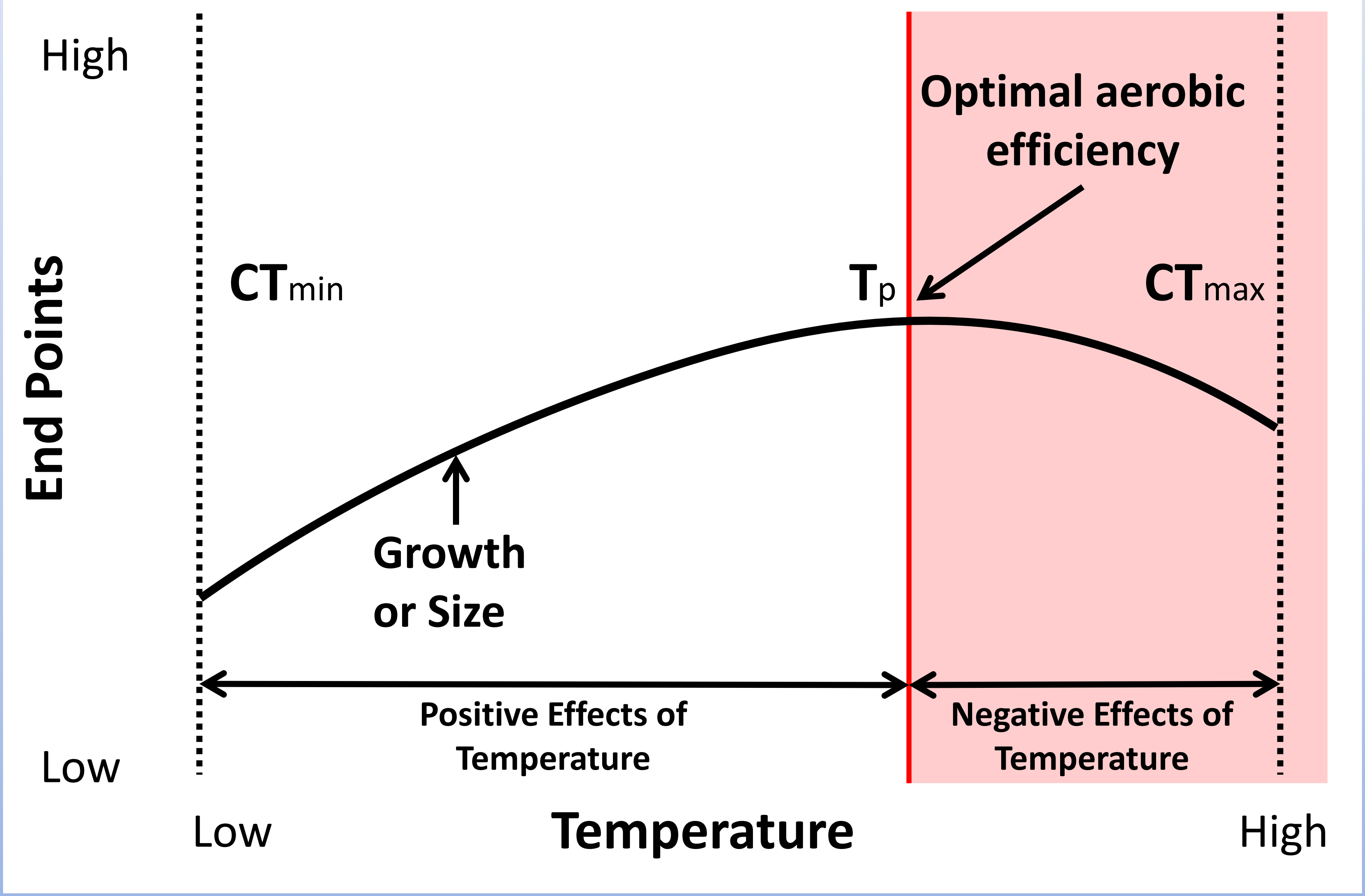
Result: Functional hypoxia

→Warm, unpolluted waters **met lower oxygen demands**

→Warm, <u>polluted</u> waters **may not meet higher oxygen demands**

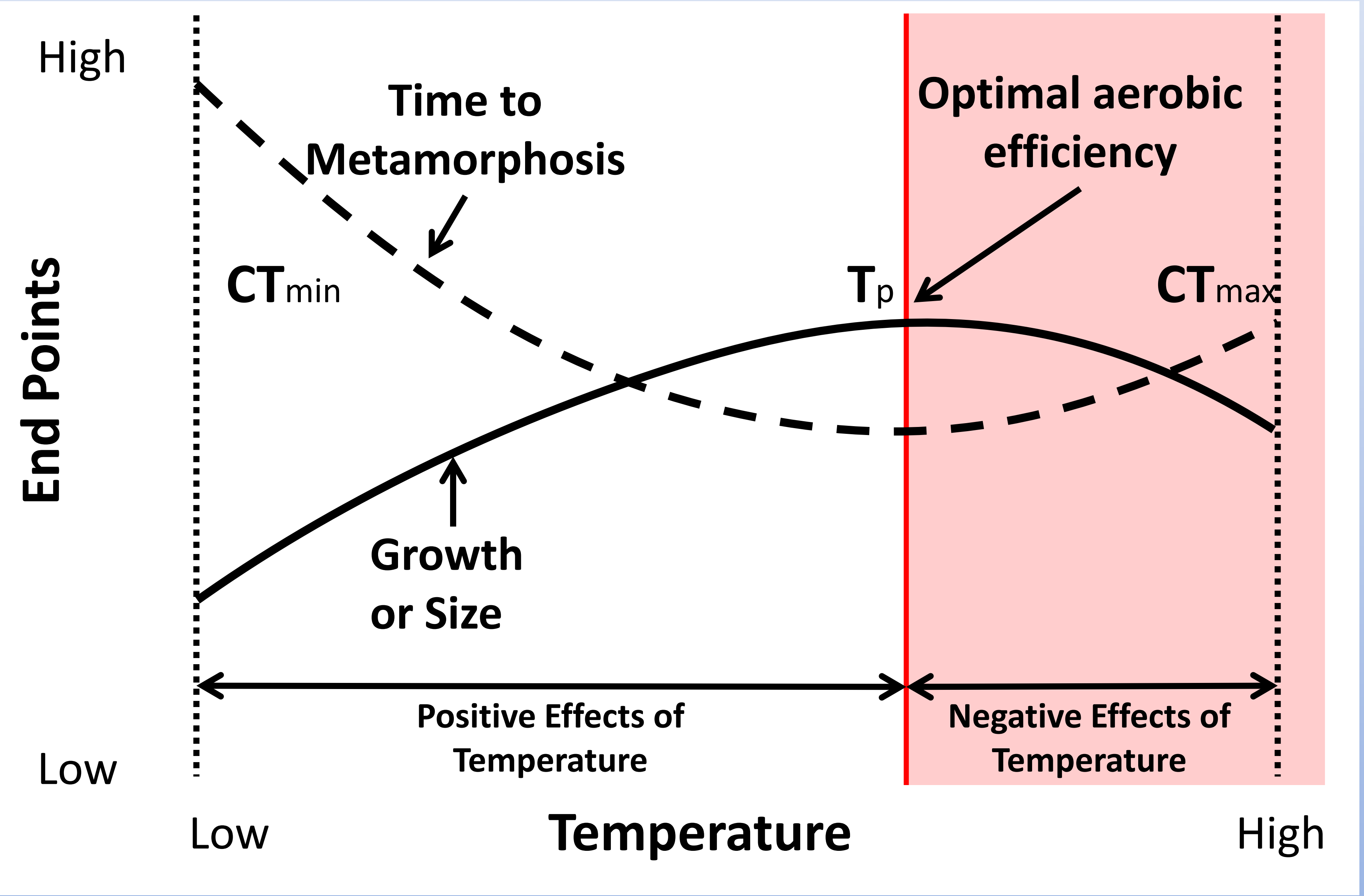
Temperature, Energy, and Chronic Endpoints

Warming speeds growth up to a point—pejus temperature (Tp)



Temperature, Energy and Chronic Endpoints

In unpolluted waters, warming speeds growth and shortens time to metamorphosis



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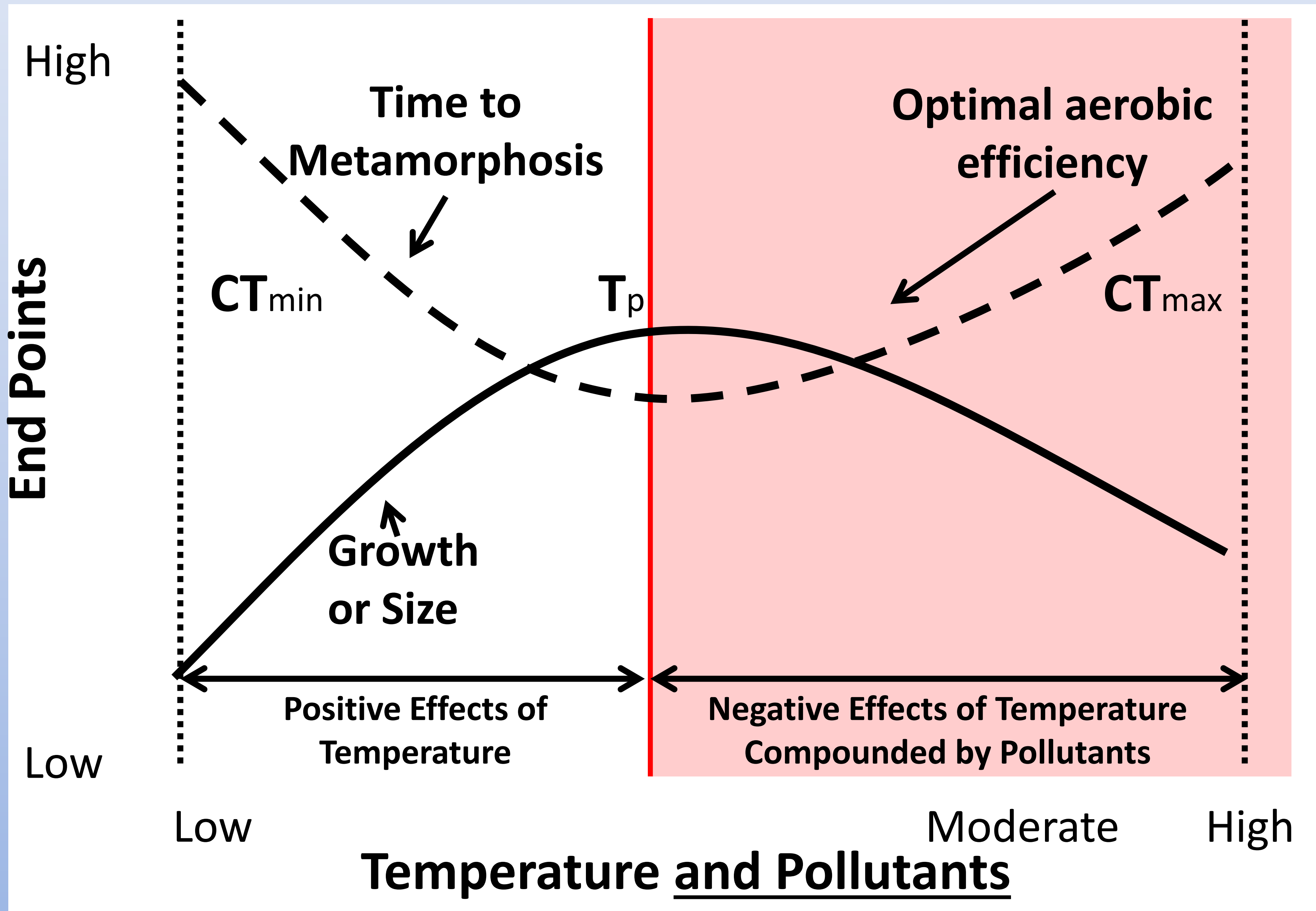
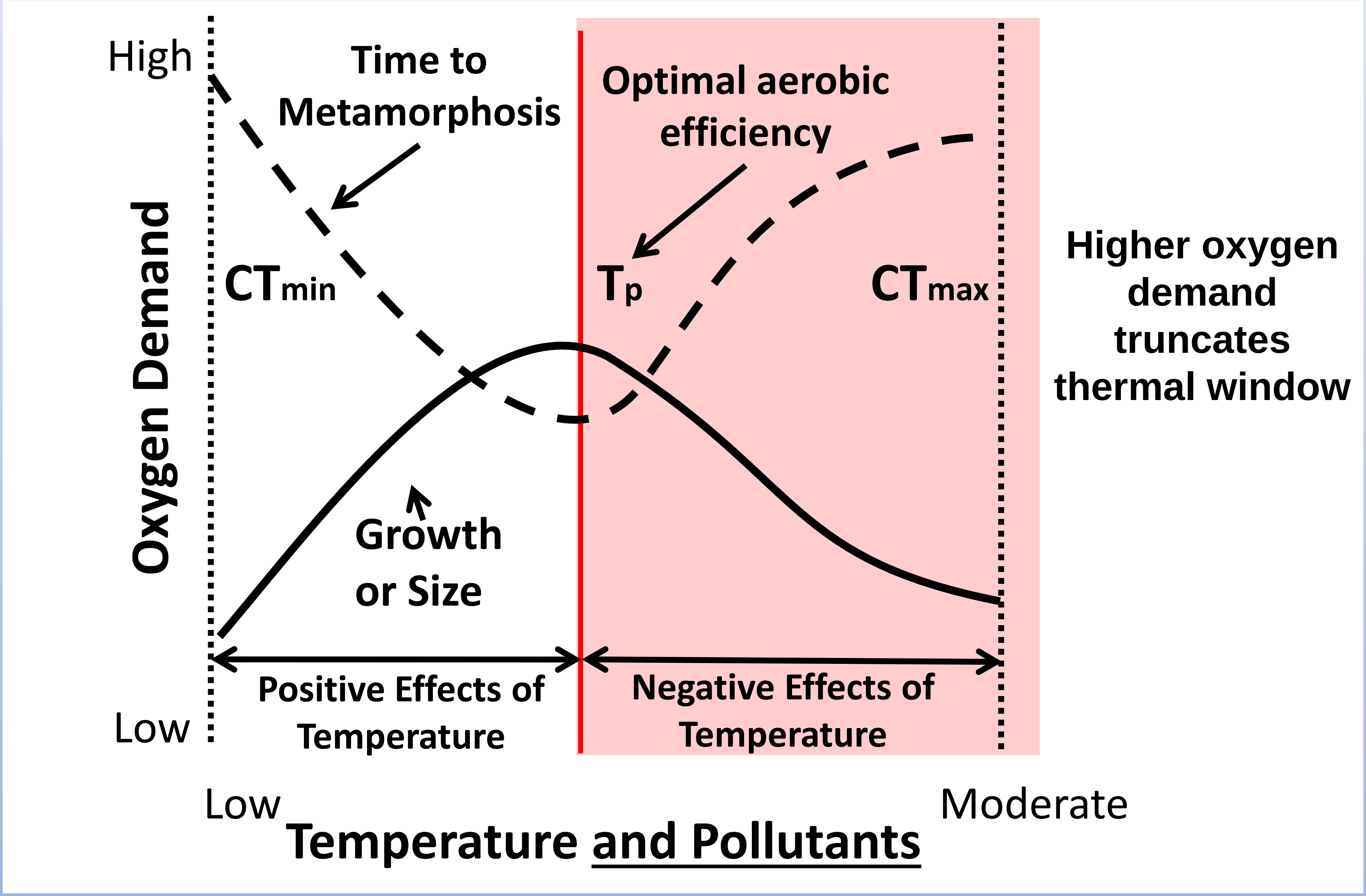


Temperature, Energy and Chronic Endpoints

Contaminants mediate temperature tolerance



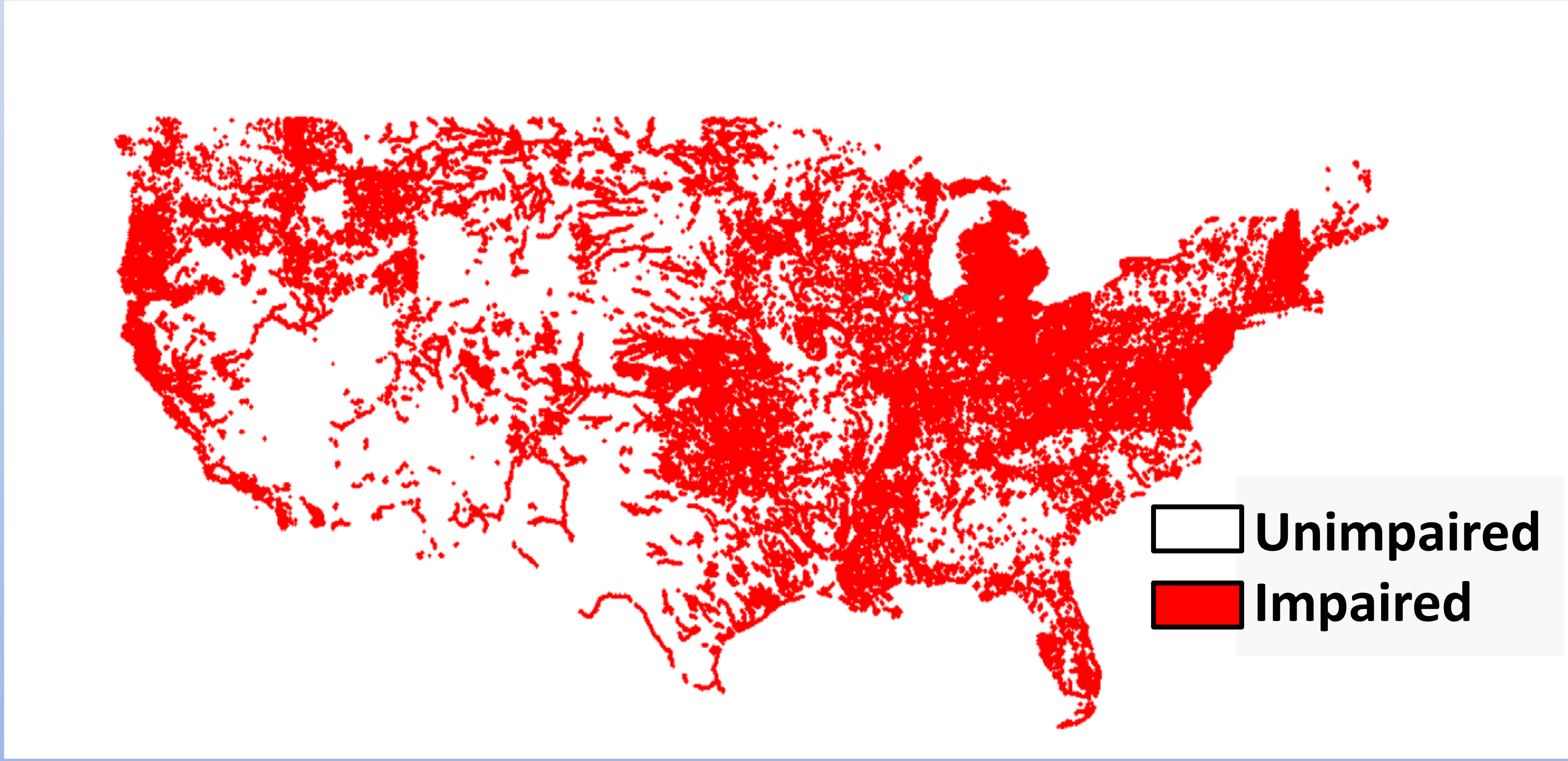
Stressors Without Borders:

Widespread Pollution, 303 (d) Listing

Waters that chronically exceed Maximum Contaminant Levels (MCLs)

chronic criteria concentrations are 1% to 10% of MCLs

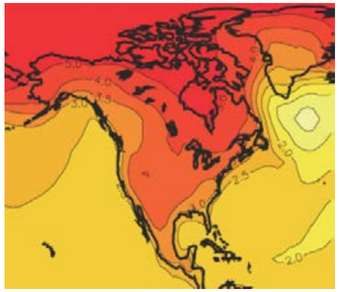
Use MCLs as a worst-case geospatial proxy for CCC



USEPA (2012) WATERS Program Washington, D.C. www.epa.gov/waters/data/

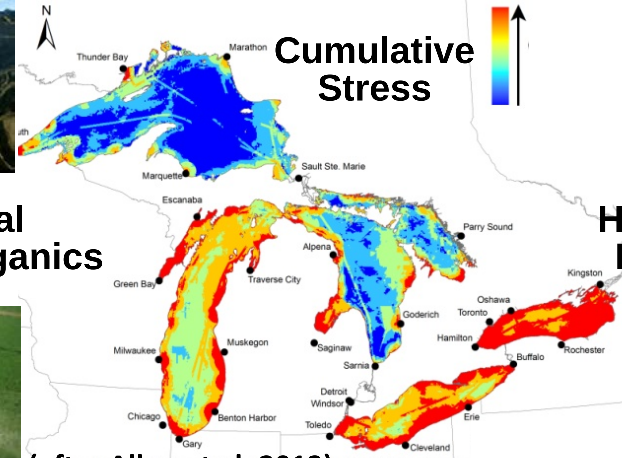
Environmental Drivers:

Contaminants, Nutrients, Temperature



Increasing Temperatures

Sublethal Metals & Organics



Cumulative Stress

(after Allen et al. 2013)

High Nutrients & Harmful cyano

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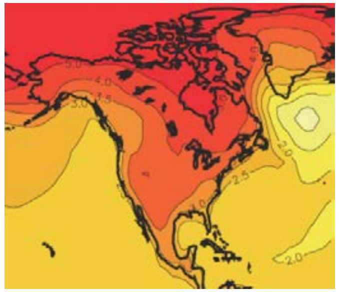

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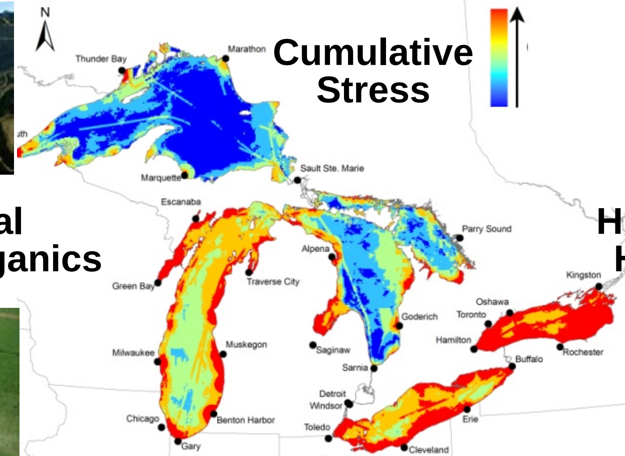

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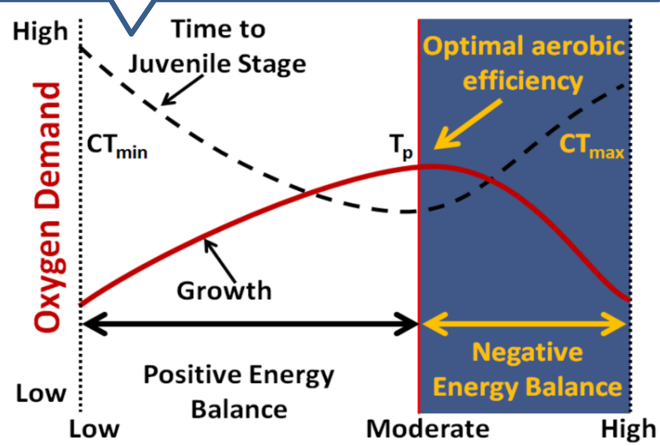
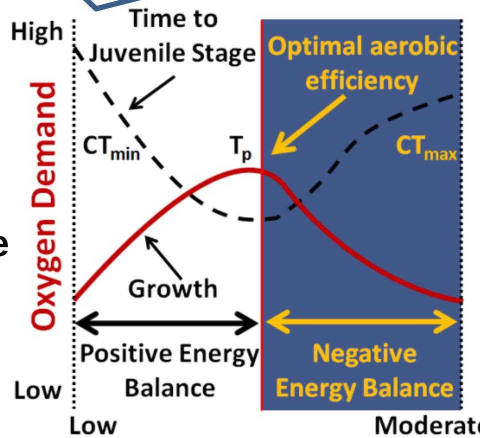


Warming

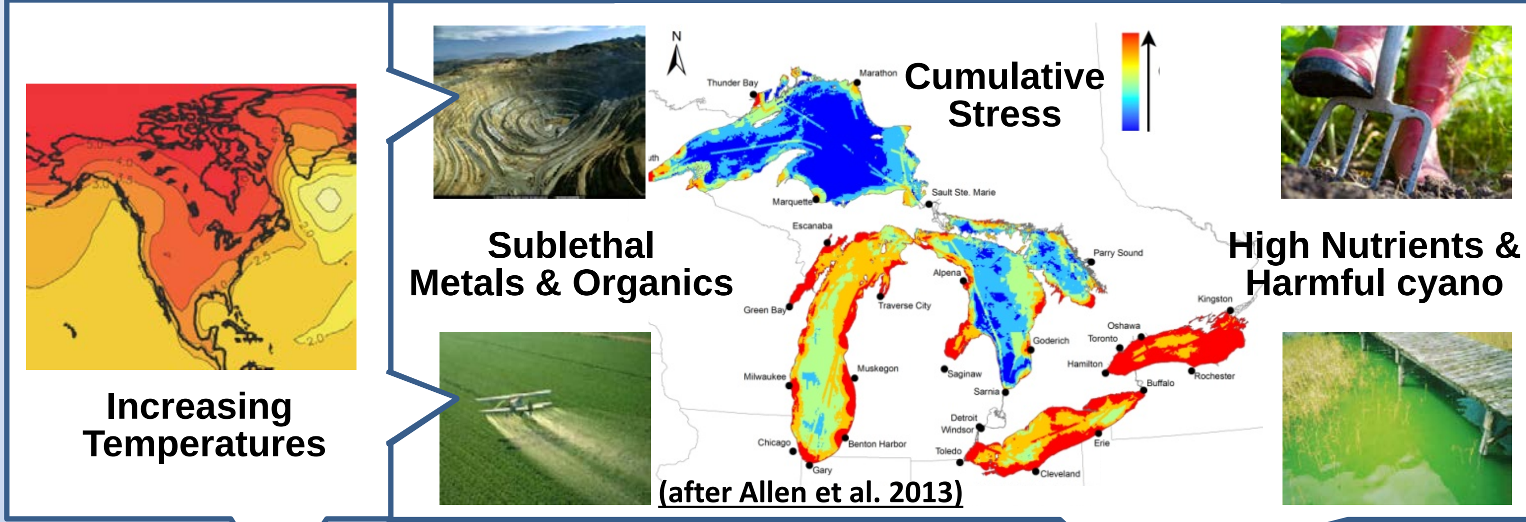
Toxins truncate thermal window



Warming and Pollutants

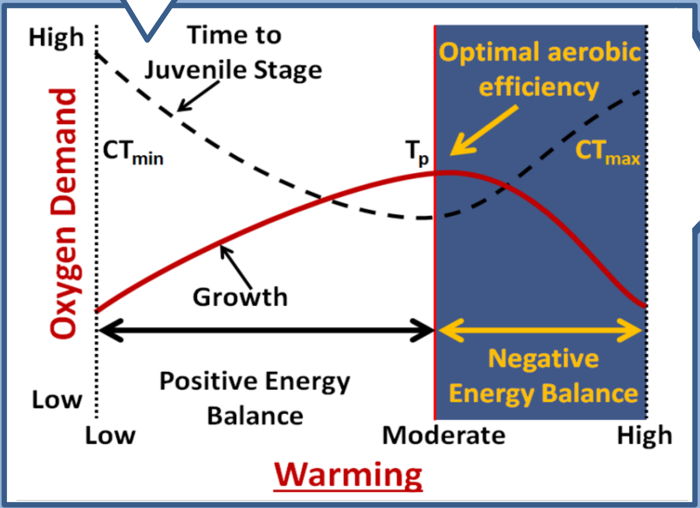
Environmental Drivers:

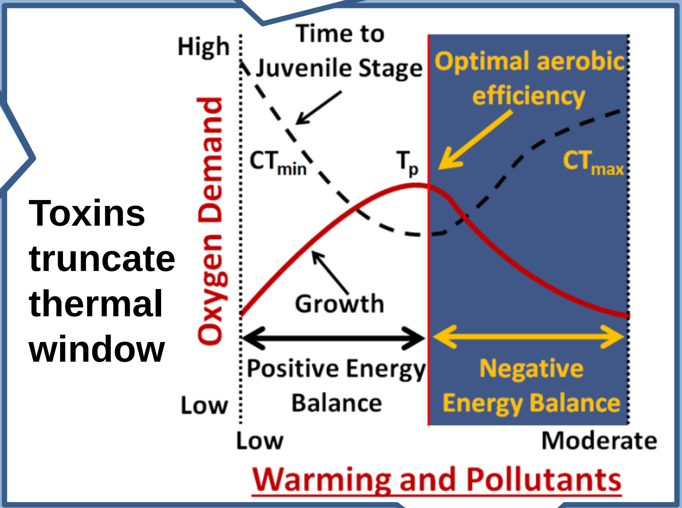
Contaminants, Nutrients, Temperature



Biologic Response:

- **Parabolic Metabolism, Oxygen & Energy Demand**
- **Truncated Thermal Window**





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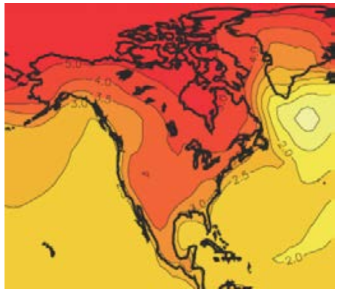

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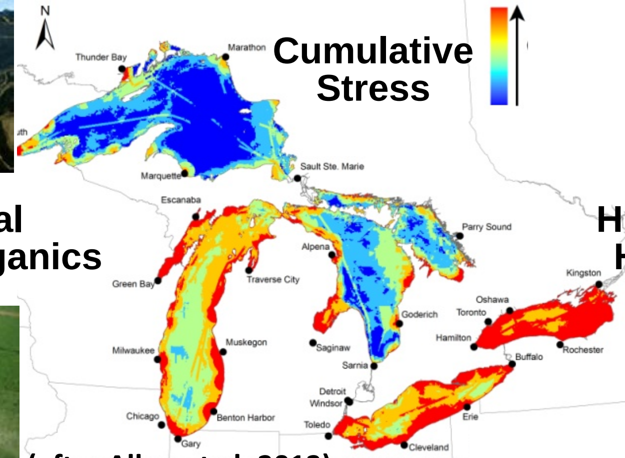

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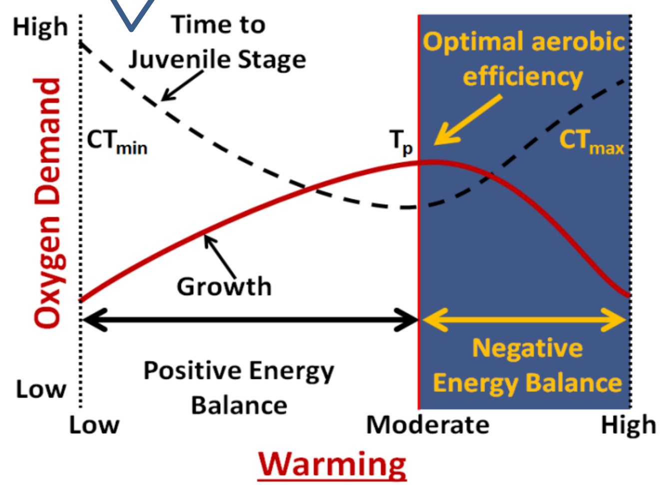
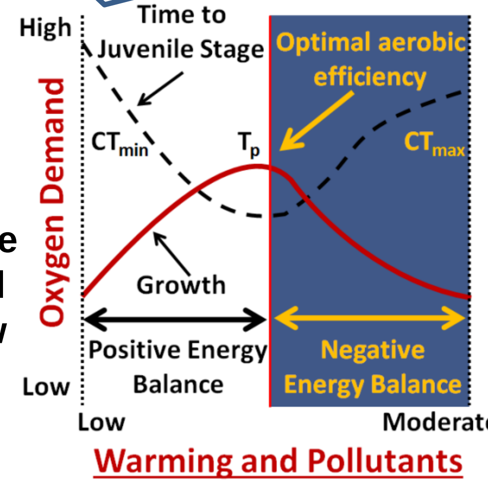
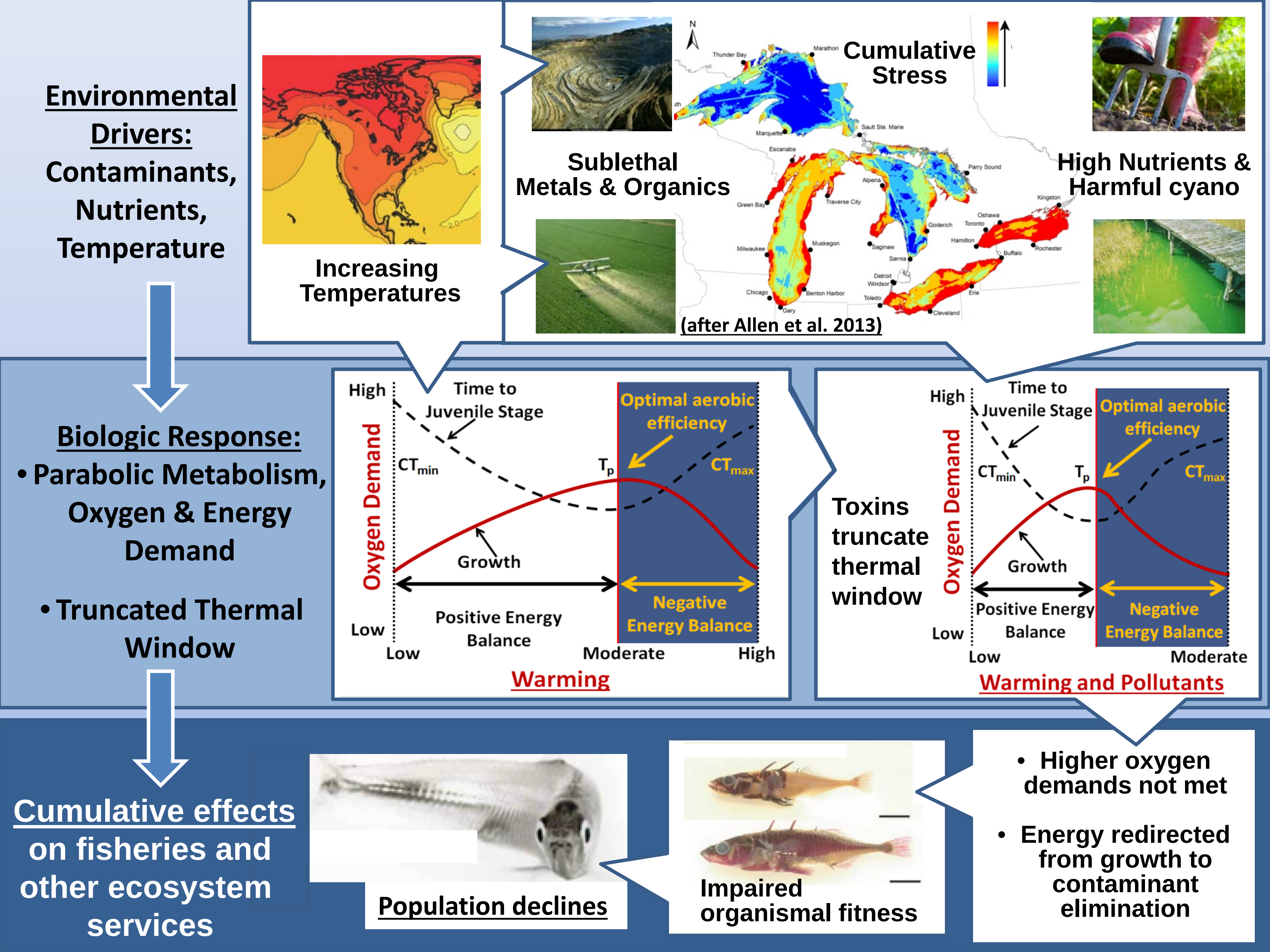


Toxins truncate thermal window



Impaired organismal fitness

- Higher oxygen demands not met
- Energy redirected from growth to contaminant elimination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• Truncated Thermal Window
High
Low
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CTmin
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Optimal aerobic efficiency
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Warming and Pollutants
Cumulative effects on fisheries and other ecosystem services
Population declines
Impaired organismal fitness
• Higher oxygen demands not met
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Challenges

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Case Study Methods: Chronic Bioassay

- Cope's Grey Tree Frog
  - Wide biogeographic range and high fecundity
  - Large thermal window (2 to 41.5 ^{o}C)
- Duration
  - **Larvae:** Gosner Stage 25-26 – Metamorphosis
  - **Adults:** 20 d Monitoring of Post-Metamorphic Growth
- Factorial design:
  - 3 Temperature Regimes x 6 Levels of Cu, Cd, and Pb mixtures
- Outdoor facility
  - Diel and seasonal light and temperature fluctuations
- Natural Water

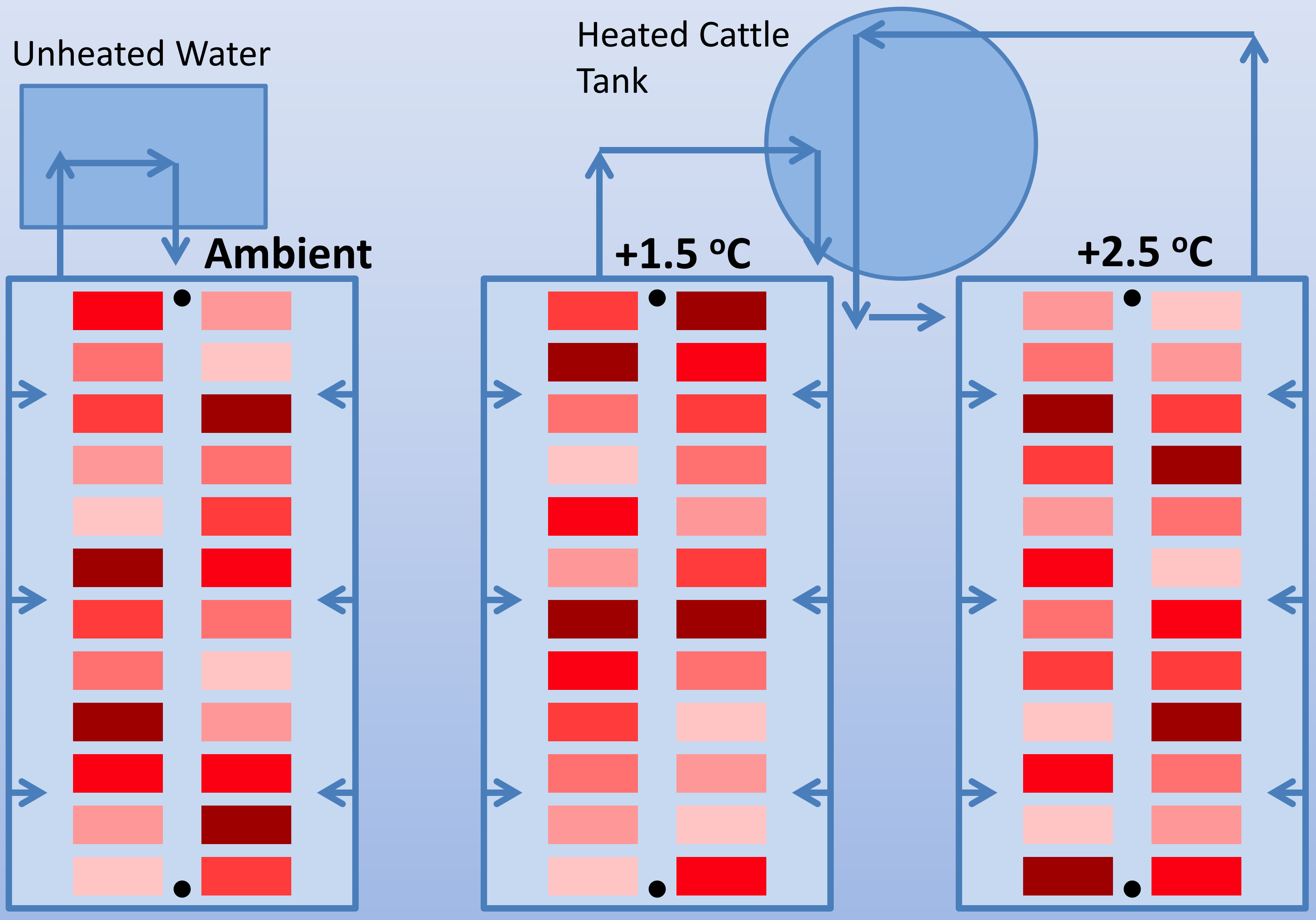
Metals expressed as bioavailable fractions—ionic activity

Bioavailable Chronic Criterion Units (BCCU): multiples of the bioavailable metals relative to the freshwater criterion for each metal

.

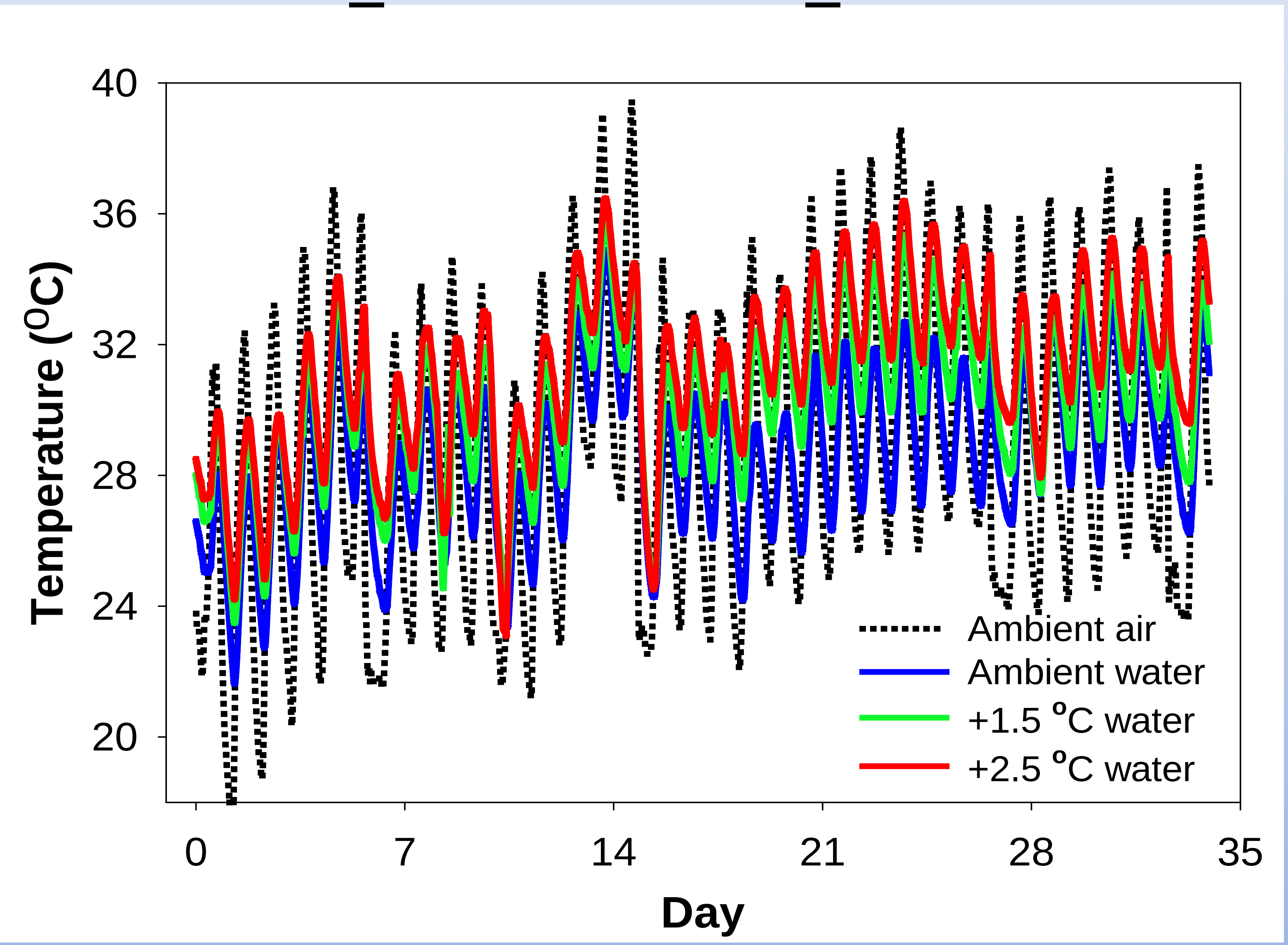
$$\mathrm{BCCU} = \sum \left(\frac{\{\mathrm{Cd}\}}{\mathrm{BC}_{Cd}}\right) + \left(\frac{\{\mathrm{Cu}\}}{\mathrm{BC}_{Cu}}\right) + \left(\frac{\{\mathrm{Pb}\}}{\mathrm{BC}_{Pb}}\right)$$

Chronic Bioassay Design: 33 d Duration



Counter-Current Bioassay Heating

+1.5 <u>+</u> 0.05 and +2.5 <u>+</u> 0.05 S.E.



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Results: PERMANOVA on Larval Energetics

Dissimilarity matrix on Euclidean distance between growth and condition biometrics

Source	df	SS	MS	F	P
Temperature	2	16.20	8.10	12.68	**0.001***
BCCU	5	9.46	1.89	2.96	**0.021***
Temp x BCCU	10	10.67	1.07	1.67	0.112
Residual	54	34.48	0.64		
Total	71	70.81			

Surprisingly, no significant interaction

Hallman and Brooks ***(in review)***

Results: PERMANOVA on Larval Energetics
a posteriori t-tests by metals concentrations

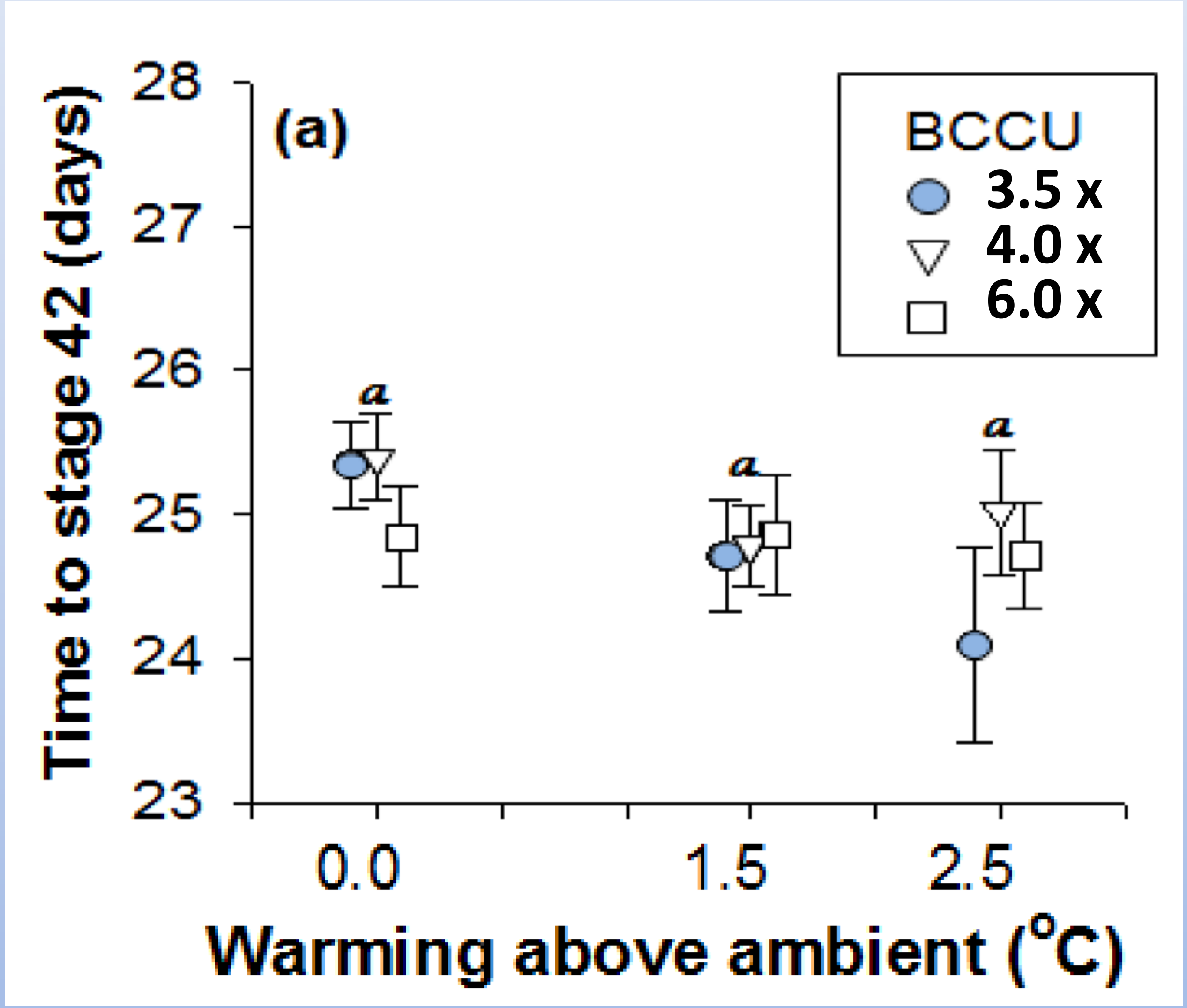
Comparisons within metals mixtures

3.5	**t**	**P**	**10**	**t**	**P**
Ambient versus +1.5 ºC	1.292	0.228	Ambient versus +1.5 ºC	2.754	**0.031***
Ambient versus +2.5 ºC	1.684	0.135	Ambient versus +2.5 ºC	2.289	0.119
+1.5 ºC versus +2.5 ºC	0.802	0.392	+1.5 ºC versus +2.5 ºC	0.992	0.275
4.0			**14.5**		
Ambient versus +1.5 ºC	1.475	0.202	Ambient versus +1.5 ºC	2.413	**0.033***
Ambient versus +2.5 ºC	0.717	0.483	Ambient versus +2.5 ºC	1.299	0.264
+1.5 ºC versus +2.5 ºC	0.452	0.657	+1.5 ºC versus +2.5 ºC	1.746	0.163
6.0			**27**		
Ambient versus +1.5 ºC	0.075	0.914	Ambient versus +1.5 ºC	3.910	**0.029***
Ambient versus +2.5 ºC	0.266	0.806	Ambient versus +2.5 ºC	2.799	**0.027***
+1.5 ºC versus +2.5 ºC	0.270	0.766	+1.5 ºC versus +2.5 ºC	0.542	0.576

- **Significant when metals increased →greater energy demand**
- **Metals mediate temperature response**

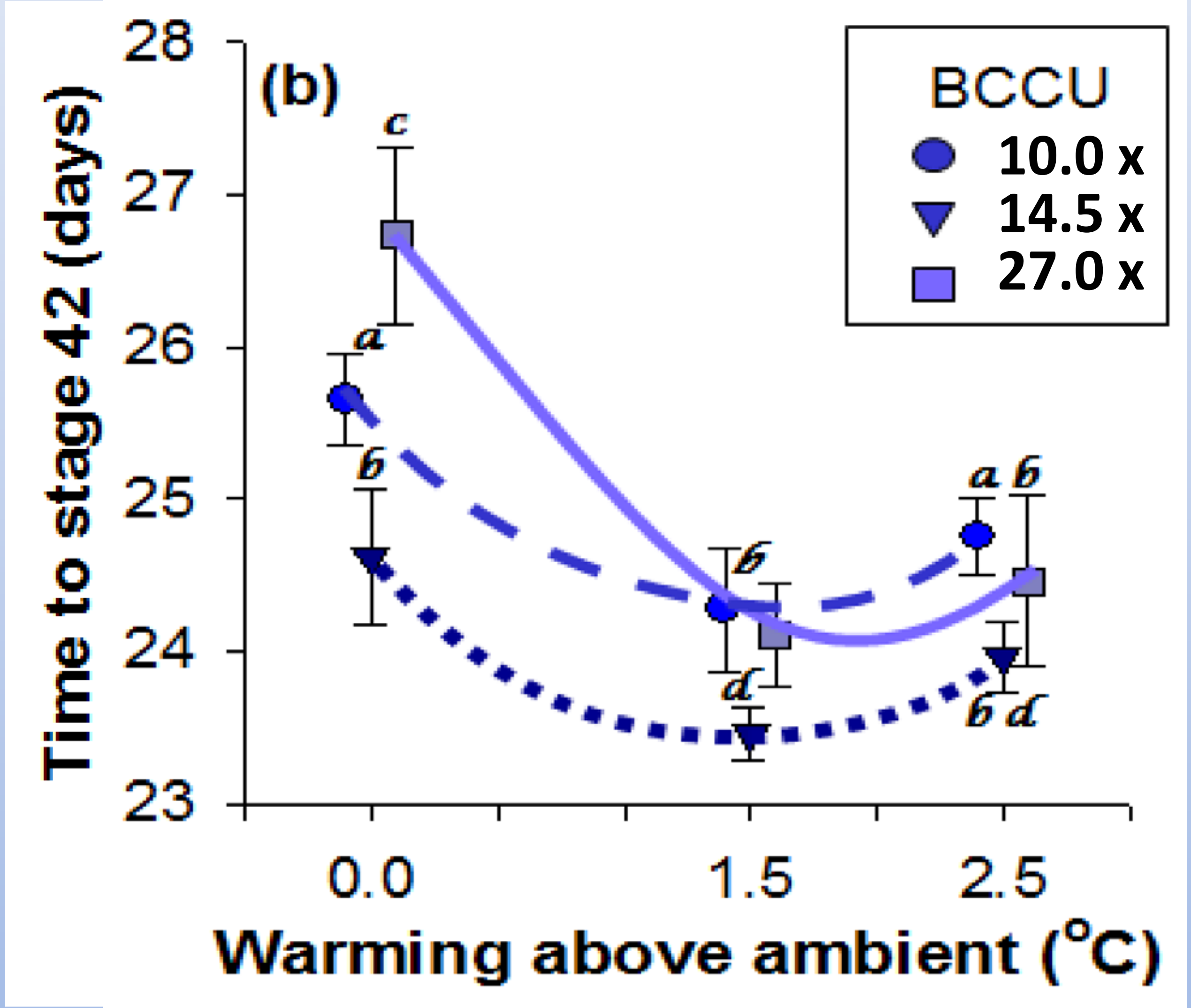
Hallman and Brooks *(in review)*

Results: Low level metals, time to stage 42



If metals are low, time to metamorphosis is not significantly faster at higher temperatures

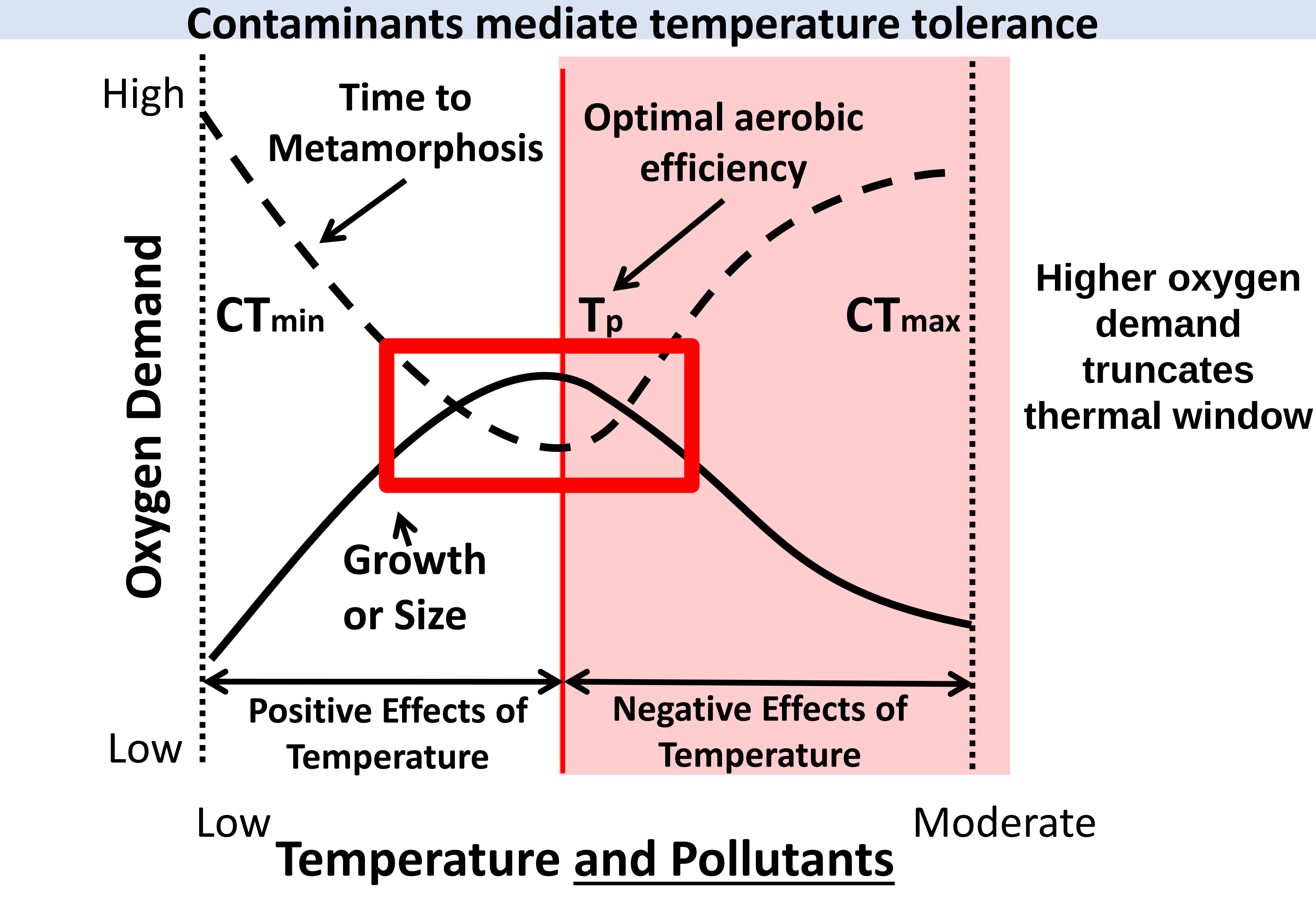
Results: High metals, time to stage 42



High metals levels significantly sped metamorphosis

20-d post metamorphs had 50% lower Body Condition

Temperature, Energy and Chronic Endpoints



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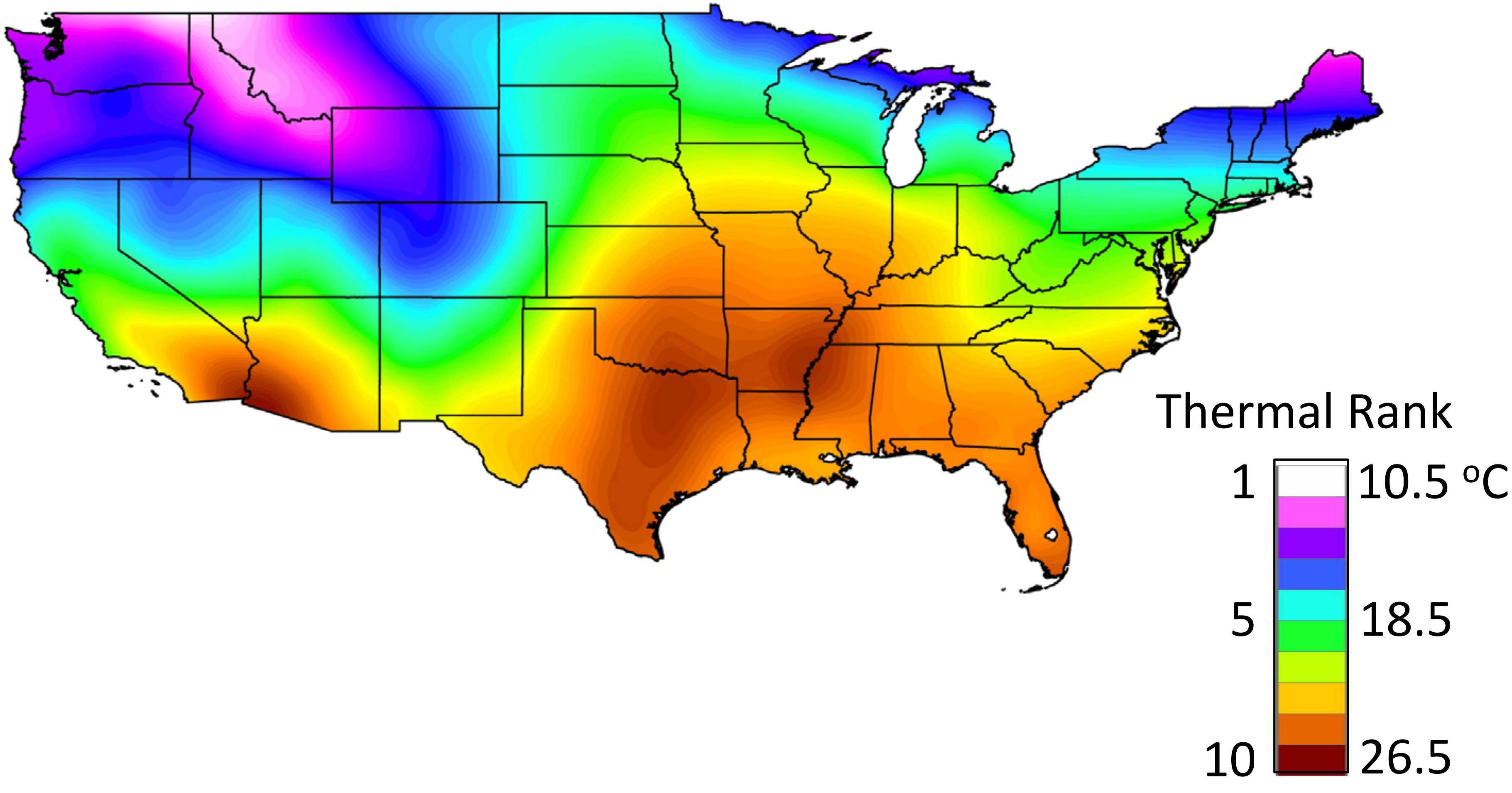
Biogeographic Implications to Fitness:

Current average summer temps

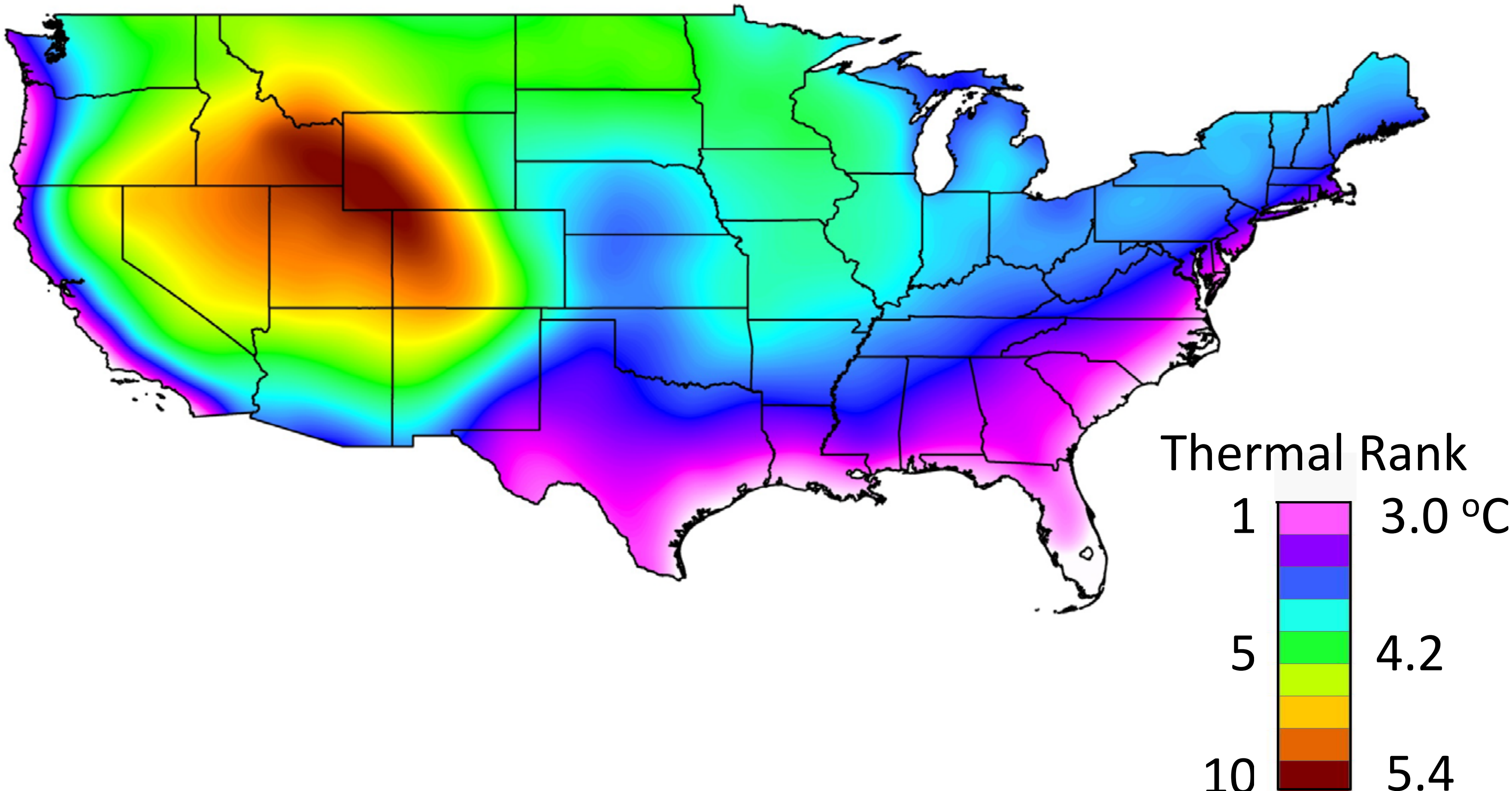


NCAR, GIS Program through Climate Change Scenarios, www.gisclimatechange.org

Biogeographic Implications to Fitness:

Predicted temperature increases

(IPCC 2007, A2 Scenario)



Meehl, et al. 2007. *The Physical Science Basis. 4th Report IPCC*

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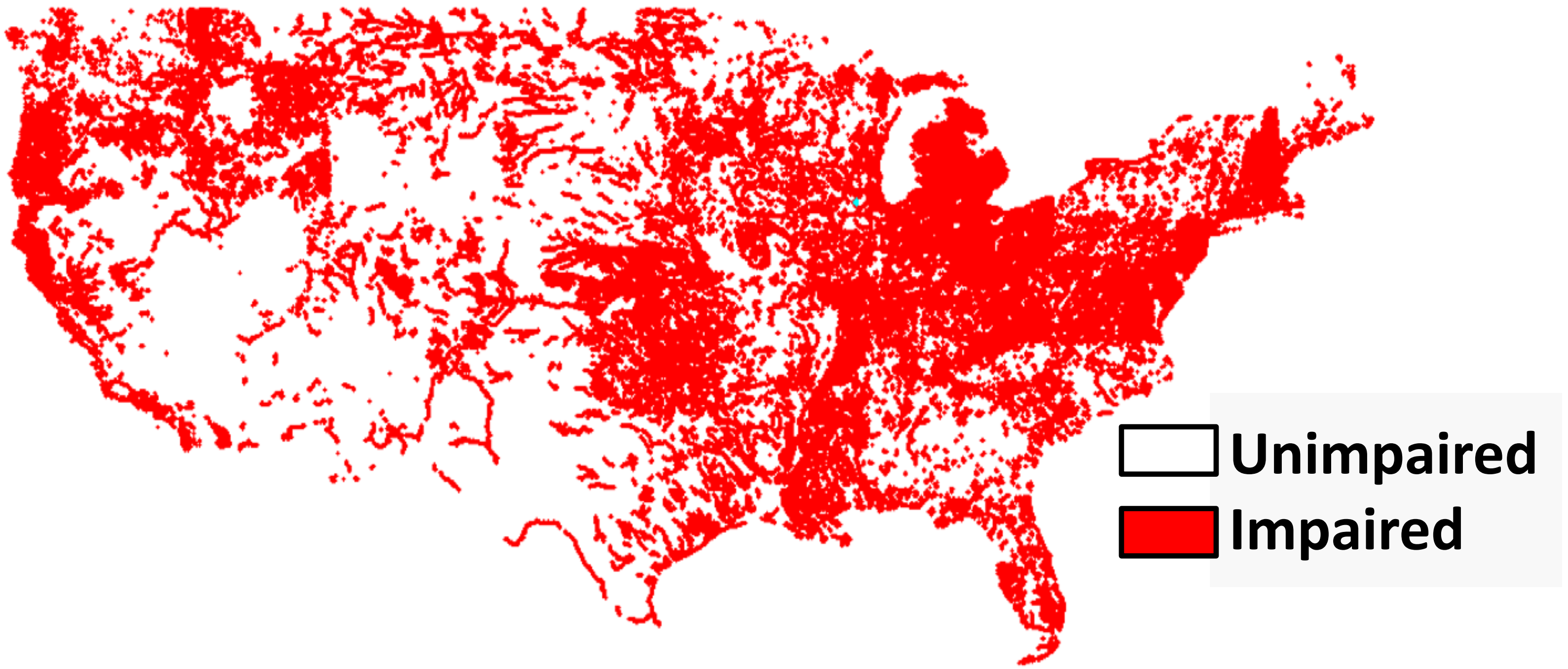
Analog for Criteria Chronic Concentrations

Widespread Pollution, 303 (d) Listing



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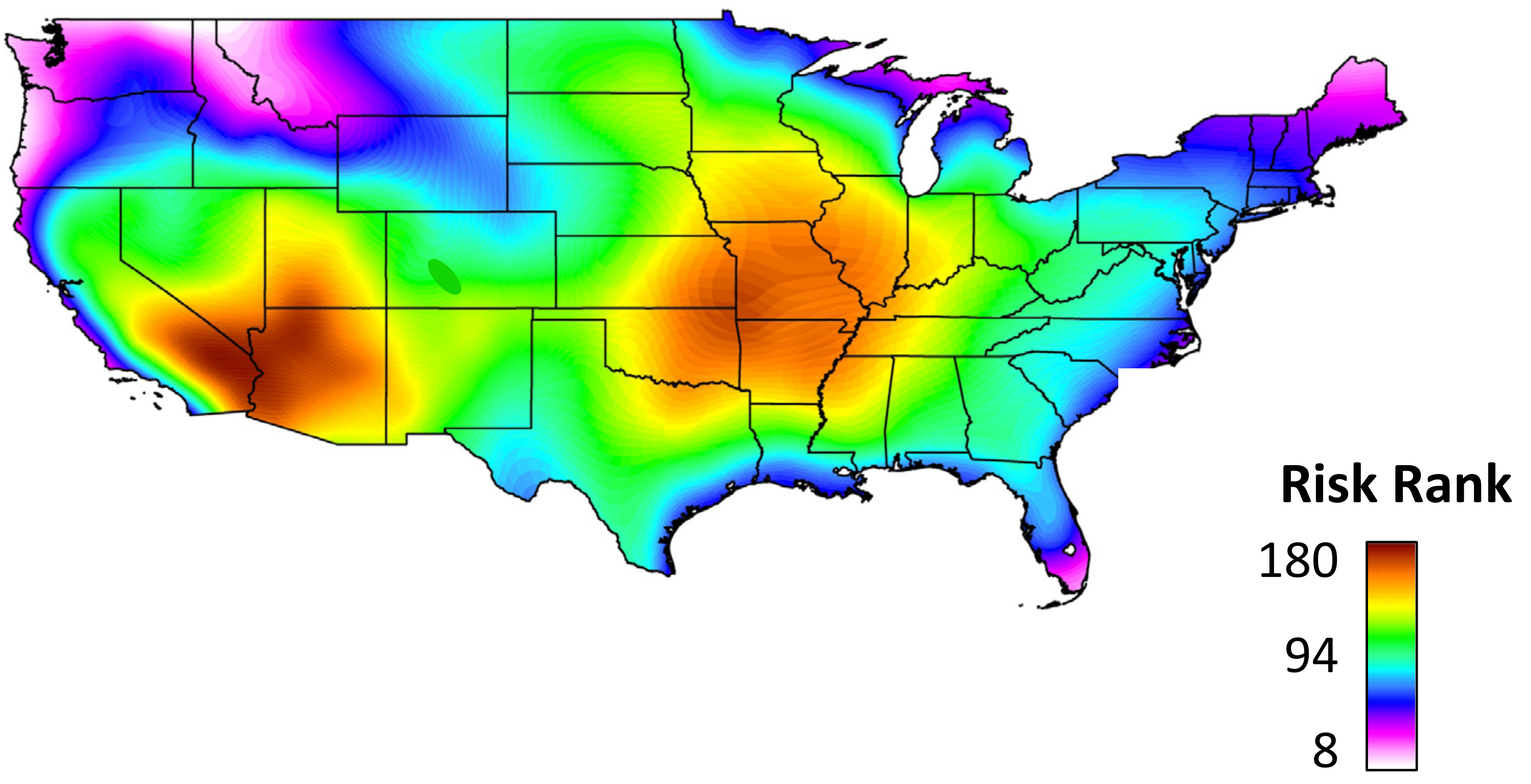
Biogeographic Implications of Compounding Stressors: Geospatial Risk Ranking for Population Viability



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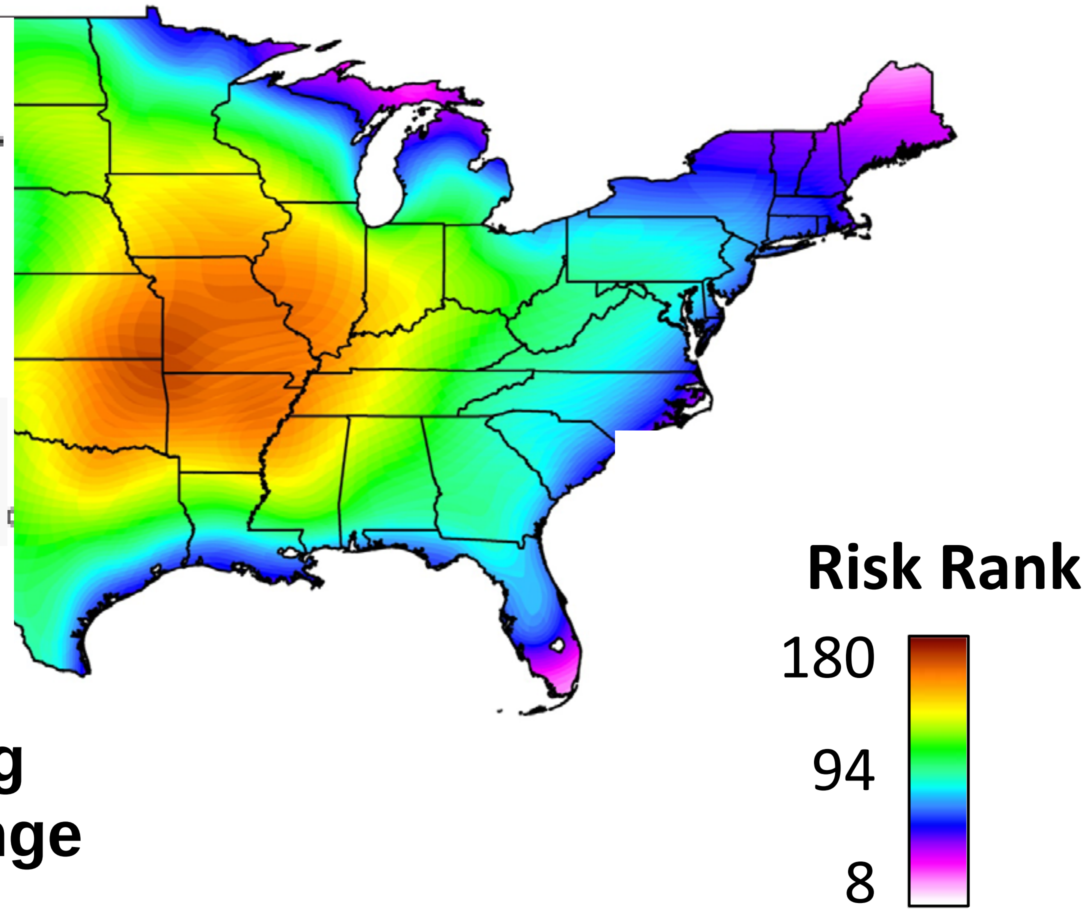
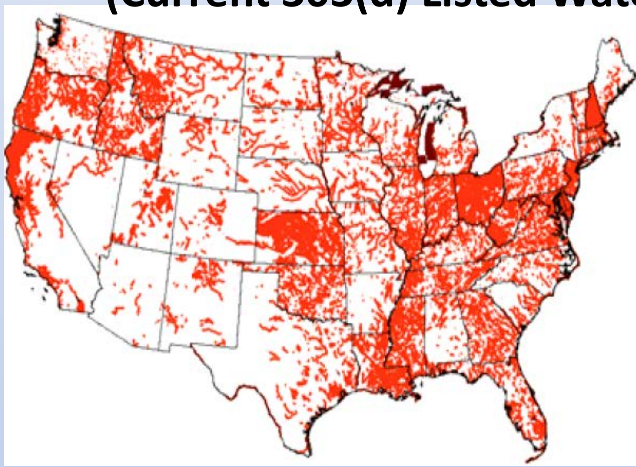
Home Range: *H. chrysoscelis*



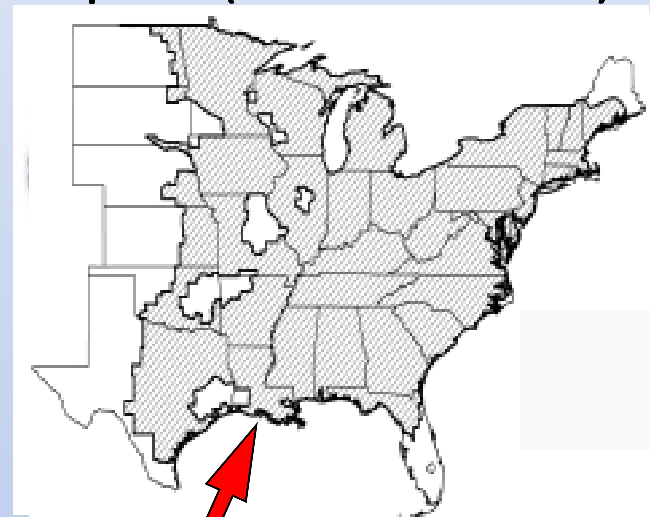
Geospatial risk ranking compared to home range

USEPA, 2012. WATERS Program Washington, D.C. www.epa.gov/waters/data/

Analog for chronic criteria concentrations (Current 303(d) Listed Waters)



Observed At-Risk Fish and Mussel Species (Master et al. 1998)

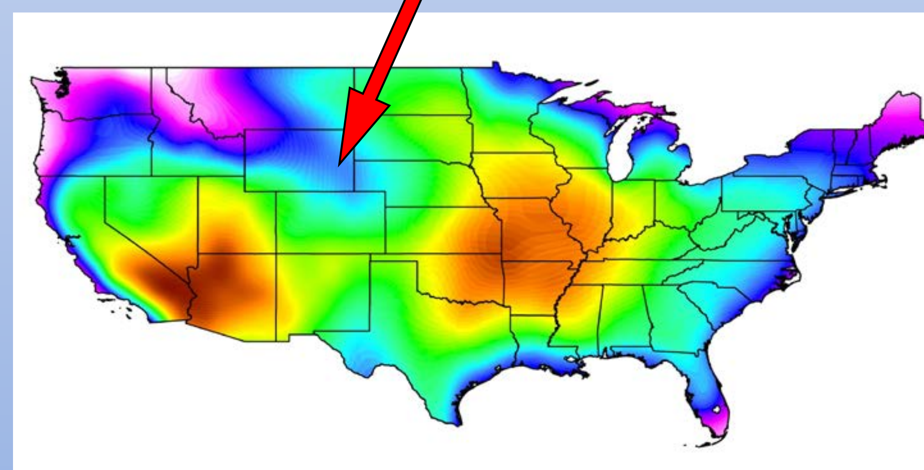


<u>DISCONNECT:</u>

Currently, unknown links between cumulative stressors and observed at-risk species.

<u>CONNECT:</u>

Only if geospatial models directly link performance metrics biomarkerrs and oxygen needs



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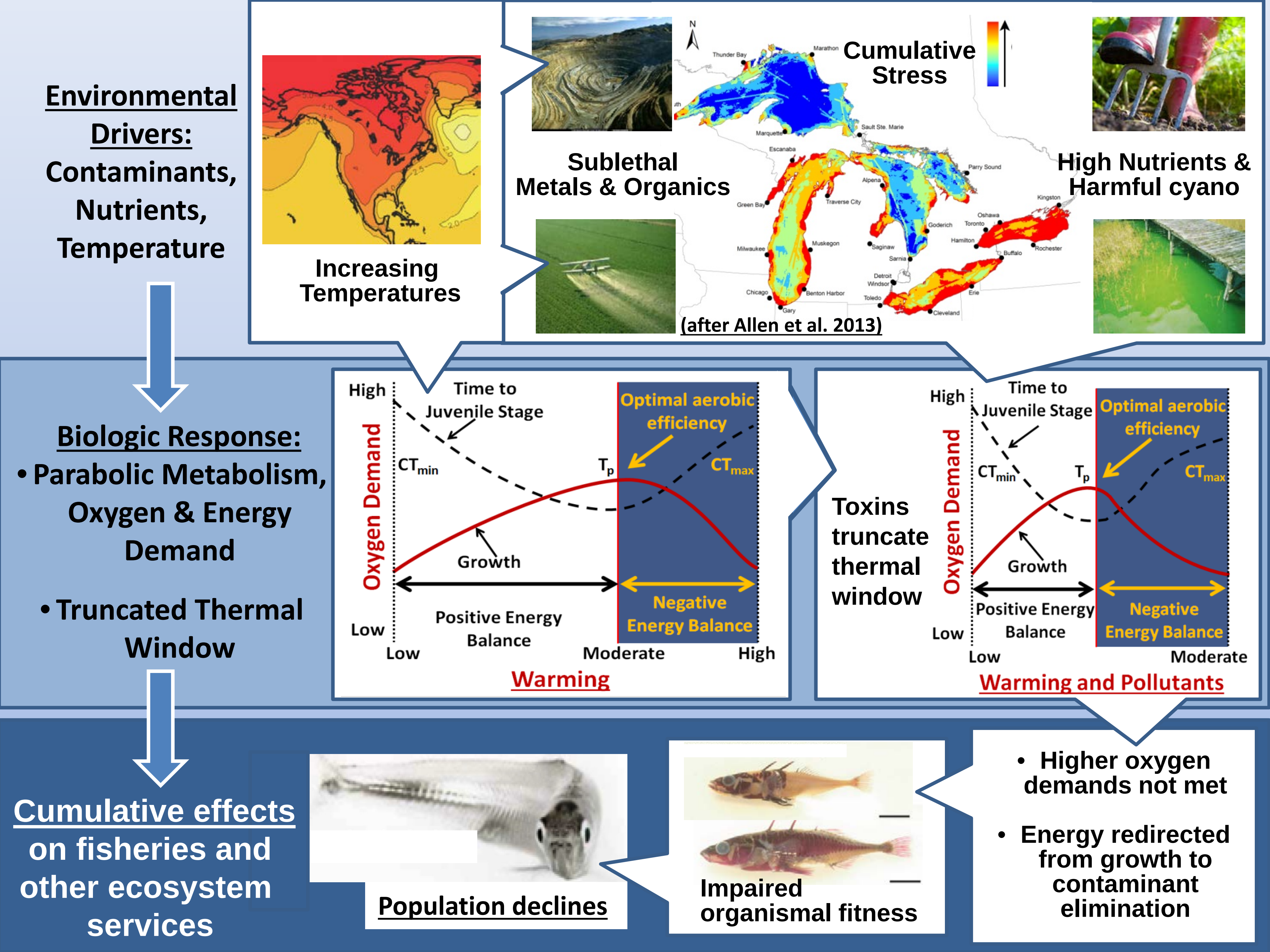
Questions?



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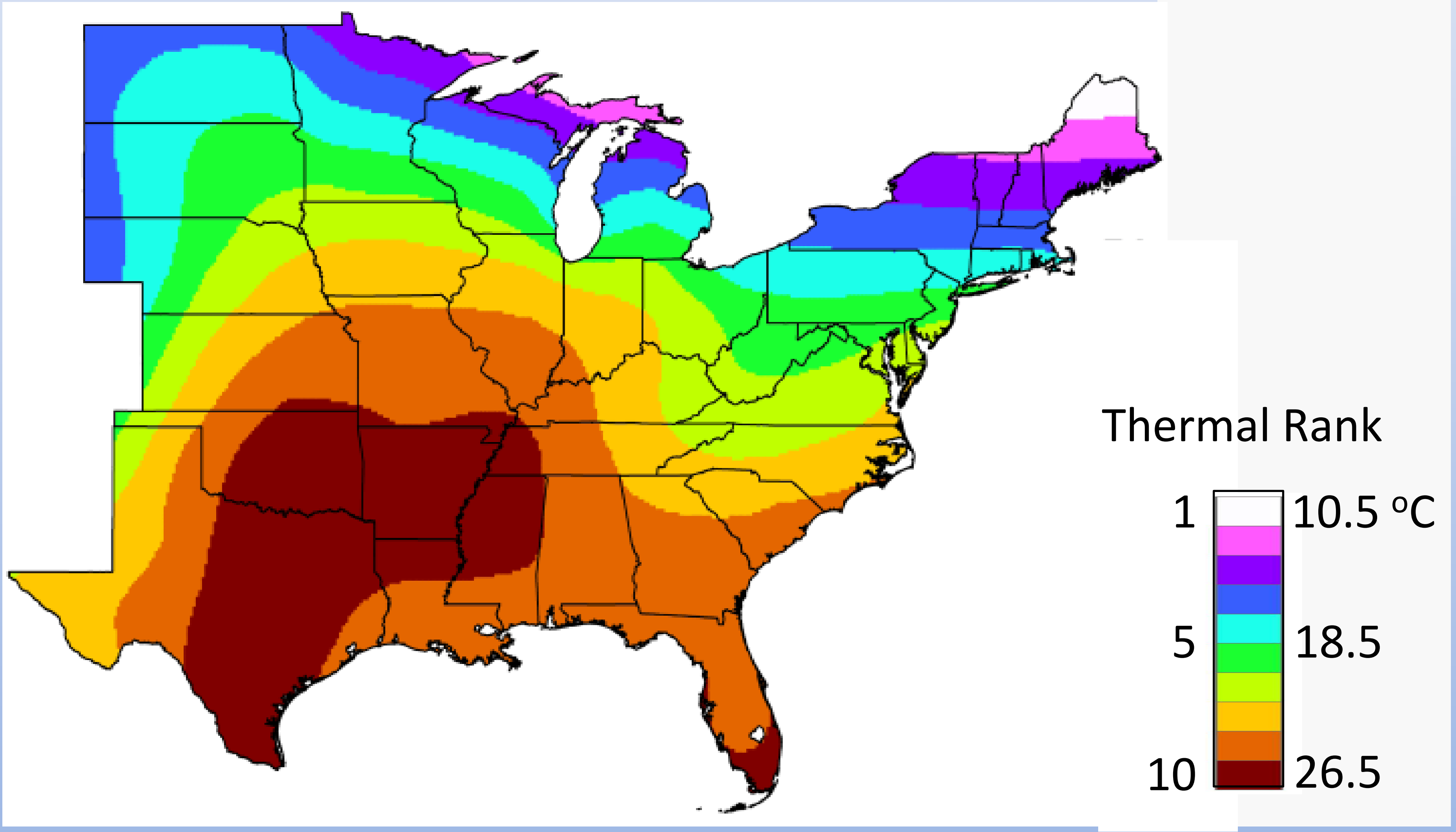

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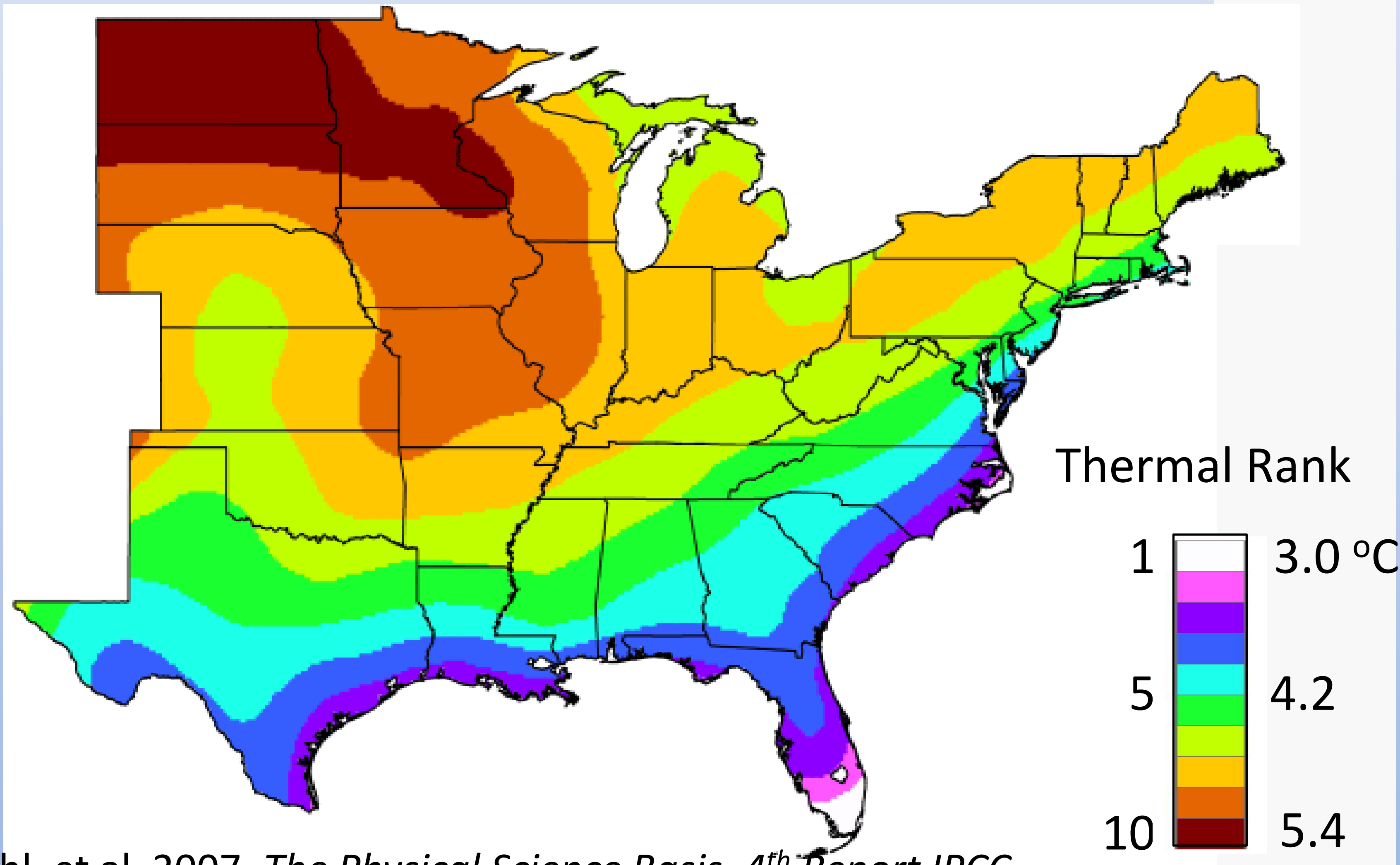

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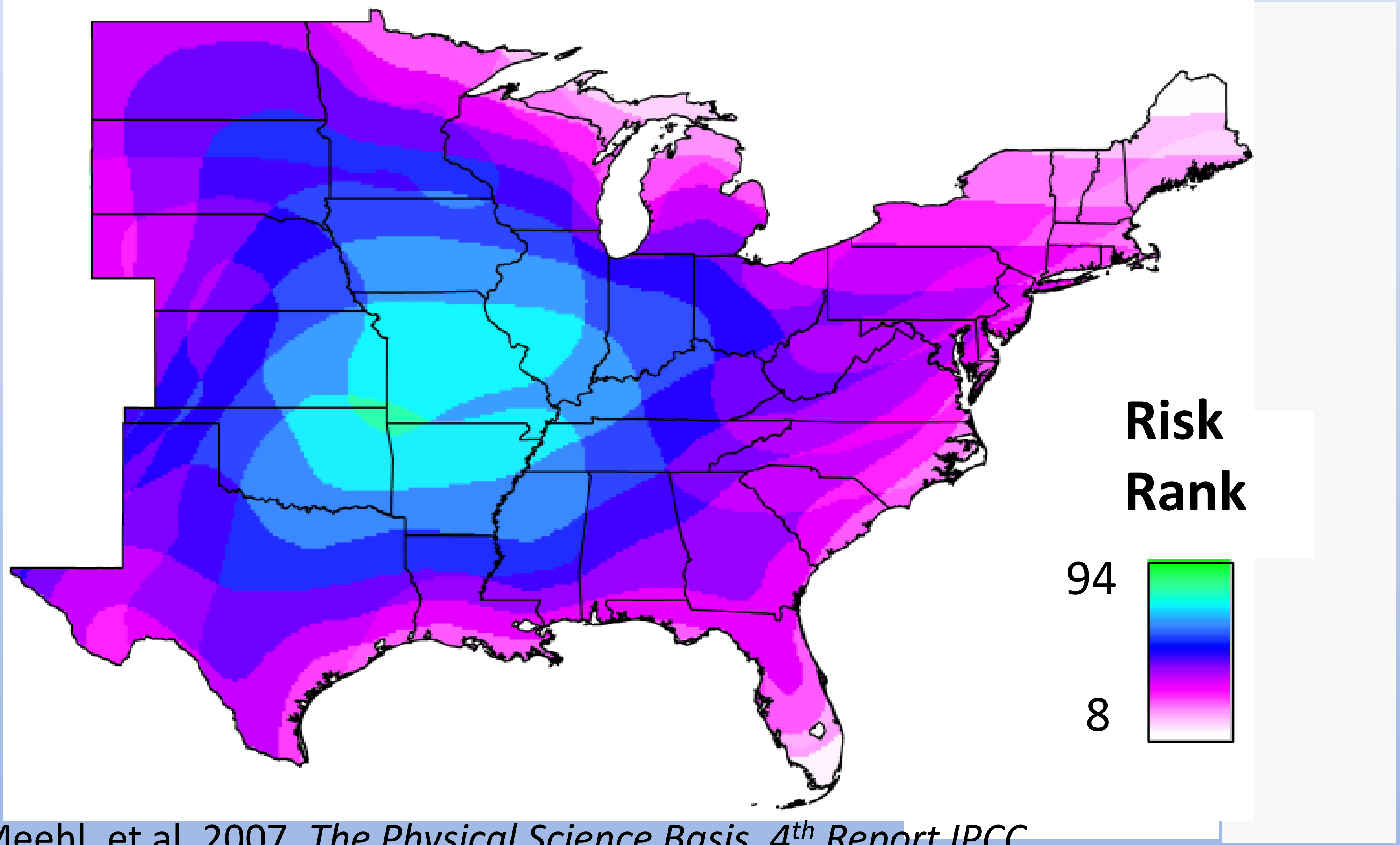
Biogeographic Implications to Fitness:

Geospatial Risk Ranking from Rising Temperatures in Summer



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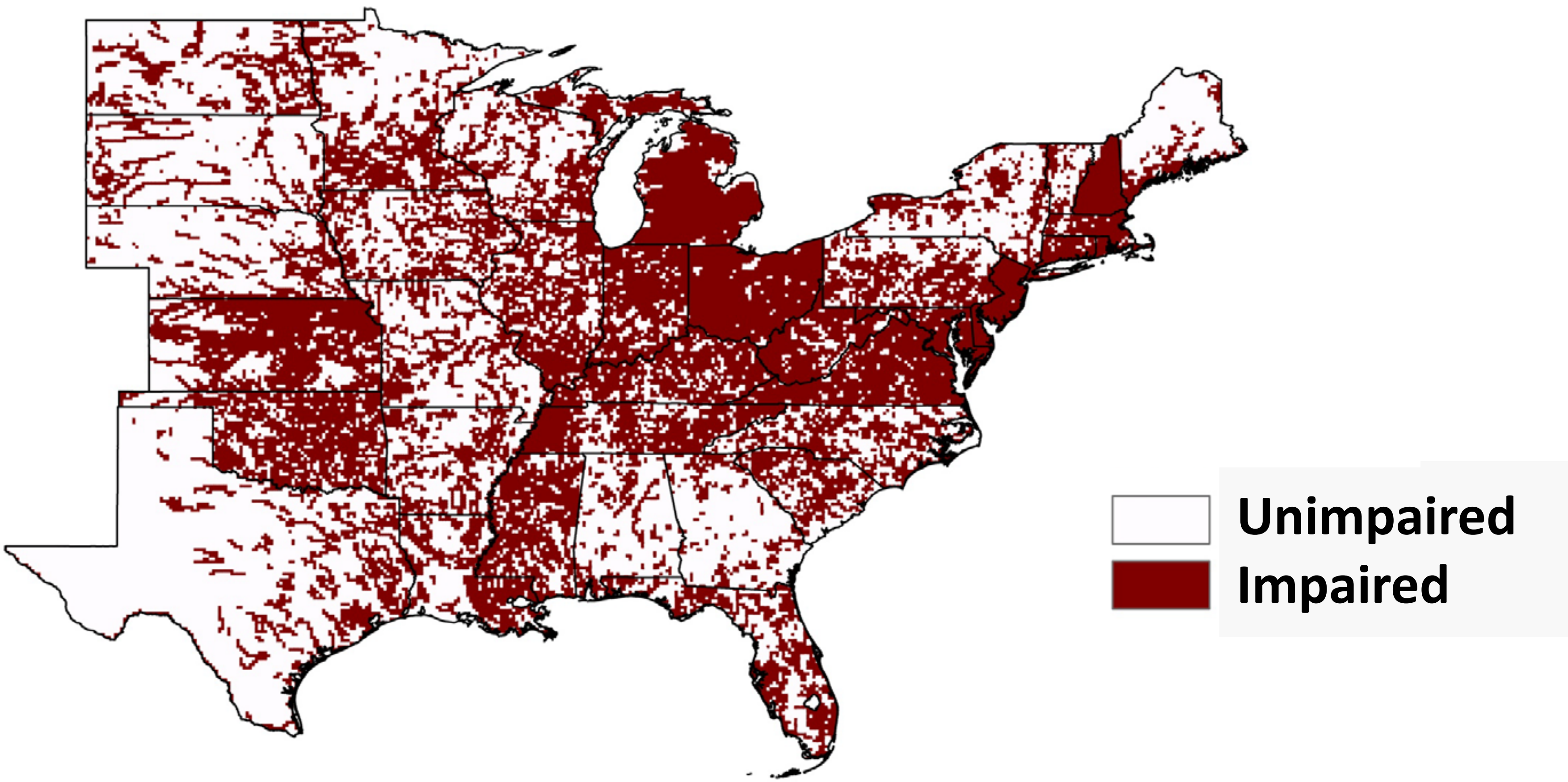
Biogeographic Implications to Fitness: Widespread Sublethal Pollution, 303 (d) Listing

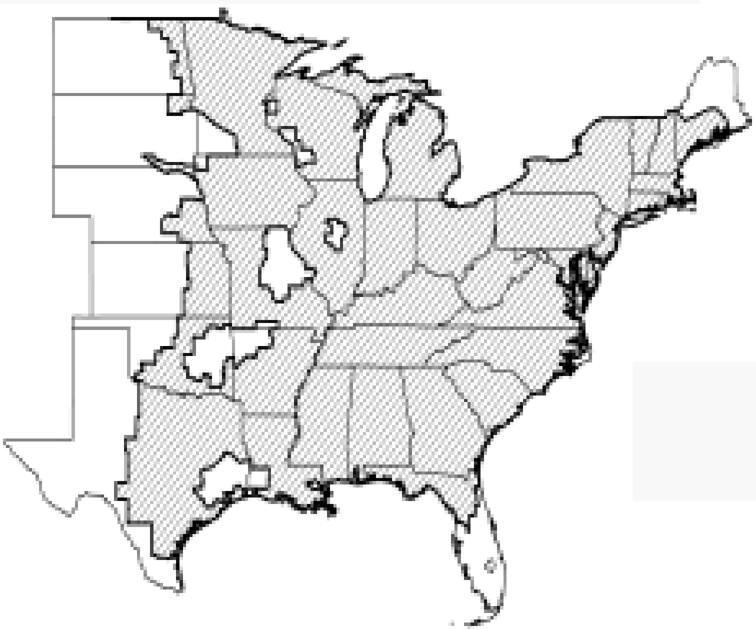
Chronically exceed Drinking Water Criteria for Maximum Contaminant Levels (MCLs)

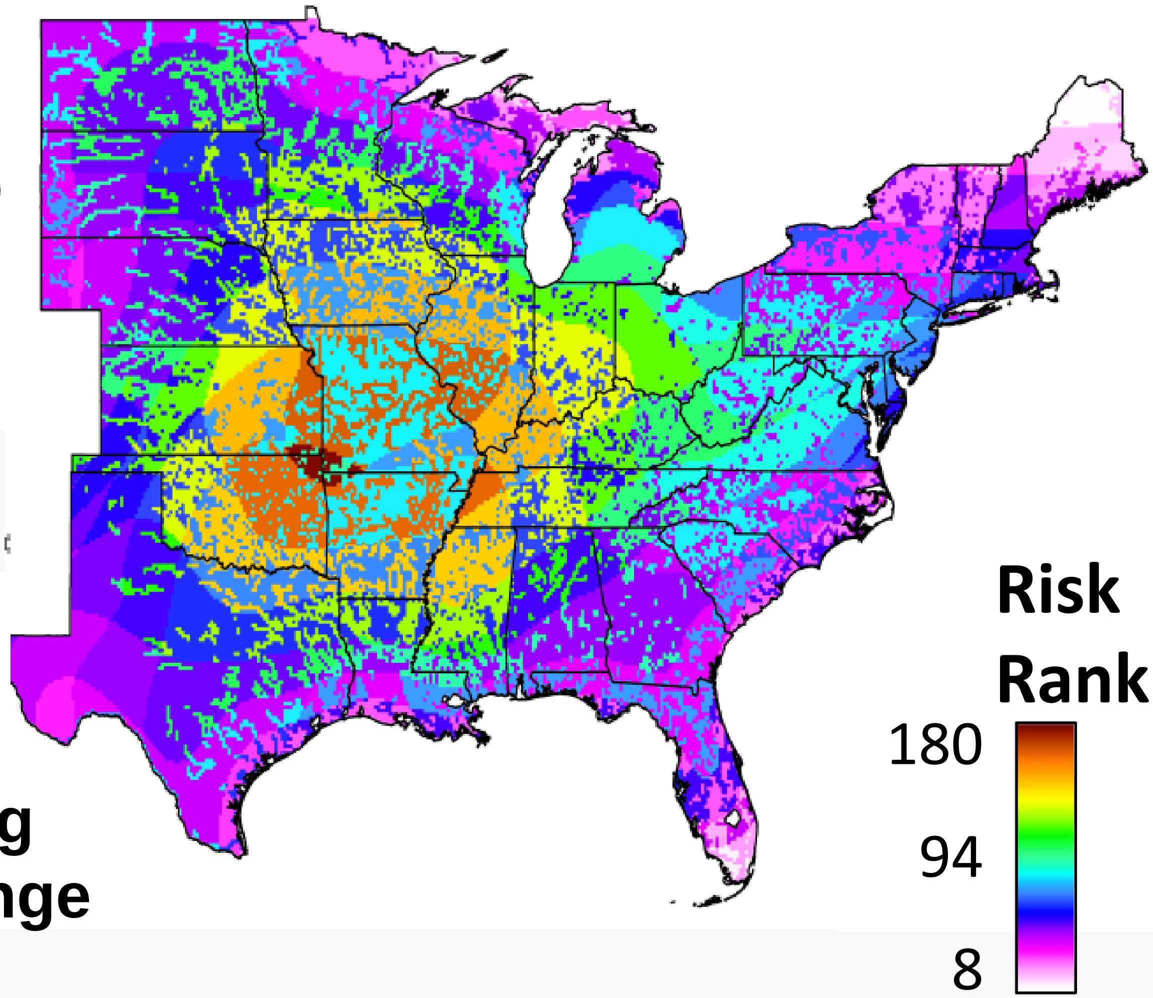


USEPA, 2012. WATERS Program Washington, D.C. www.epa.gov/waters/data/

Biogeographic Implications of Compounding Stressors

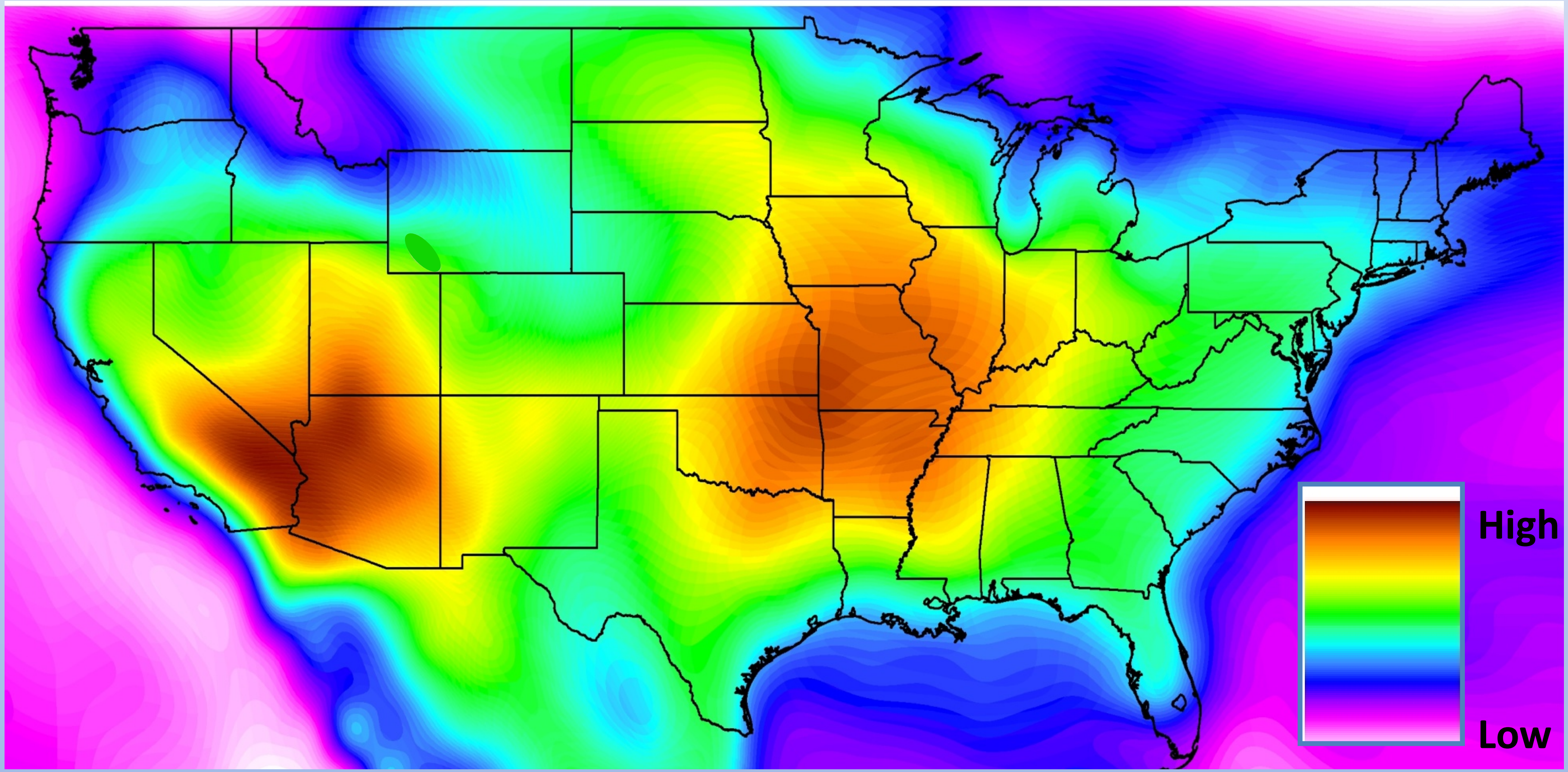
H. chrysoscelis:
Home Range





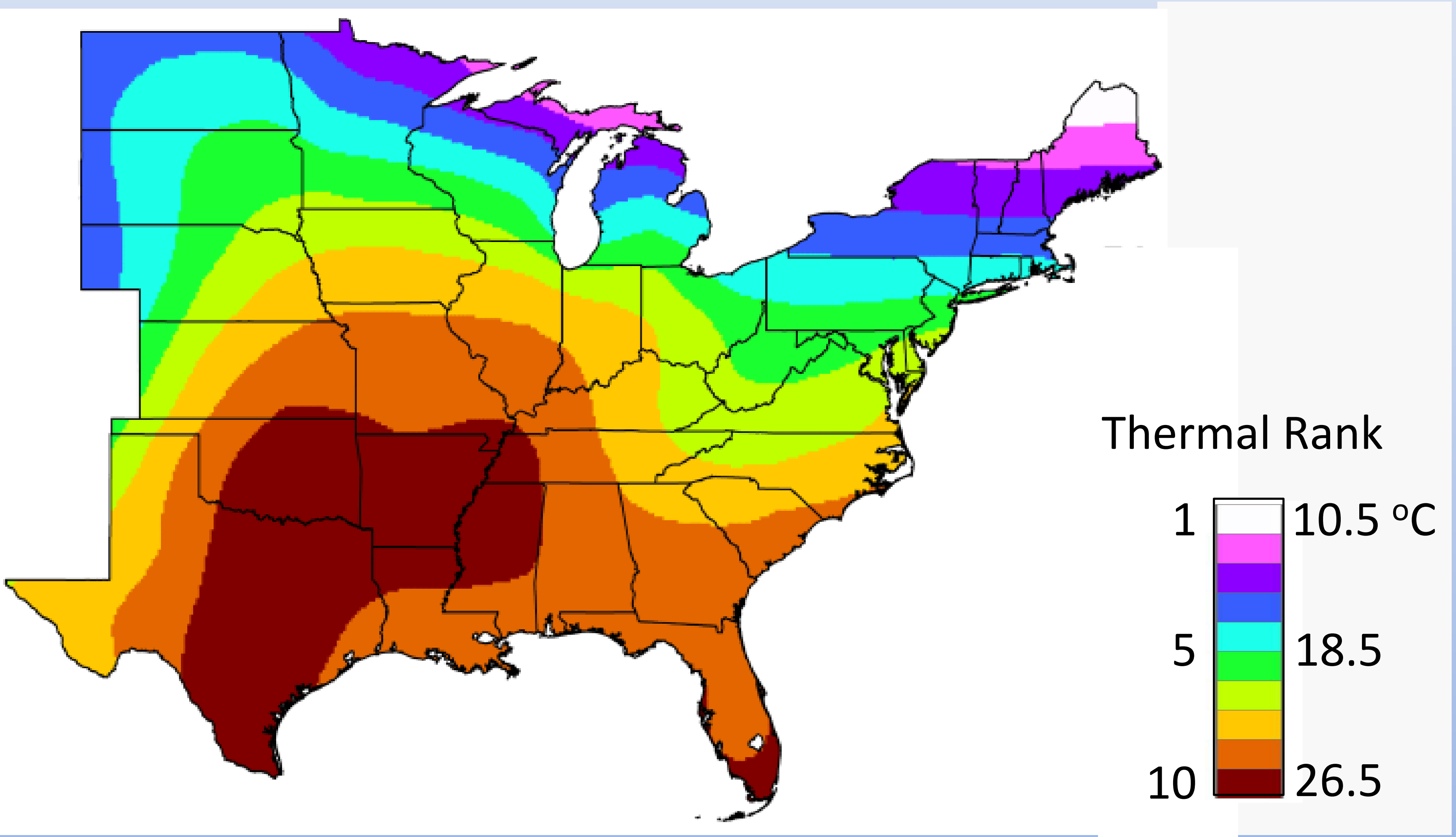
Geospatial risk ranking compared to home range

Biogeographic Implications of Compounding Stressors: Geospatial Risk Ranking for Population Viability



Biogeographic Implications to Fitness:

Current average summer temps

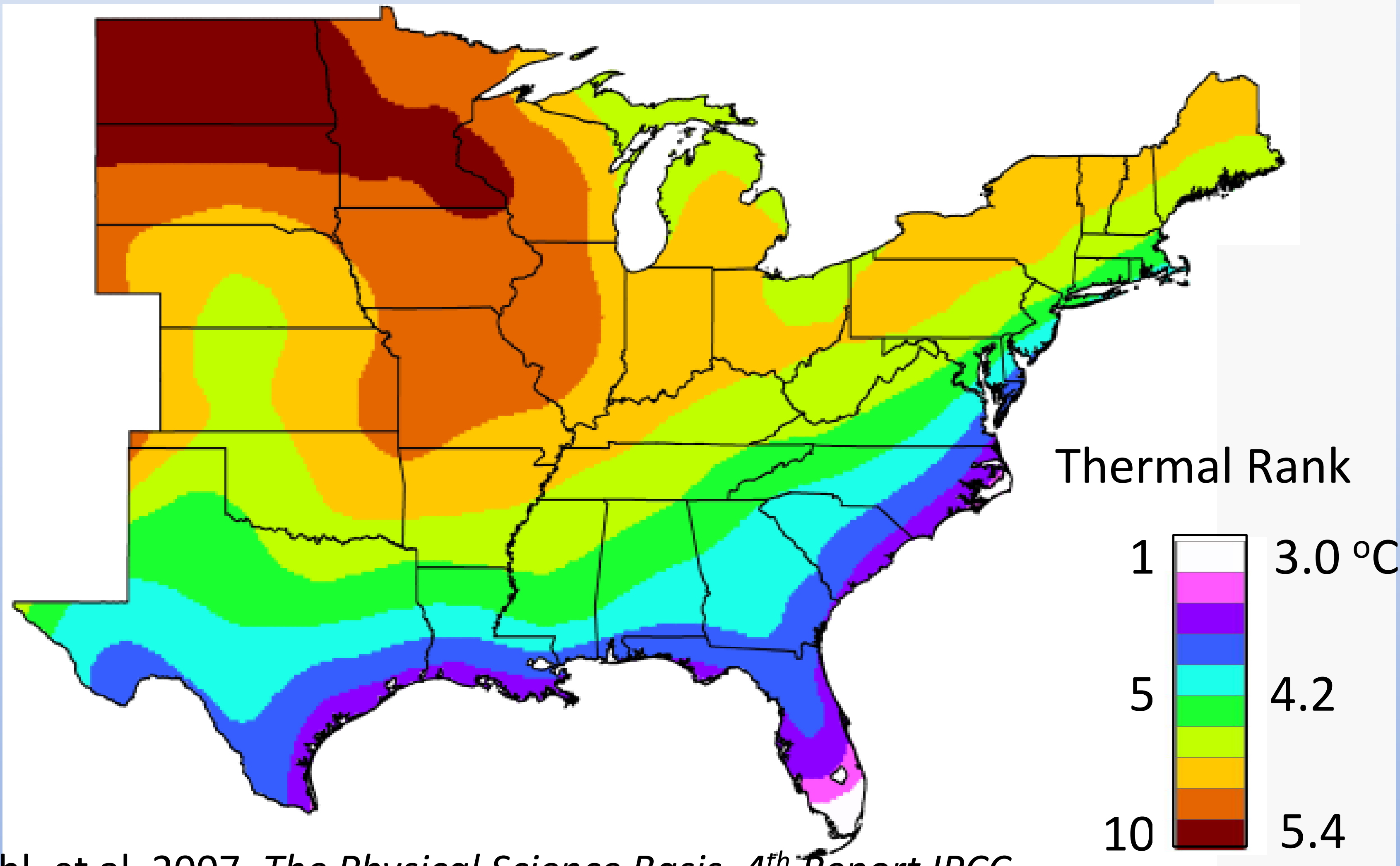


NCAR, GIS Program through Climate Change Scenarios, www.gisclimatechange.org

Biogeographic Implications to Fitness:

Predicted temperature increases

(IPCC 2007, A2 Scenario)

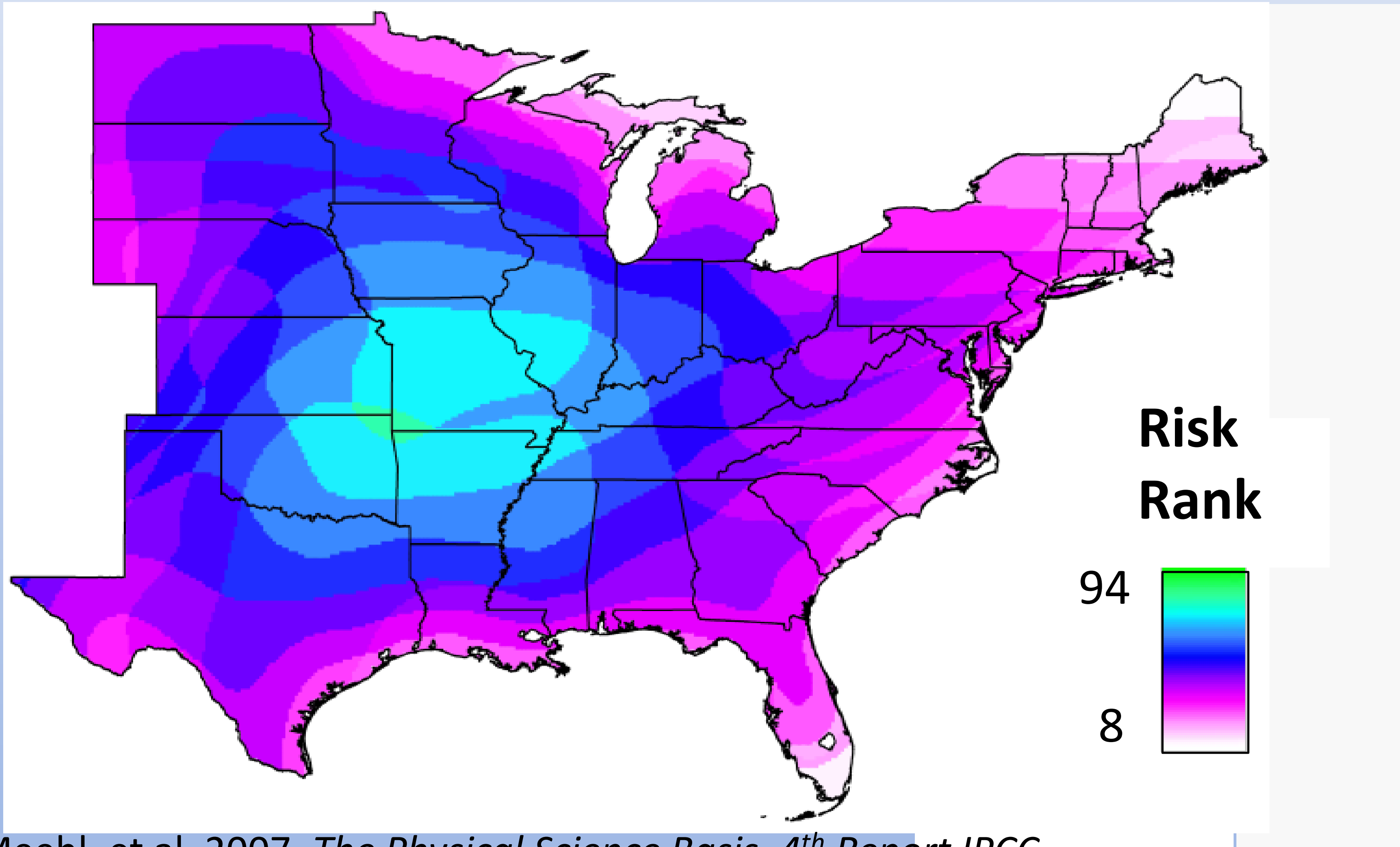


Meehl, et al. 2007. *The Physical Science Basis. 4th Report IPCC*

NCAR, GIS Program through Climate Change Scenarios, www.gisclimatechange.org

Biogeographic Implications to Fitness:

<u>Geospatial Risk Ranking</u> from Rising Temperatures in Summer



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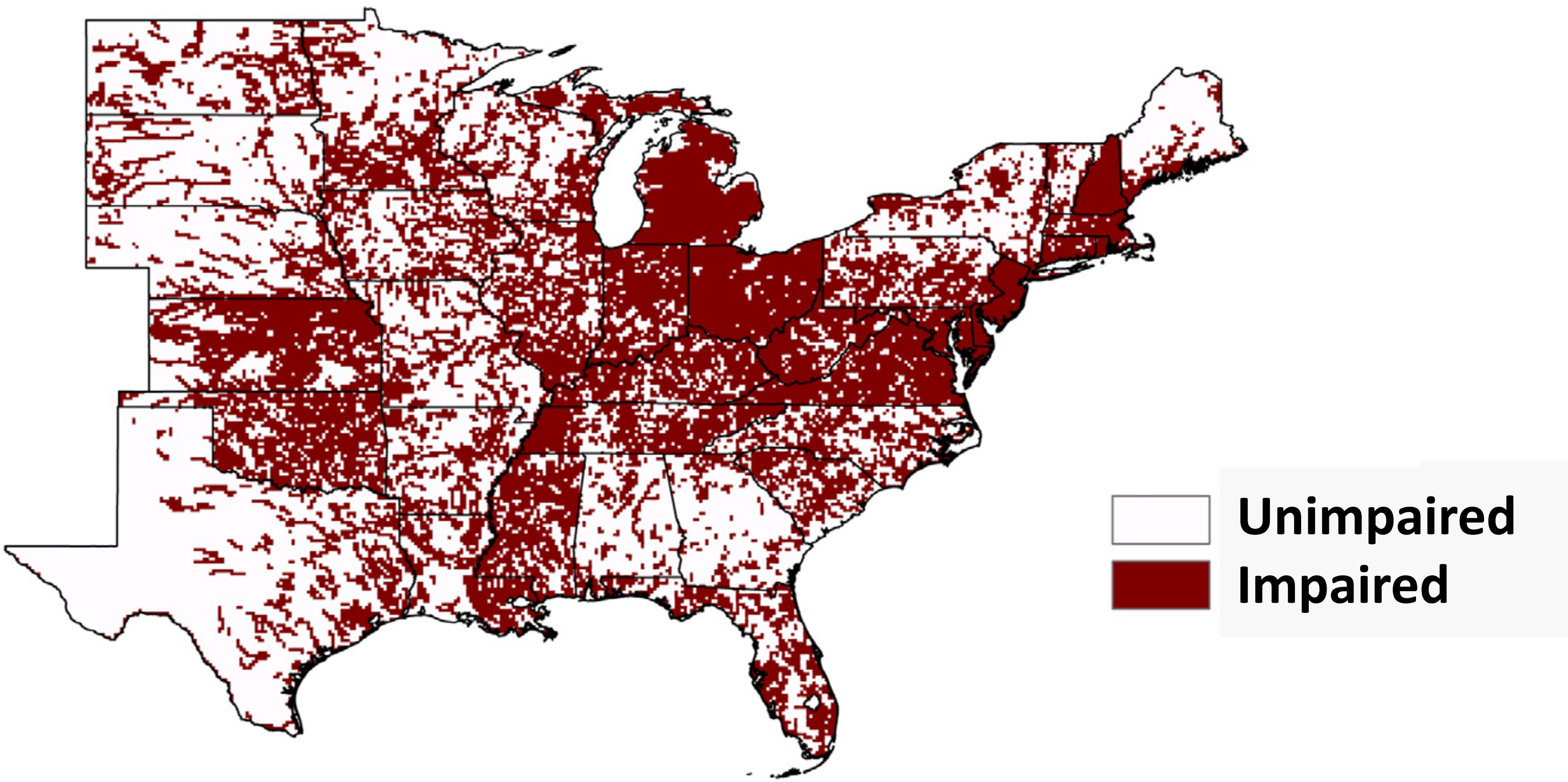

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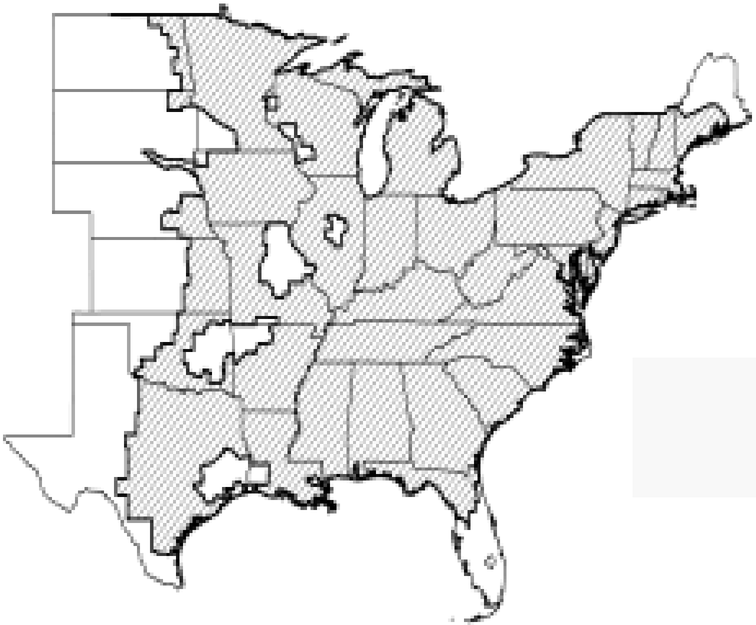
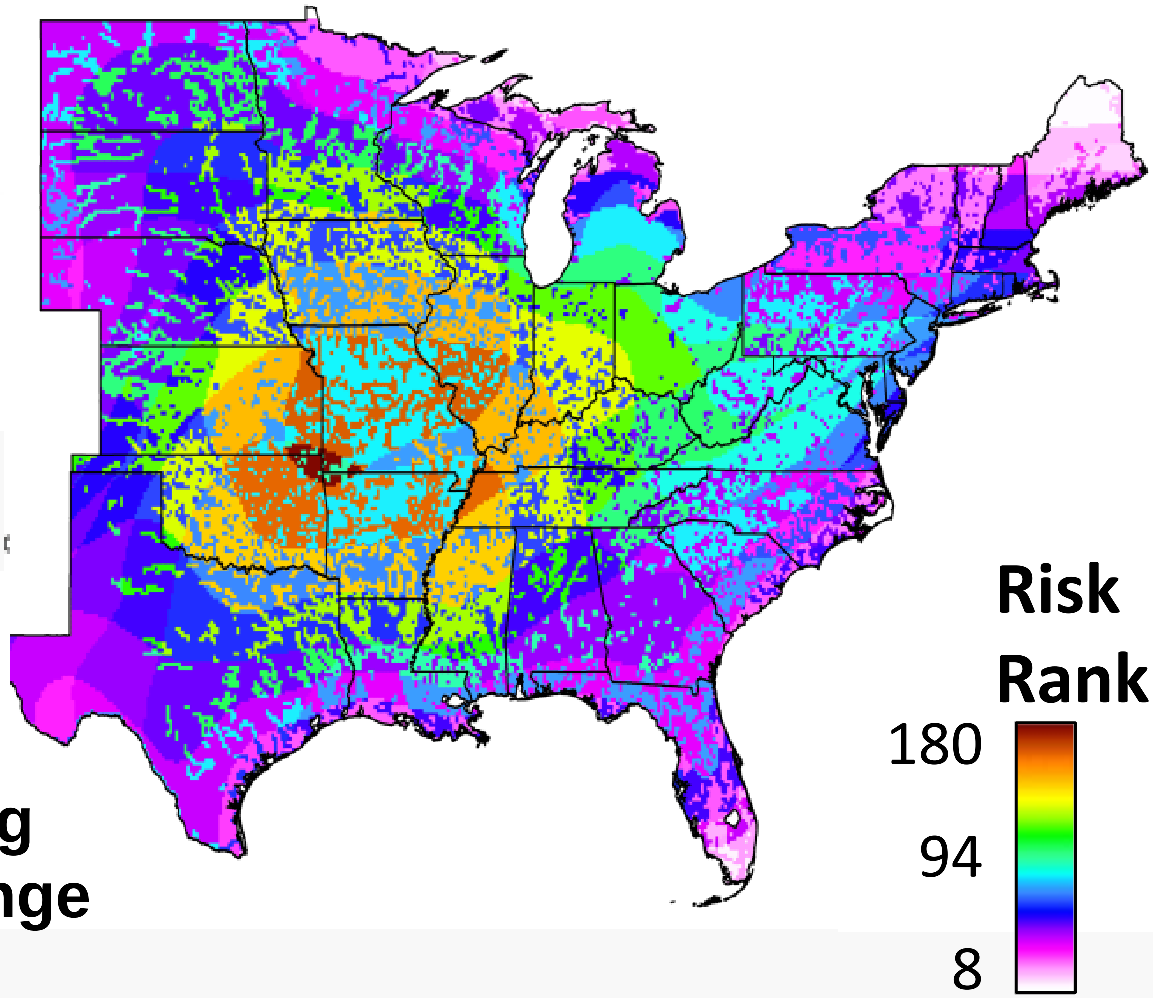
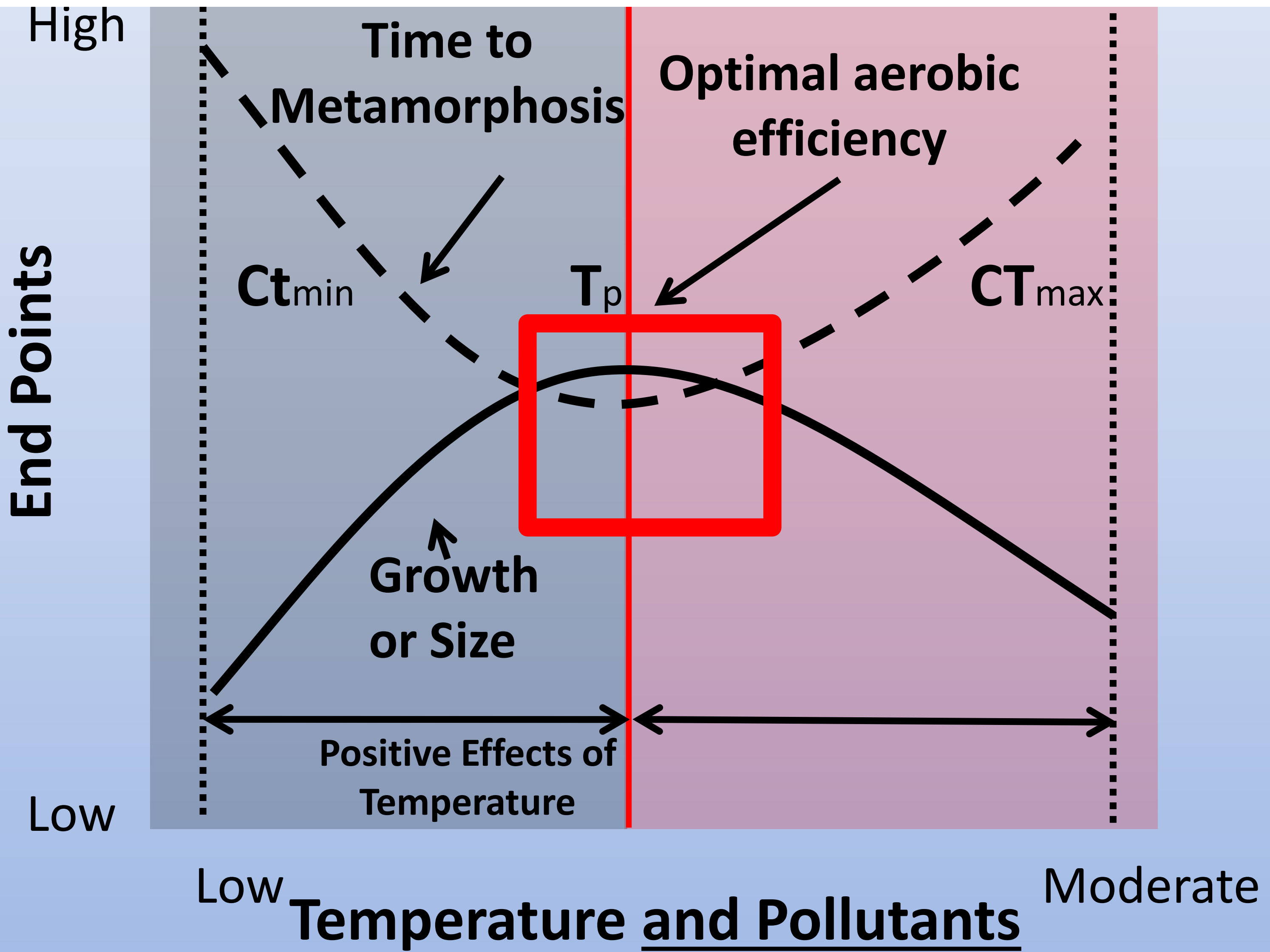




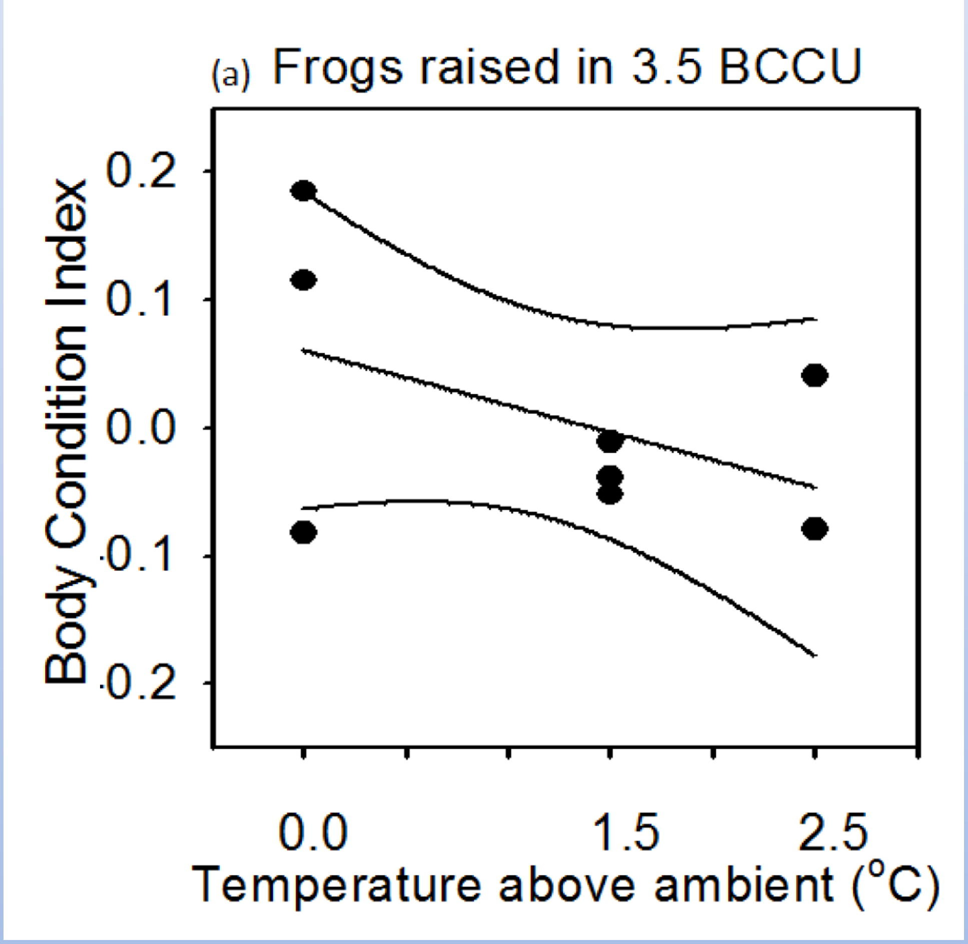
Geospatial risk ranking compared to home range

Temperature, Energy and Chronic Endpoints



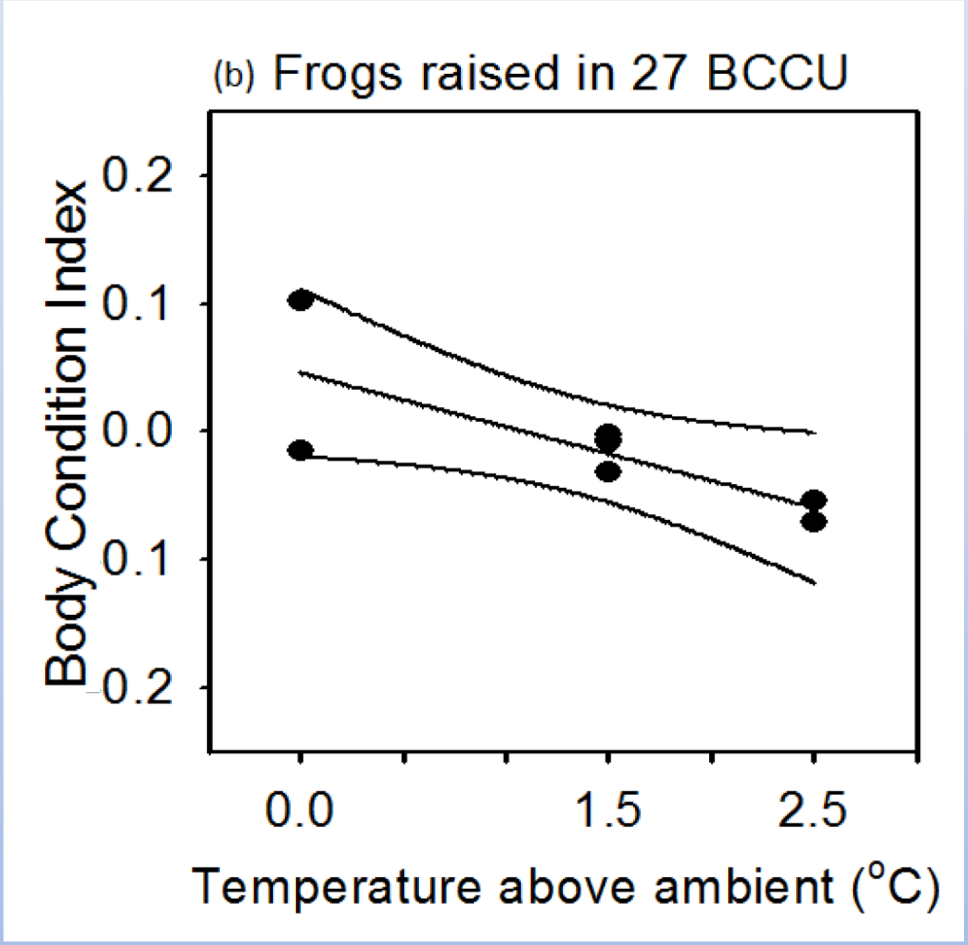
Metals mediate temperature tolerance

Results: 20 d post metamorphic body condition of adults raised in ambient, +1.5 and +2.5 ^oC and low metals



- **If metals are low, body condition does not significantly differ among adults**

Results: 20 d post metamorphic body condition of adults raised in ambient, +1.5 and +2.5 ºC and high metals



- In high metals, body condition in +2.5 ºC was 100% worse than animals raised at high metals but ambient temperatures
- Reproductive success is largely determined by body condition

Intellectual Challenge:

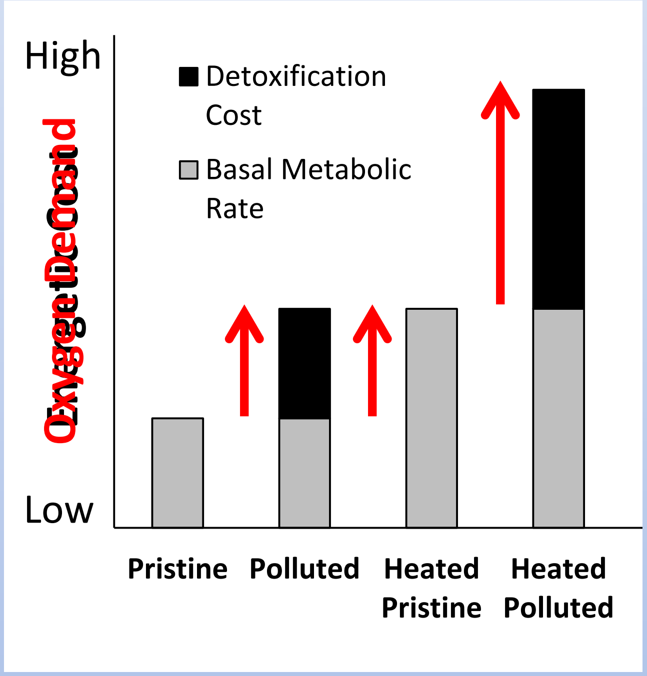
Sublethal Energetic Interactions

Example: Energetic Costs of Metals

- Cellular repair
- Detoxification and excretion
  - Metallothionein
  - Glutathione and other antioxidants

Energetic Costs of Temperature

- Metals can disproportionately elevate the metabolic response to temperature



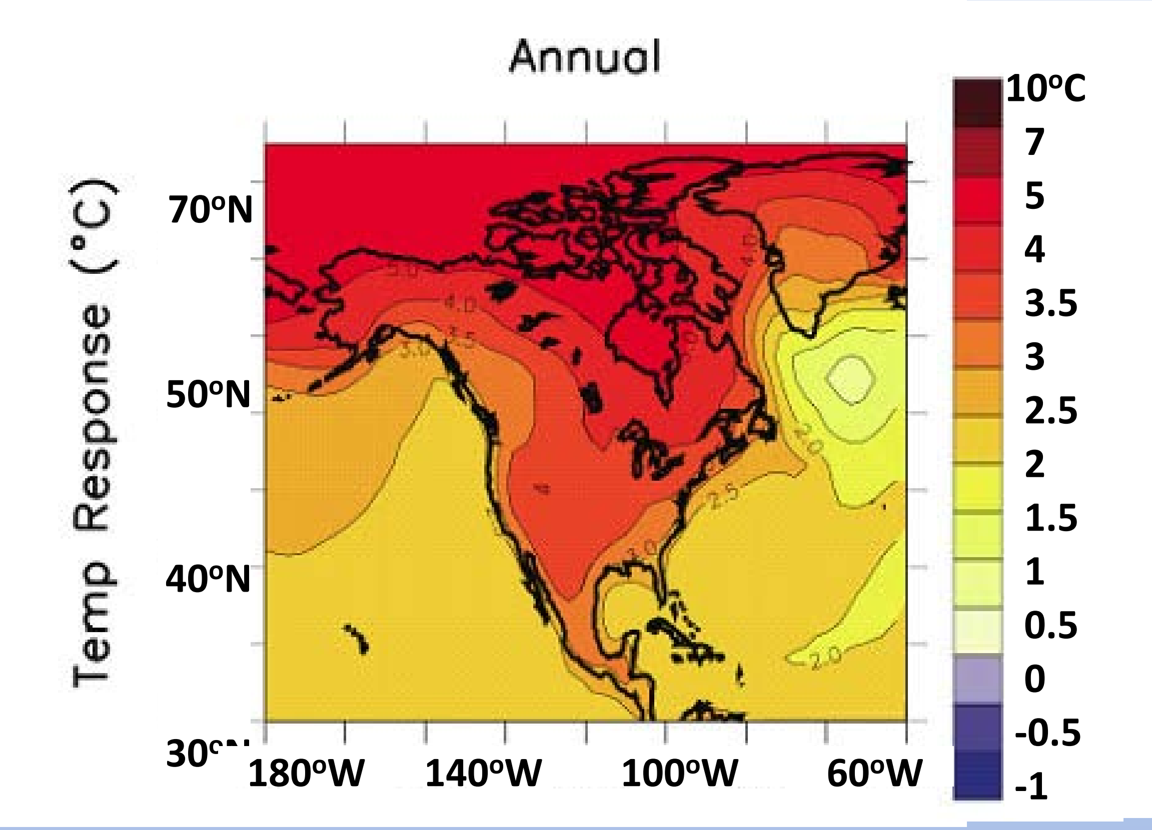
→Result: Functional hypoxia

→Warmer waters that **met lower oxygen demands** in unpolluted water may not meet higher oxygen demand in chronically polluted waters

Stressors Without Borders:
Global Warming and Biogeographic Impacts

Important considerations:

- Warming has positive and negative effects depending on season
- Geographic variation
- One of many multiple stressors



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