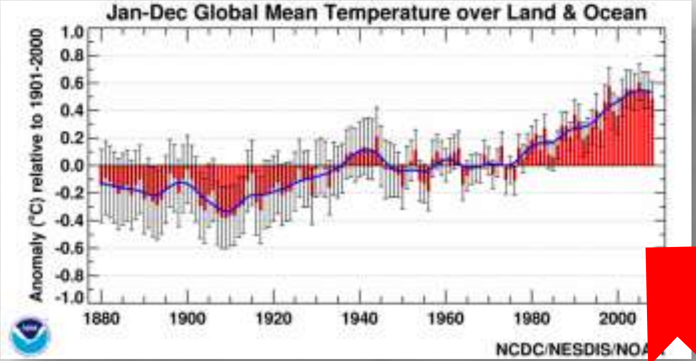
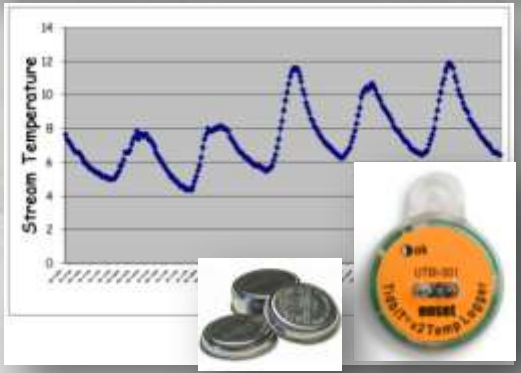
Monitoring & Modeling Stream Temperatures: Lessons Learned in the Rocky Mountains with Utility for Alaska?

Dan Isaak, US Forest Service

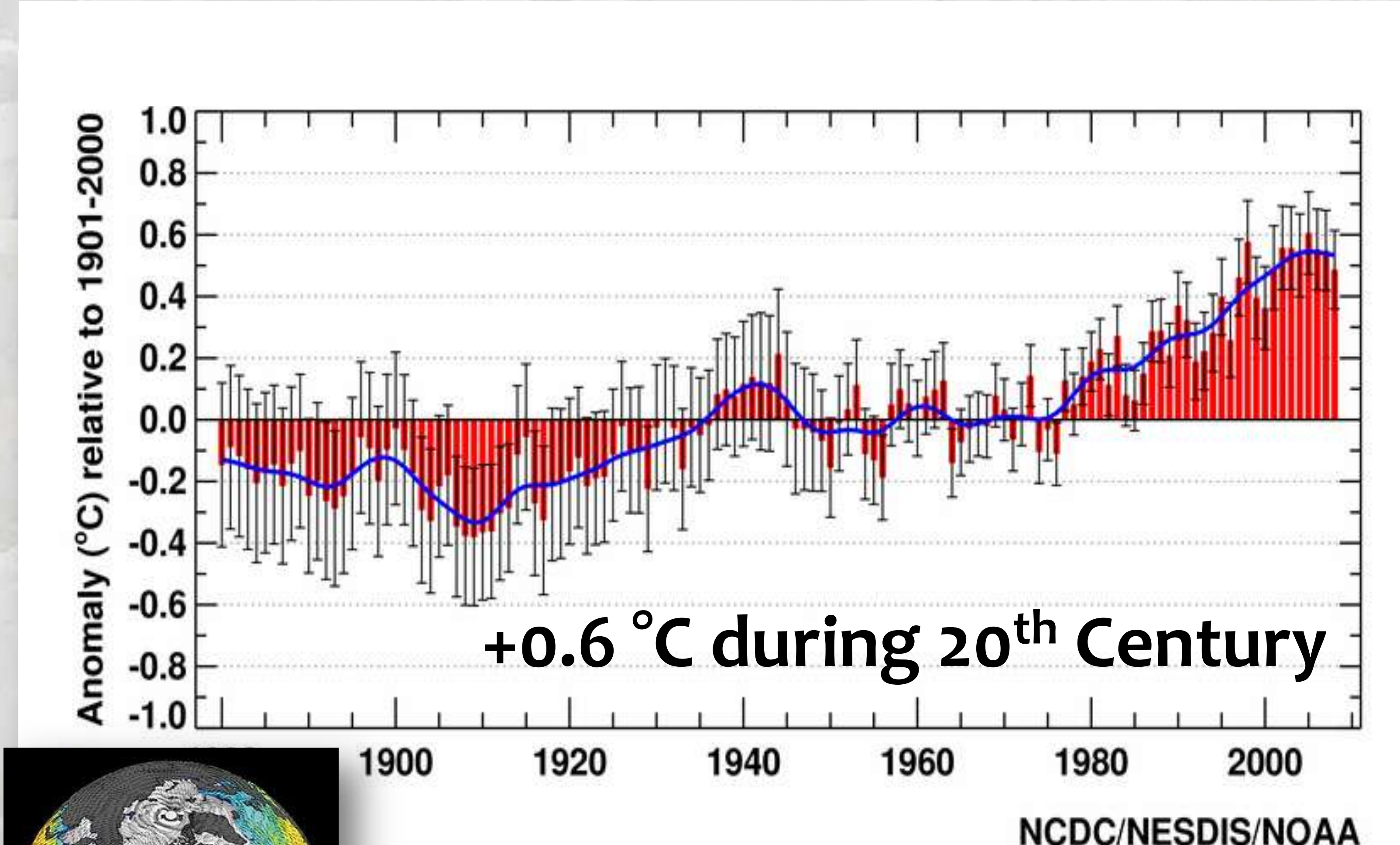


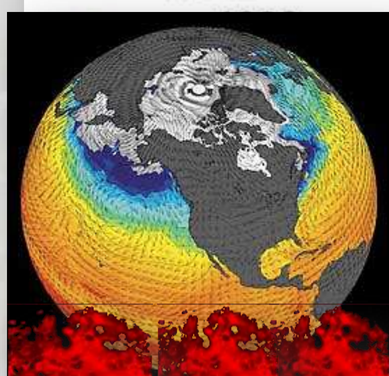


General outline:

1) Relevance of climate change and temperature to aquatic biotas
2) Trends in stream/lake temperatures
3) Stream temperature monitoring & sampling designs
4) Extracting climate relevant information from stream temperature data
5) Possible next steps & stream temperature resources

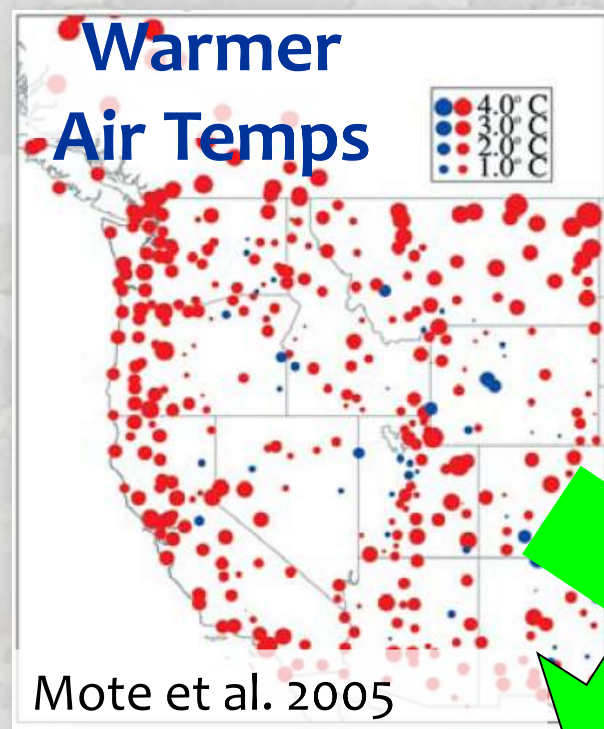
Global Trends in Air Temperatures





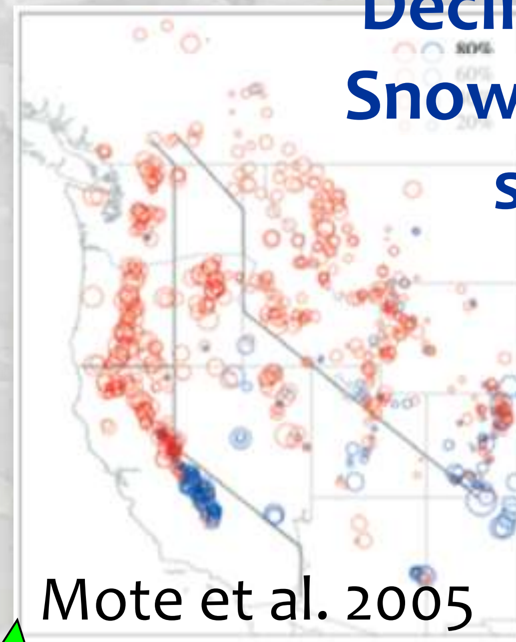
Western US – 20th Century Observed Trends

Warmer Air Temps



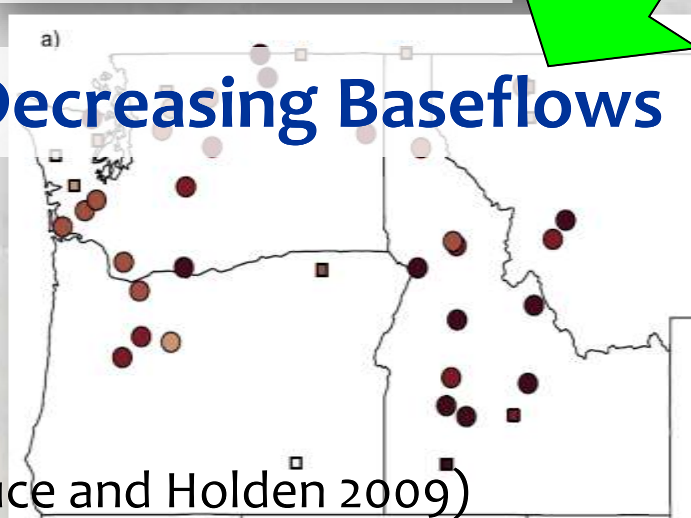
Mote et al. 2005

Declining Snowpacks



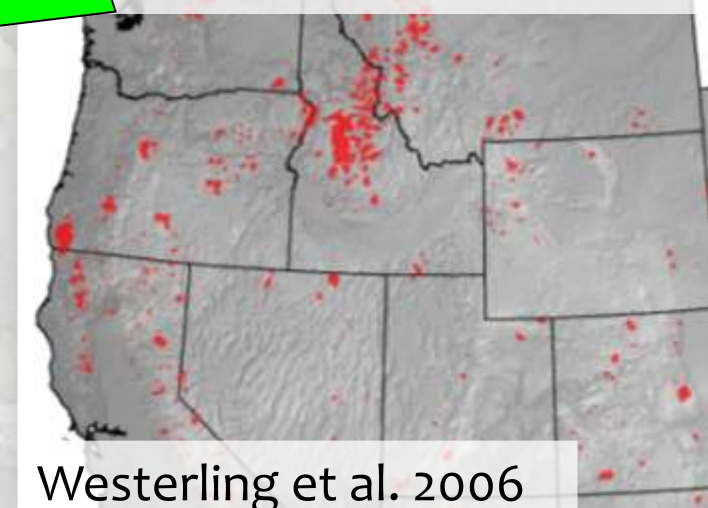
Mote et al. 2005

Decreasing Baseflows



(Luce and Holden 2009)

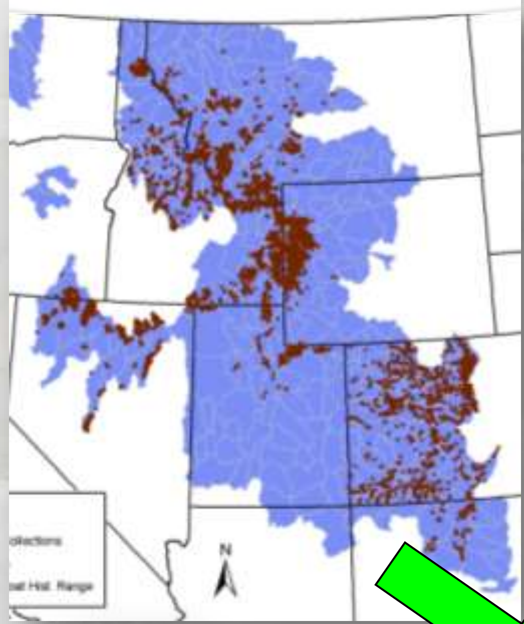
Wildfire Increases



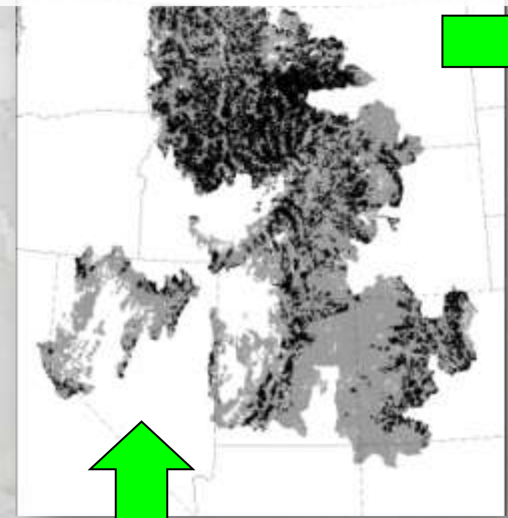
Westerling et al. 2006

Western Trout Climate Assessment

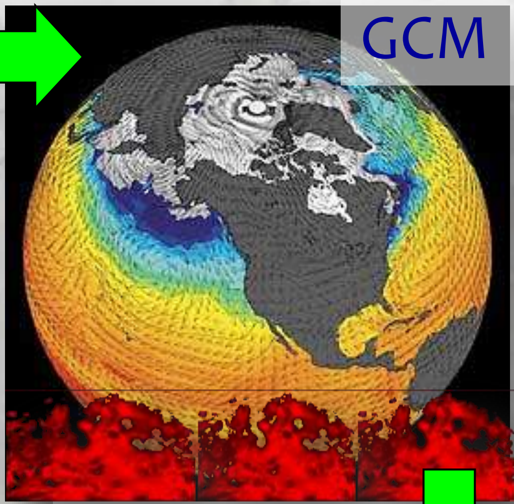
Fish survey database
~10,000 sites



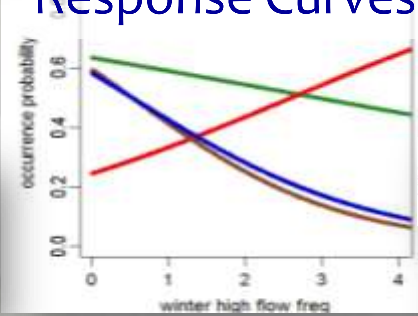
Historic Distributions



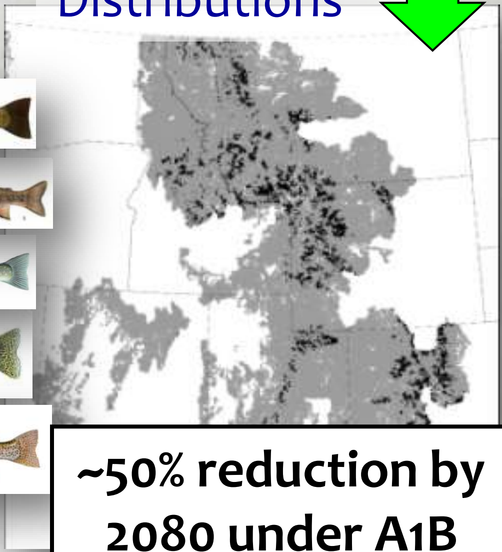
GCM



Species-Specific
Habitat
Response Curves



Future A1B
Distributions



TROUT UNLIMITED

National Fish and Wildlife Foundation

USGS
science for a changing world

Colorado State University

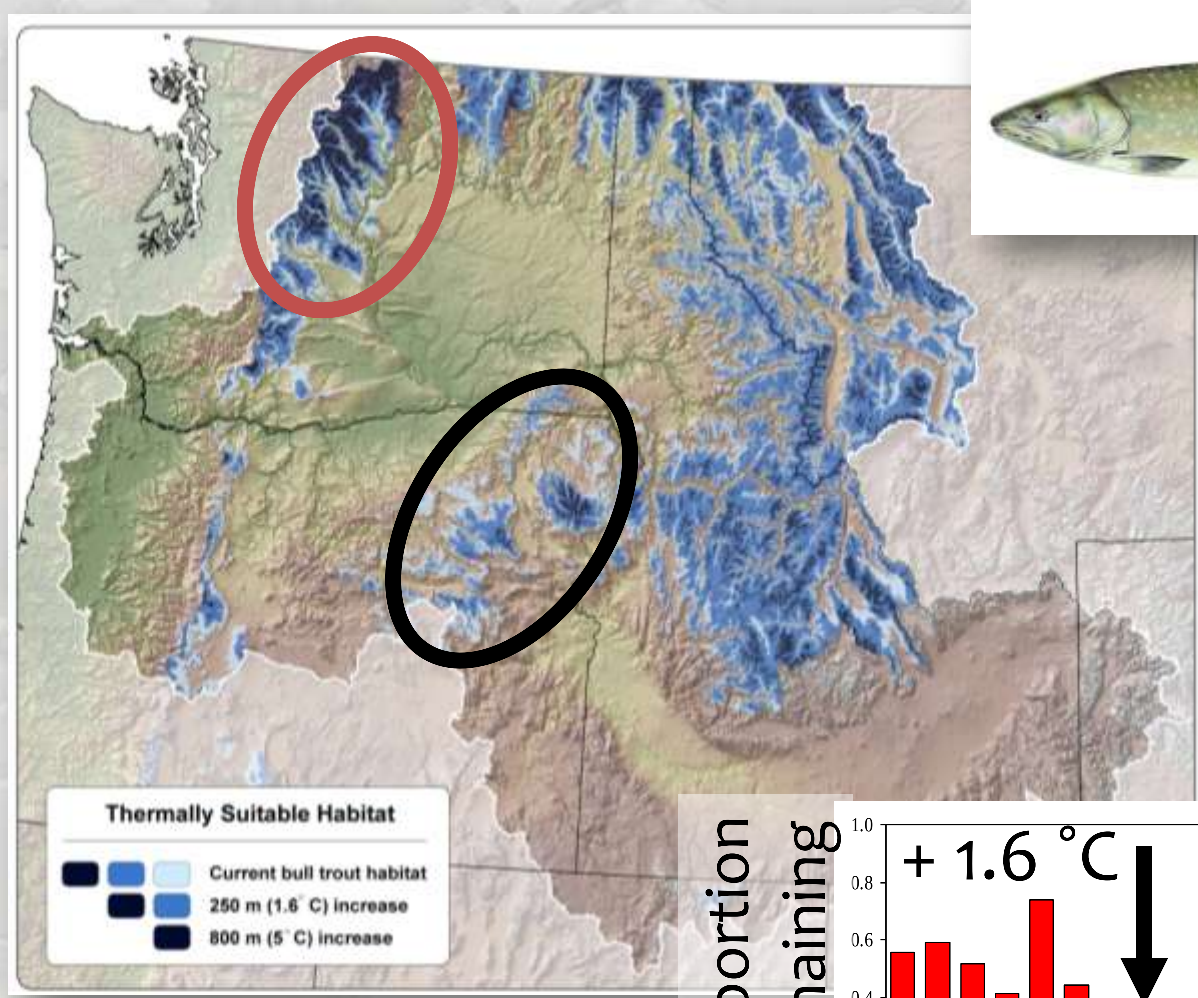
Rocky Mountain Research Station

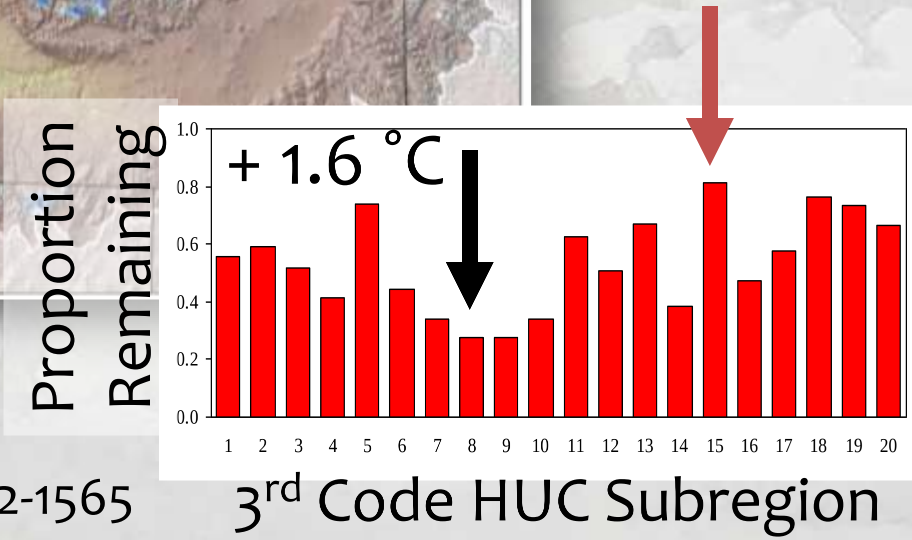
CLIMATE IMPACTS GROUP

~50% reduction by 2080 under A1B

Wenger et al. 2011. *PNAS* **108:**14175-14180

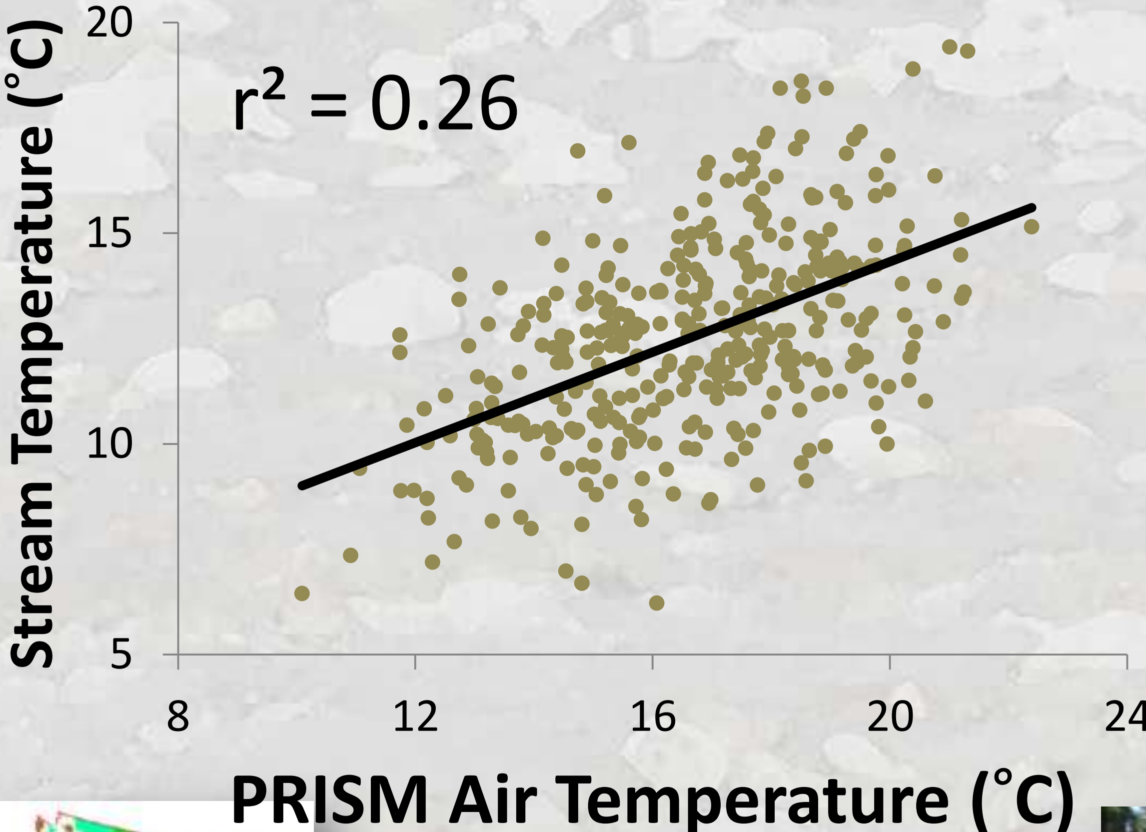
Spatial Variation in Future Changes

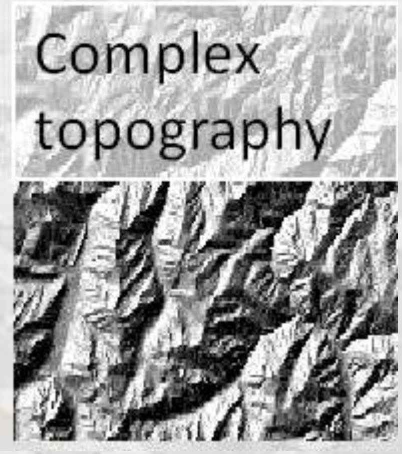




Rieman et al. 2007. *TAFS* **136**:1552-1565

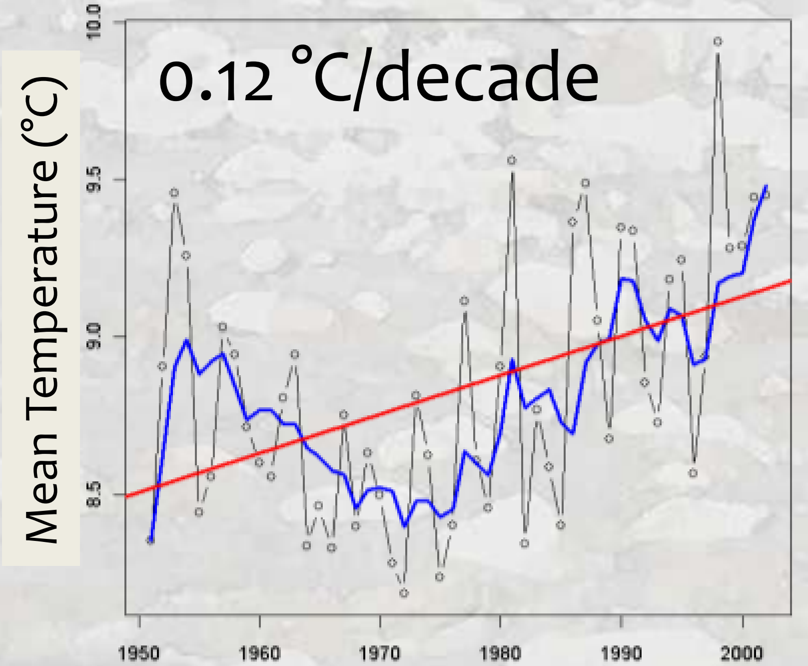
Spatial Air Pattern ≠ Stream Temp





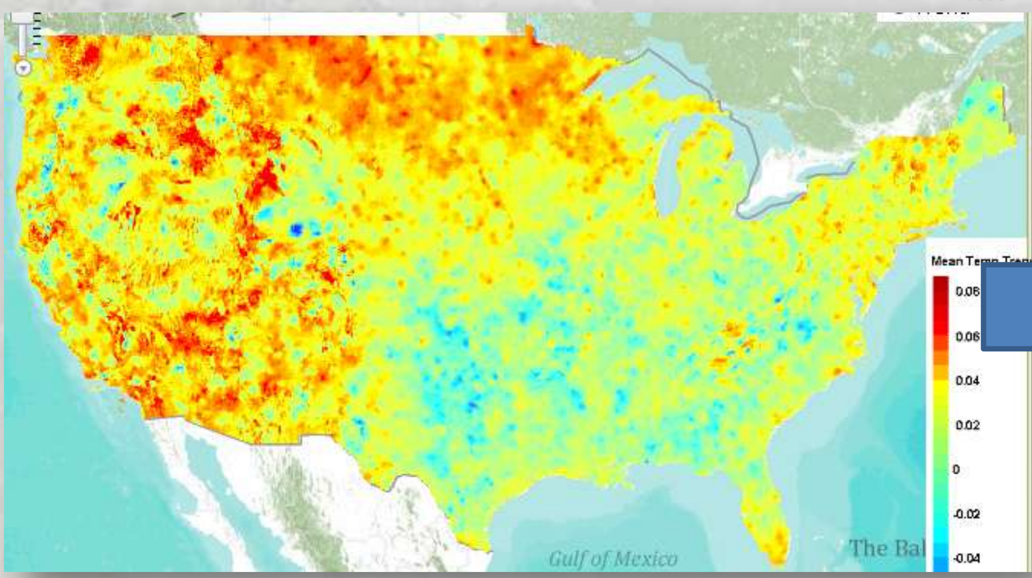
Changing Fast in Rocky Mountains & Northern 48

(1951 – 2002)



Climate Wizard Tool

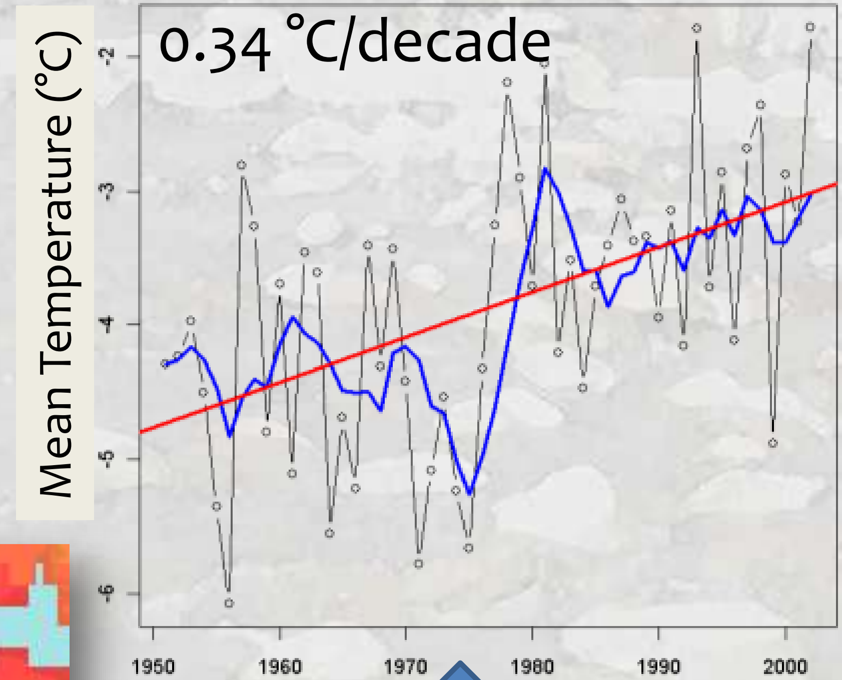
(www.climatewizard.org)

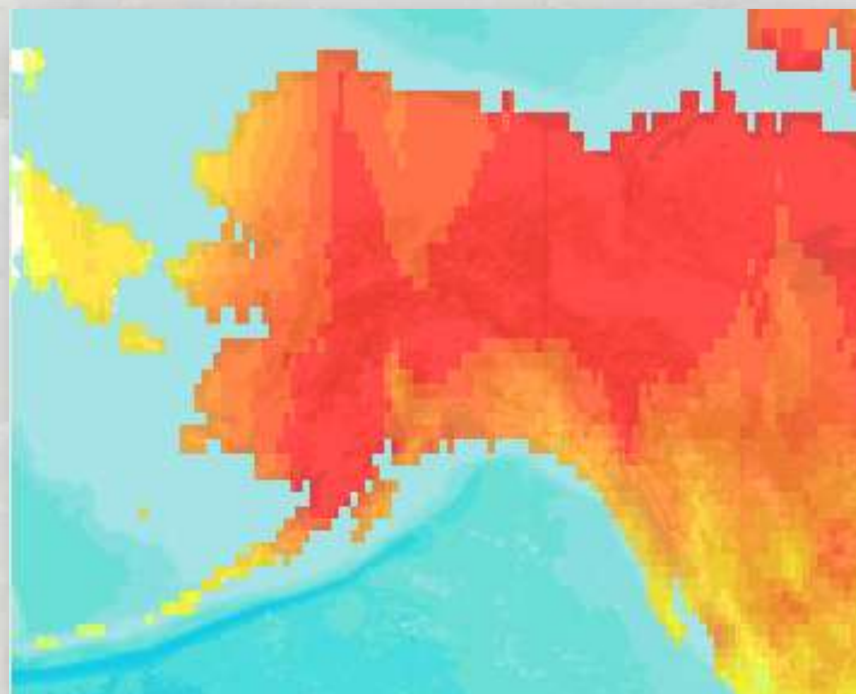


Girvetz et al. 2009. PLoS ONE **4**(12): e8320.

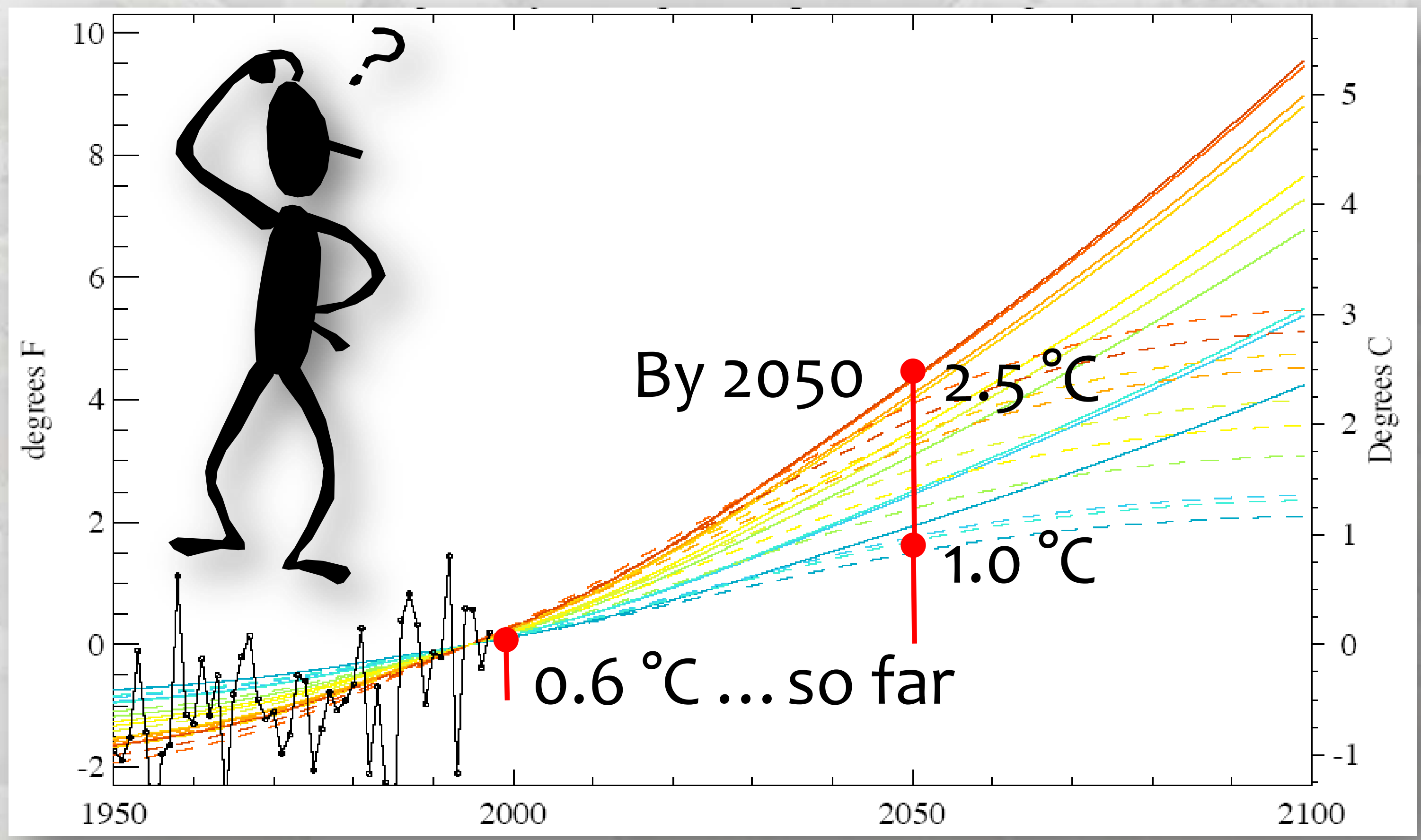
Changing 2x – 3x Faster in Alaska

(1951 – 2002)





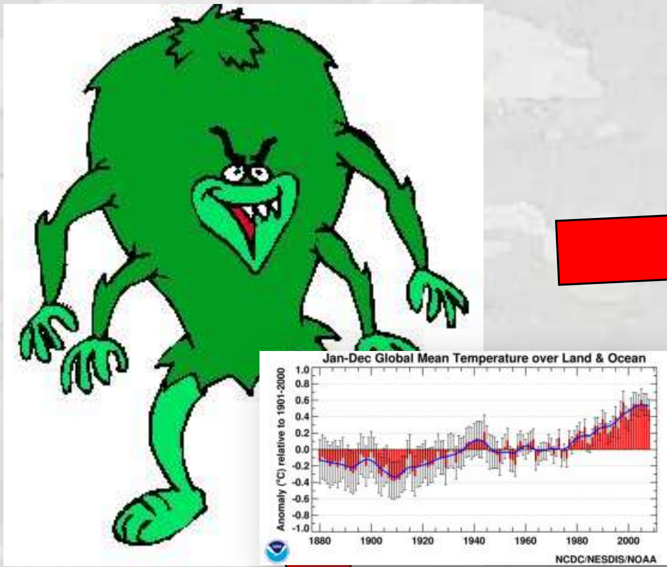
Warming Trends Will Continue (& Accelerate?)



Mote et al. 2005; 2008

There's A Lot on the Line…

Climate Boogeyman



Recreational Fisheries

Low Flows Prompt Fishing Closure On Upper Beaverhead River And Reduced Limits On Clark Canyon Reservoir

Wednesday, September 29, 2004
Fishing

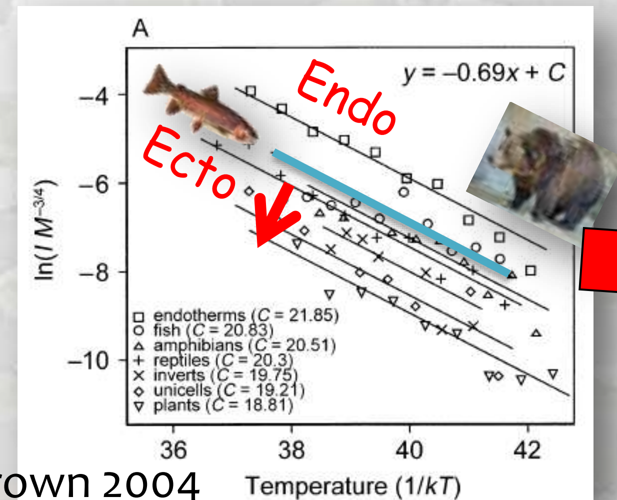
High Water Temperature In Grande Ronde Kills 239 Adult Spring Chinook
Columbia Basin Bulletin, August 14, 2009 (PST)

ESA Listed Species

Land Use & Water Development

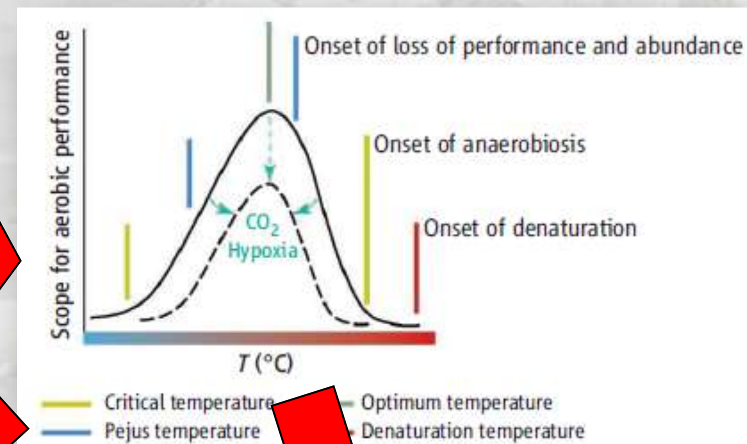
Temperature is Primary Control for Aquatic Ectotherms

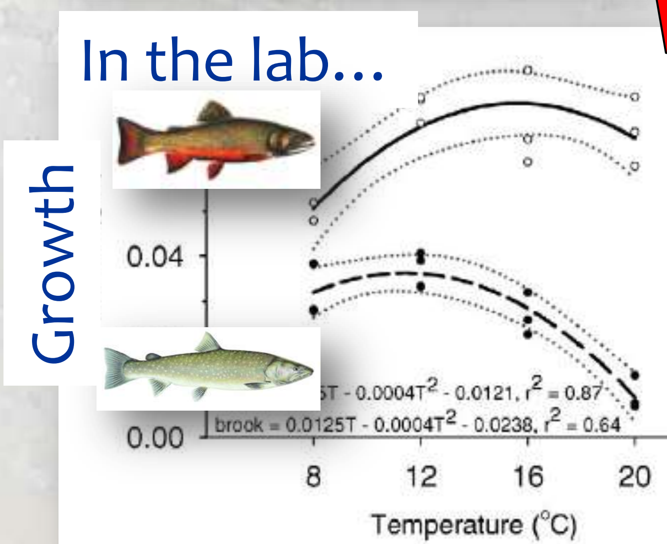
Metabolism

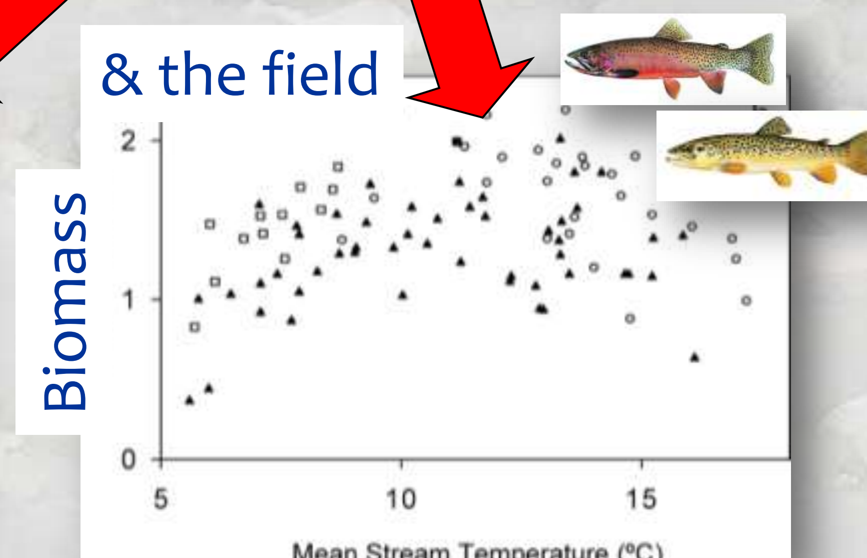


Brown 2004

Thermal Niche





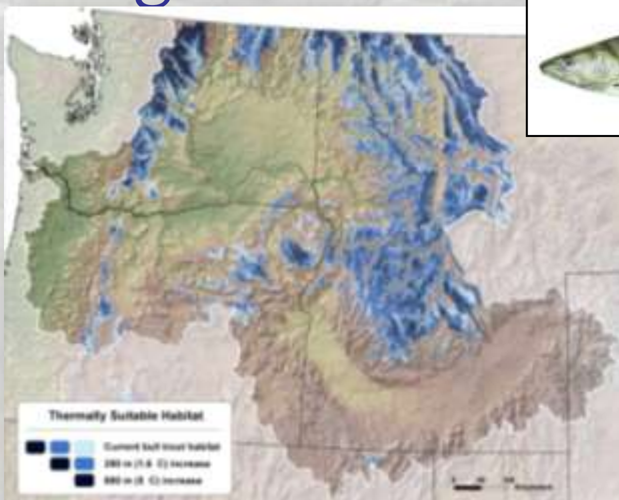


McMahon et al. 2007

Isaak & Hubert 2004

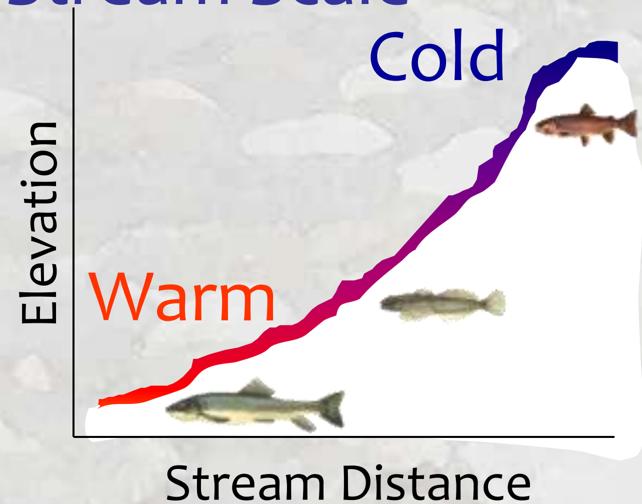
Temperature Regulation – Spatial Distributions

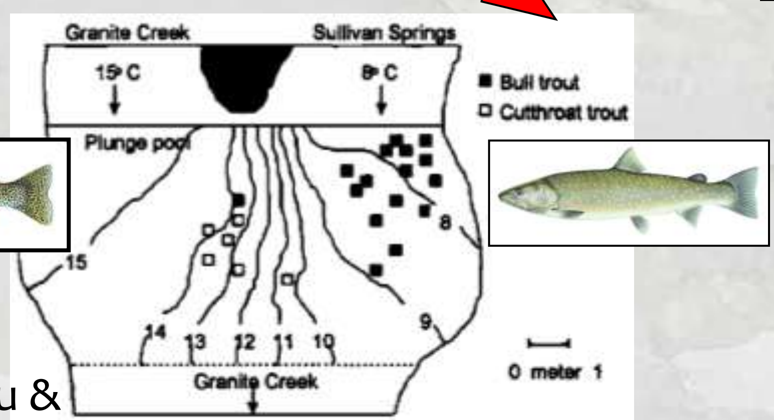
Regional Scale



Rieman et al. 2007

Stream Scale

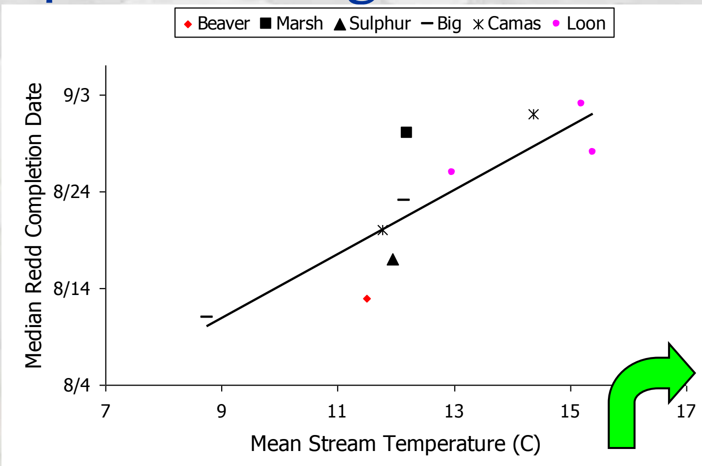




Bonneau & Scarnecchia 1996

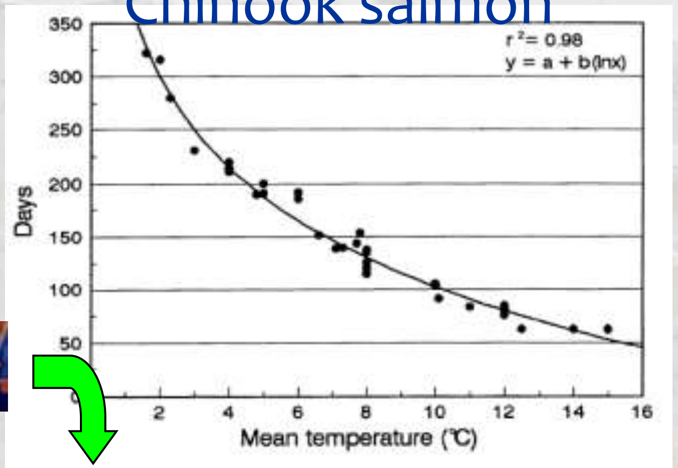
Temperature Regulation - Life Cycle

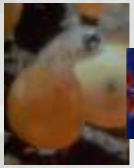
Spawn timing - Chinook salmon



Thurow, unpublished

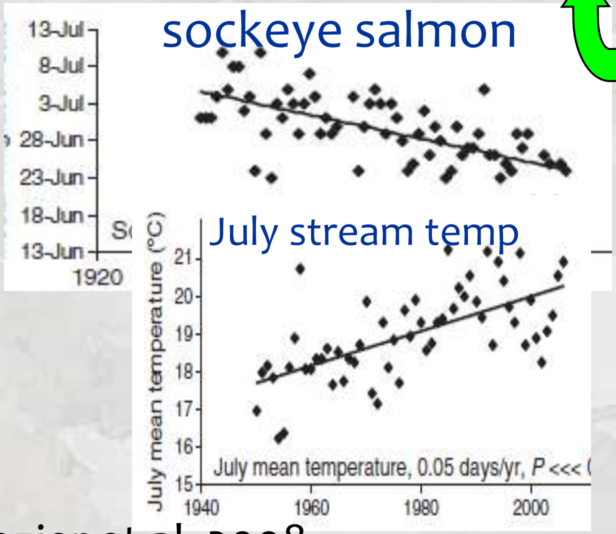
Incubation length - Chinook salmon





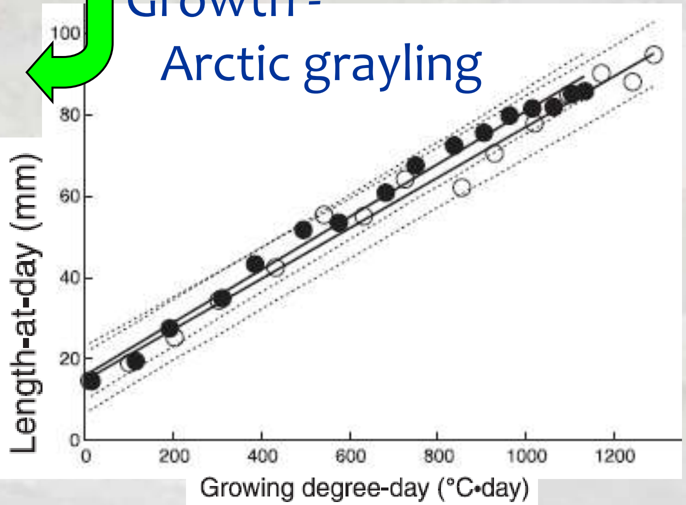
Brannon et al. 2004

Migration timing - sockeye salmon



Crozier et al. 2008

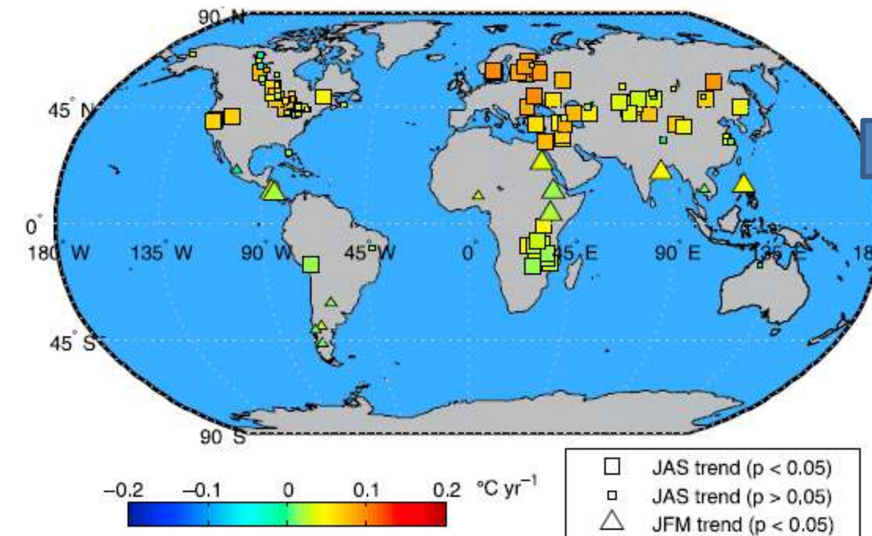
Growth - Arctic grayling



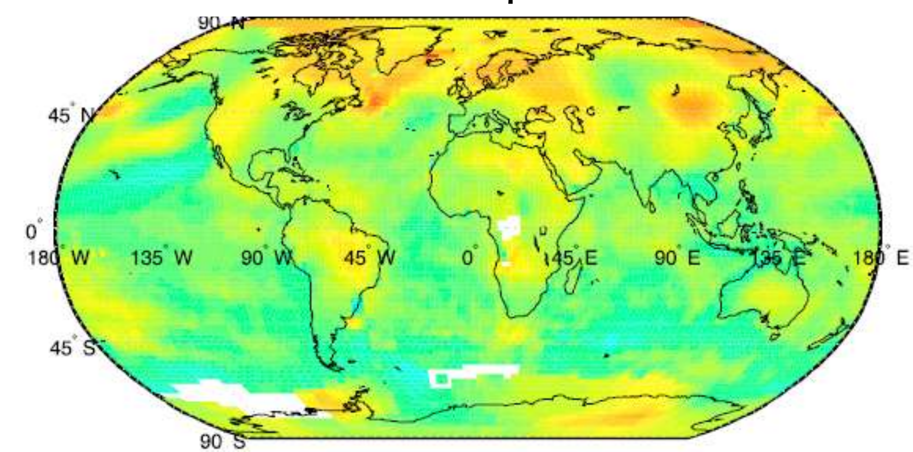
Dion and Hughes 1994

Observed Trends - Lake Temperatures

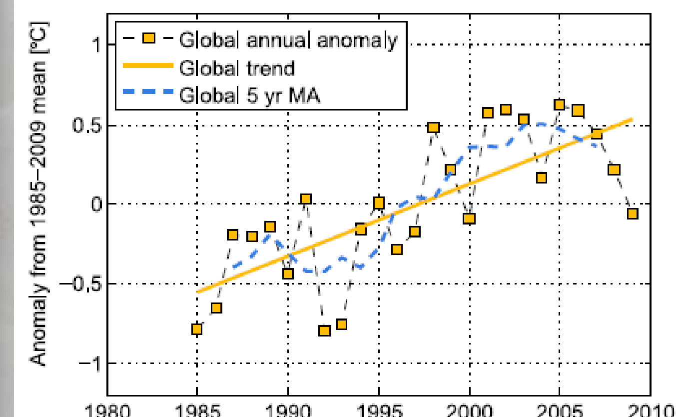
Individual Lake Temperature Trends



Concurrent Air Temperature Trends



Global Lake Temperature Trend

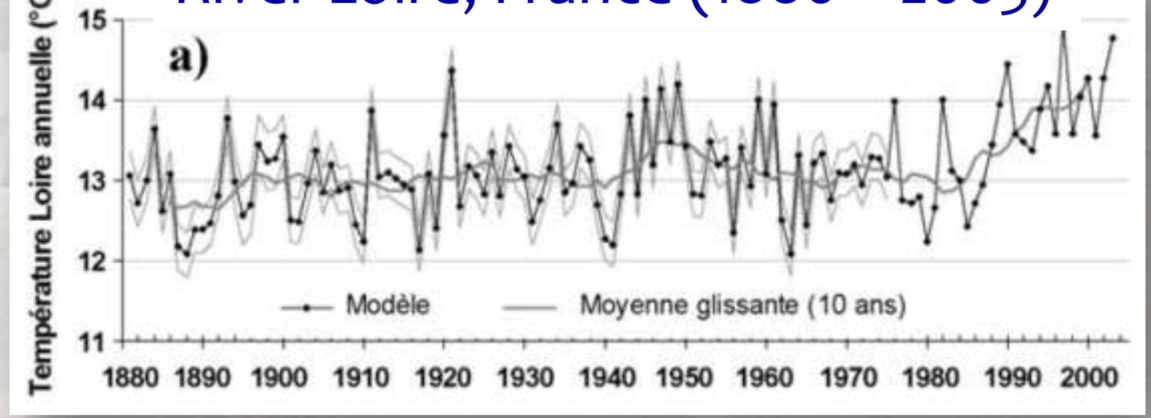


+0.45°C/decade from 1985-2009

Schneider & Hook 2010. *Geophysical Research Letters* **37** doi:10.1029/2010GL045059

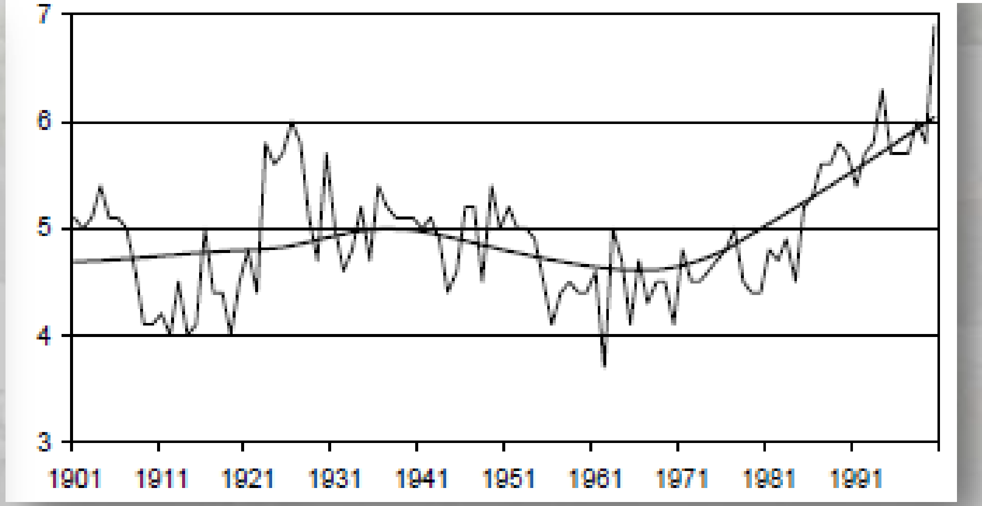
Global Trends in River Temperatures

River Loire, France (1880 – 2003)



Moatar and Gailhard 2006

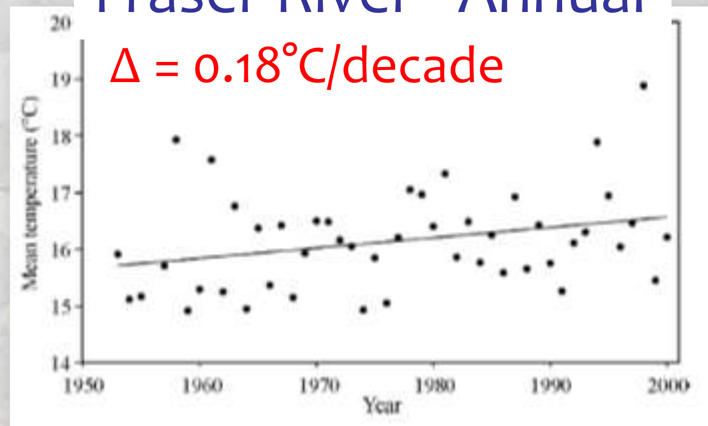
Danube River, Austria (1901 – 2000)



Webb and Nobilus 2007

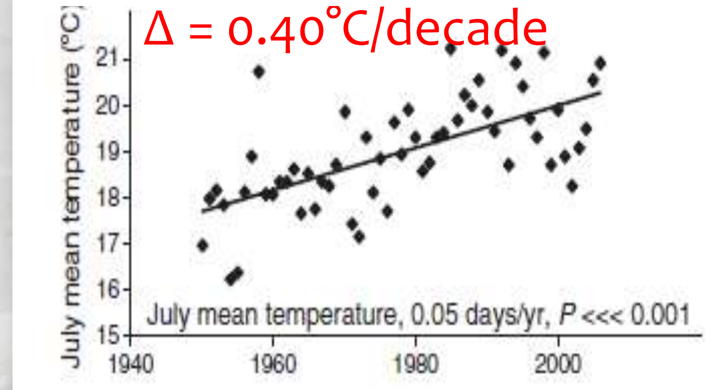
Regional Trends In Northwest Rivers

Fraser River - Annual



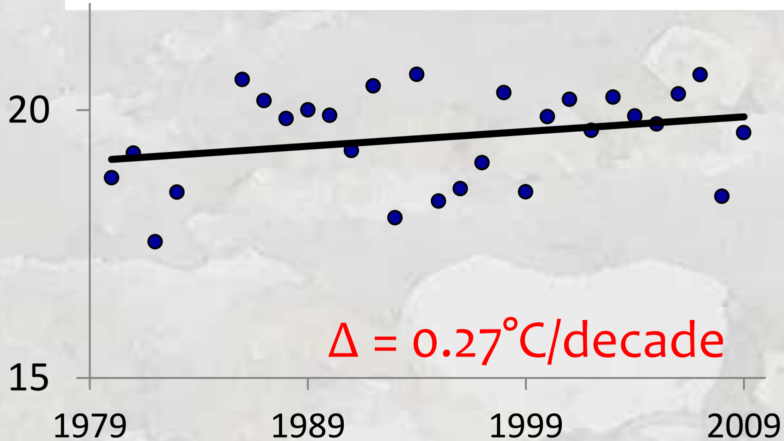
Morrison et al. 2002

Columbia River - Summer

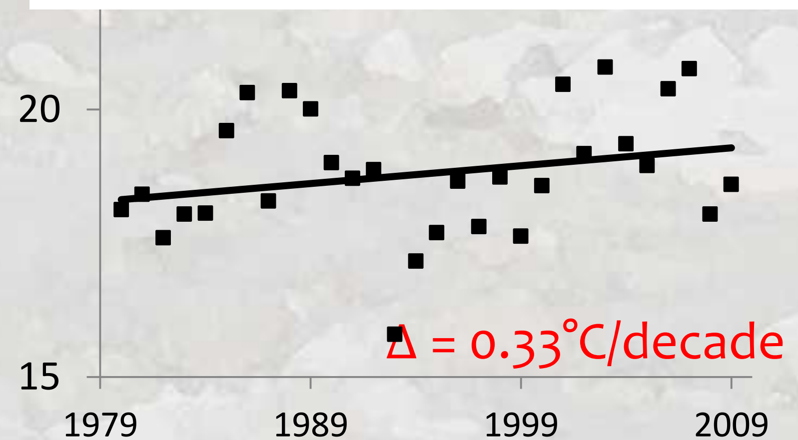


Crozier et al. 2008

Snake River, ID - Summer



Missouri River, MT - Summer

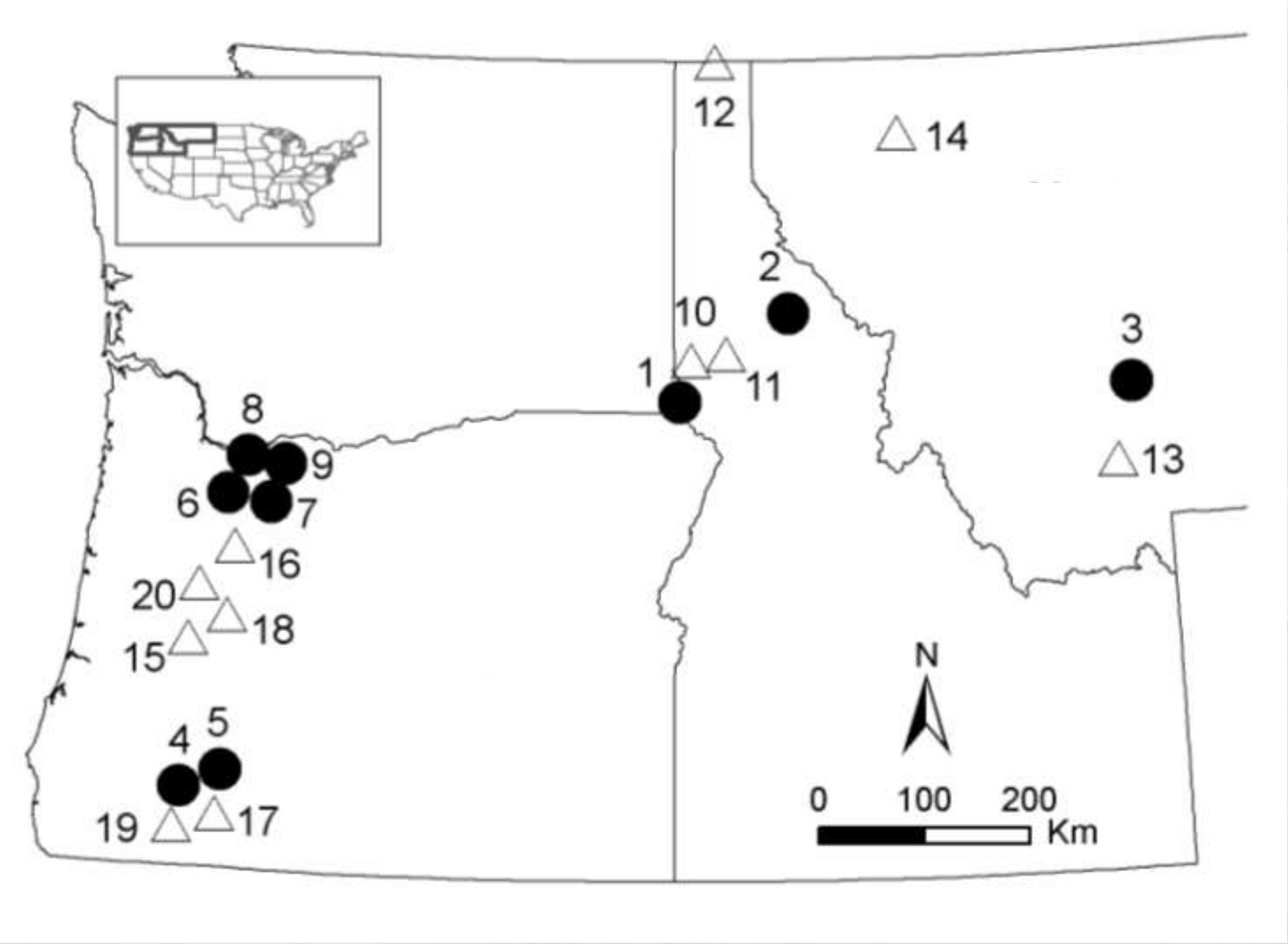


Isaak et al. 2012. *Climatic Change* **113**:499-524.

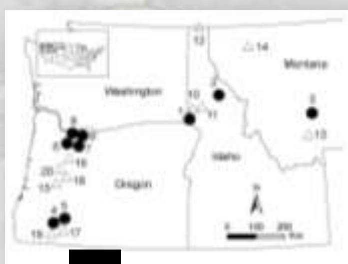
30+ Year Monitoring Sites in NW U.S.

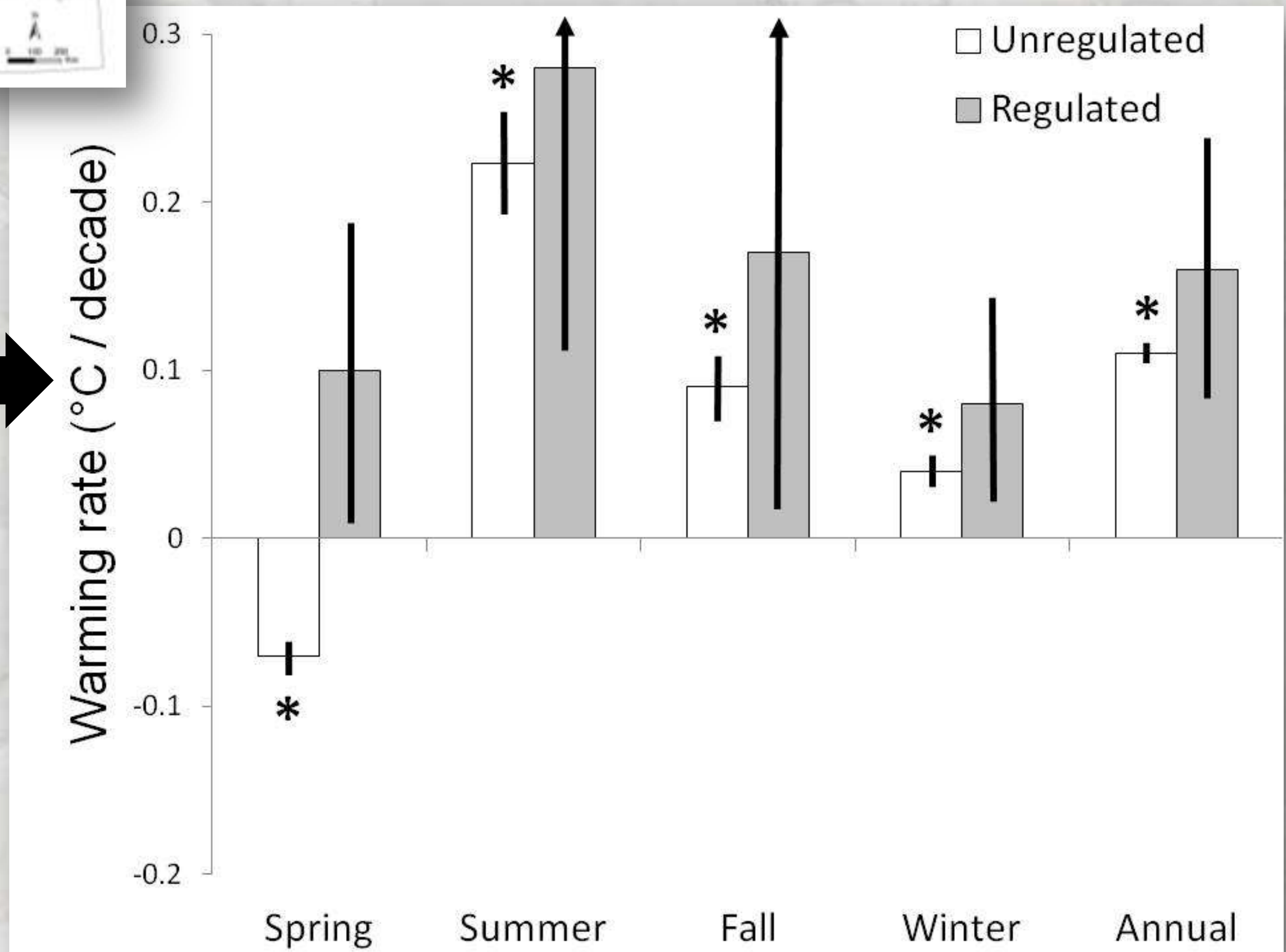
USGS NWIS Monitoring Sites (1980 – 2009)

△ = regulated (11) ● = unregulated (7)



Seasonal Trends In Temperatures (1980-2009)

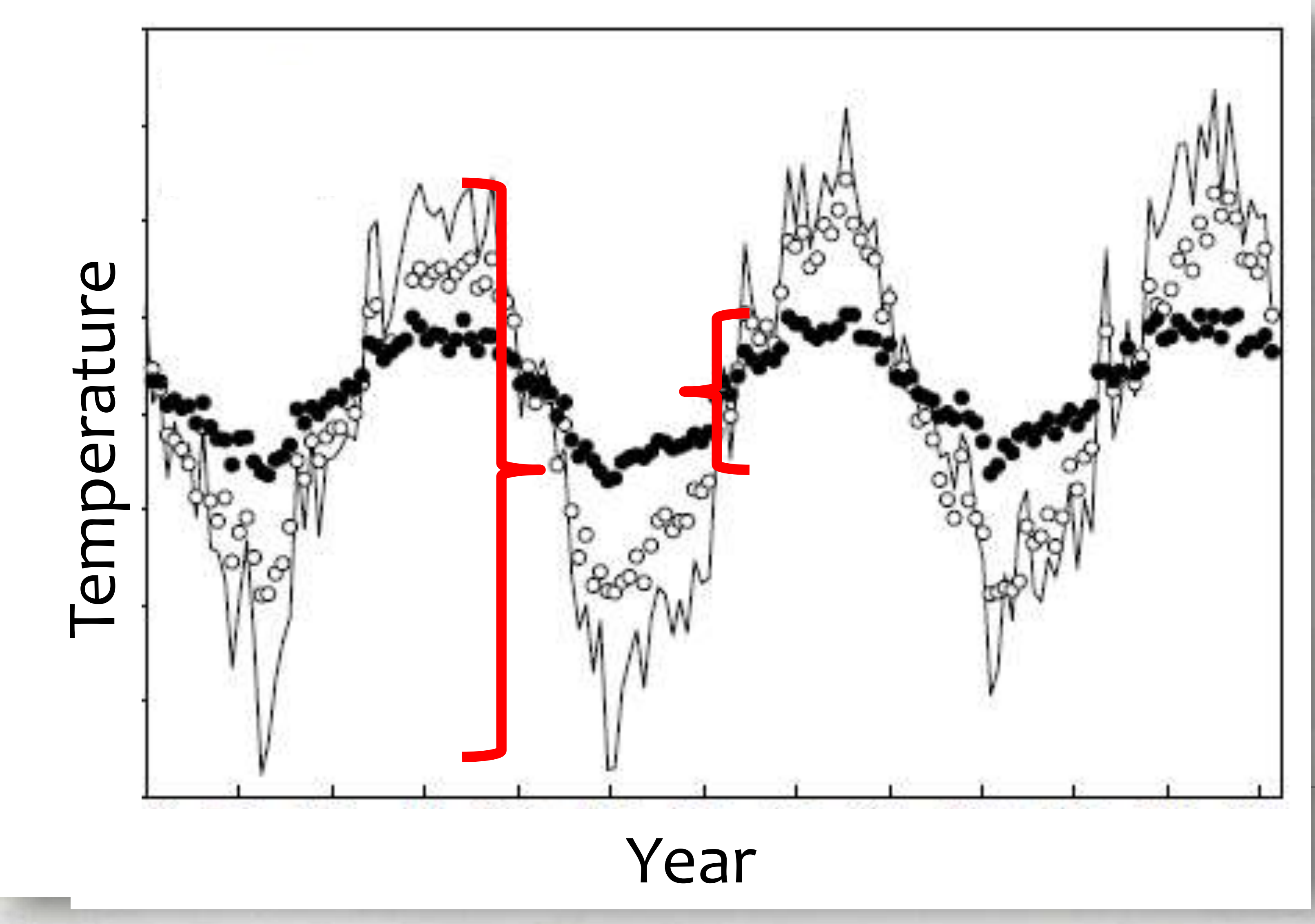




Isaak et al. 2012. *Climatic Change* **113**:499-524.

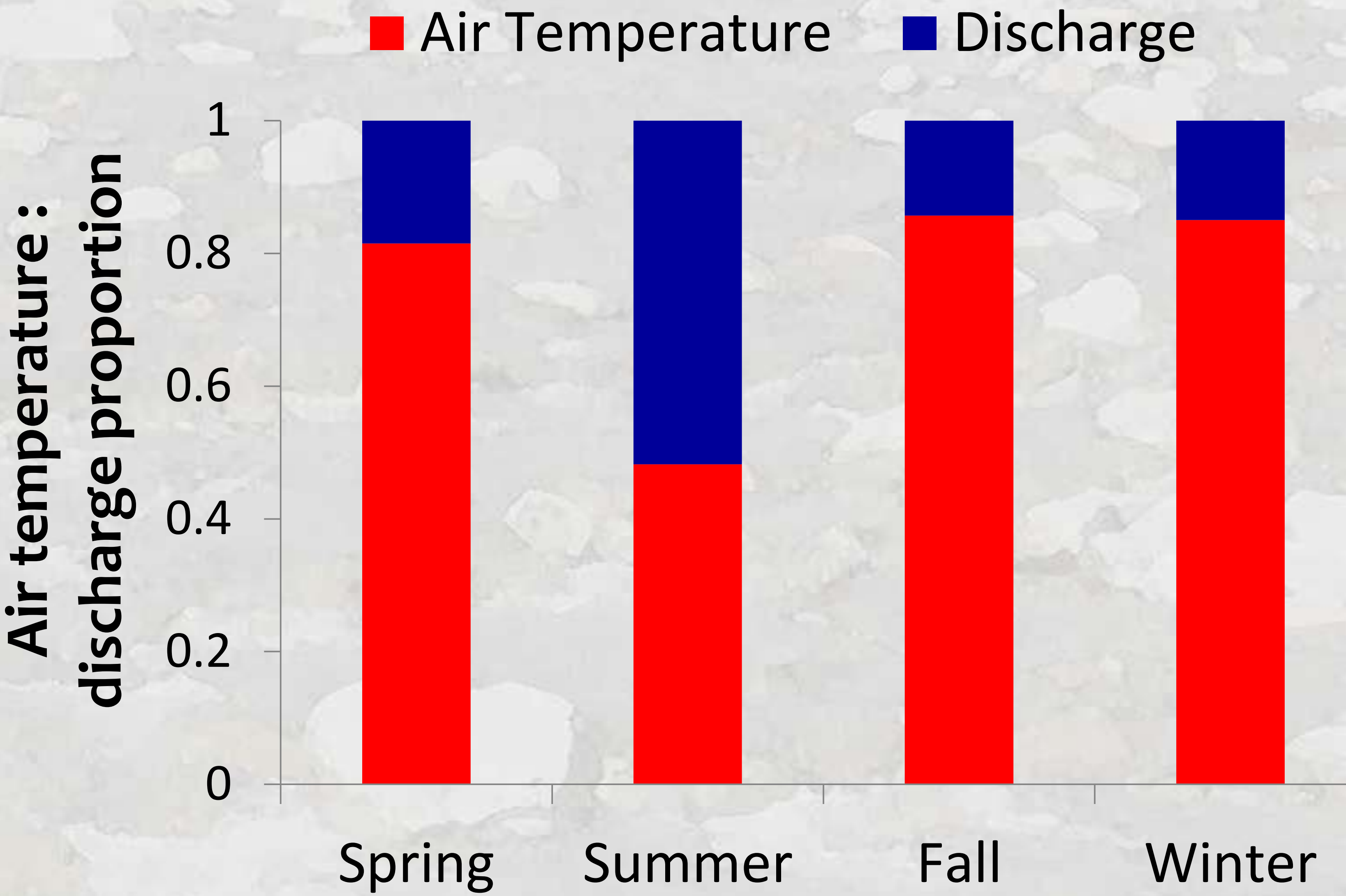
Attribution of Stream Warming Trends

Inter-annual variation ~ environmental noise



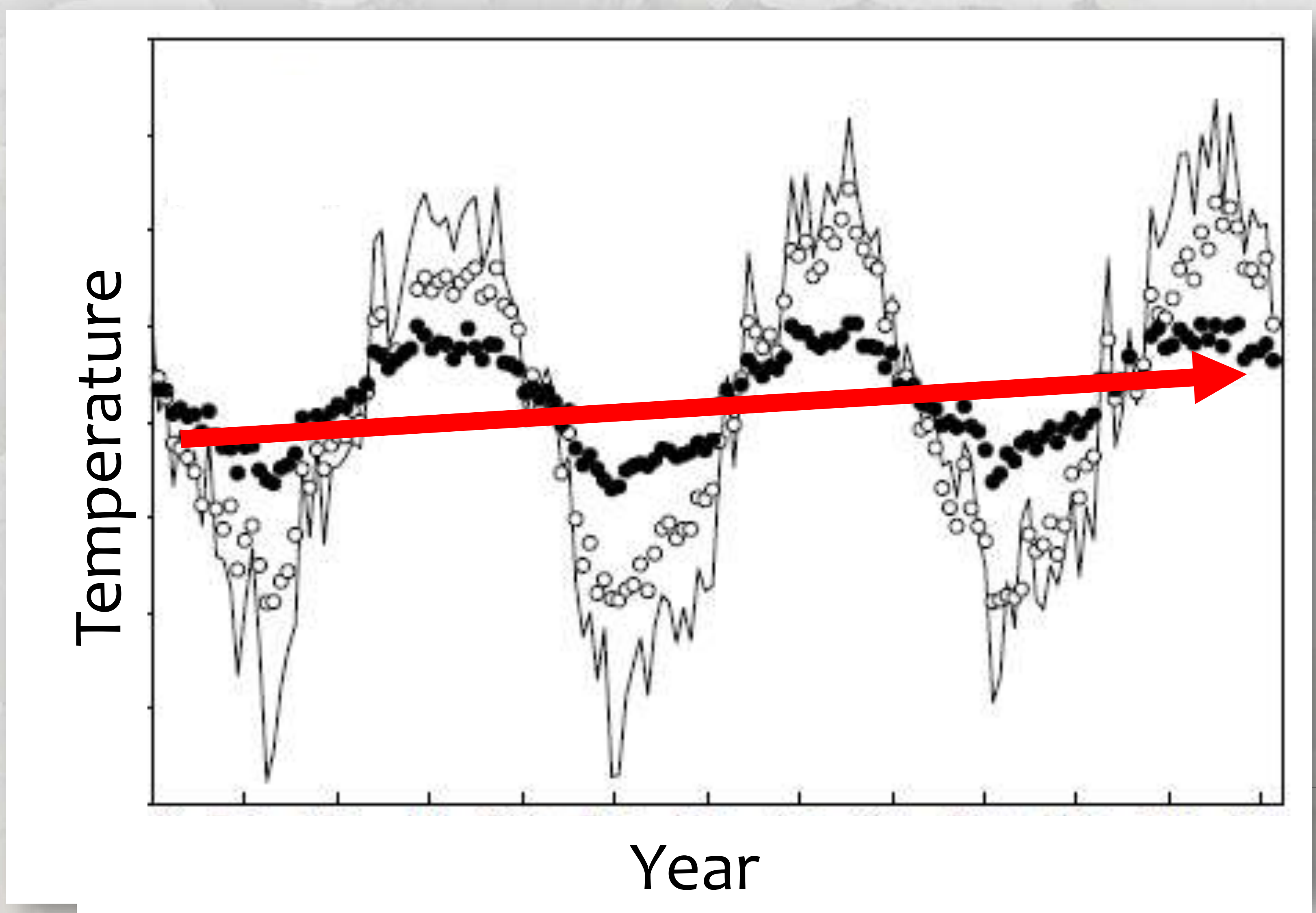
Attribution of Stream Warming Trends

Inter-annual variation ~ environmental noise



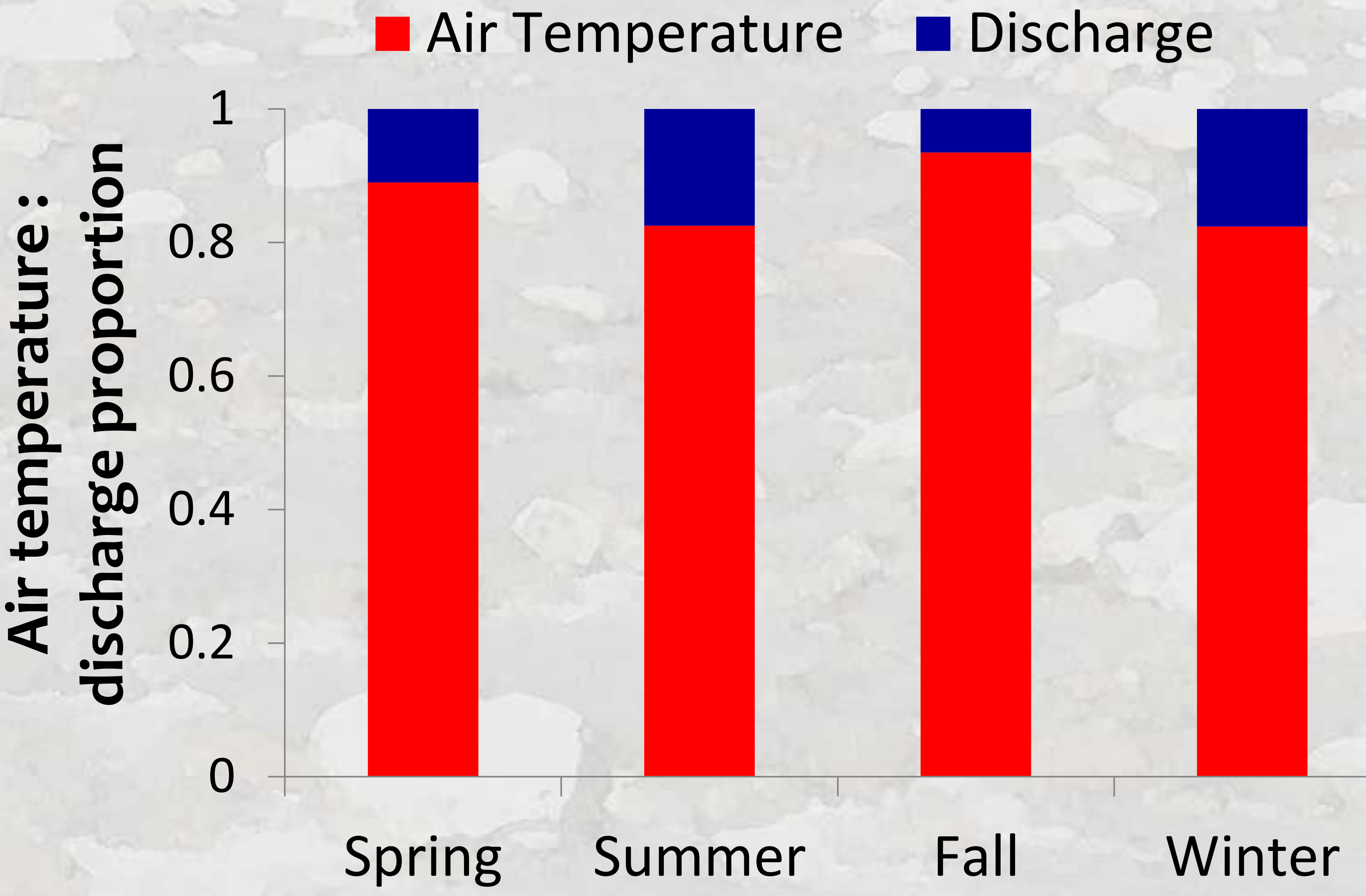
Attribution of Stream Warming Trends

Long-term trend ~ environmental signal

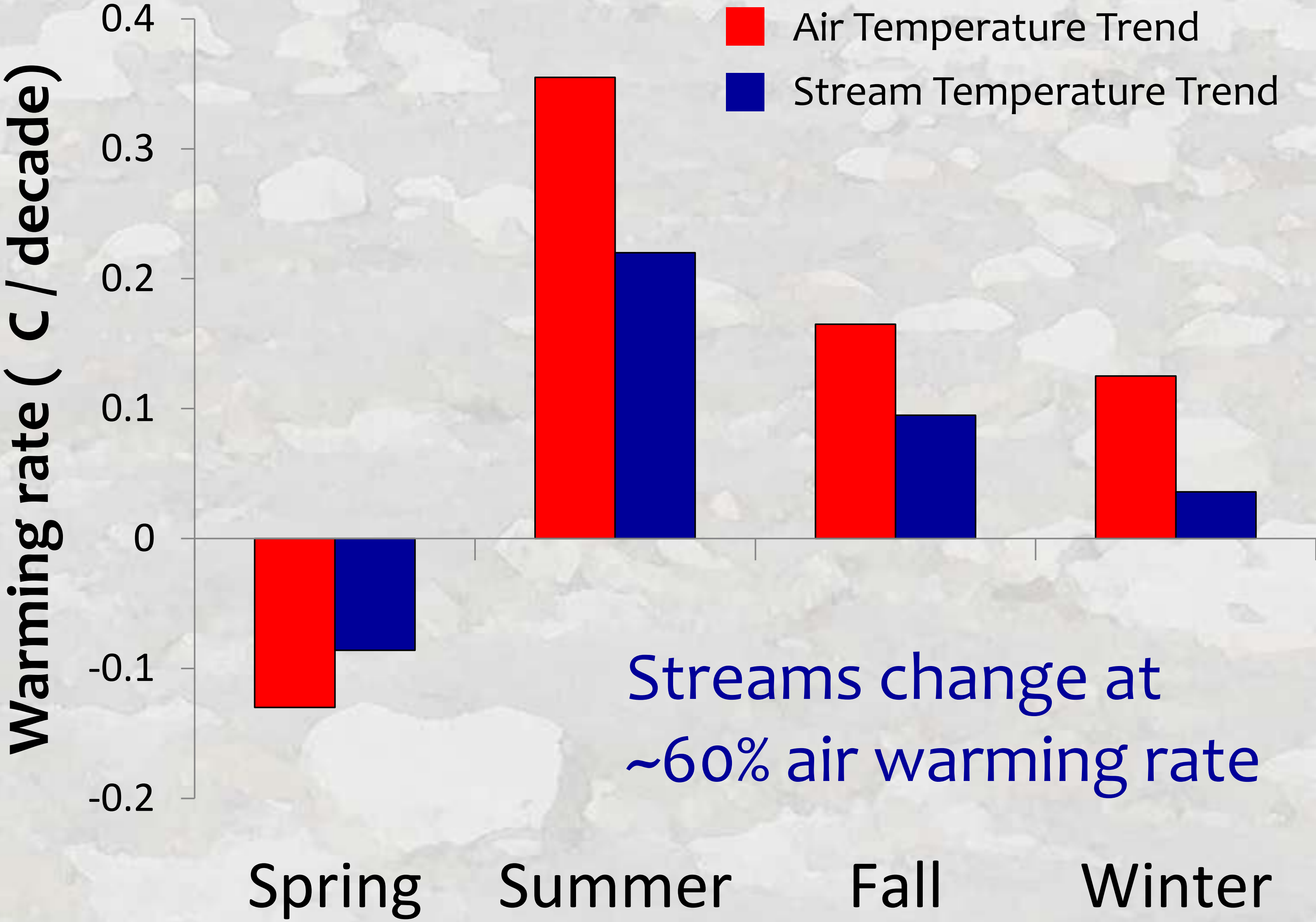


Attribution of Stream Warming Trends

Long-term trend ~ environmental signal

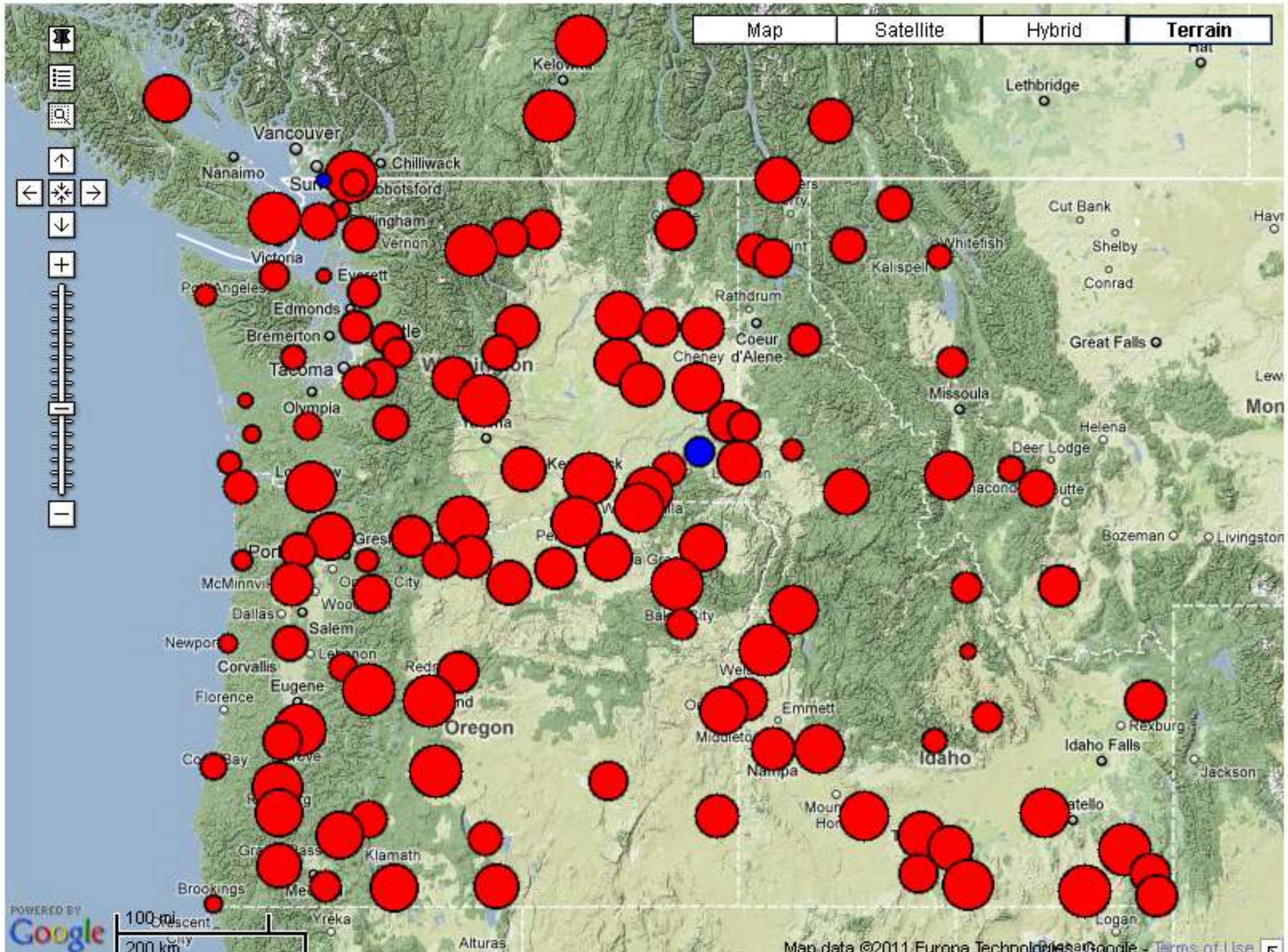


Streams Track Air Temperature Trends



Air Trends as Stream Trend Surrogates?

Mean **Summer** Air Temp Trends (1980 – 2009)



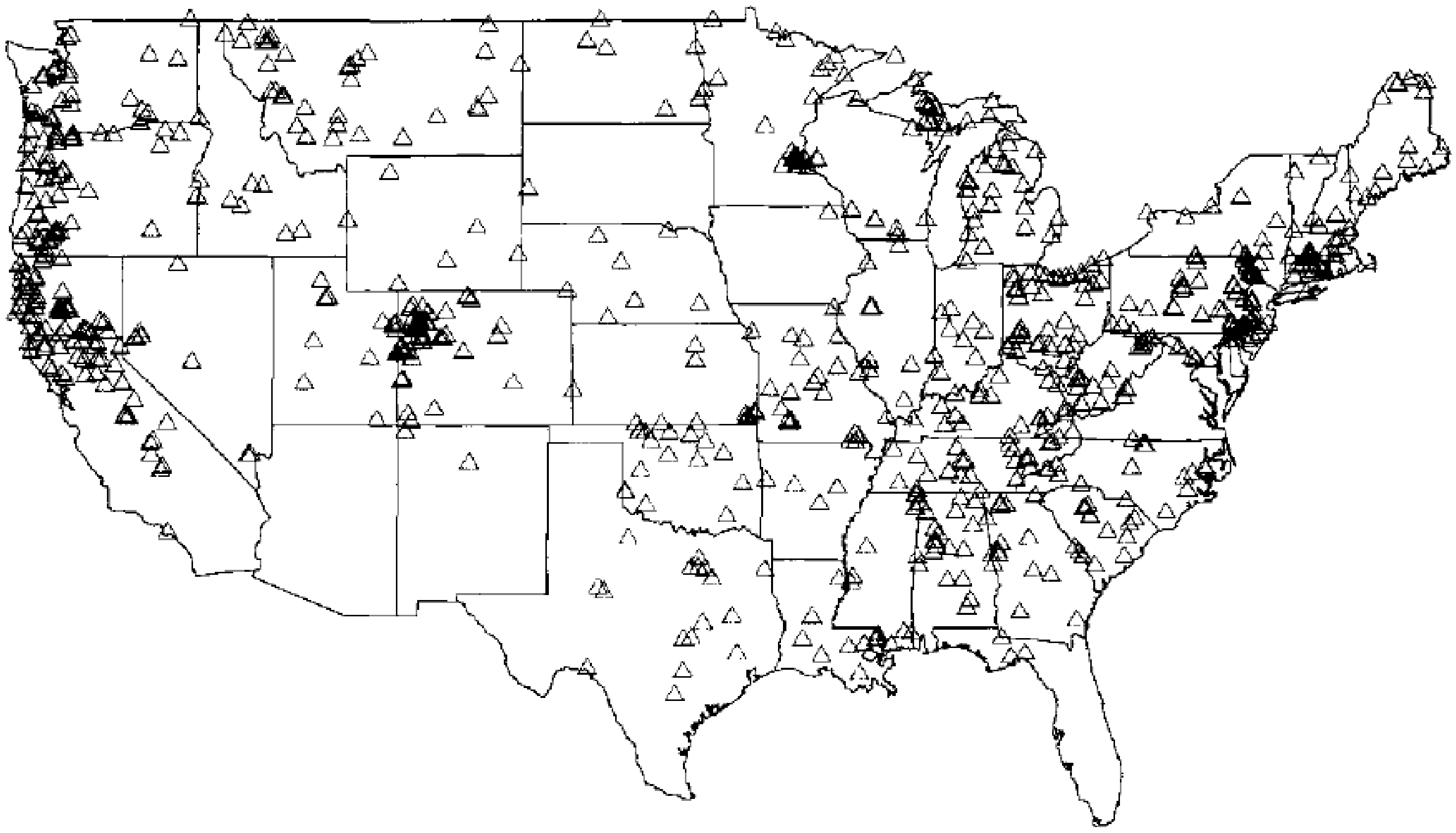
OWSC Climate Tool map

http://www.climate.washington.edu/trendanalysis/

Long-term Stream Temperature Data?

764 USGS gages in lower 48 have some data

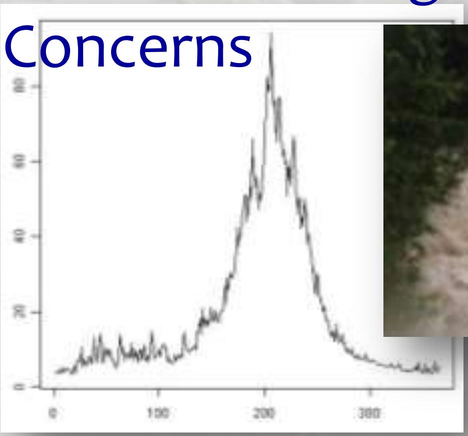
USGS NWIS Database (http://waterdata.usgs.gov/nwis)



Easy Method for Full Year Monitoring

Underwater Epoxy Protocol

Annual Flooding Concerns



Underwater epoxy

$130 = 5 years of data

Data retrieved from underwater

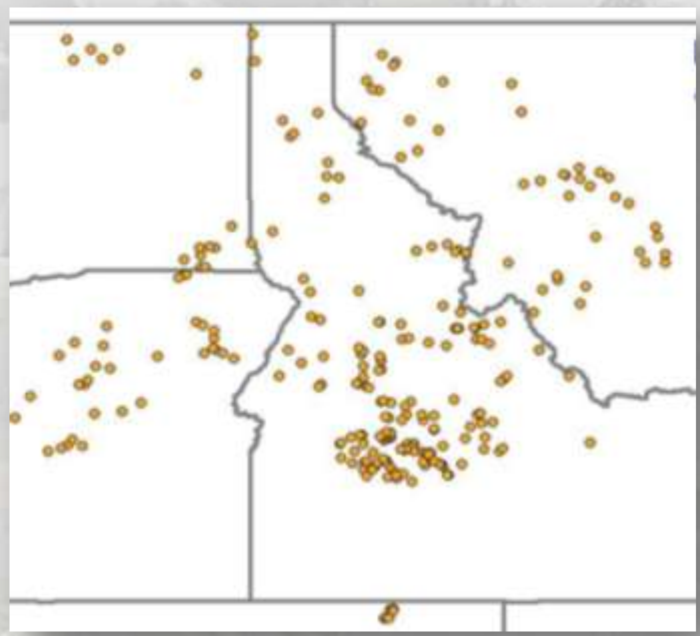
Sensors or PVC housings glued to large boulders

Isaak & Horan 2011. ***NAJFM*** 31:134-137

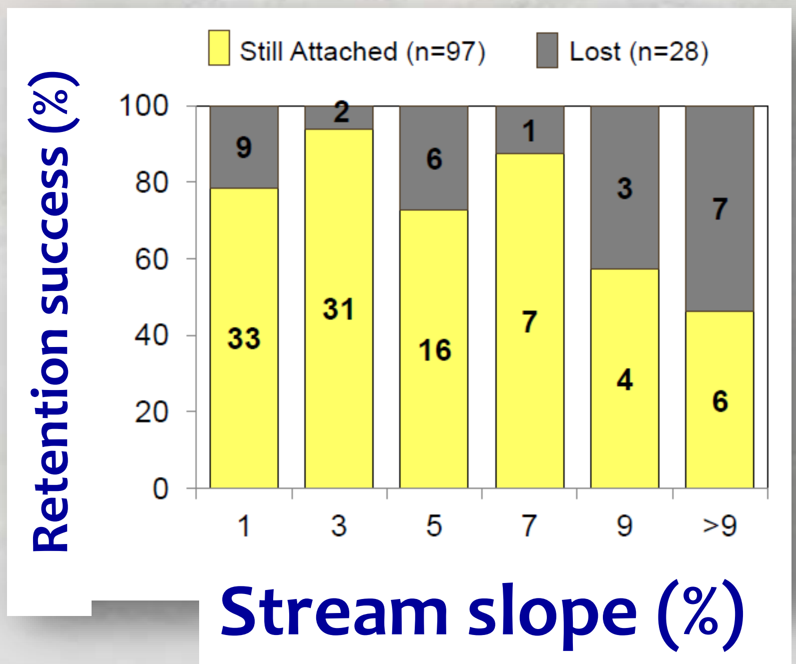
Big Boulders & Small Sensors

Bridge pilings, roadbed riprap…

Large Scale Field Durability Assessment



•300 sensors deployed in 2010
•Stream slopes ranging from 0.1% - 16%



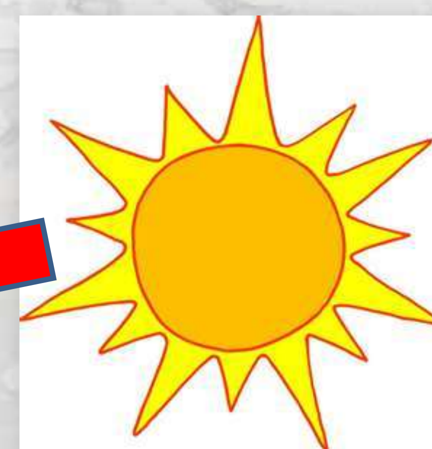
Year 1 retention:

85% (64/75) retained in stream slopes ≤3%

Year 2 retention:

>90% retention

Rock Heat Conduction Effect? No



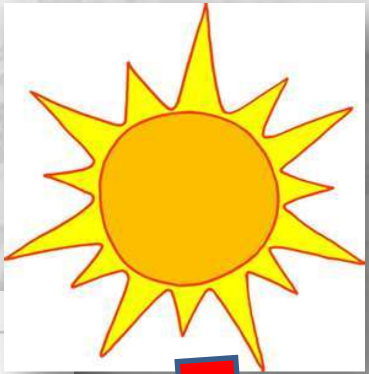
Sensor

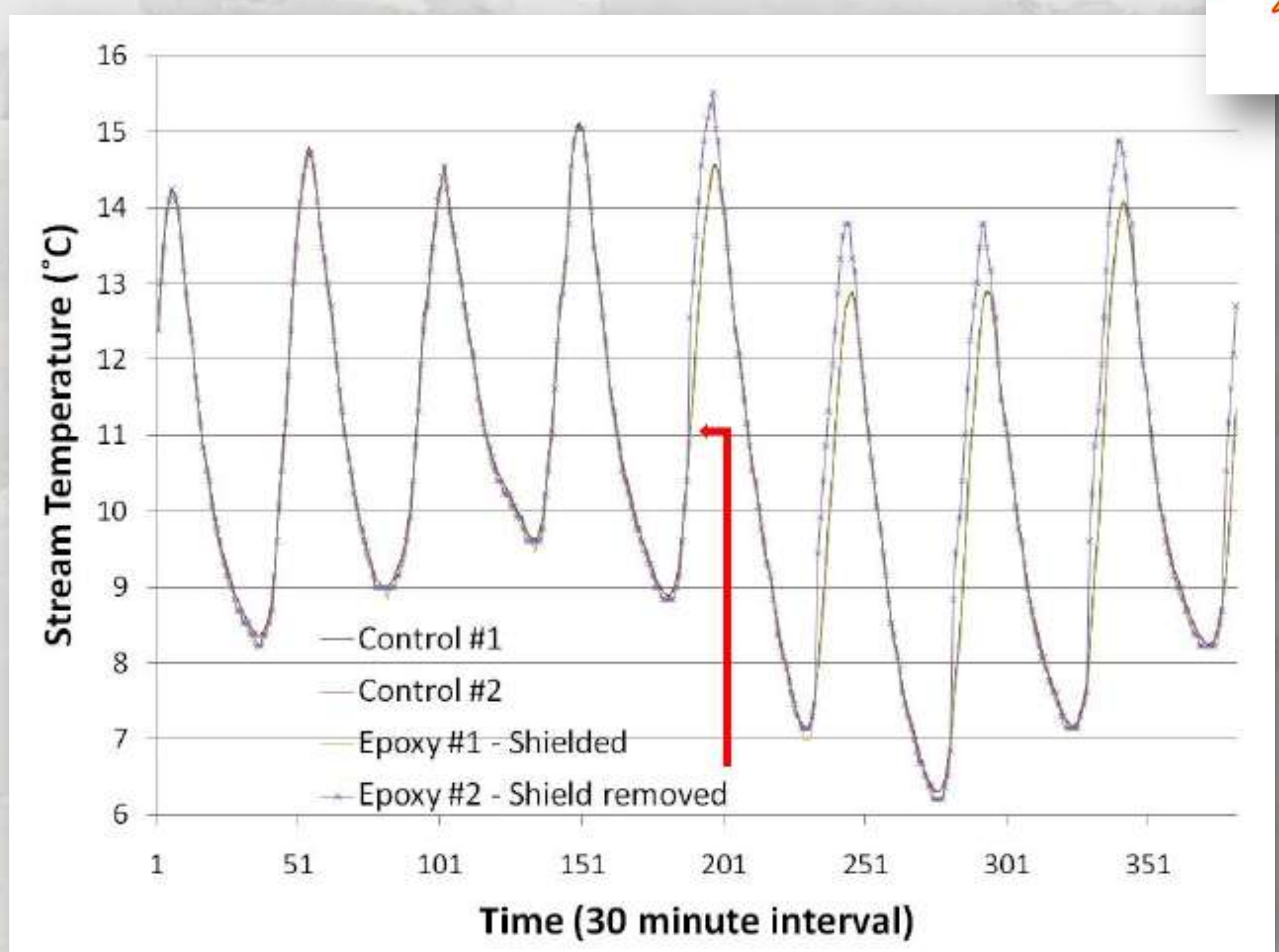
	Temperature attribute (°C)		
Stream site name	Minimum	Mean	Maximum
Canyon Creek	0.10	0.00	-0.06
Grimes Creek, rock 1	-0.01	-0.02	-0.08
Grimes Creek, rock 2	0.06	0.02	-0.03
Little Rattlesnake Creek	0.07	0.02	-0.15
Mores Creek, rock 1	0.11	0.07	0.16
Mores Creek, rock 2	-0.11	-0.07	-0.02
Mores Creek, rock 3	-0.13	0.10	0.31
Mores Creek, rock 4	-0.03	0.01	0.16
No Name Creek	0.13	0.09	0.03
Rattlesnake Creek	0.02	0.00	0.00
Average difference[1] =	0.02 (-0.05, 0.09)	0.02 (-0.02, 0.06)	0.03 (-0.07, 0.13)

[1] = values after the average difference are 95% confidence intervals

Direct Sunlight Effect? Yes

Solar Shields are Mandatory

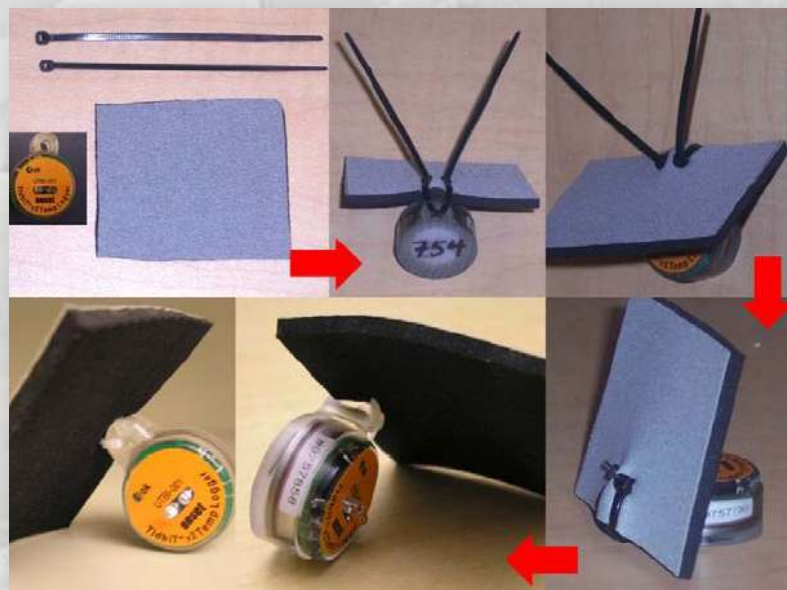




Sunlight biases measurements ~0.2 – 0.5 C

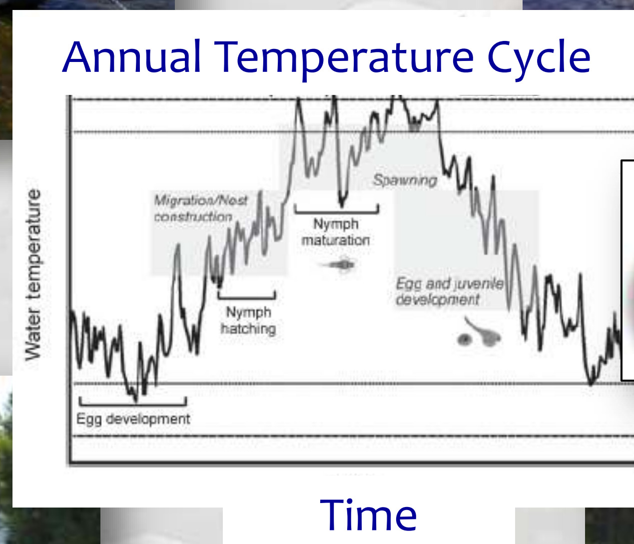
Solar Shield Alternatives…

Neoprene flap & directly glue sensor to rock

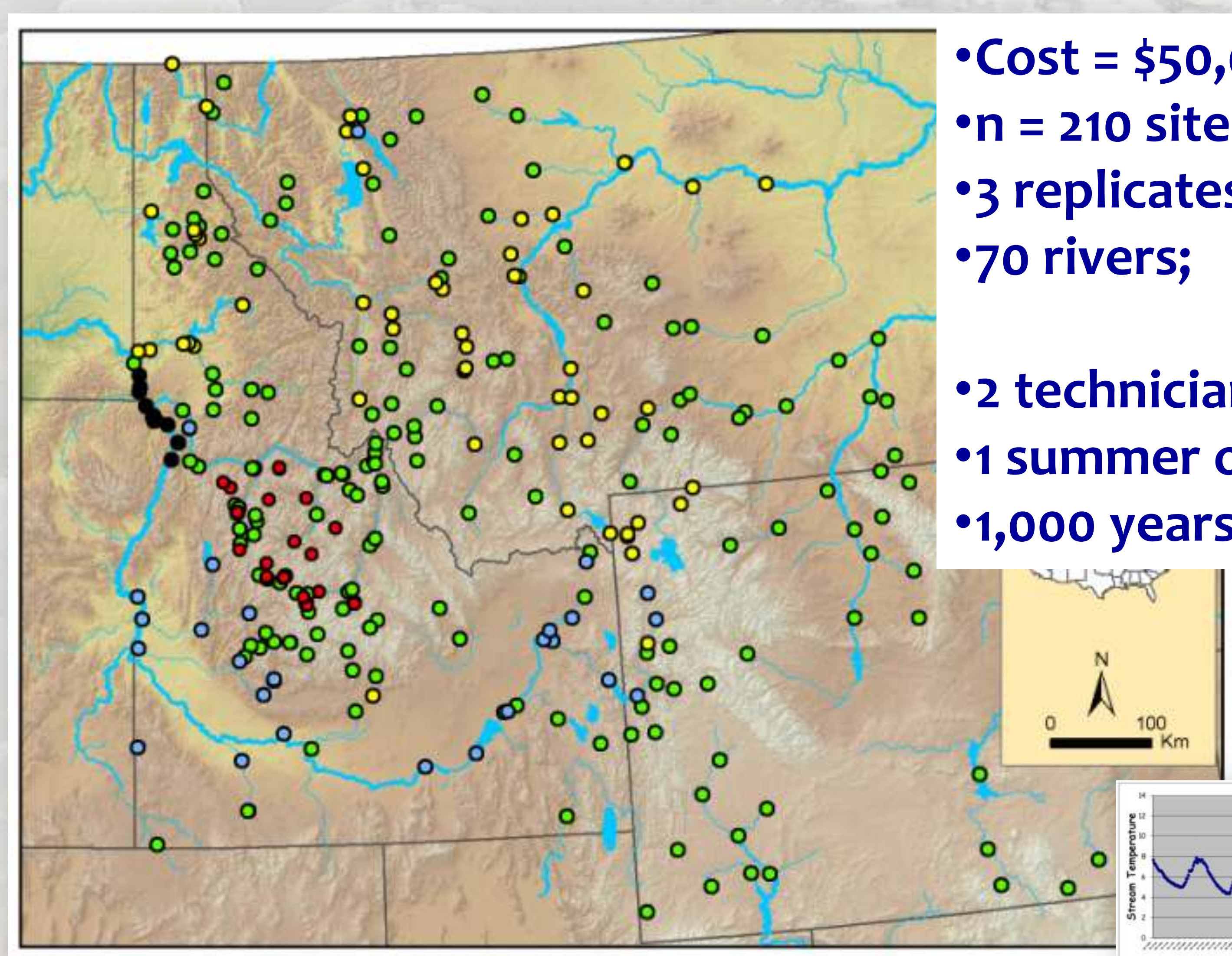


PVC housing protects sensor & easy to retrieve data or replace sensor (preferred method)

Large Rivers and Streams as a Monitoring Priority

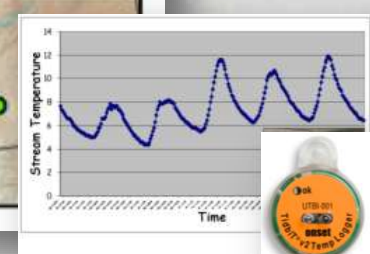


NoRRTN: Northern Rockies River Temperature Network



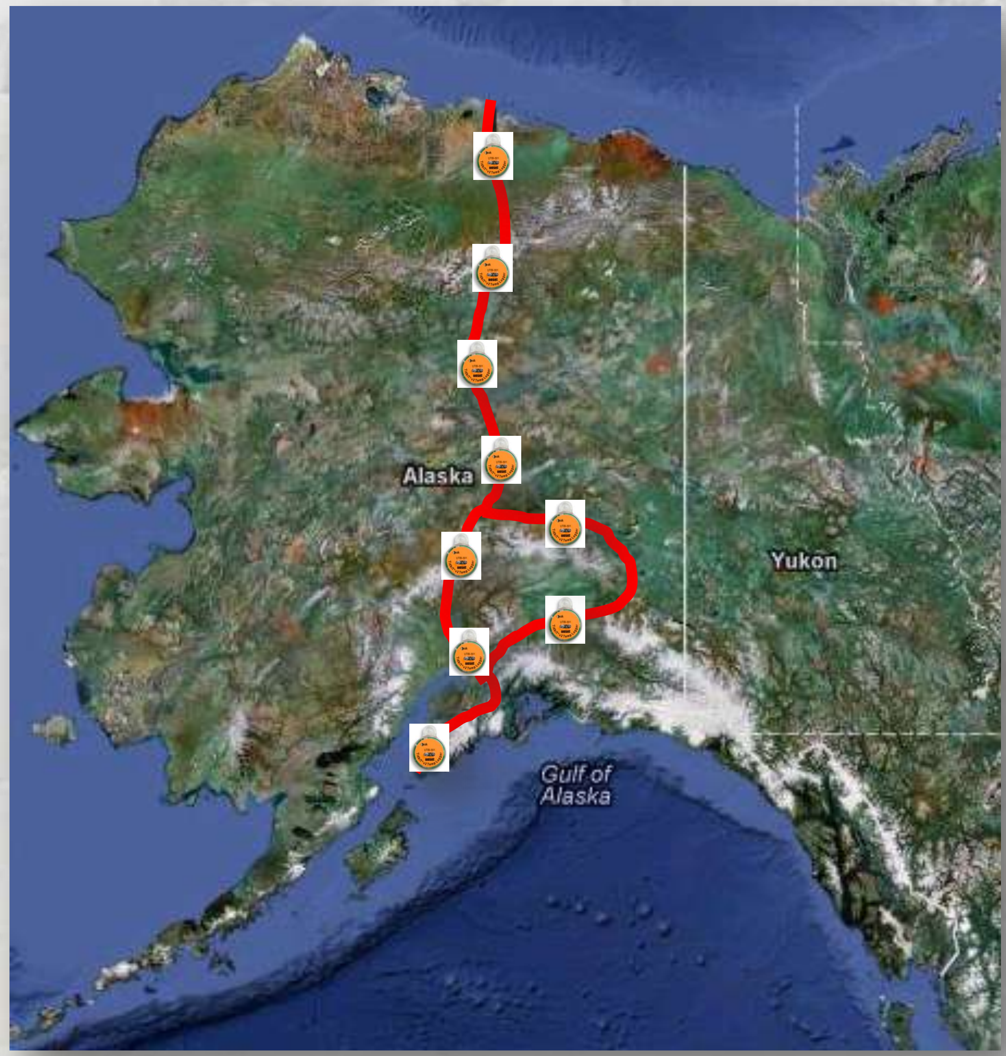
- •Cost = $50,000;
- •n = 210 sites;
- •3 replicates/river;
- •70 rivers;

- •2 technicians;
- •1 summer of work;
- •1,000 years of data

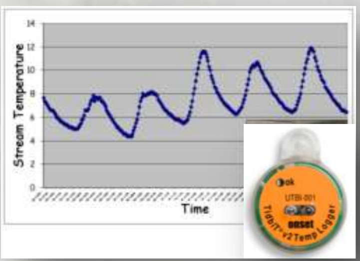


Trans-Alaskan ~~Pipeline~~ River Temperature Network?

Backbone of statewide monitoring network?

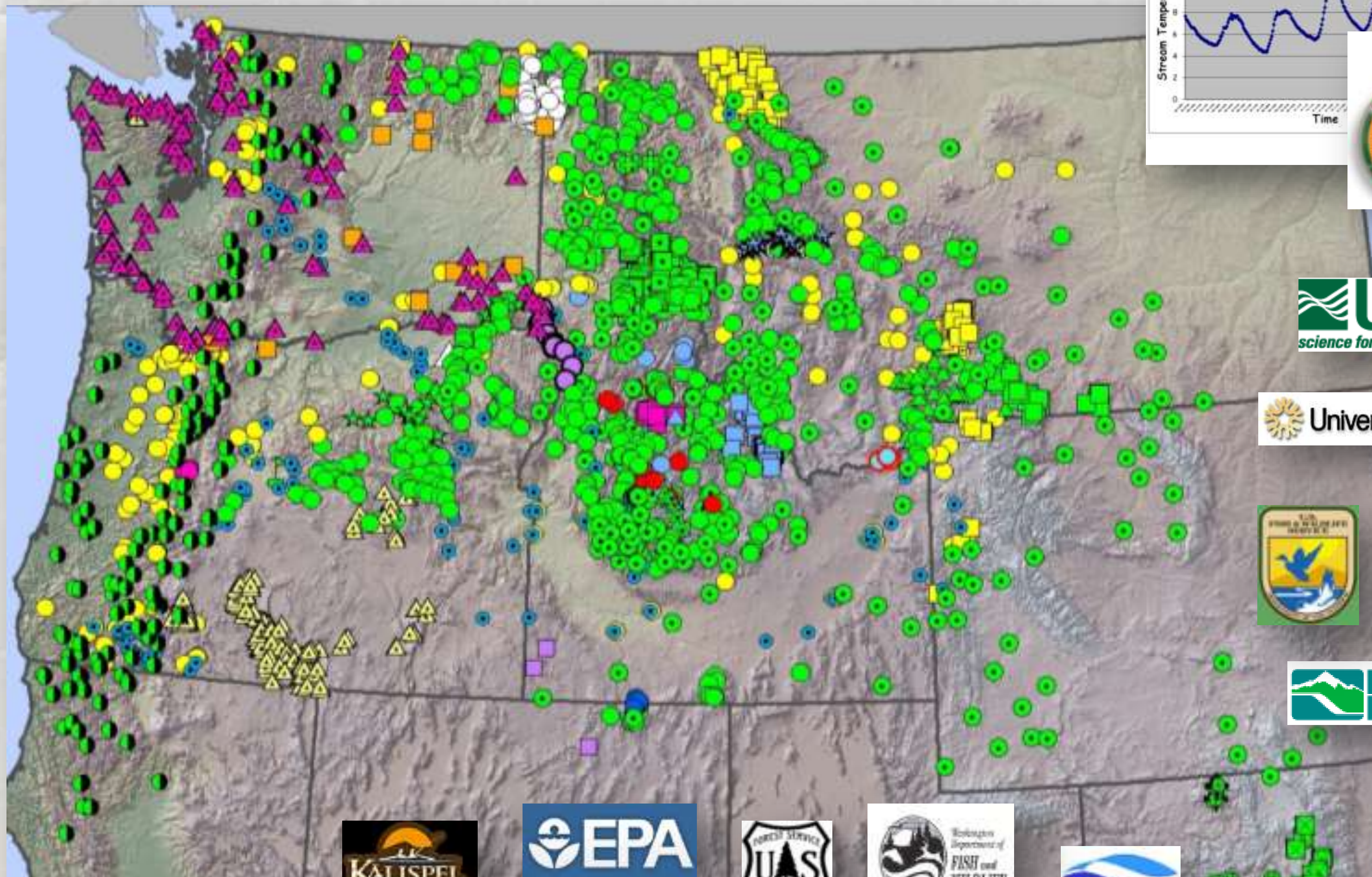


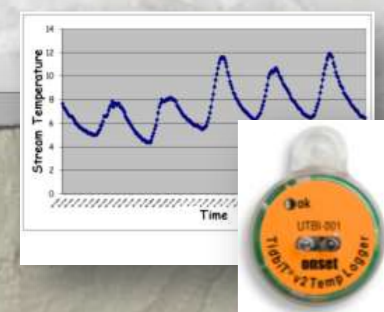
- Instrument rivers @ road crossings & easy access points
- Continue building from there…



Full Year Stream Temperature Monitoring Becoming Popular...

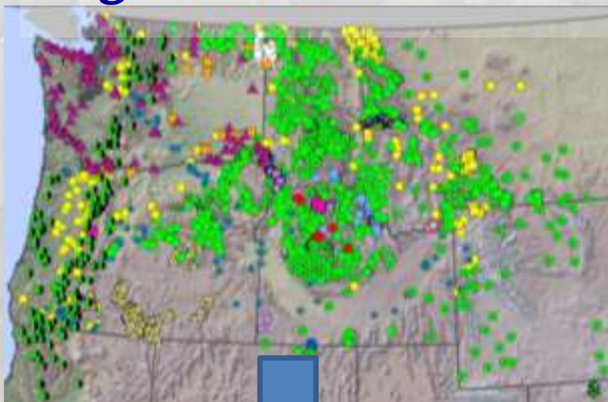
2,761 Current full-year monitoring sites
~1,000 New deployments last year





A GoogleMap Tool for Dynamic Queries of Temperature Monitoring Sites

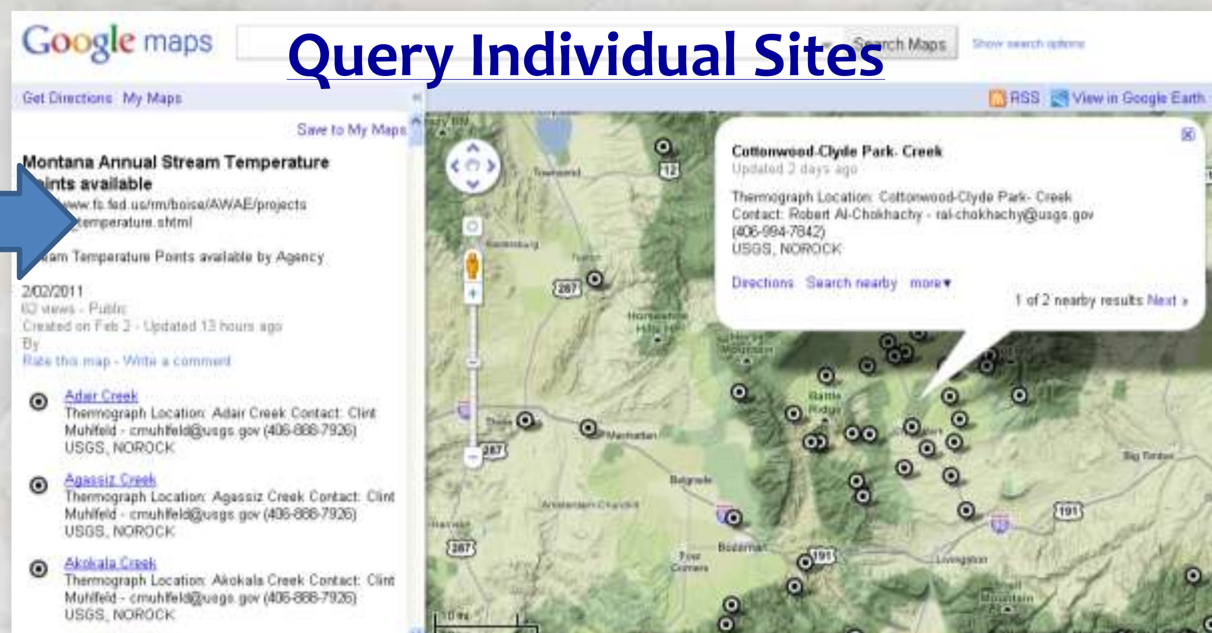
Regional Sensor Network



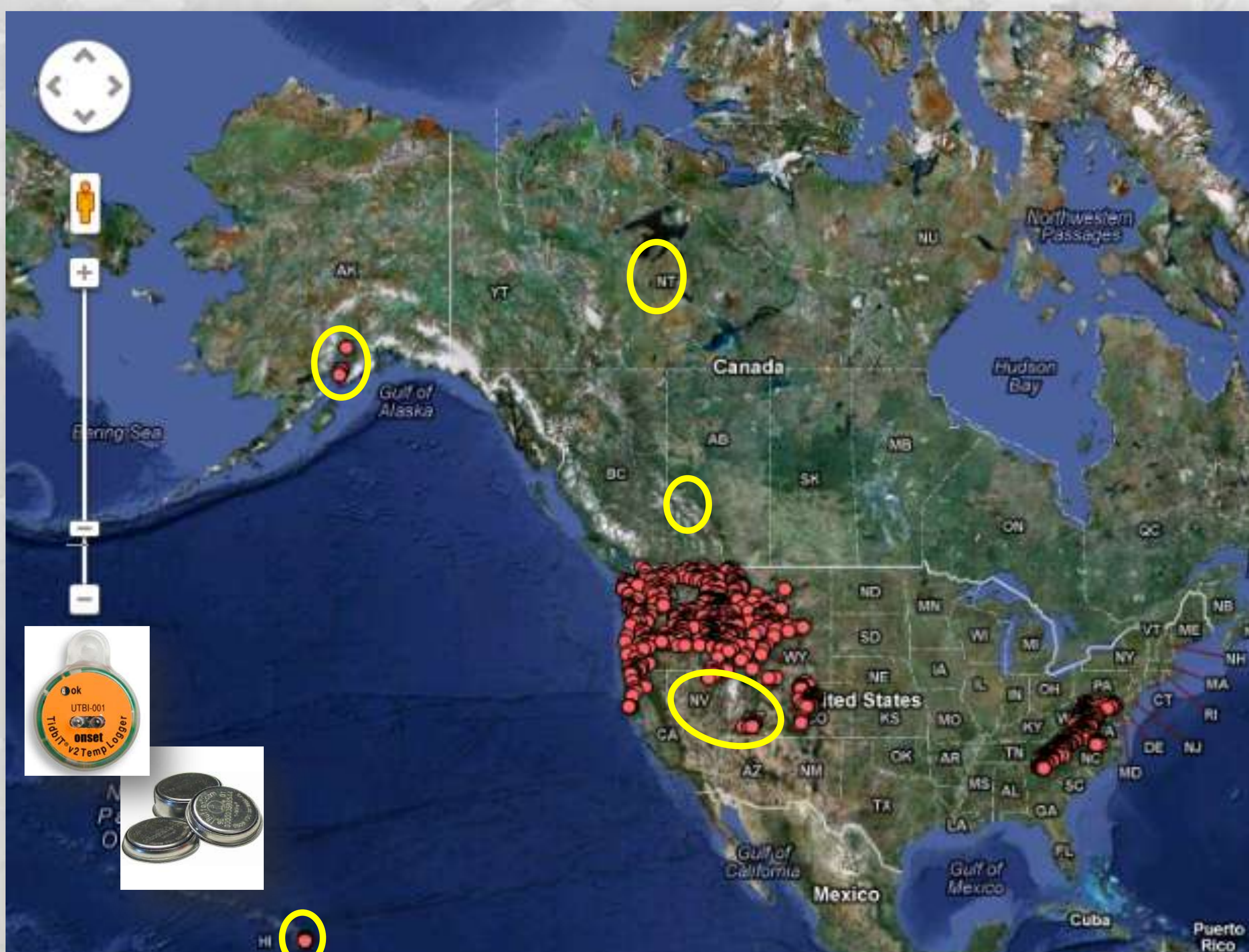
Site Information

- Stream name
- Data steward contact information
- Agency
- Site Initiation Date

Query Individual Sites

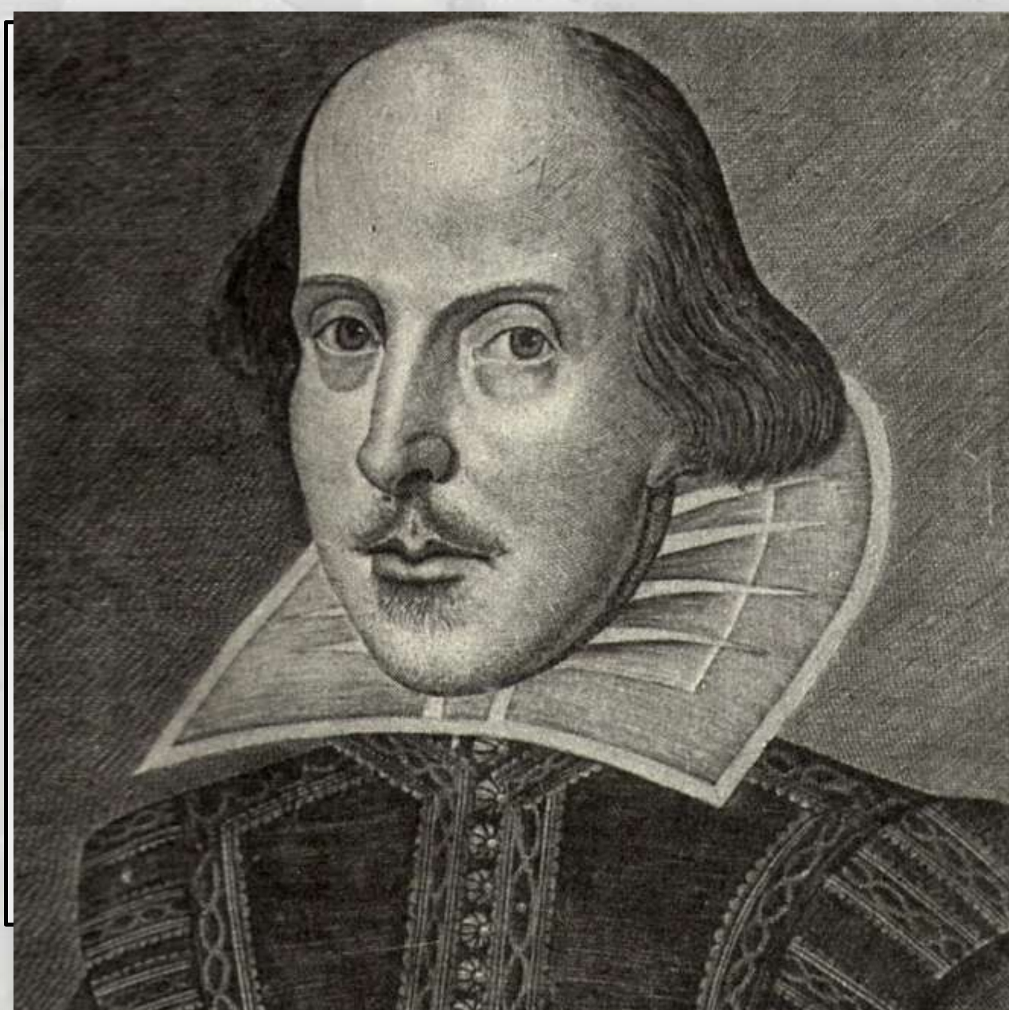


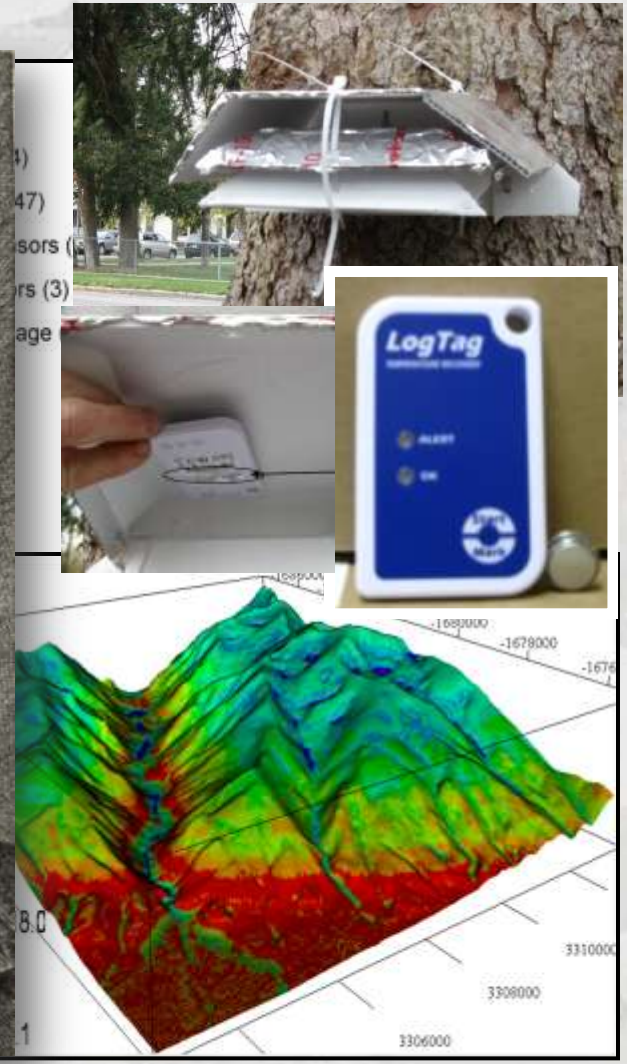
GoogleMap Tool Full Year Stream Temperature Monitoring Sites



To Pair (With Air), or Not to Pair?

That is the question…

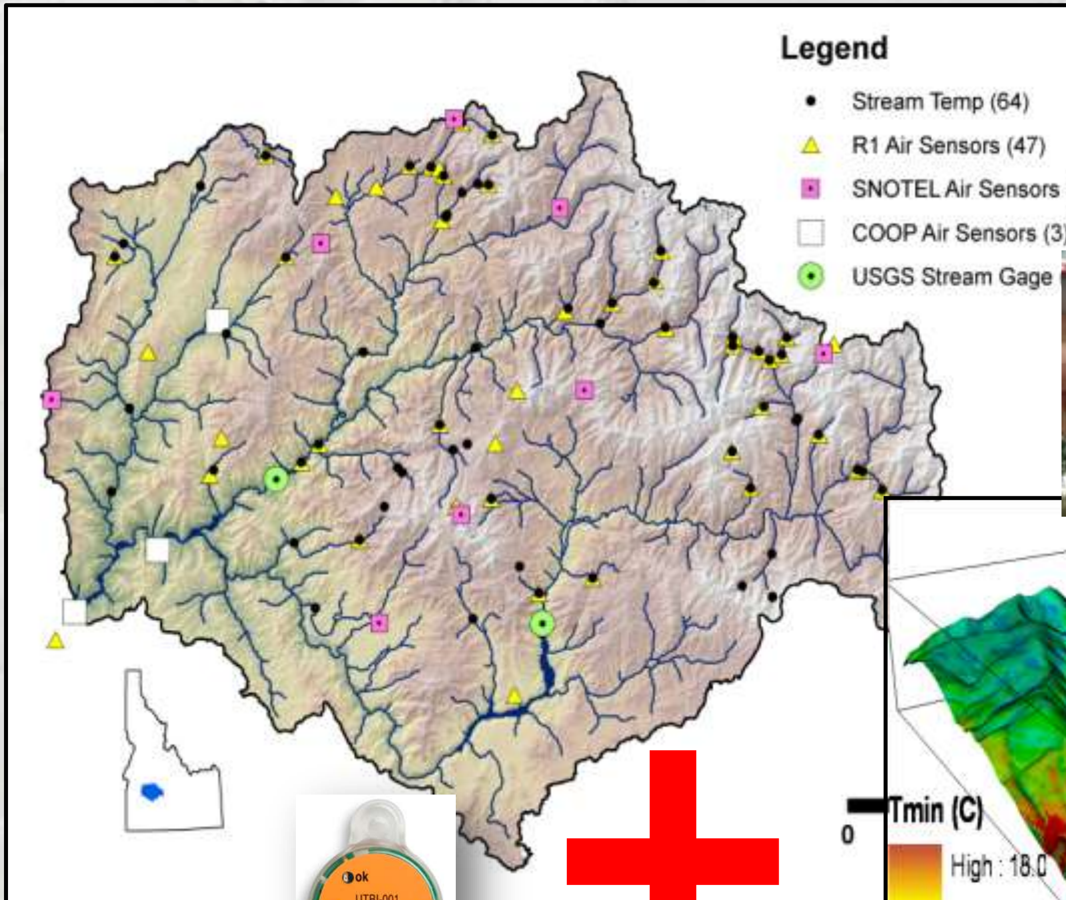


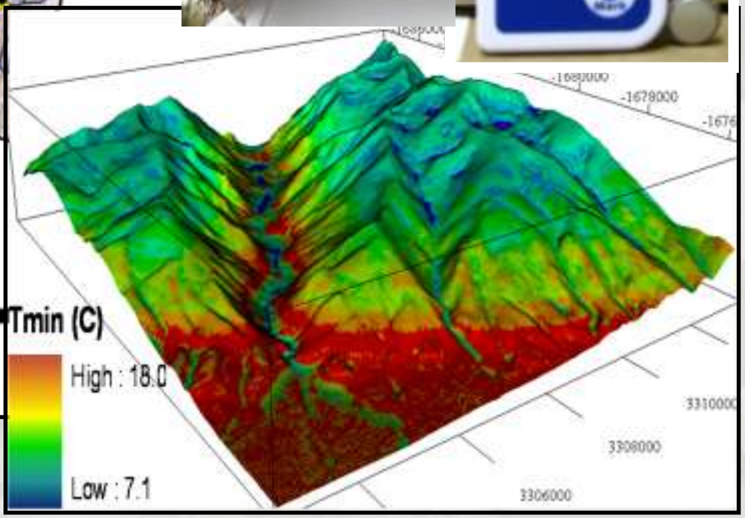


There are trade-offs, so answer depends…

To Pair (With Air), or Not to Pair?

That is the question…





There are trade-offs, so answer depends…

Logistics & Efficient Data Collection

Logistics & Efficient Data Collection

Crews deploy multiple sensor types?

Integrated terrestrial-aquatic monitoring?

Stream sensors
($20 - $120)

Air sensors ($20 - $100)

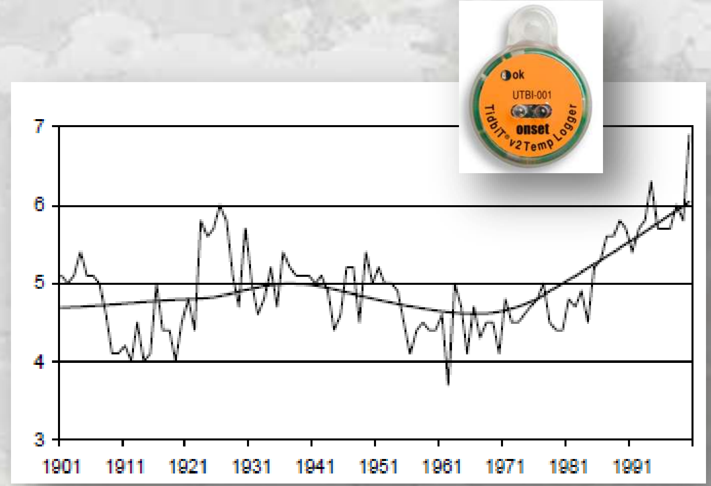
Miniature sensors & multiyear memory / battery life

Pressure transducers for stream discharge ($500)

Standardized protocols needed

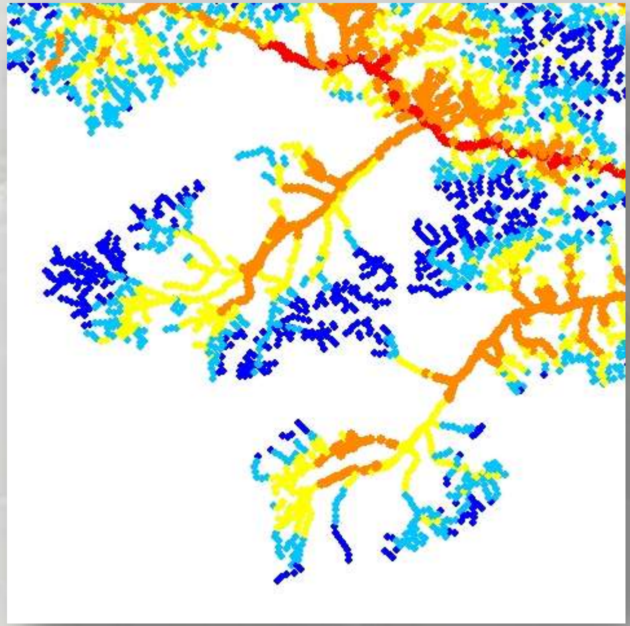
How Long Should Temperatures be Monitored?

Long-term records are rare…



Webb and Nobilus 2007

So some sites should be monitored indefinitely

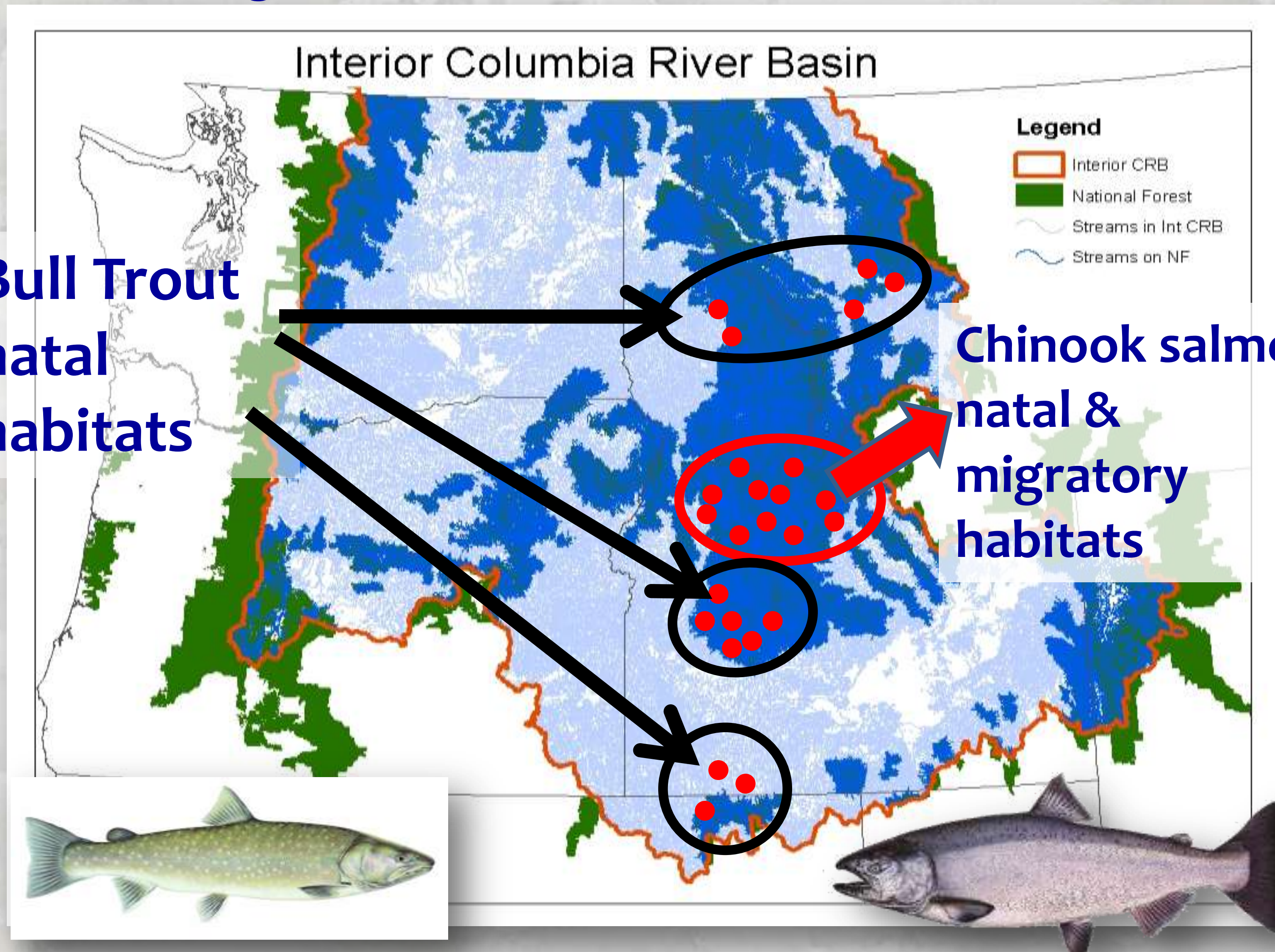


…but spatial variation among sites contains majority of “information” about thermal regimes

So some sites could be monitored for short periods (2 – 3 years) & sensors rotated to new sites.

Other Reasons for Temperature Monitoring

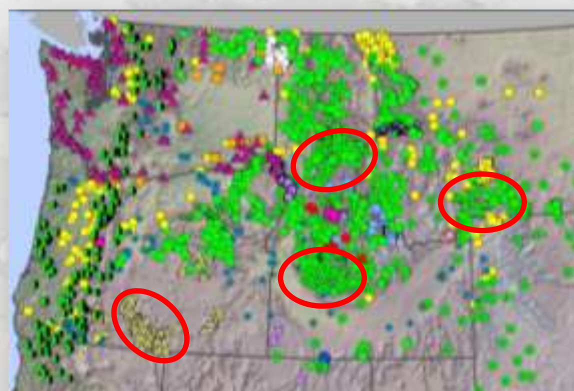
Ecological Temperature Sensor Networks



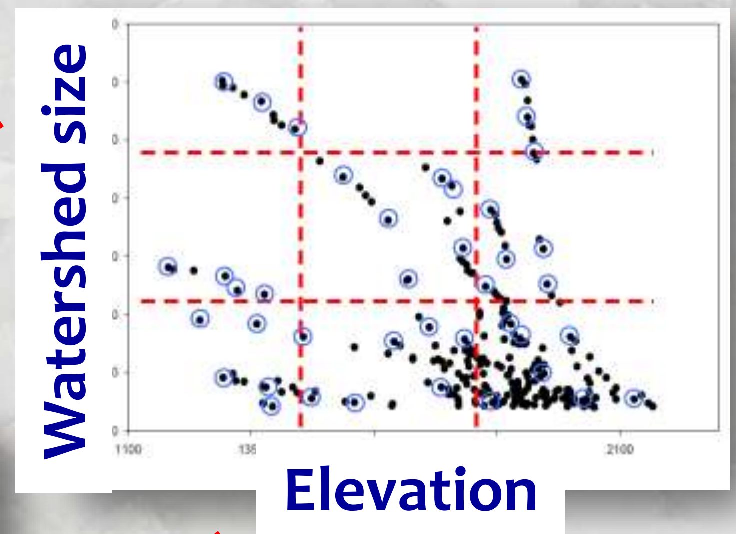
Other Reasons for Temperature Monitoring

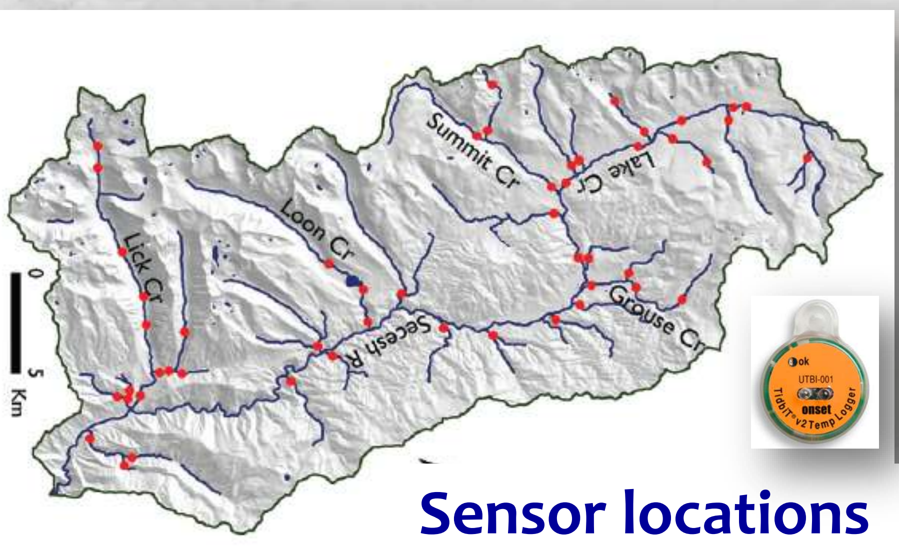
Describing Network Scale Spatial Heterogeneity

Pick few key watersheds



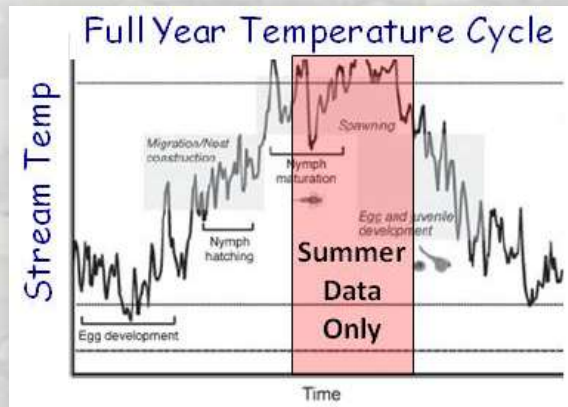
Stratify network (easy with GIS) & densely sample to represent strata





Information from Data:

1) Basic descriptors of stream climate



Spatial Patterns

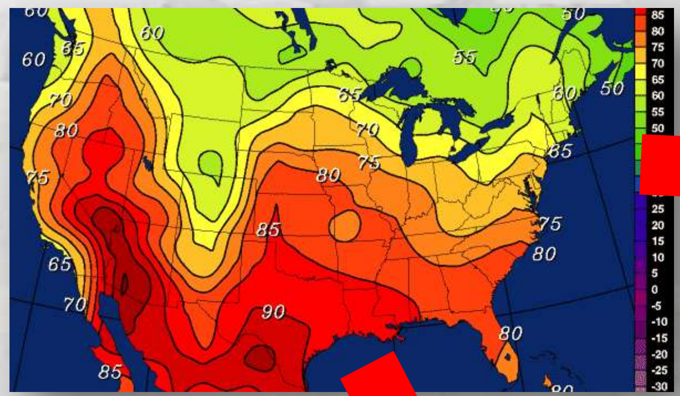
Seasonal/Temporal Relationships

	Fall mean	Fall SD	Winter Mean	Winter SD	Spring mean	Spring SD	Summer Mean
Fall SD	0.87	---					
Winter Mean	0.50	0.02	---				
Winter SD	0.70	0.35	0.83	---			
Spring mean	0.95	0.76	0.51	0.78	---		
Spring SD	0.69	0.77	-0.05	0.29	0.74	---	
Summer Mean	**0.91**	**0.92**	**0.23**	**0.45**	**0.88**	**0.87**	---
Summer SD	0.62	0.77	-0.02	0.15	0.48	0.49	**0.65**

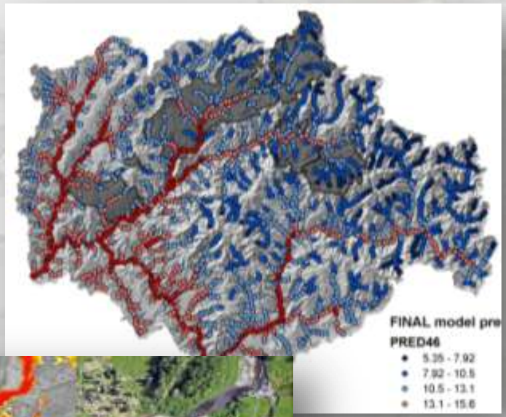
What is an Isotherm?

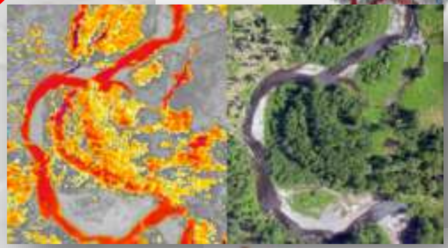
How Does it Apply to Streams?

Line connecting locations with equal temperatures

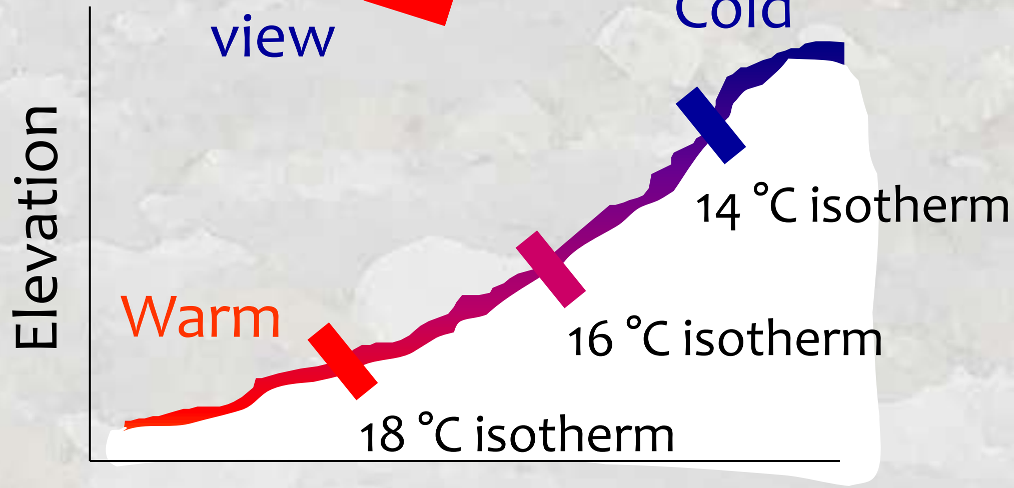


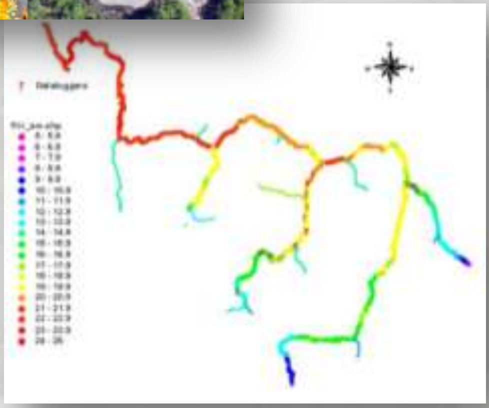
Plan view





Longitudinal view

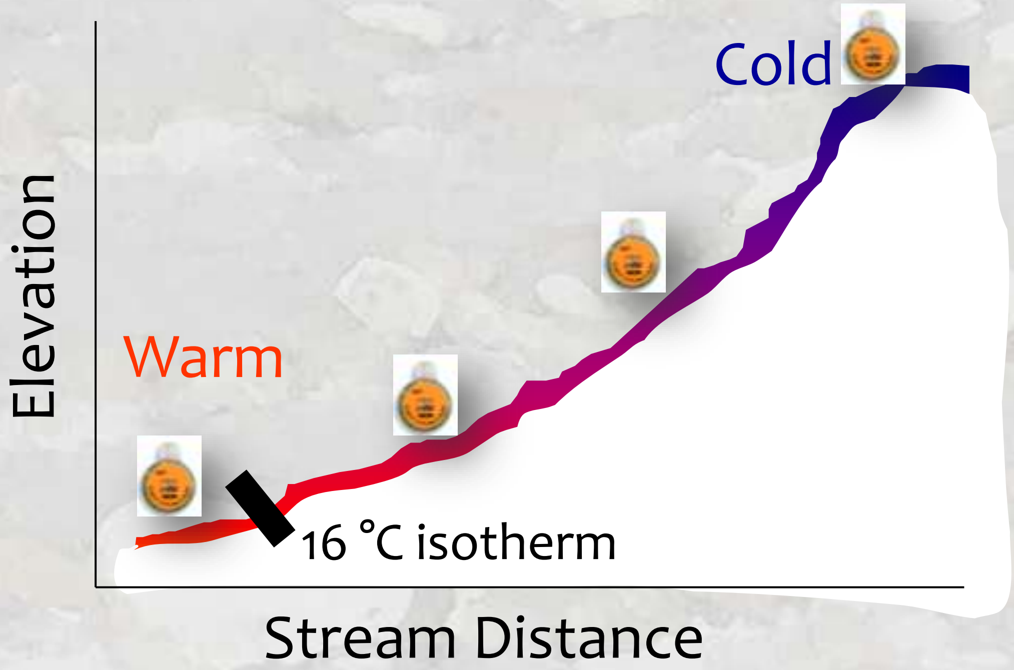




Salmon River FLIR profile

Stream-Specific Predictions of Isotherm Shifts Add Precision

1) Stream temperature lapse rate (°C / 100 m)
2) Long-term stream warming rate (°C / decade)
3) Stream slope (degrees)
4) Stream sinuosity



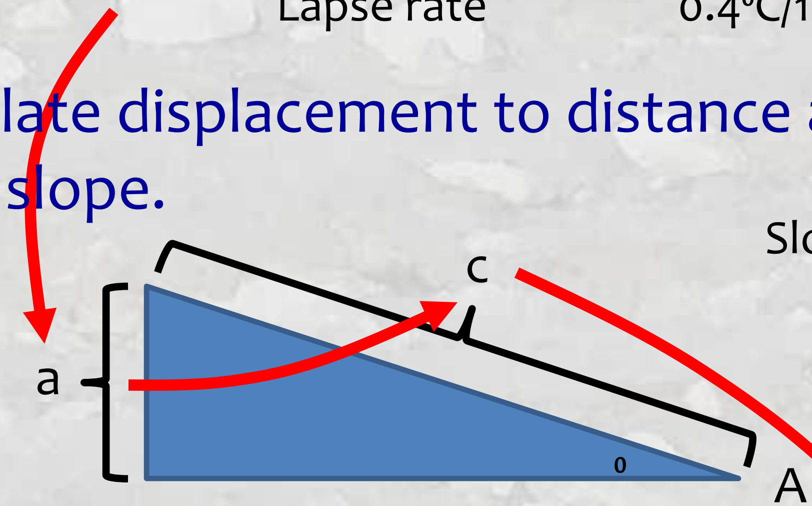
A Use for High School Trigonometry!

1. Calculate vertical displacement for a given stream lapse rate and long-term warming rate.

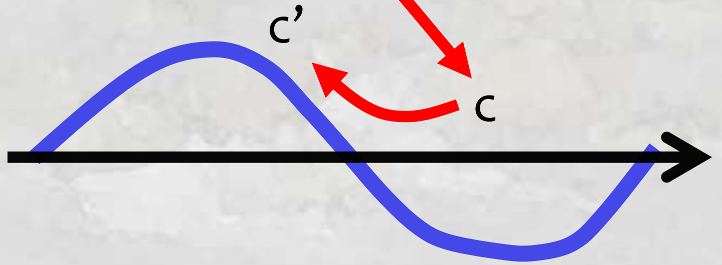
$$\text{Displacement (a)} = \frac{\text{Warming rate}}{\text{Lapse rate}} = \frac{0.2^{0}\text{C/decade}}{0.4^{0}\text{C/100m}} = +50\text{m/decade}$$

2. Translate displacement to distance along stream of a given slope.

$$\text{Slope distance (c)} = \frac{a}{\sin A^{0}}$$

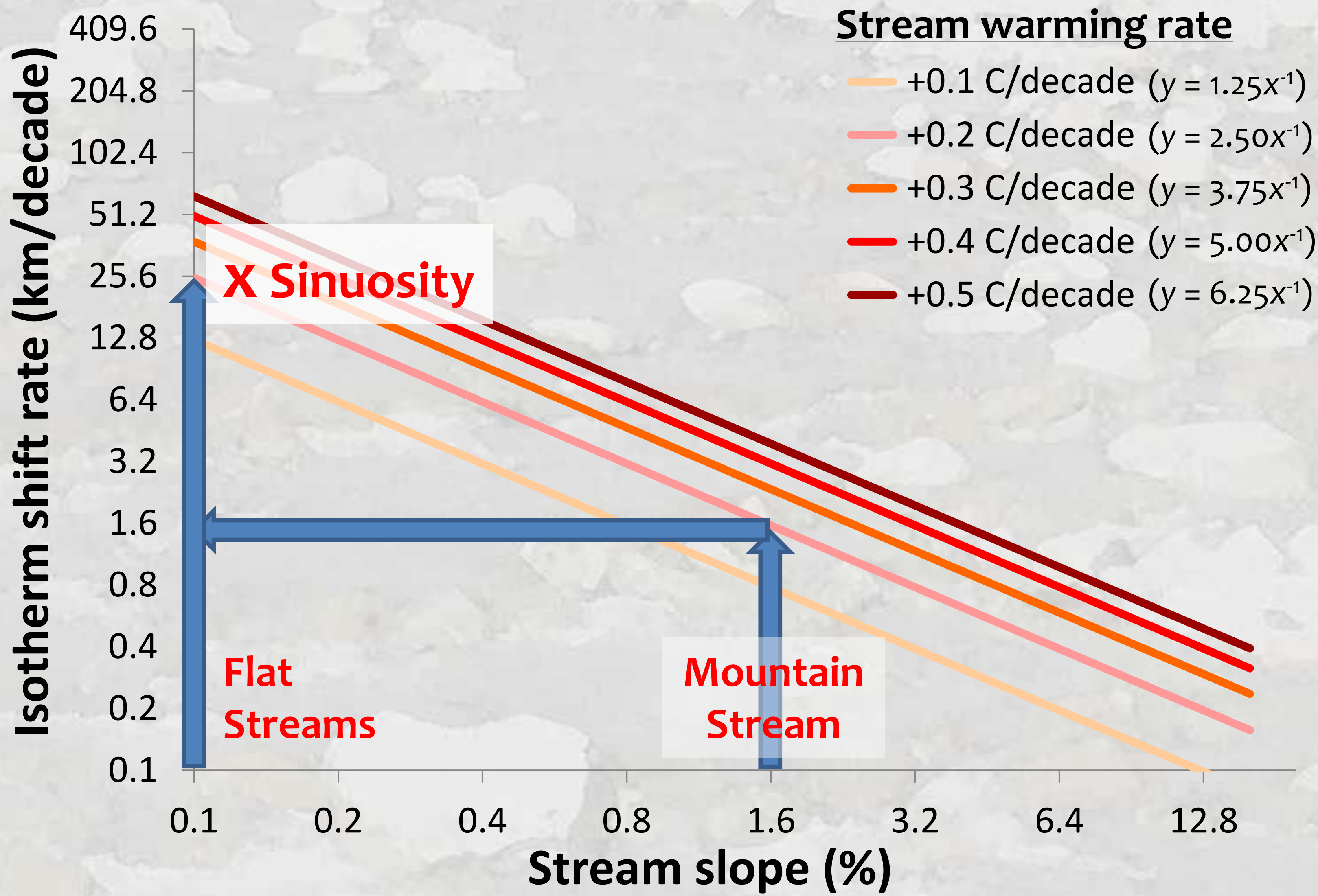


3. Multiply slope distance by stream sinuosity ratio in meandering streams.



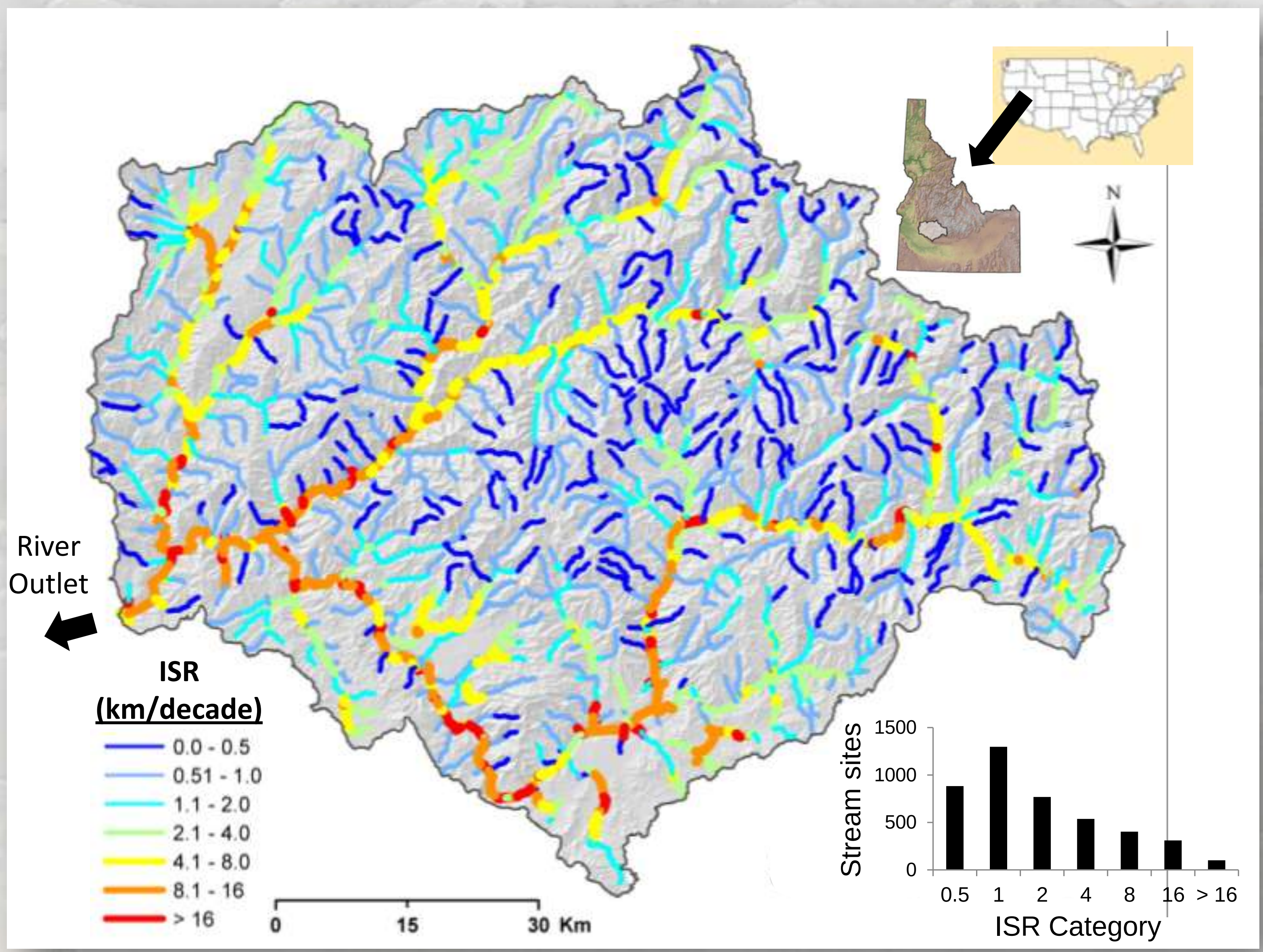
Isotherm Shift Rate Curves

Stream lapse rate = 0.8 °C / 100 m



Isaak & Rieman. 2012. *Global Change Biology* **18**, doi: 10.1111/gcb.12073

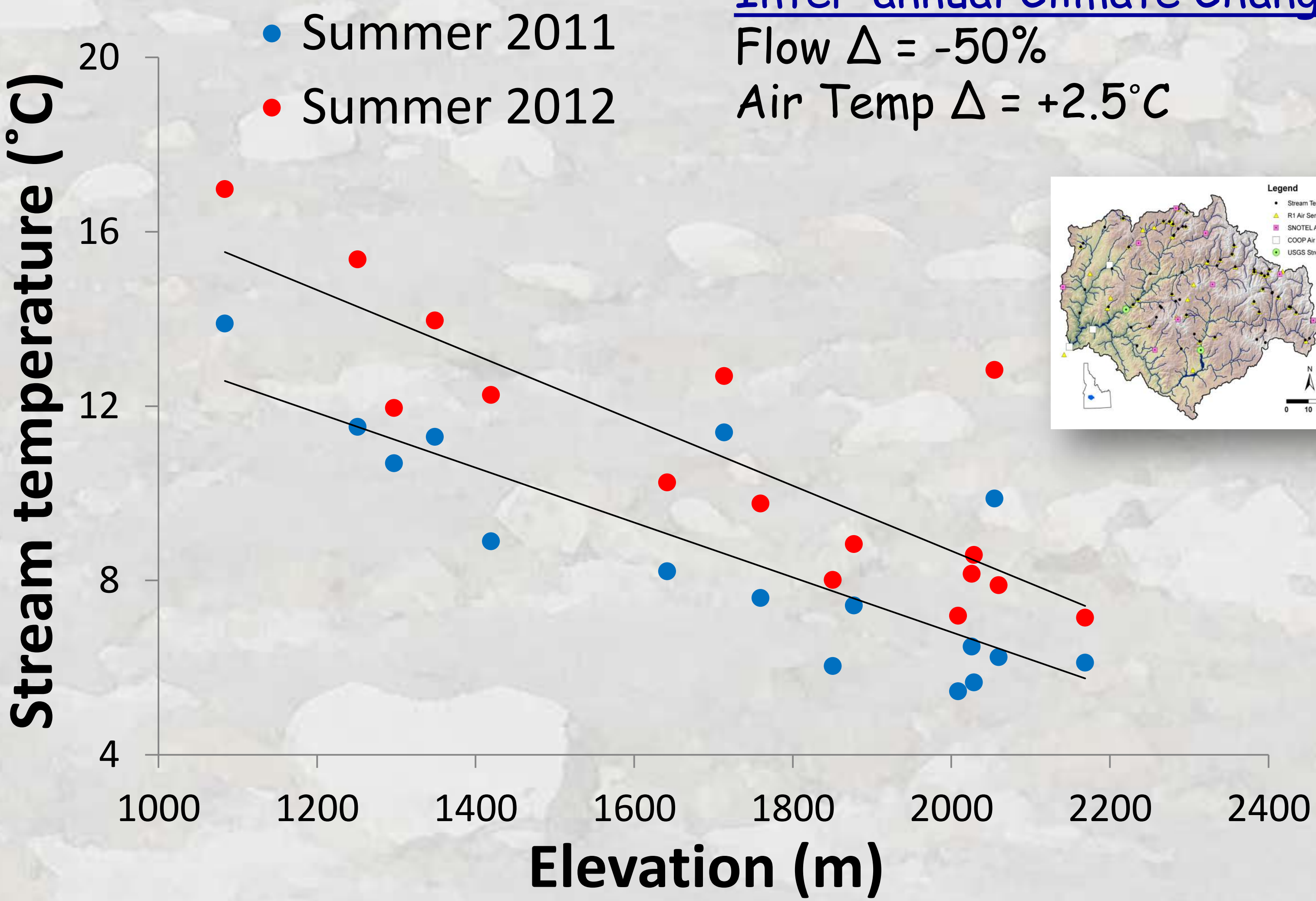
Mapping Climate Change "Velocity"



sensu Loarie et al. 2009. *Nature* **462**:1052-1055.

Information from Data:

2) Short-term sensitivity analysis

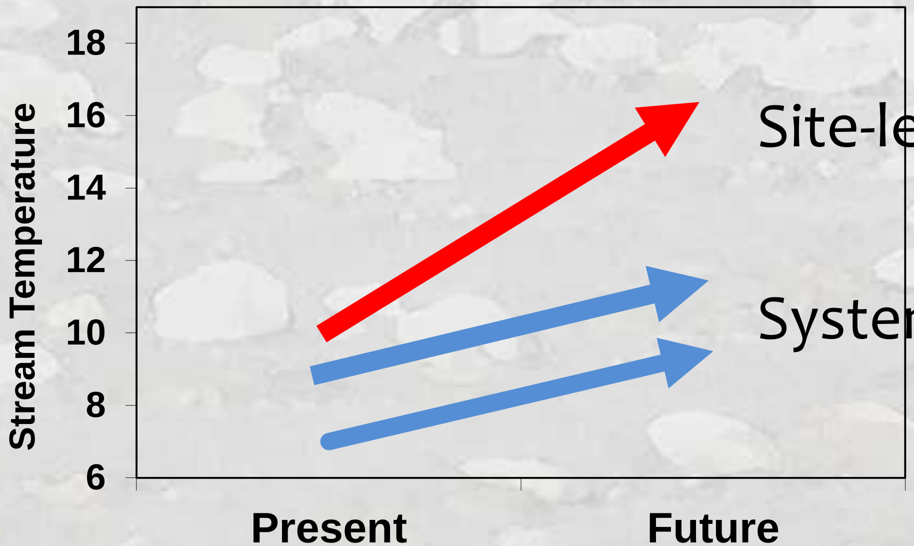


<u>Inter-annual Climate Change</u>

Flow Δ = -50%

Air Temp Δ = +2.5°C

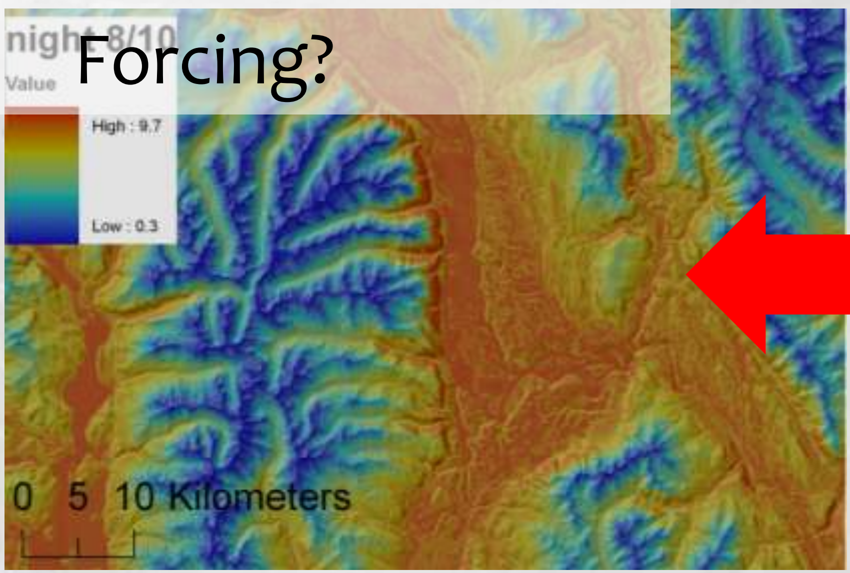
Spatial Variation in Temperature Changes



Site-level Change?

Systematic Change?

Different Climate Forcing?



Or Different Sensitivity?

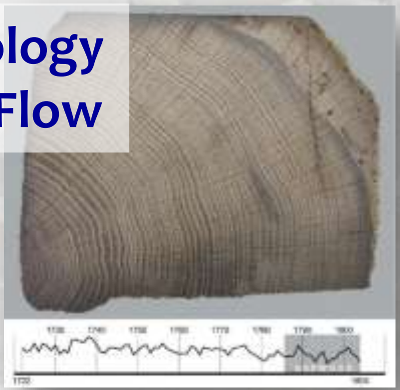
Glacial Valley Buffering?

Information from Data:

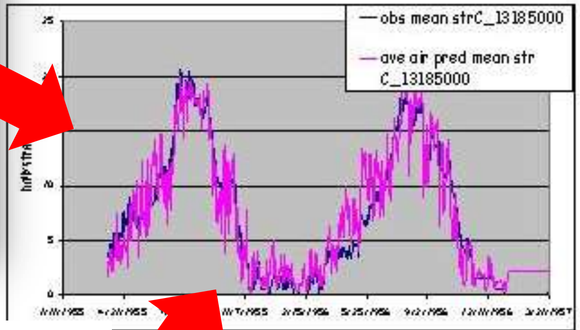
3) Site reconstructions of stream thermal chronologies

Long-Term Air Records

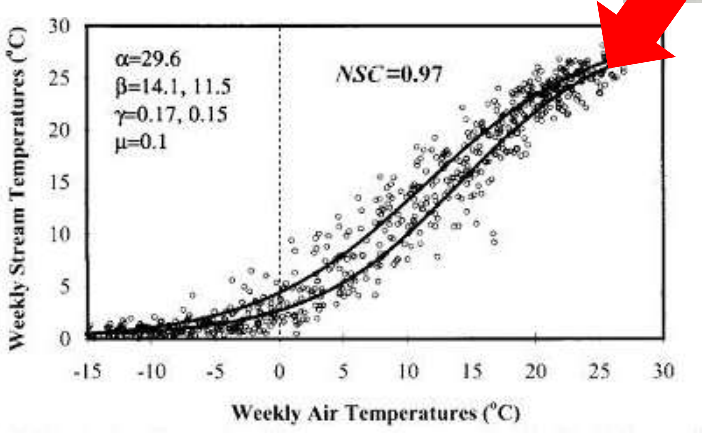
Dendrochronology for Stream Flow



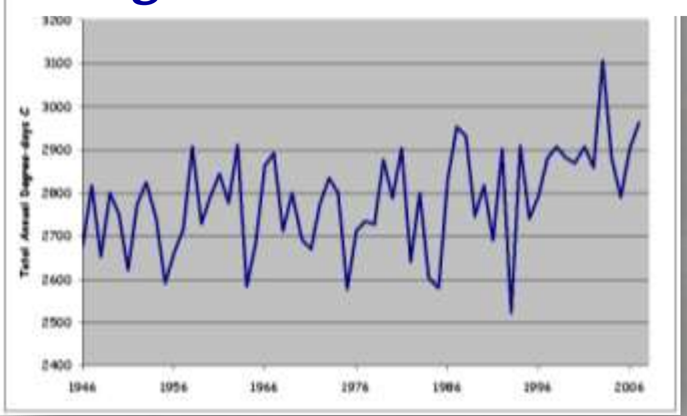
Few years stream temp data



Air-Stream Link Functions

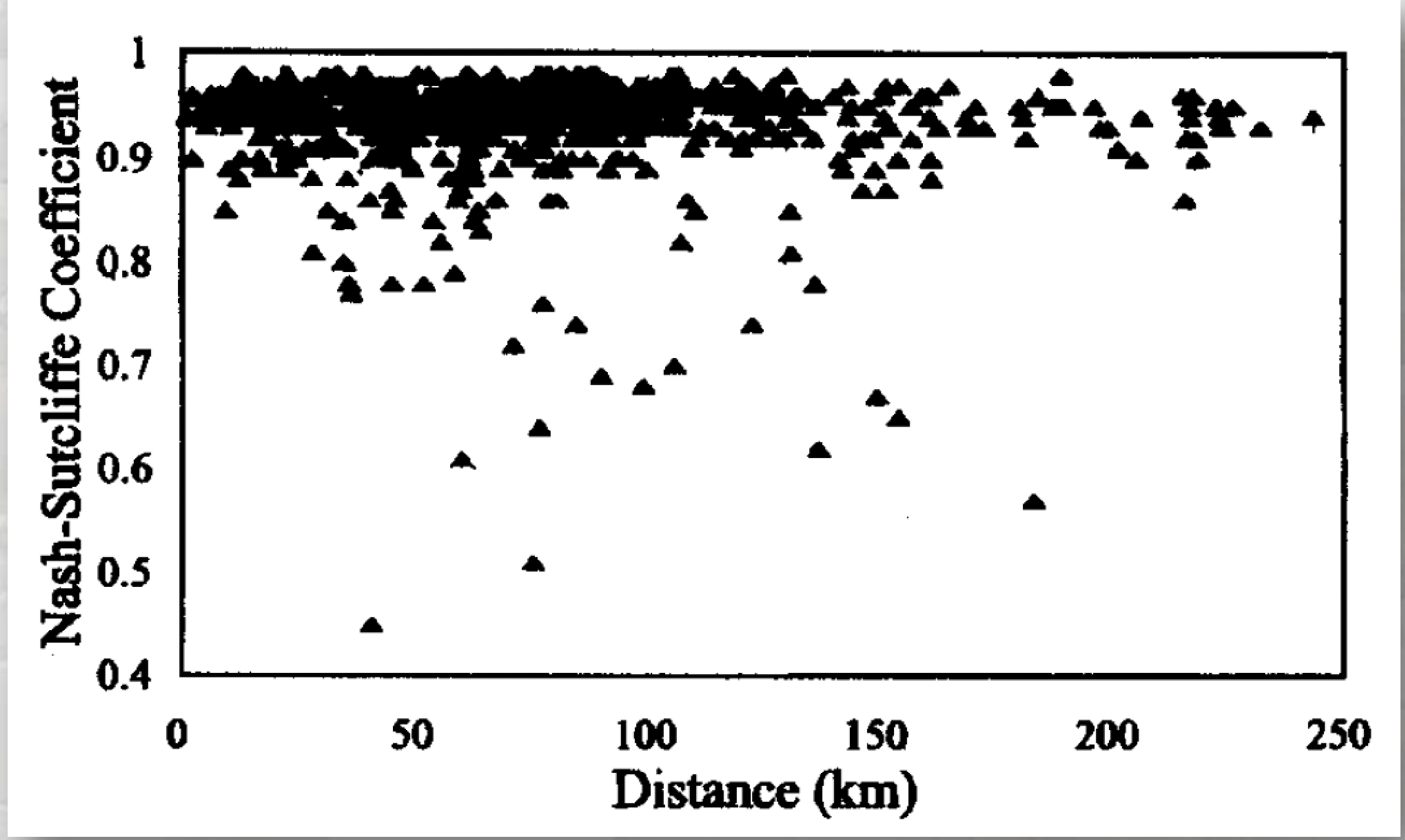


Long-Term Stream Record



Mohseni et al. 1998. *WRR* **34**; van Vliet et al. 2011. *WRR* **47**

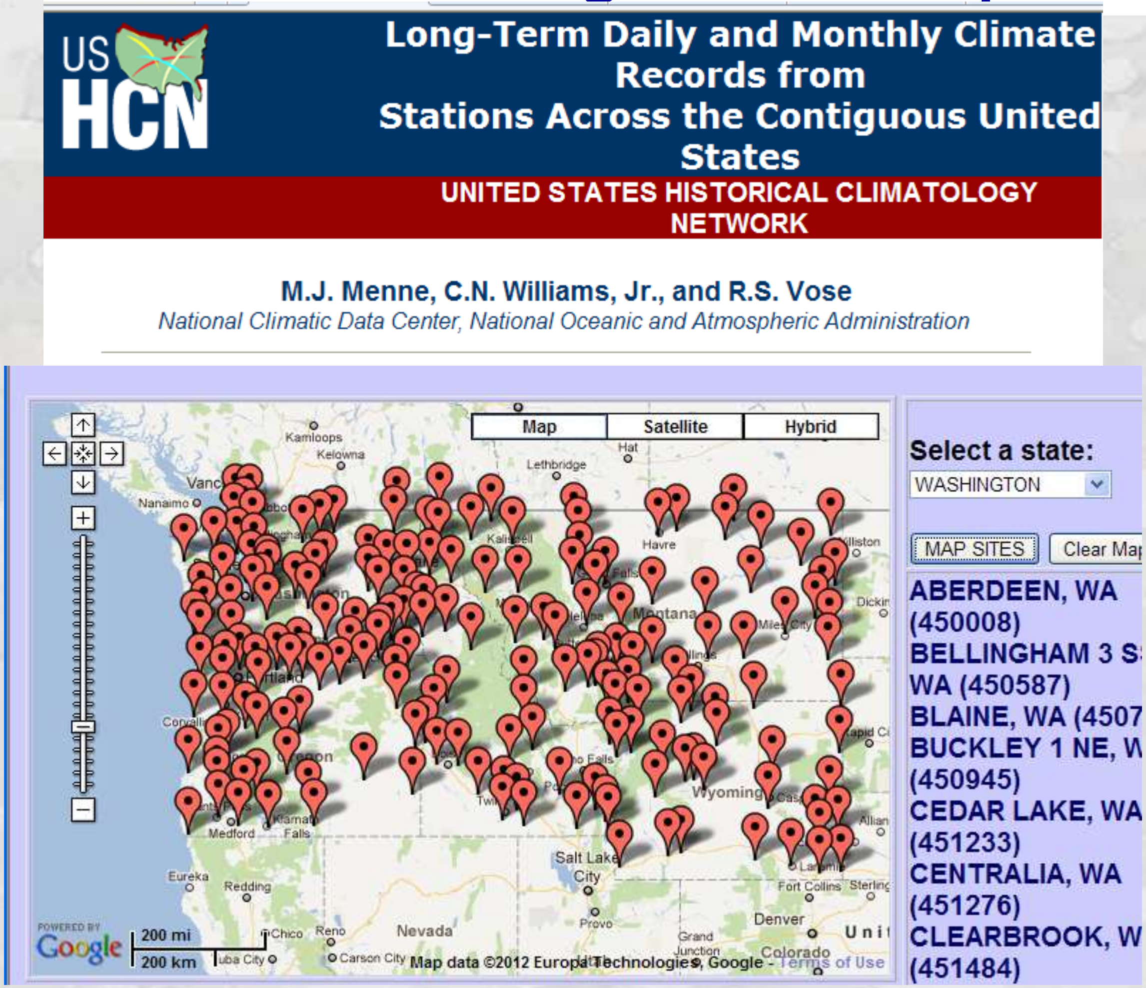
How Far is Too Far for Air Temperatures?



Mohseni et al. 1998. *WRR* **34**:2685-2692.

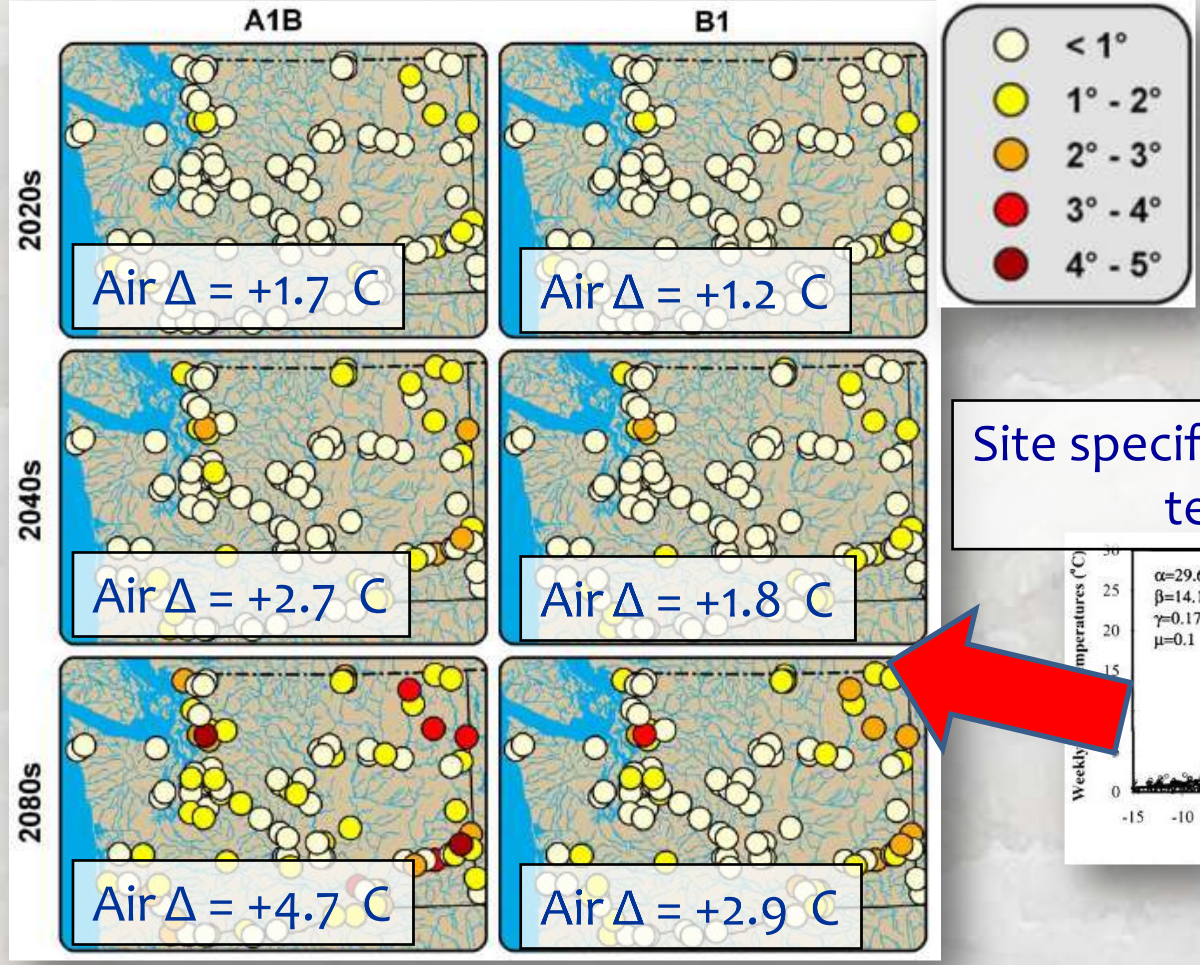
How Far is Too Far for Air Temperatures?

Where are best long-term air temperature records?

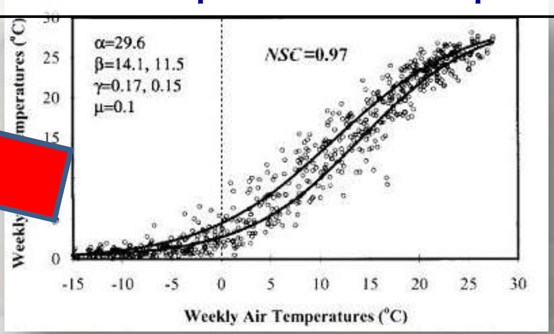


Projecting Temp Increases from Short-Term Records

Maximum Weekly Stream Temperature Increases



Site specific air-stream temp relationships



$r^2 = 0.7 - 0.9$

Mantua et al. 2010. *Climatic Change* **102:**187-223.

Information from Data:

4) Stream temperature climate maps

NorWeST: A Regional Stream Temperature Database & Model for High-Resolution Climate Vulnerability Assessments

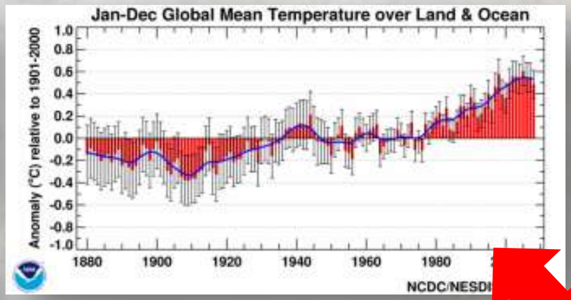
Dan Isaak, Seth Wenger[1], Erin Peterson[2], Jay Ver Hoef[3] Charlie Luce, Steve Hostetler[4], Jason Dunham[4], Jeff Kershner[4], Brett Roper, Dave Nagel, Dona Horan, Gwynne Chandler, Sharon Parkes, Sherry Wollrab

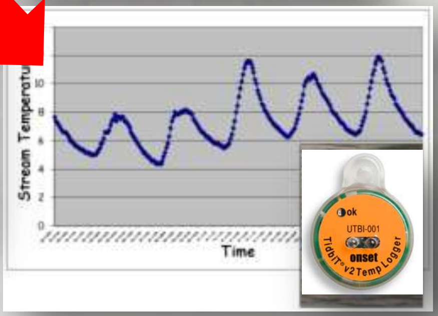
TROUT UNLIMITED

CSIRO

NOAA

USGS science for a changing world

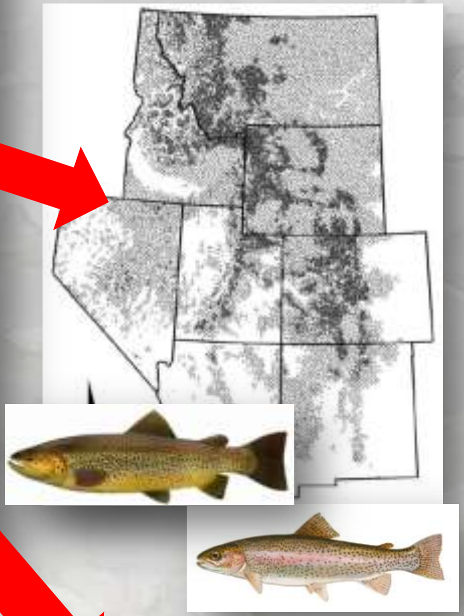


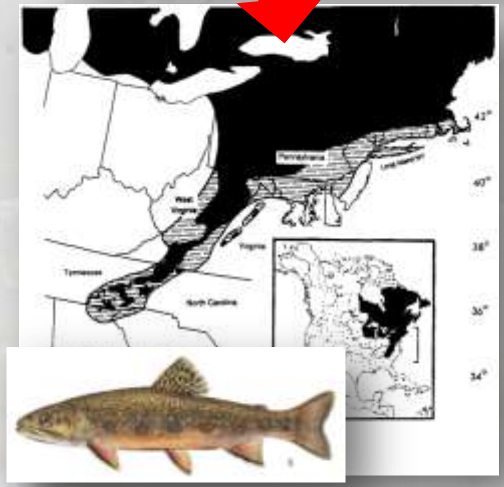


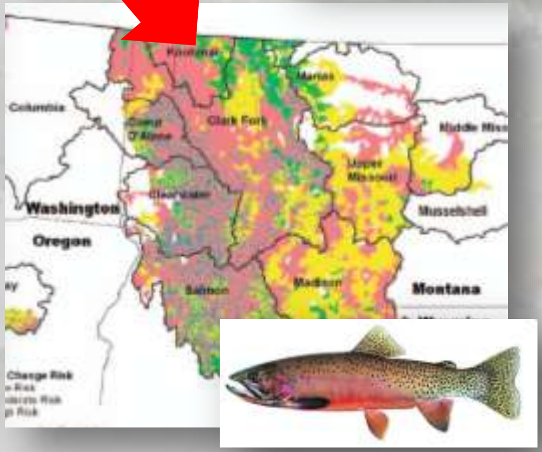
Great Northern
LANDSCAPE CONSERVATION COOPERATIVE

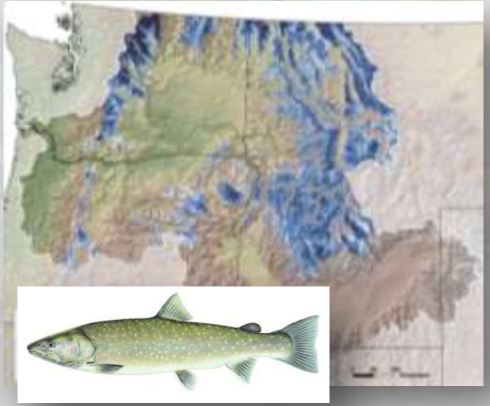
Regional BioClimatic Assessments

No stream temperature component





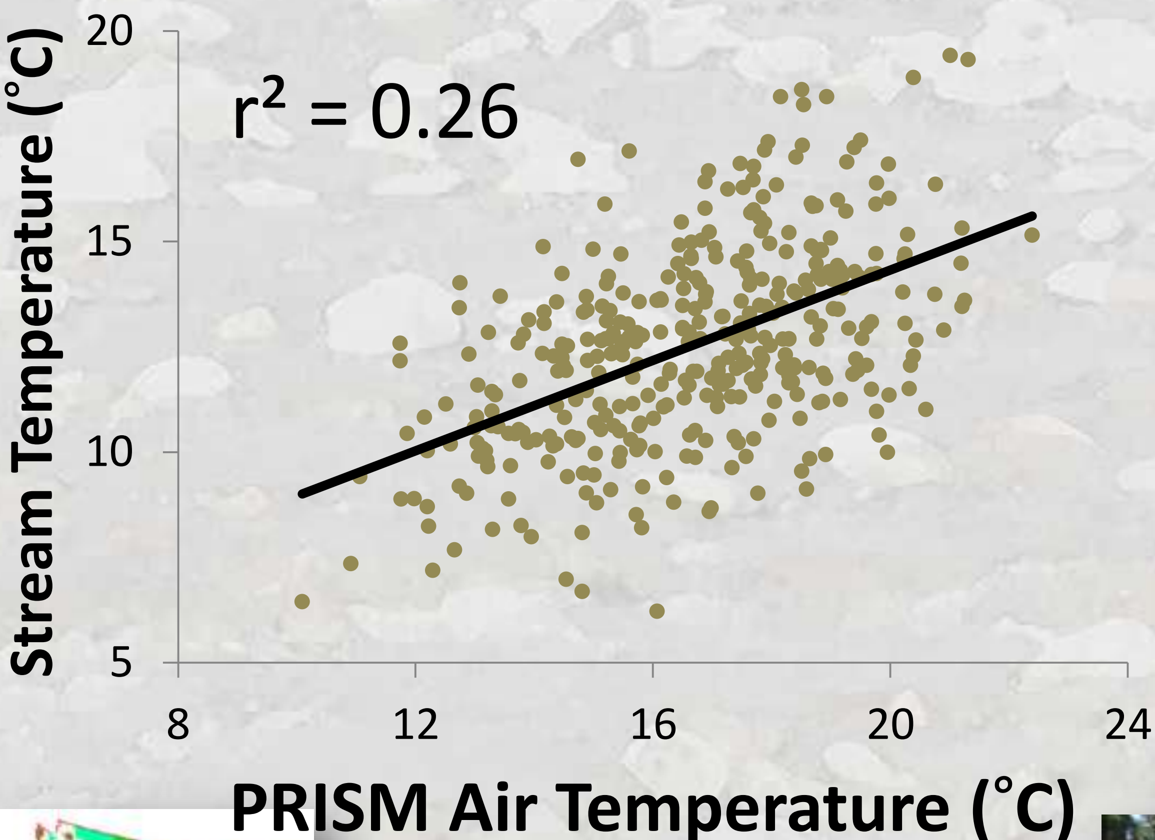


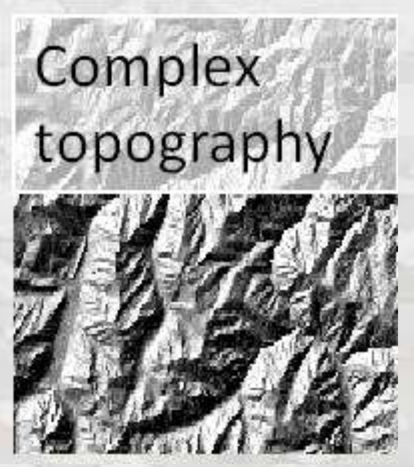


Air Temperatures…

- Meisner 1988, 1990
- Eaton & Schaller 1996
- Keleher & Rahel 1996
- Rahel et al. 1996
- Mohseni et al. 2003
- Flebbe et al. 2006
- Rieman et al. 2007
- Kennedy et al. 2008
- Williams et al. 2009
- Wenger et al. 2011
- Almodovar et al. 2011
- Etc.

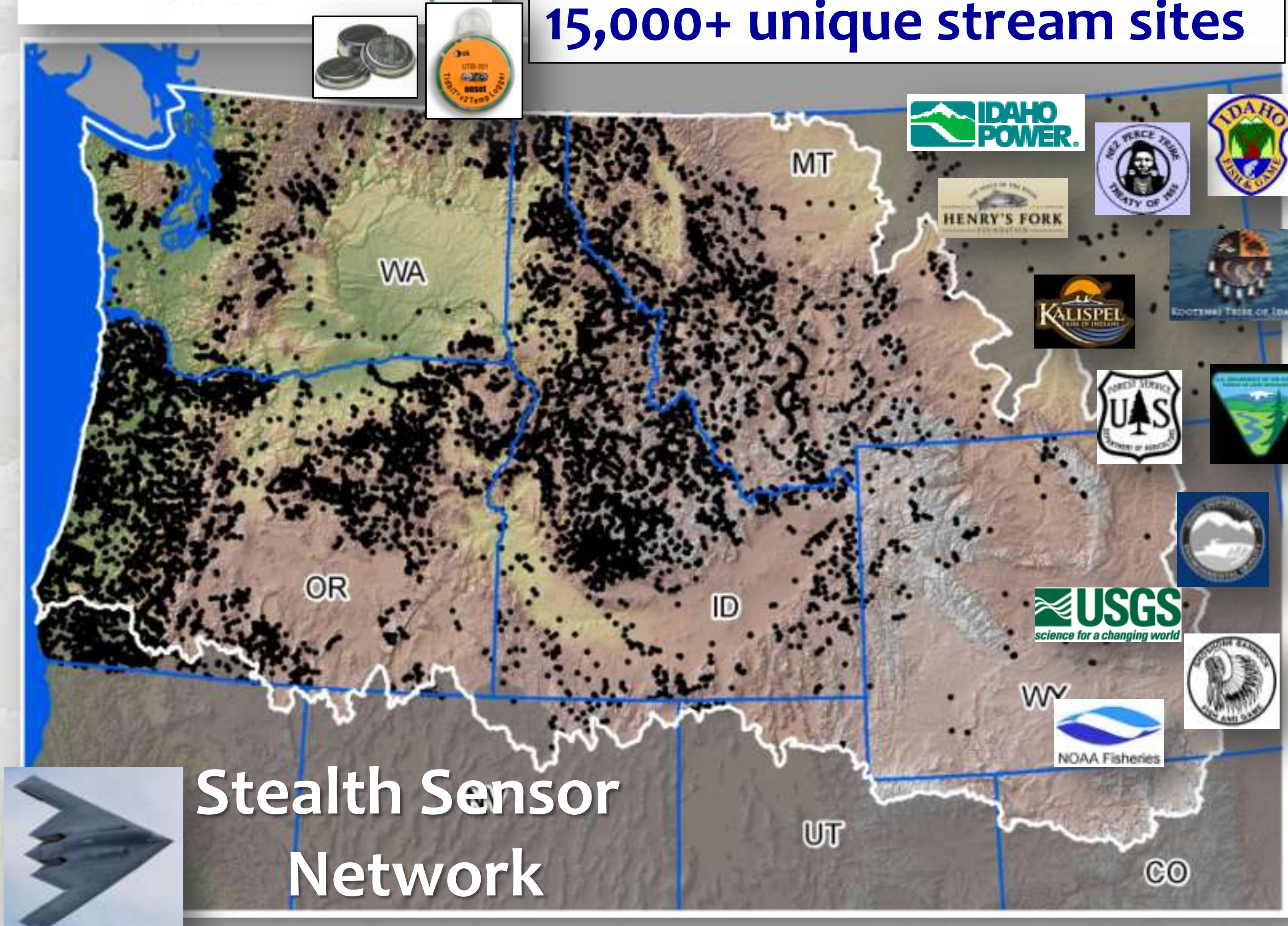
Spatial Air Pattern ≠ Stream Temp





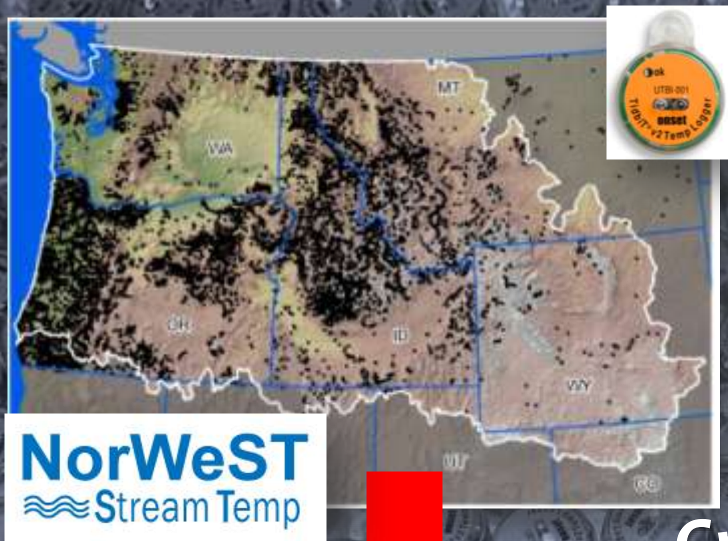
NorWeST Stream Temp

45,000,000+ hourly records
45,000+ summers measured
15,000+ unique stream sites

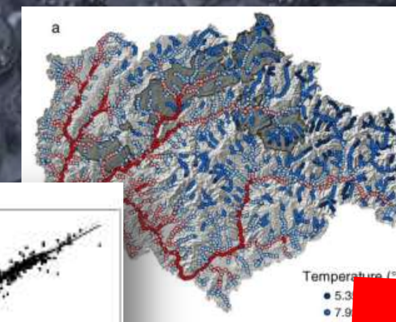


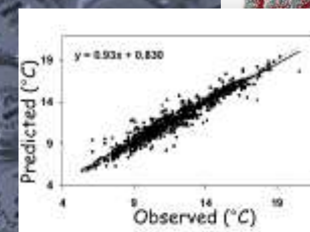
Stealth Sensor Network

Regional Temperature Model

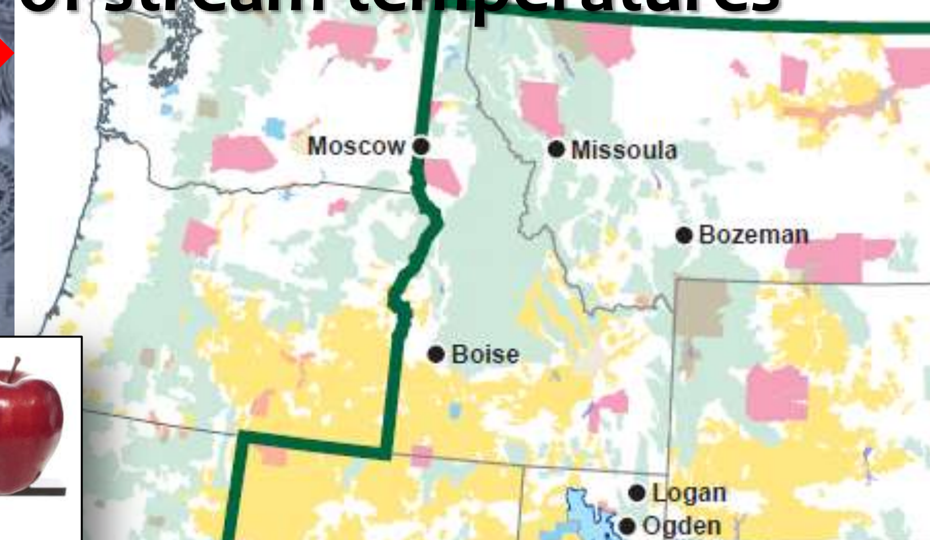


Accurate temperature models

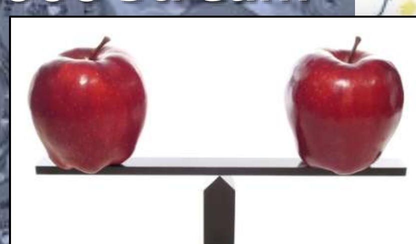




Cross-jurisdictional "maps" of stream temperatures

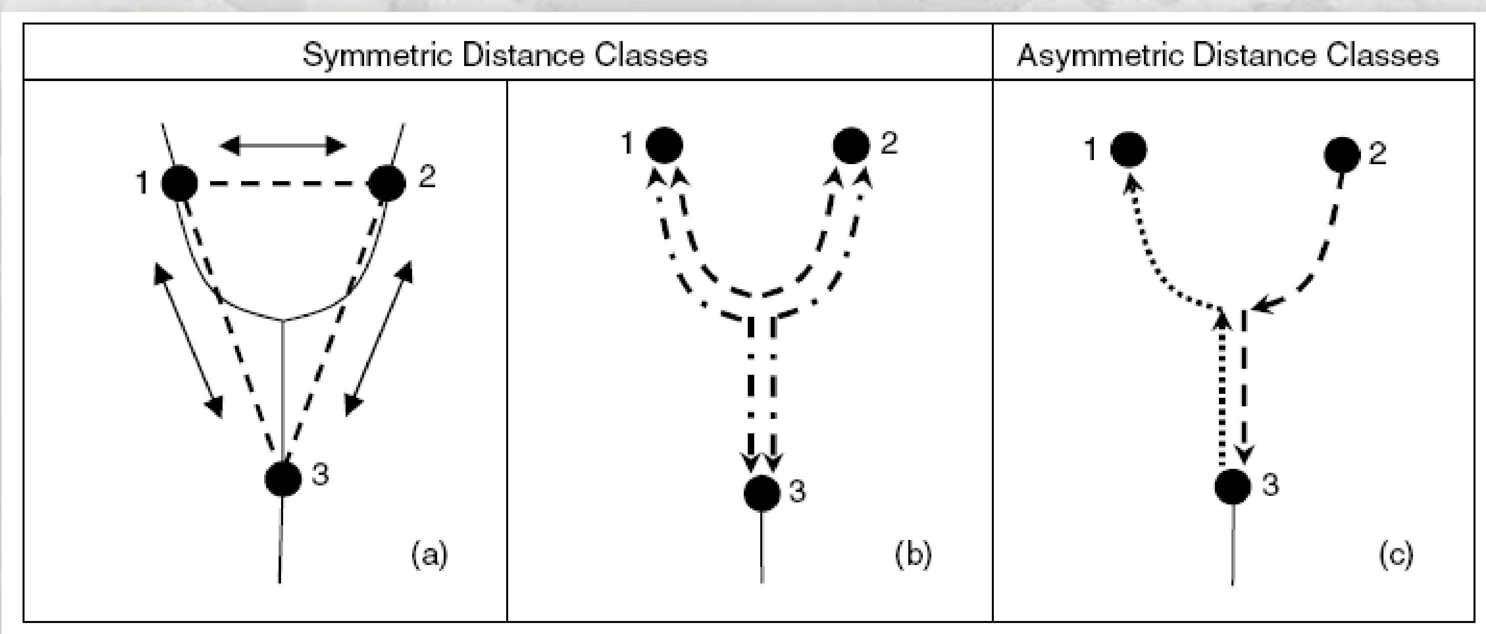


Consistent datum for strategic assessments across 350,000 stream kilometers



Spatial Statistical Stream Models

Valid means of estimation on networks



Advantages:

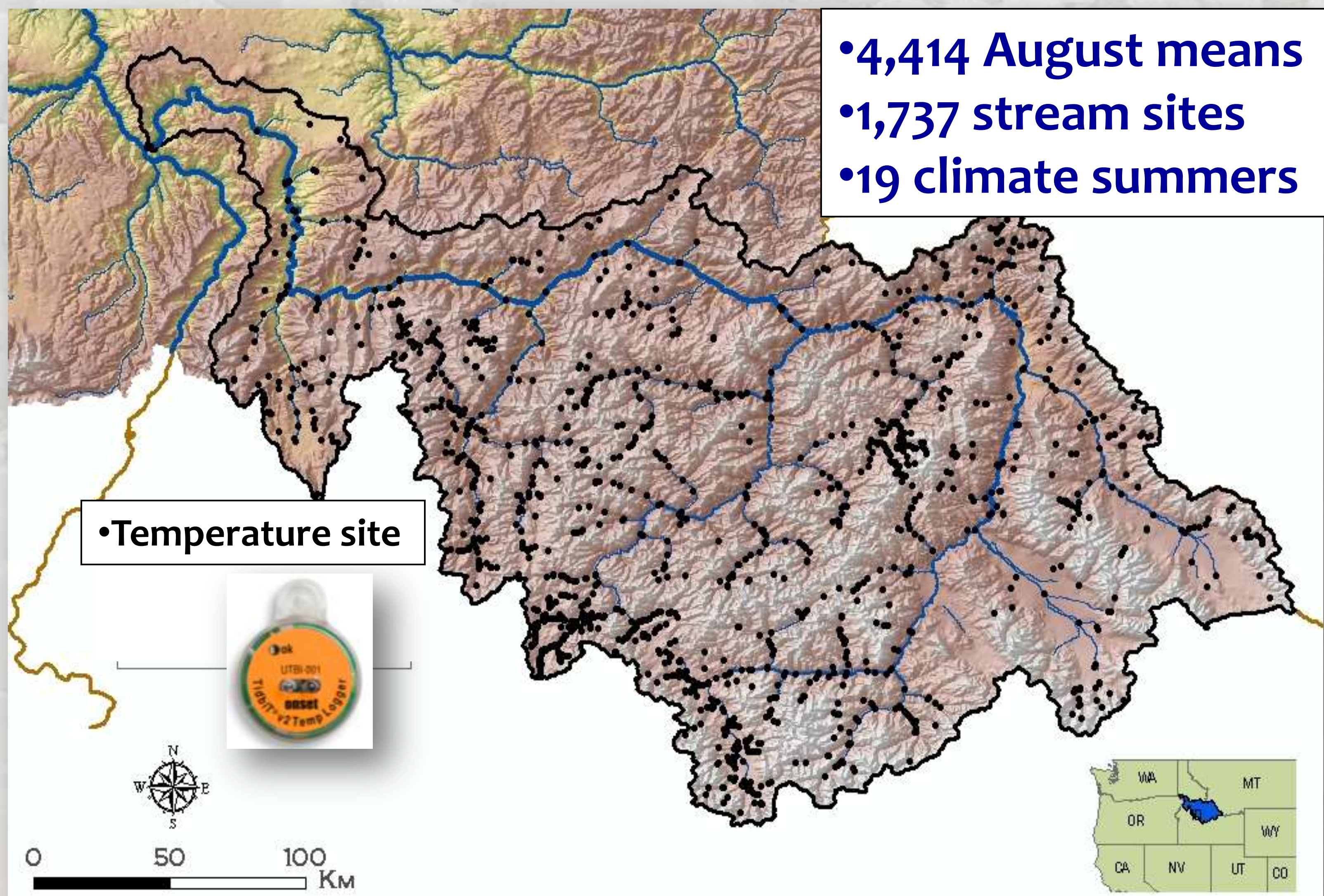
- Flexible & valid covariance structures that accommodate network topology & autocorrelation
- Much improved predictive ability & parameter estimates relative to non spatial models

Ver Hoef et al. 2006; Peterson & Ver Hoef 2010; Ver Hoef & Peterson 2010

Example: Salmon River Basin

Data extracted from NorWeST

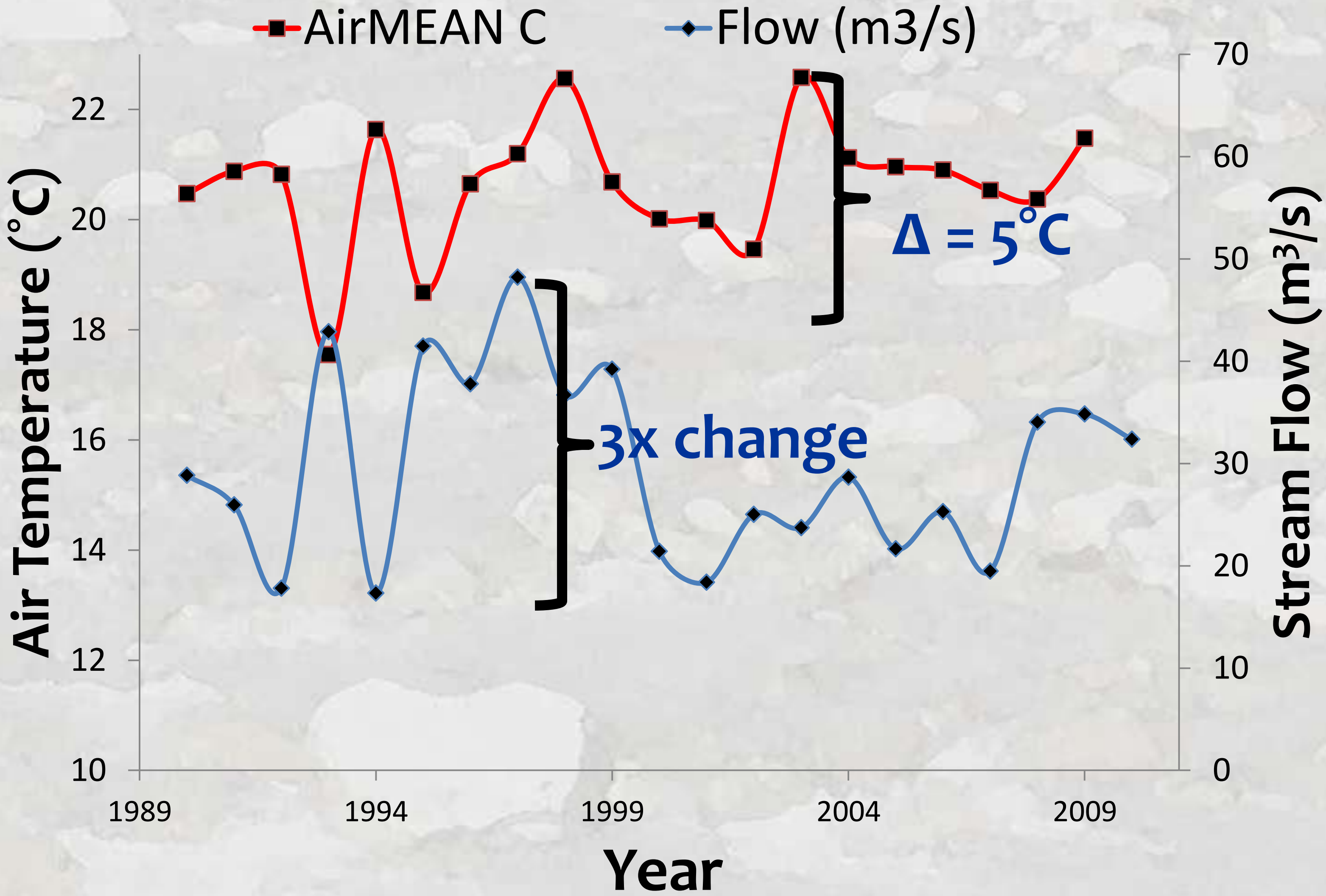
- 4,414 August means
- 1,737 stream sites
- 19 climate summers



- Temperature site

Climatic Variability in Historical Record

Extreme years include late 21st-Century “averages”



Salmon River Temperature Model

n = 4,414

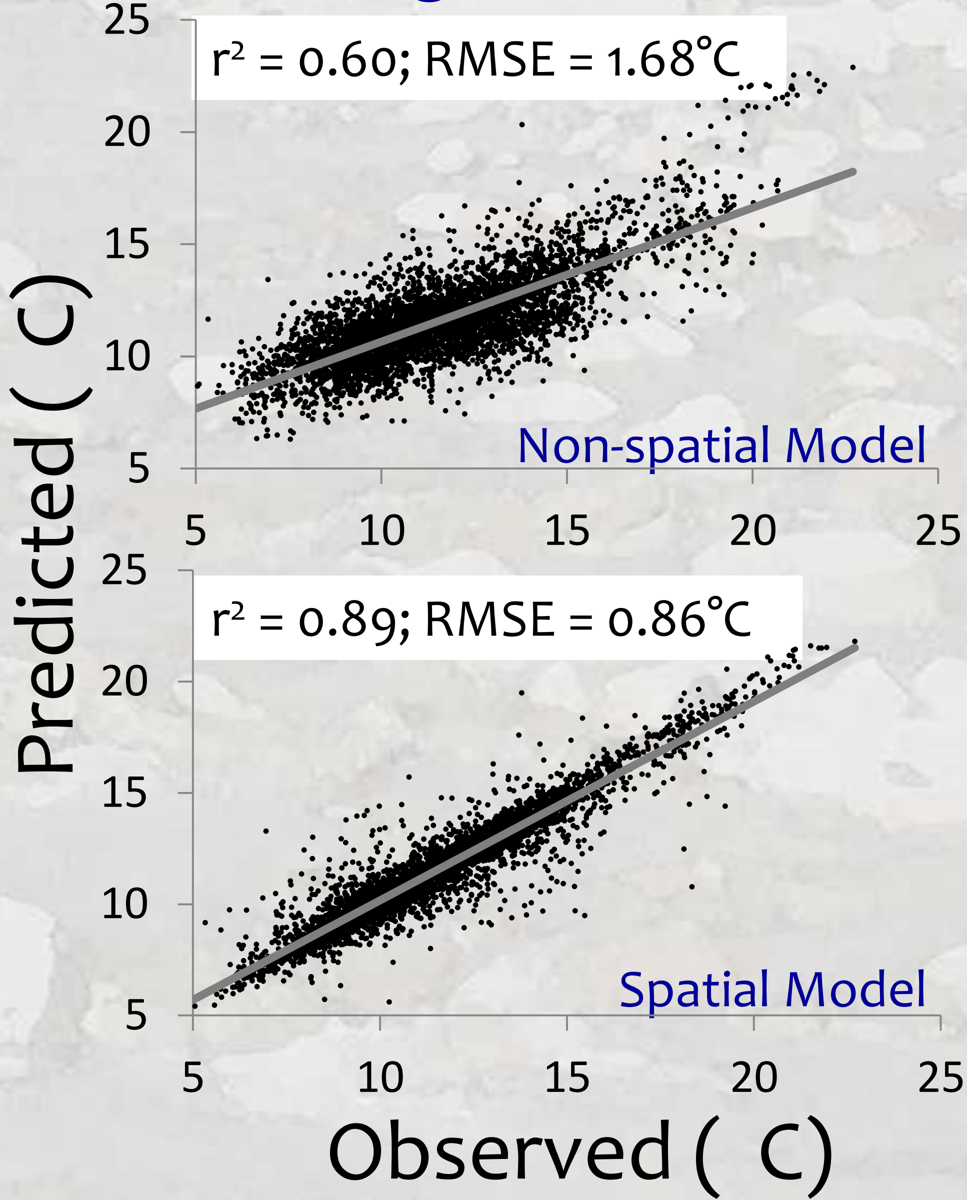
Covariate Predictors

1. Elevation (m)
2. Canopy (%)
3. Stream slope (%)
4. Ave Precipitation (mm)
5. Latitude (km)
6. Lakes upstream (%)
7. Glaciers upstream (%)
8. Baseflow Index
9. Watershed size (km^2)
10. Discharge (m^3/s)*
11. Air Temperature (˚C)#

* = USGS gage data

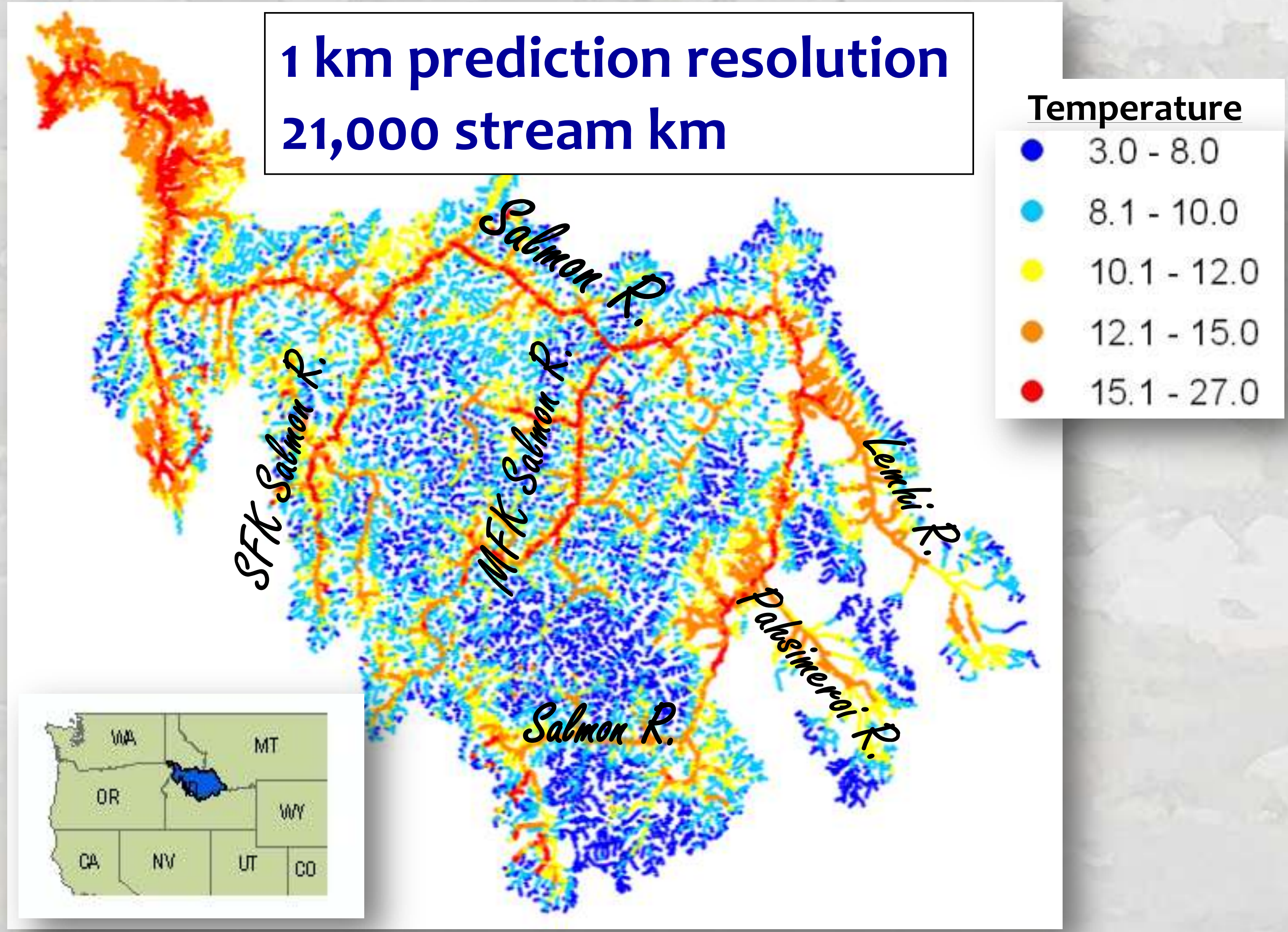
= NCEP RegCM3 reanalysis

Mean August Temperature



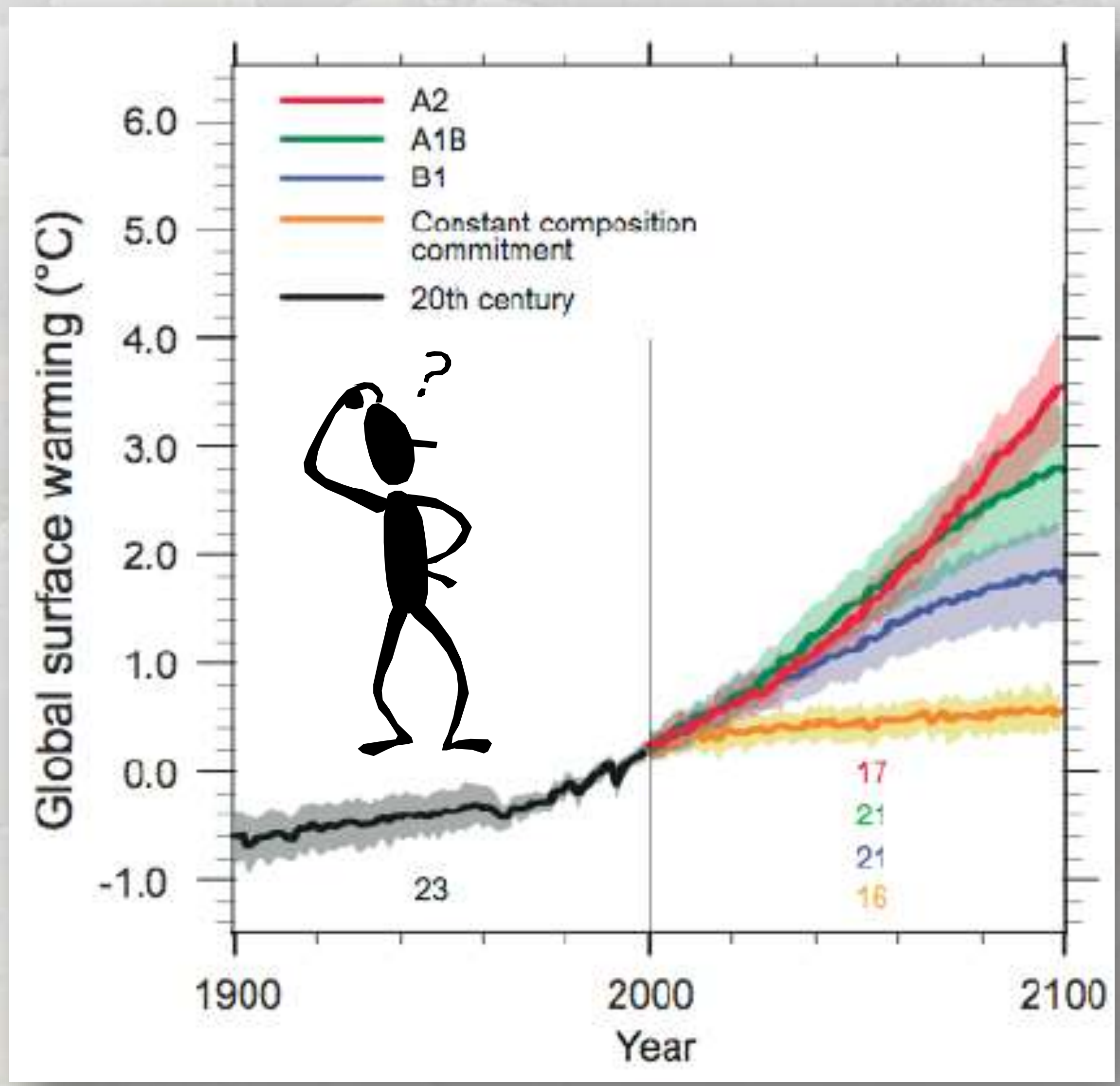
Salmon River Temperature Map

2002-2011 mean August stream temperatures



Climate Scenario Maps

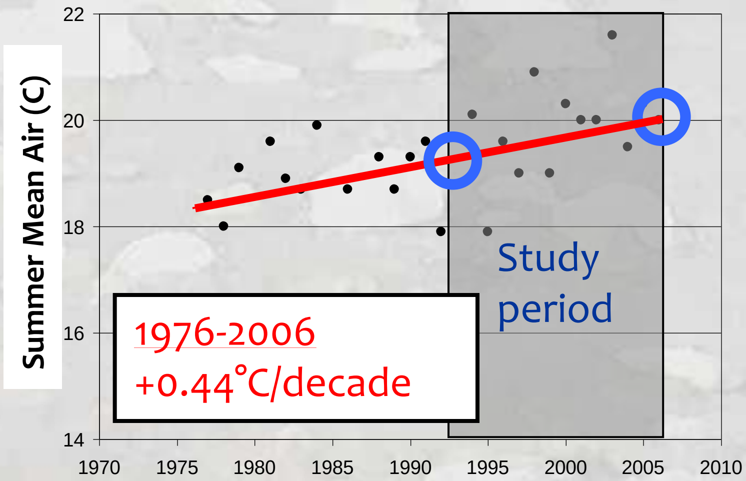
Many possibilities once model exists…



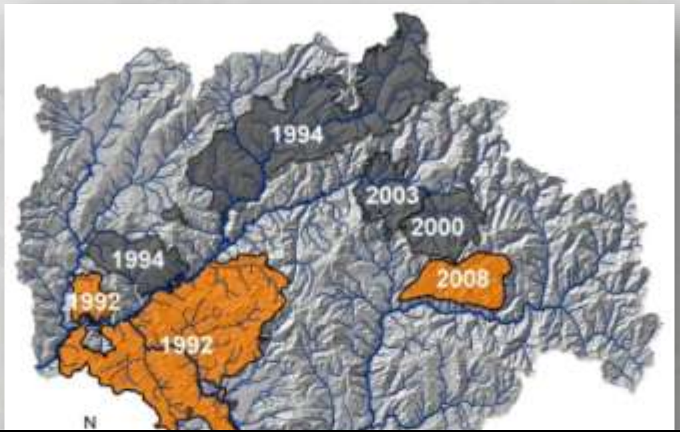
Adjust air & discharge values to represent scenarios

Historical Climate Changes…

Summer Air Temperature

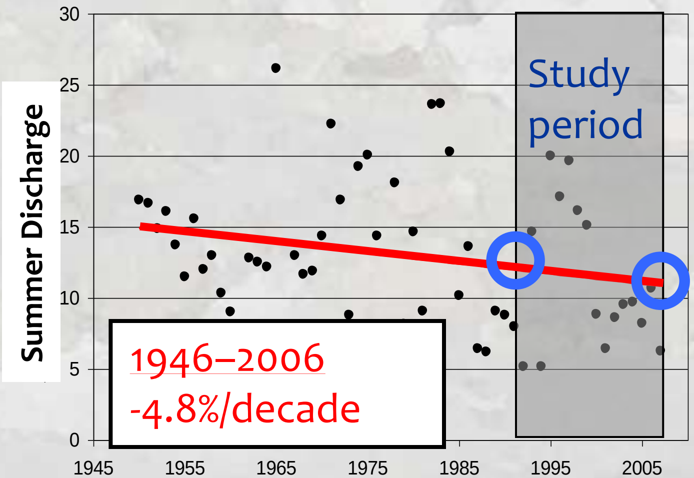


Recent Wildfires



14% burned during 93–06 study period
30% burned from 92-08

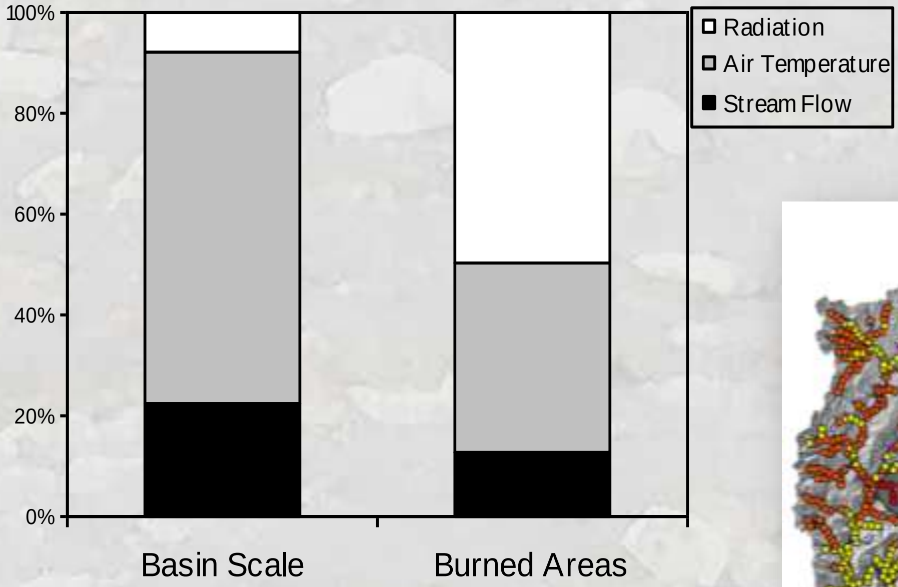
Summer Stream Flow



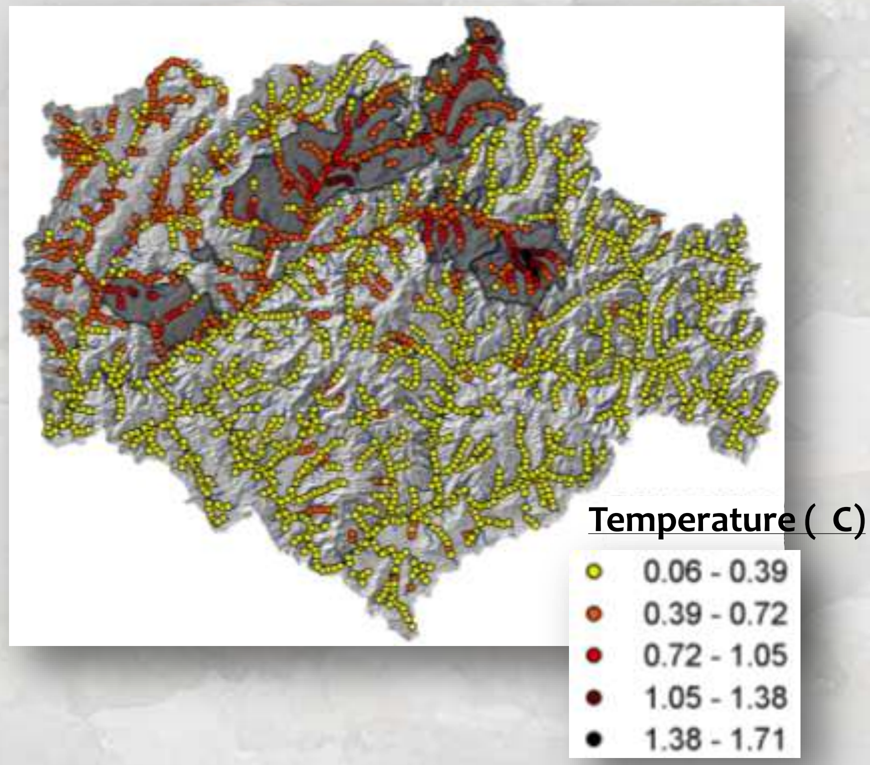
Changes in Average Summer Temperatures from 1993-2006

Δ0.38 C
0.27°C/10y

Δ0.70 C
0.50°C/10y



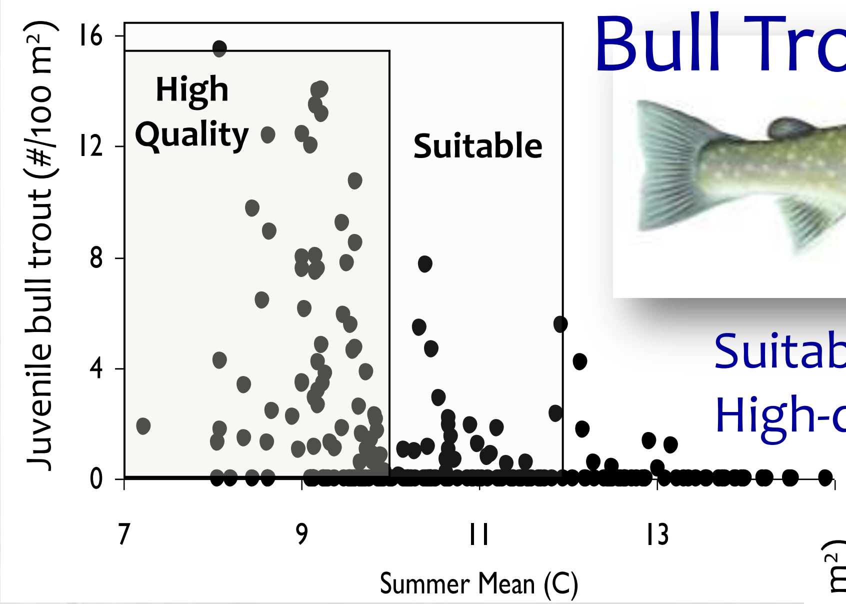
Thermal Gain Map



Isaak et al. 2010. *Ecol. Apps.* **20:**1350-1371

Effects on Thermal Habitat

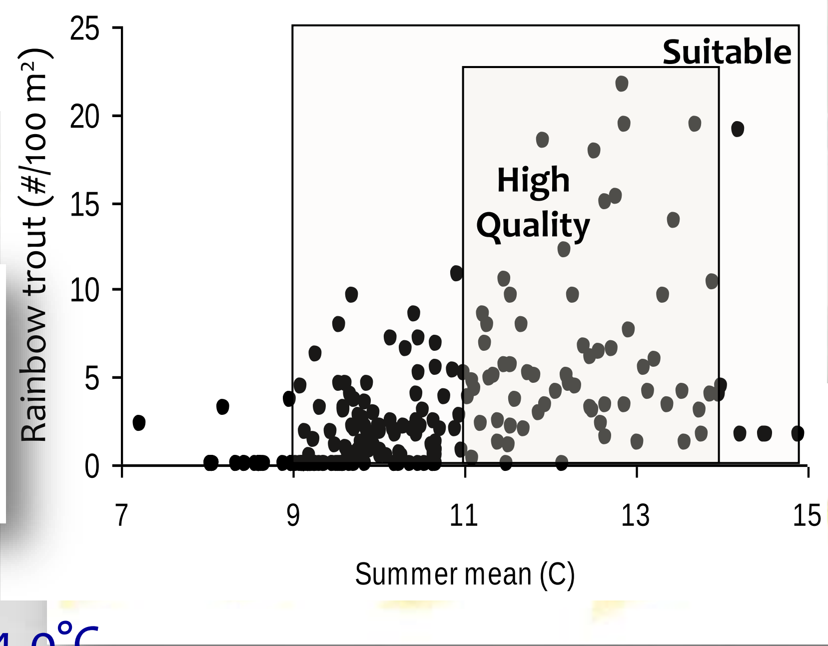
Define using thermal criteria



Bull Trout

Suitable habitat < 12.0°C
High-quality habitat < 10.0°C

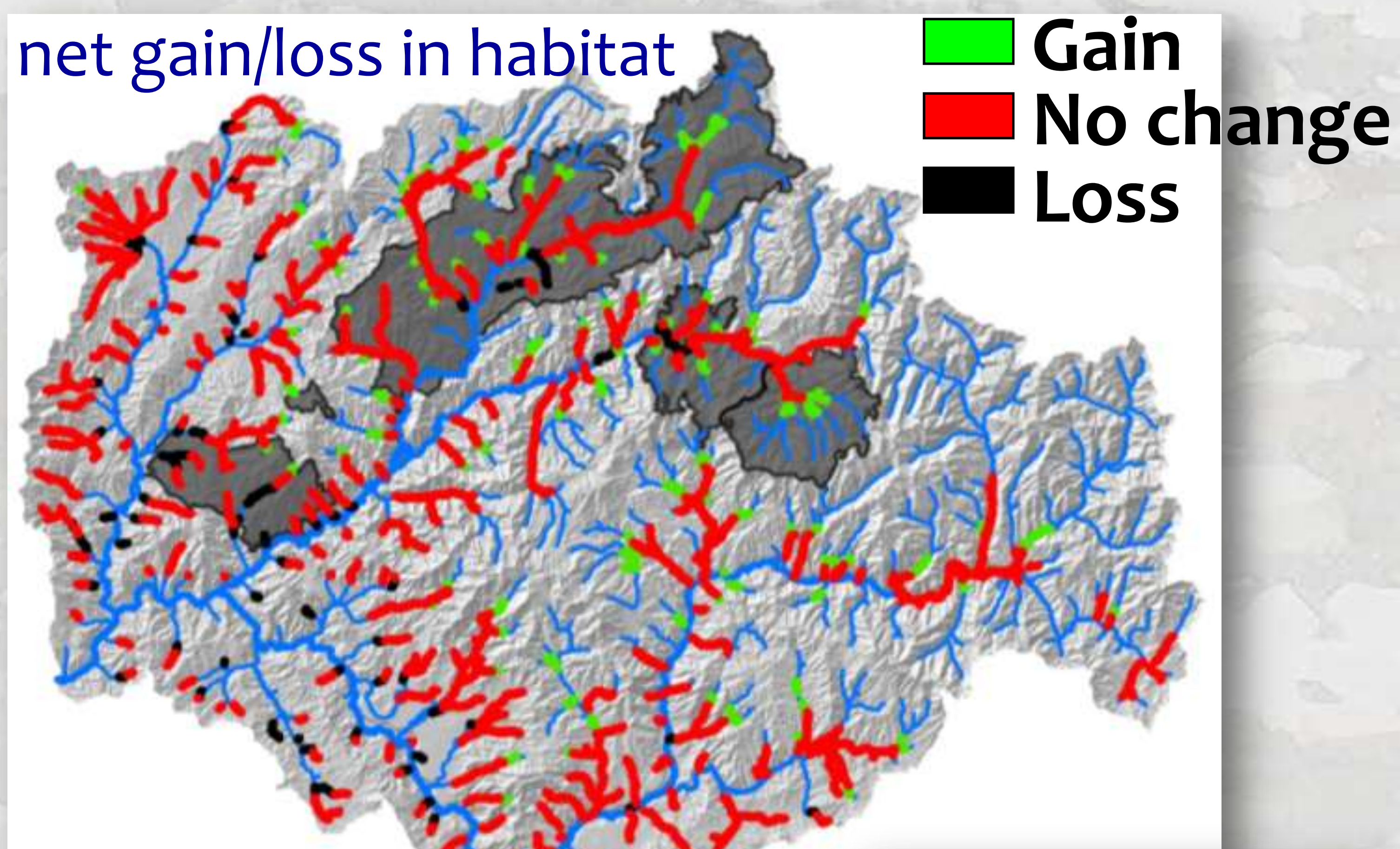
Rainbow Trout



Suitable habitat = > 9.0°C
High-quality habitat = 11.0-14.0°C

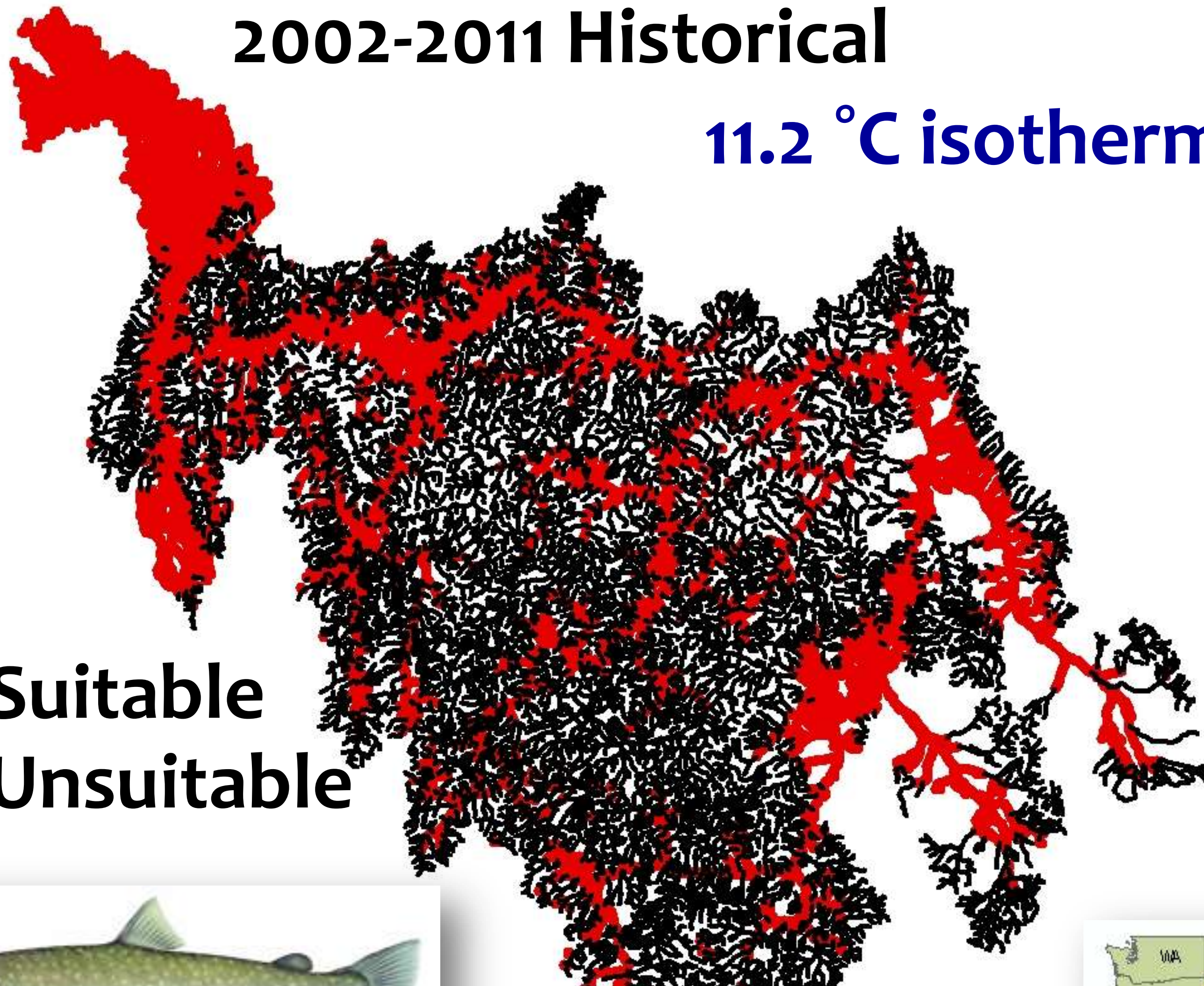
Changes in Rainbow Trout Habitat (1993-2006)

No net gain/loss in habitat

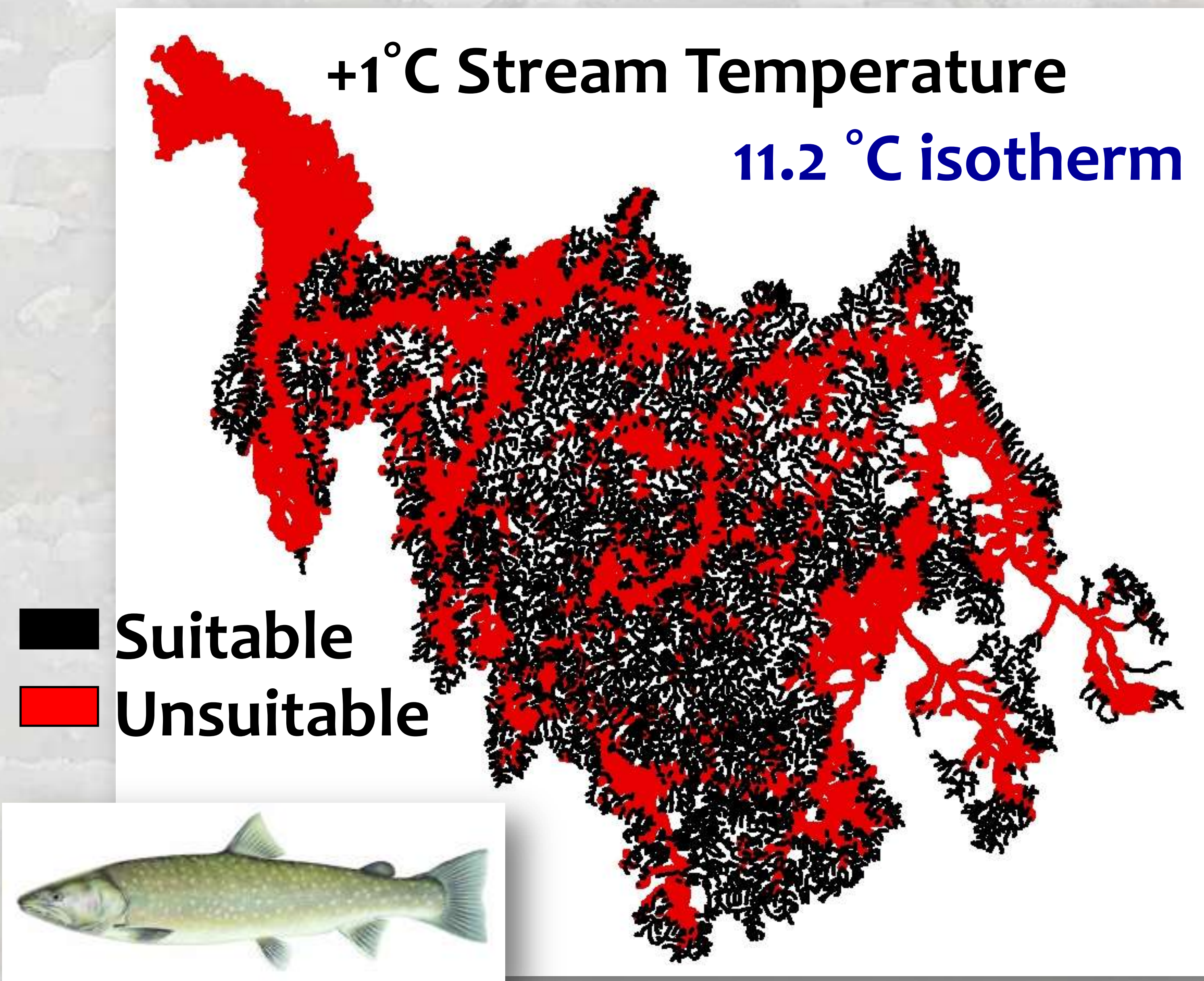


Isaak et al. 2010. *Ecol. Apps.* **20**:1350-1371

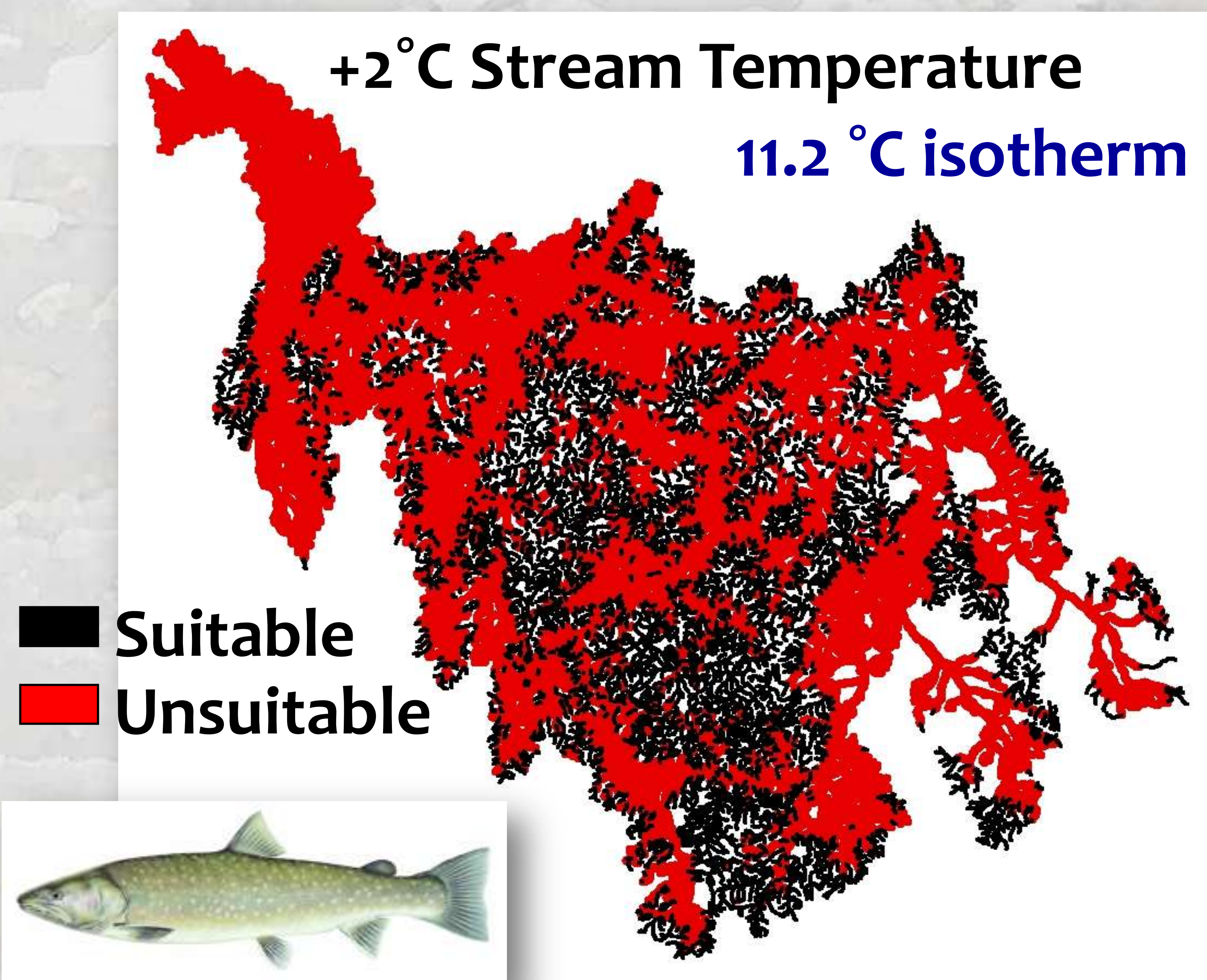
Salmon River Bull Trout Habitats



Salmon River Bull Trout Habitats

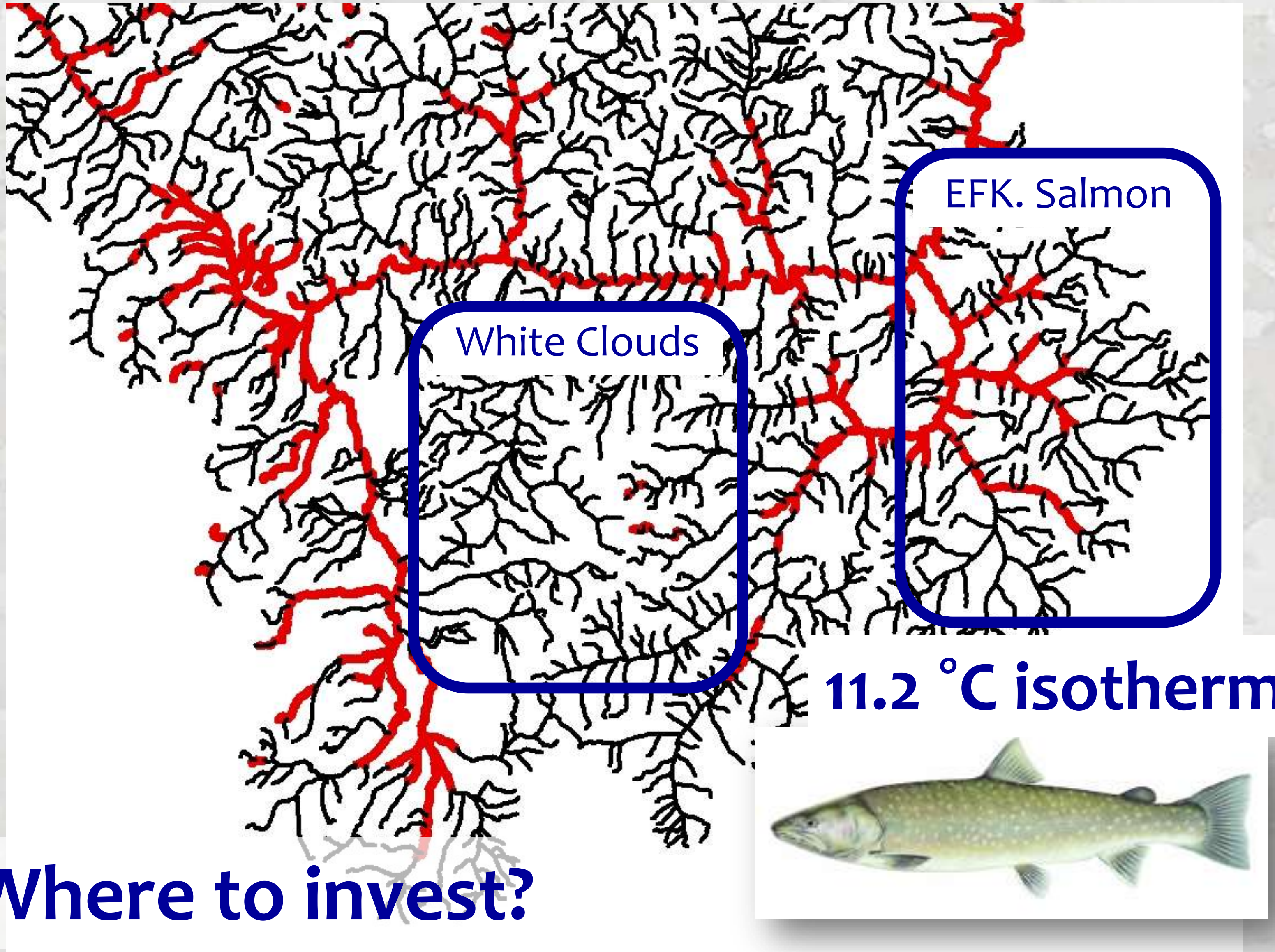


Salmon River Bull Trout Habitats



Spatial Variation in Habitat Loss

2002-2011 historical scenario

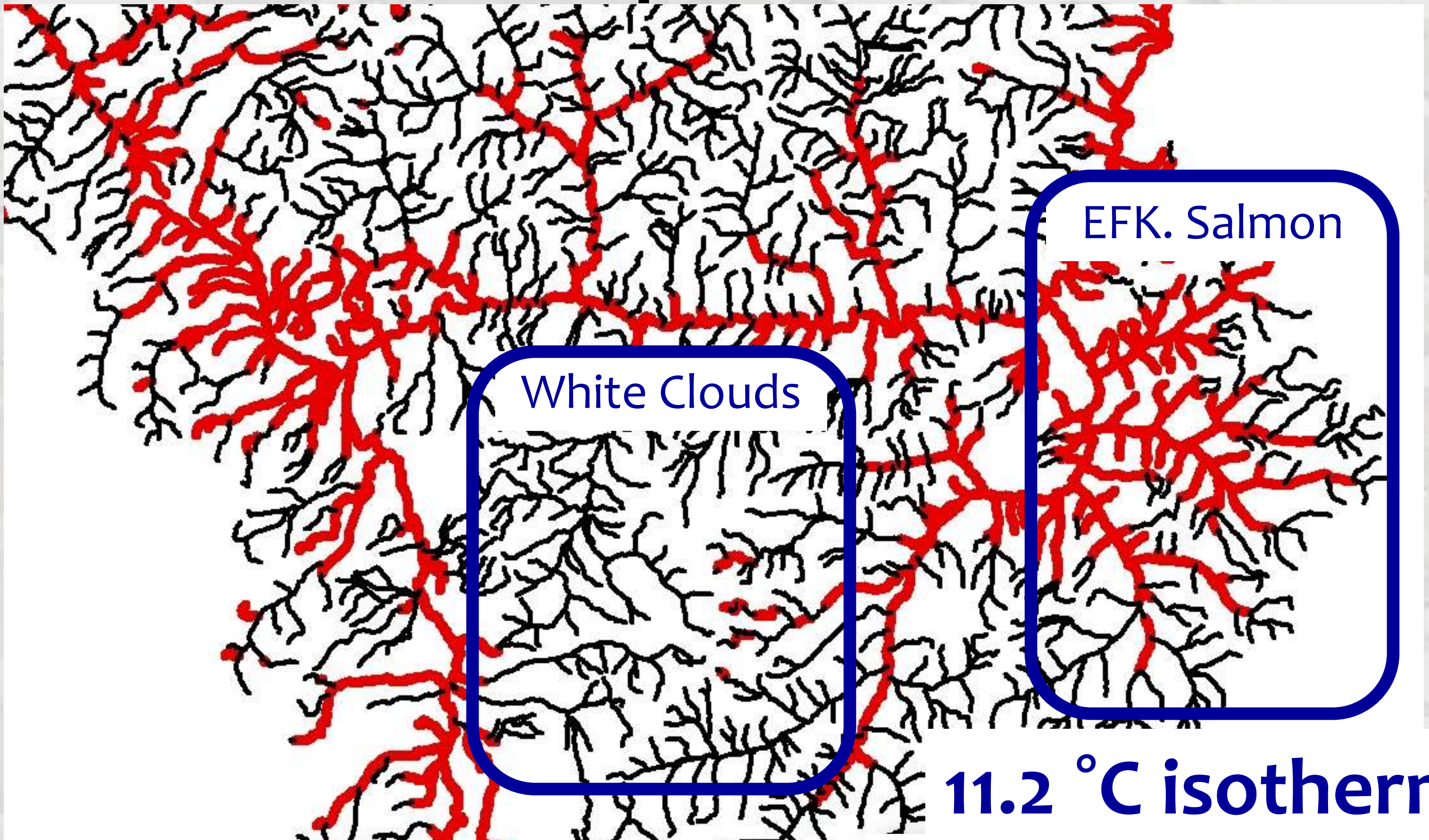


11.2 °C isotherm

Where to invest?

Spatial Variation in Habitat Loss

+1°C stream temperature scenario

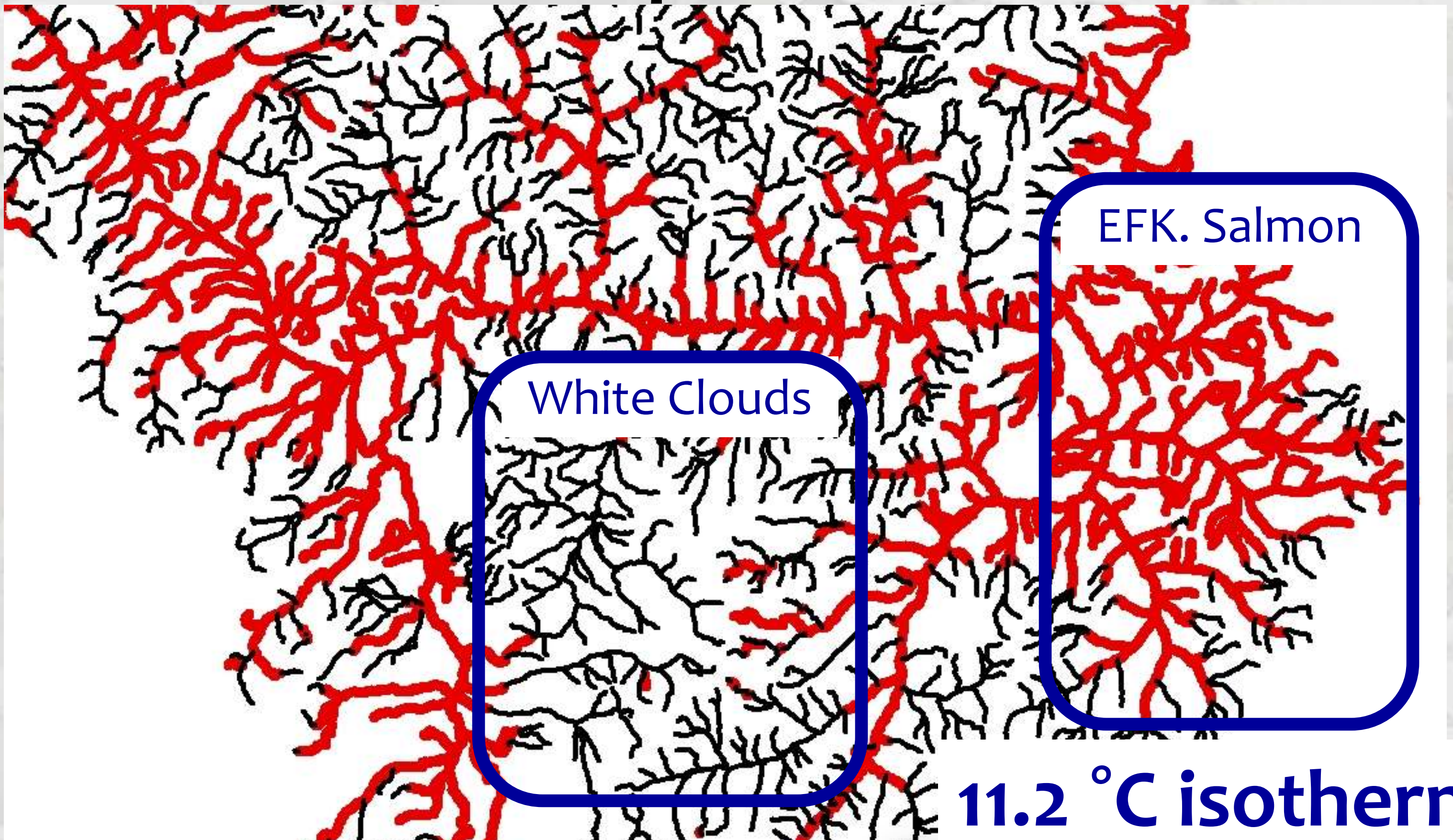


11.2 °C isotherm

Where to invest?

Spatial Variation in Habitat Loss

+2˚C stream temperature scenario



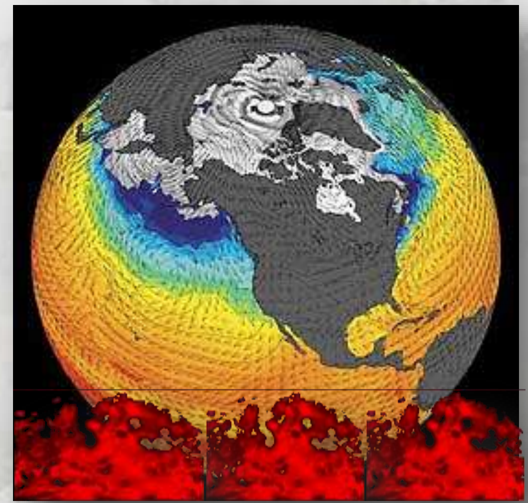
11.2 ˚C isotherm

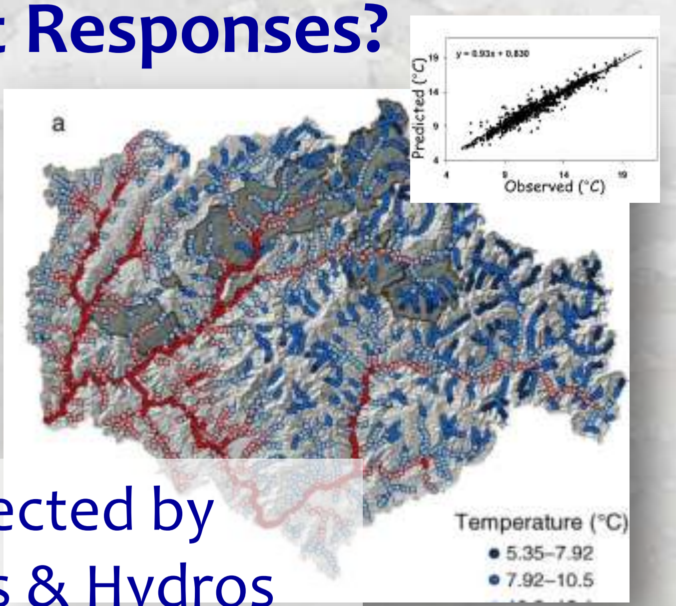
Where to invest?

Models Developed from Everyone's Data

Collaborative Management Responses?

GCM



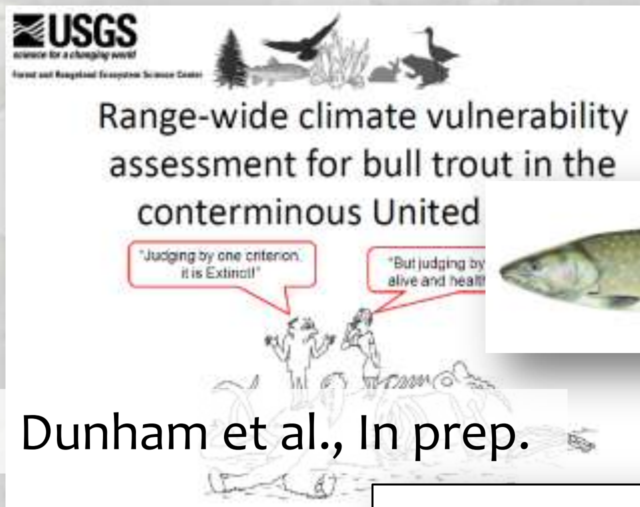


Data Collected by
Local Bios & Hydros

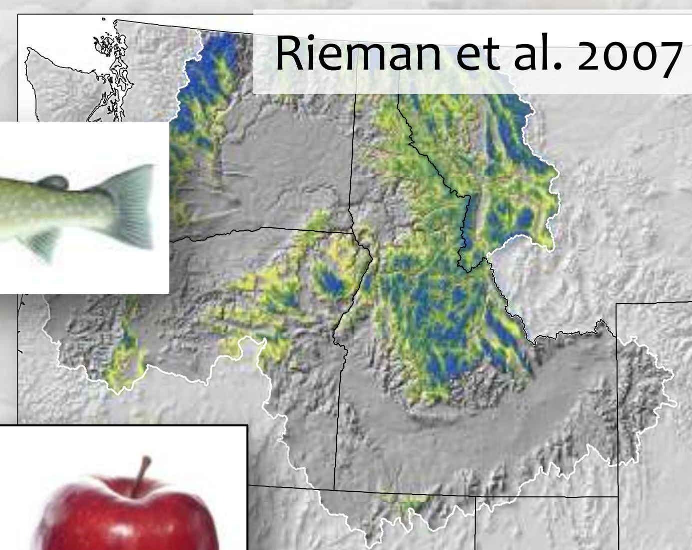
?

Management
Decisions

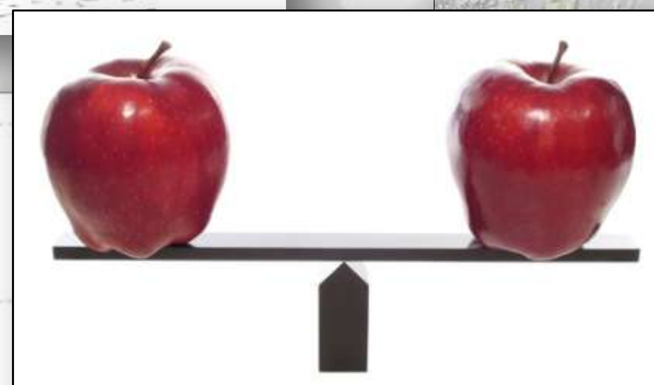
More Precise Bioclimatic Assessments

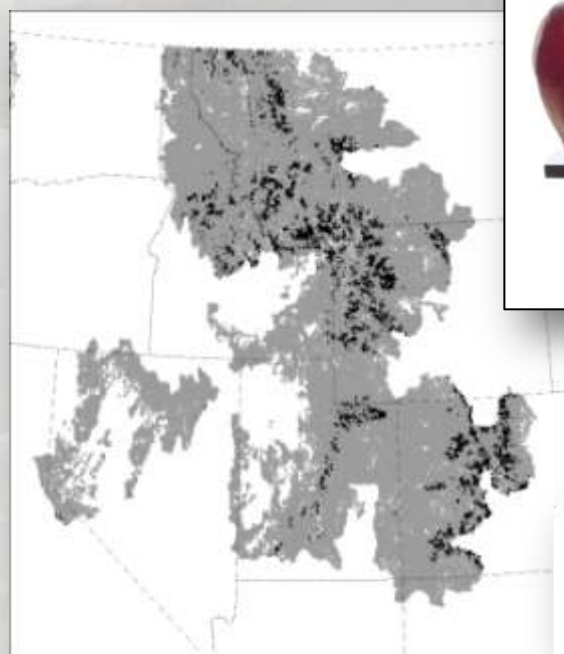


Dunham et al., In prep.

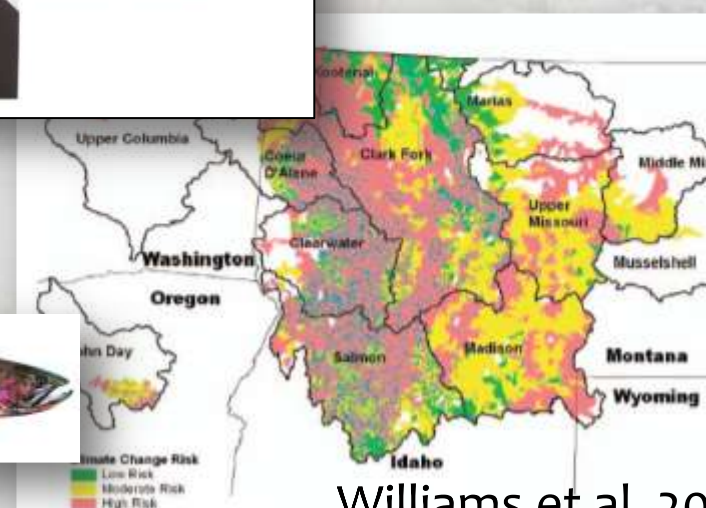


Rieman et al. 2007





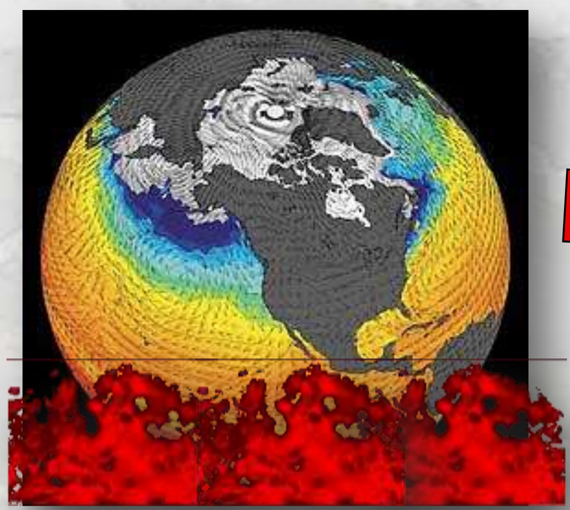
Wenger et al. 2011. *PNAS*.



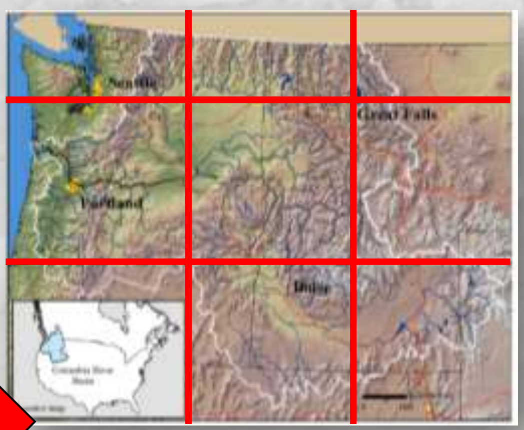
Williams et al. 2009

How Will Global Patterns Affect Temperatures in Aquatic Systems?

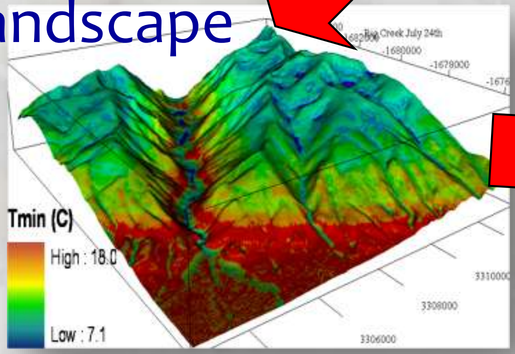
Global Climate



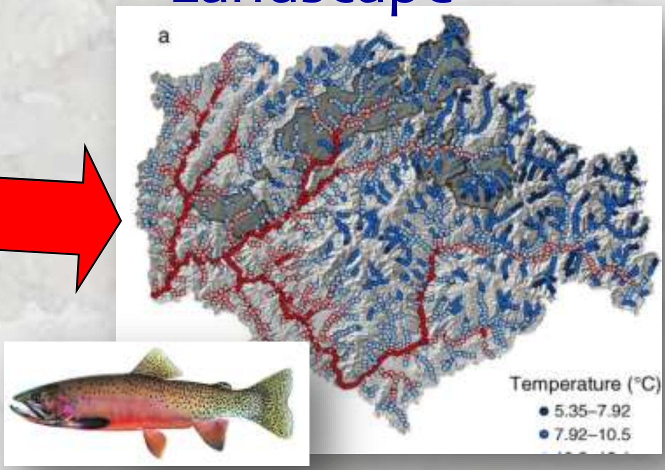
Regional



Terrestial Landscape



Riverine Landscape



Key Lessons…

1) Take stock of existing data. Simple maps showing where data exist are great organizing tools.

2) Where data are sparse, be opportunistic & aggressive with establishing new sites (worry about "perfect" later). The world is literally burning after all…

3) Use standardized protocols – georeference, monitor full year temperatures, use solar shields.

4) Long-term stream monitoring records are rare, so commit to some sites indefinitely. Supplement these with many others to describe spatial patterns (first 2 – 3 years yield most information).

5) New data will accumulate quickly, be prepared to organize and archive. Engage the research community to design procedures for extracting relevant information.

Relevant Publications…

Stream Temperature Modeling Approach…

Ecological Applications, 20(5), 2010, pp. 1350–1371
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Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network

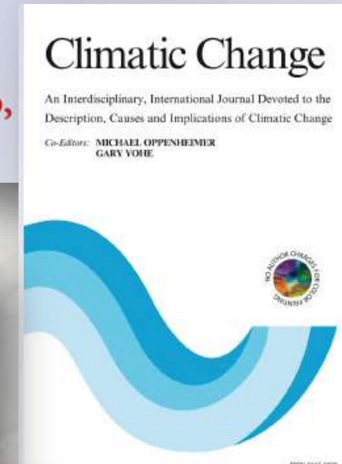
Daniel J. Isaak,[1,3] Charles H. Luce,[1] Bruce E. Rieman,[1] David E. Nagel,[1] Erin E. Peterson,[2] Dona L. Horan,[1] Sharon Parkes,[1] and Gwynne L. Chandler[1]

[1]U.S. Forest Service, Rocky Mountain Research Station, Boise Aquatic Sciences Laboratory, 322 E. Front Street, Suite 401, Boise, Idaho 83702 USA
[2]Commonwealth Scientific and Industrial Research Organisation (CSIRO), Division of Mathematical and Information Sciences, Indooroopilly, Queensland, Australia

Regional Stream Temperature Trends…

Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes

D. J. Isaak, S. Wollrab, G. Chandler



Epoxy field test and validation work …

An Evaluation of Underwater Epoxies to Permanently Install Temperature Sensors in Mountain Streams

Daniel J. Isaak* and Dona L. Horan
U.S. Forest Service, Rocky Mountain Research Station, B
322 East Front Street, Suite 401, Boise, Idaho 83702, US

RMRS — Air, Water, and Aquatic Environments Science Program

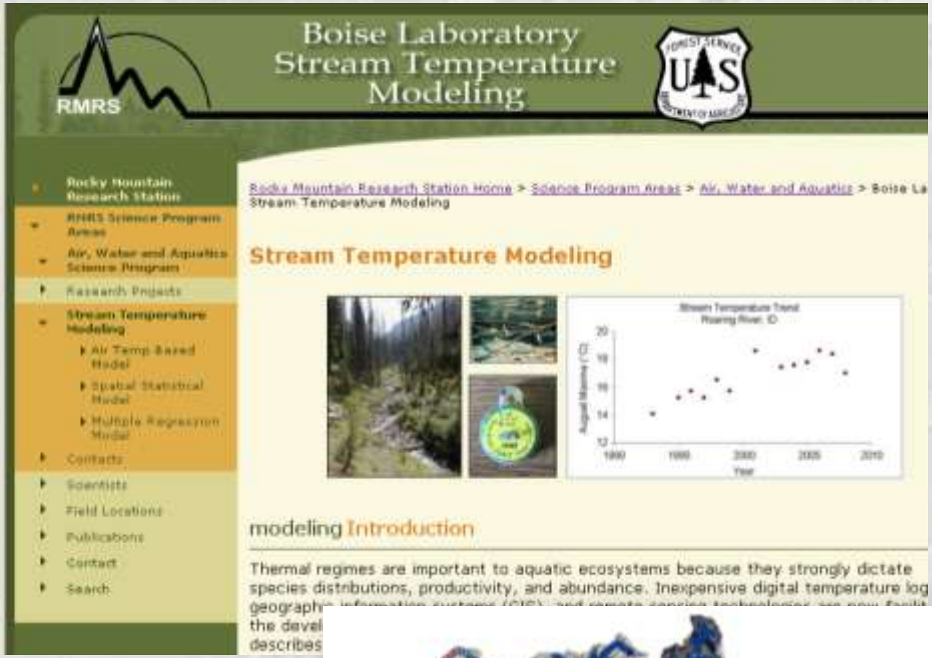
A Simple Method Using Underwater Epoxy to Permanently Install Temperature Sensors in Mountain Streams
(Version 3.12; updated 2/02/2012)

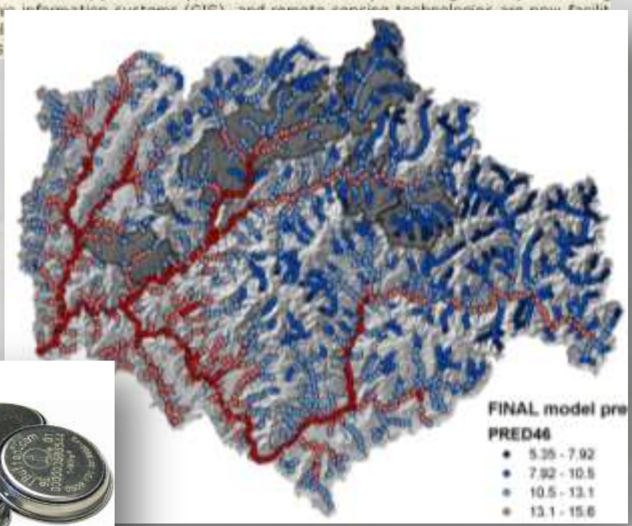
Dan Isaak (disaak@fs.fed.us), Dona Horan (dhoran@fs.fed.us), and Sherry Wollrab (sherrywollrab@fs.fed.us)

Epoxy "How-to" protocol…

Resources – Stream Temperature Website

Google " Forest Service Stream Temperature"

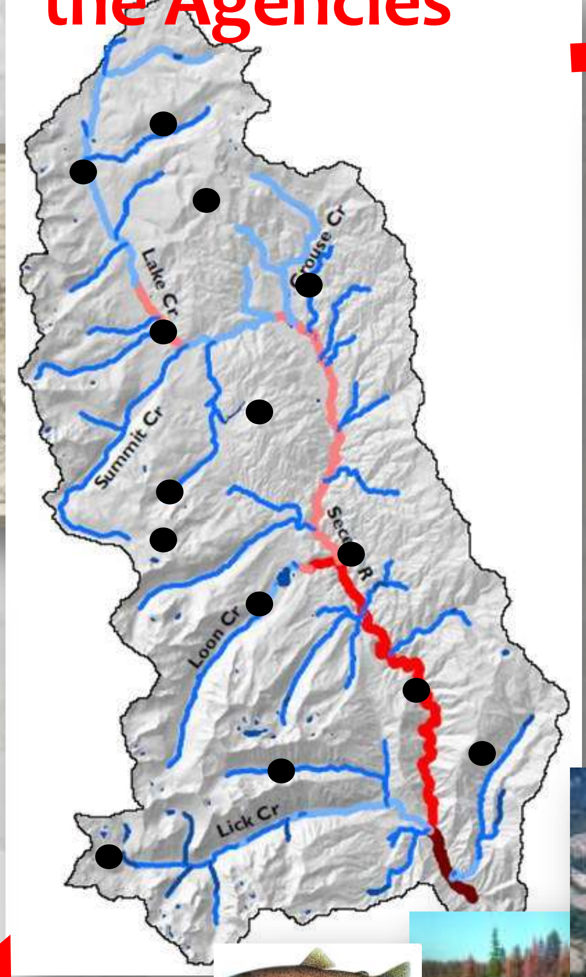




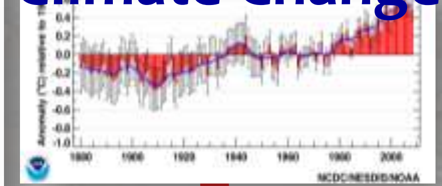
- Stream temperature publications & project descriptions & recent talks
- Protocols for temperature data collection & demonstration videos
- Processing macro for temperature data
- Dynamic GoogleMap showing current temperature monitoring sites

Connect the Dots to Map the Future

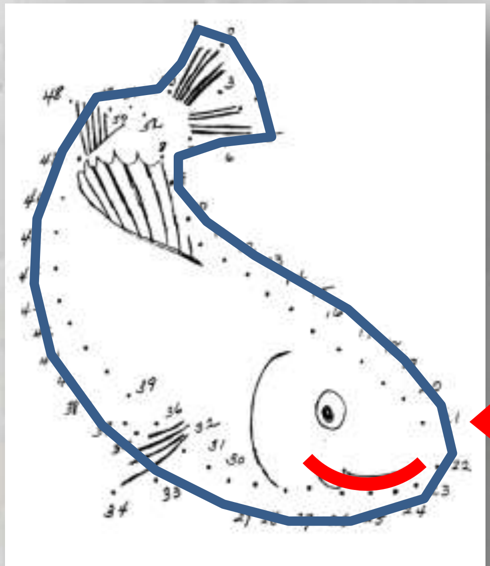
^ & the People & the Agencies



Climate Change



Urbanization & Population Growth



Land & Species Management


The End