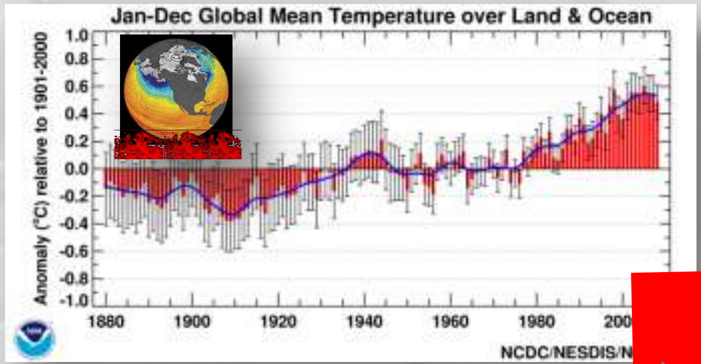
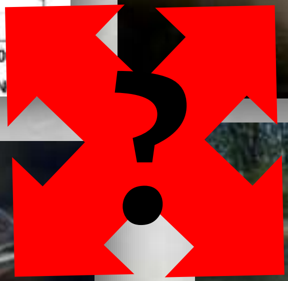
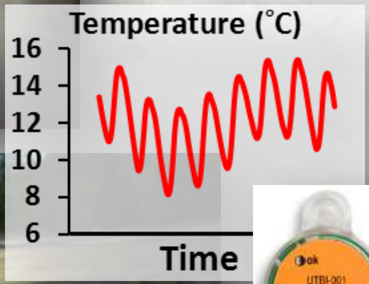
Monitoring & Modeling Stream Temperatures: Lessons Learned in the Rocky Mountains with Utility for Maine?

Dan Isaak, US Forest Service
Rocky Mountain Research Station







General outline:

1) Relevance of temperature & climate change to aquatic biotas

2) Trends in stream/lake temperatures

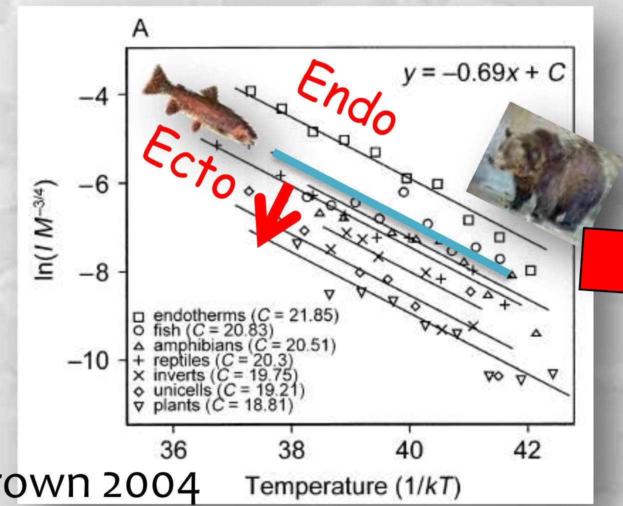
3) Monitoring protocols & sampling designs

4) Developing useful information from existing data (free money!)

5) Synergies that good temperature information creates

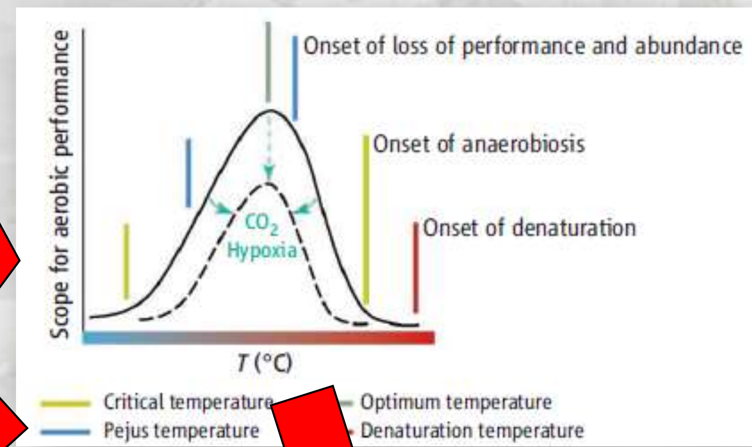
Temperature is Primary Control for Aquatic Ectotherms

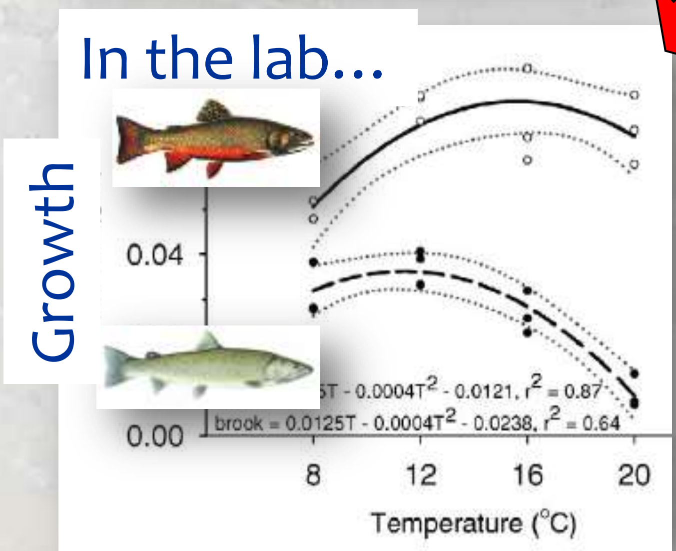
Metabolism

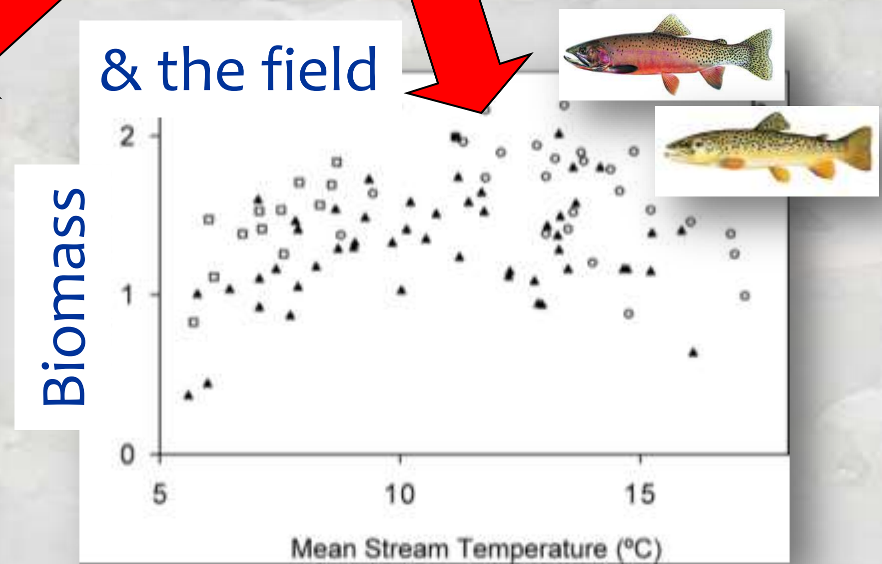


Brown 2004

Thermal Niche





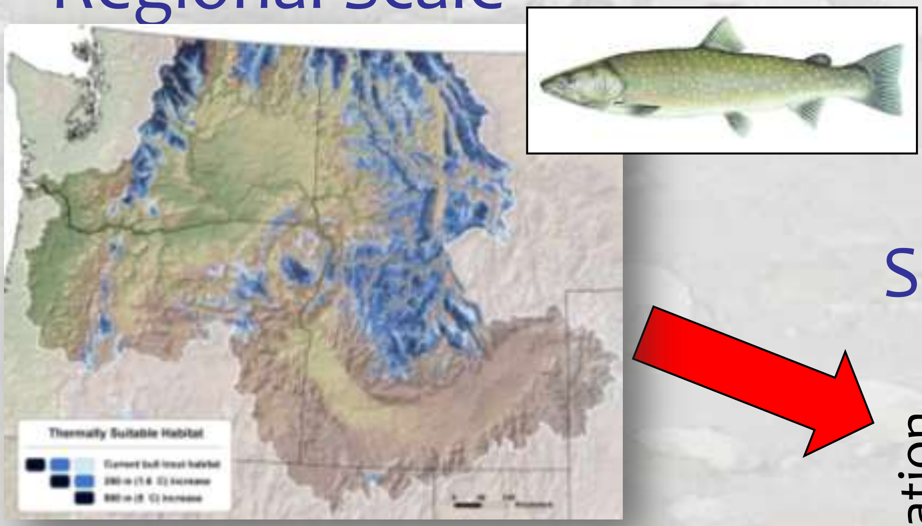


McMahon et al. 2007

Isaak & Hubert 2004

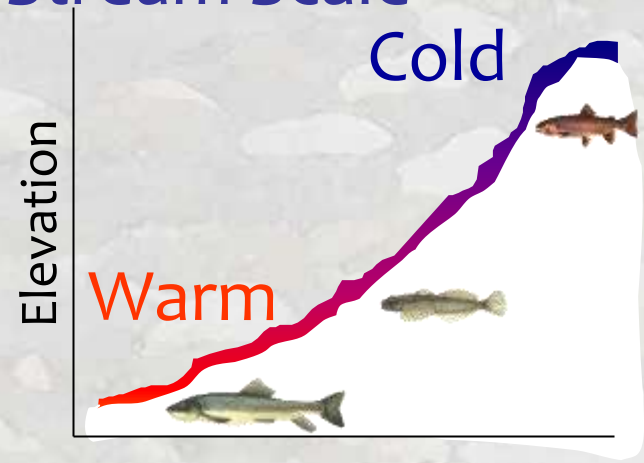
Temperature Regulation – Spatial Distributions

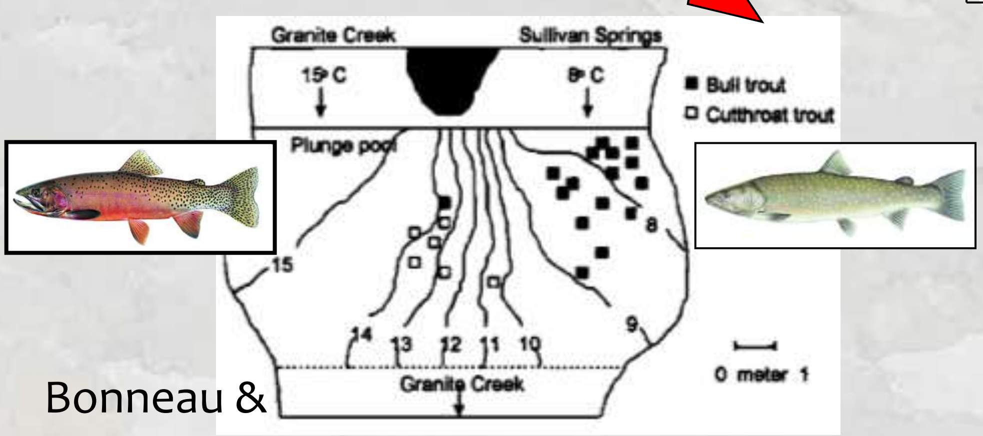
Regional Scale



Rieman et al. 2007

Stream Scale

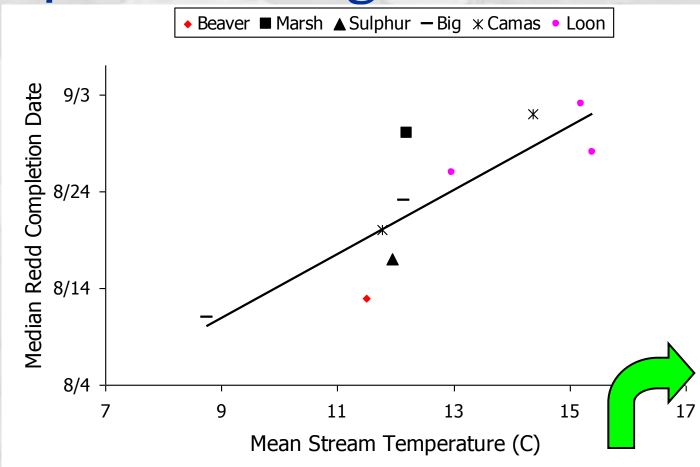




Bonneau & Scarnecchia 1996

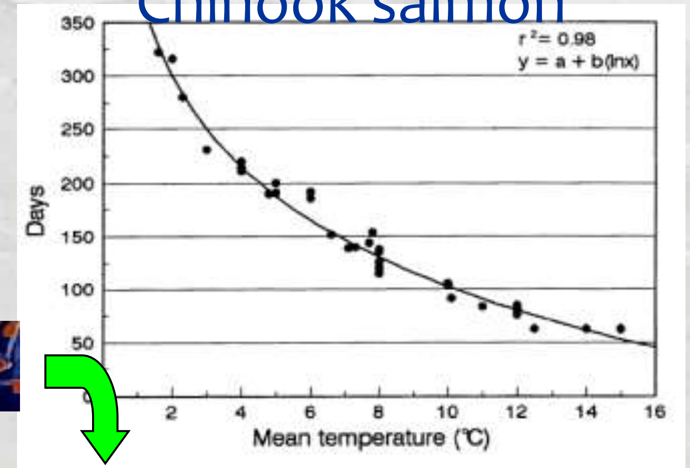
Temperature Regulation - Life Cycle

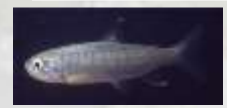
Spawn timing - Chinook salmon



Thurow, unpublished

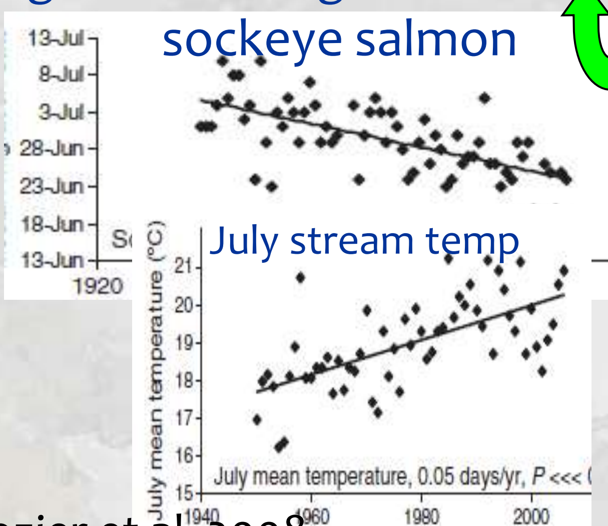
Incubation length - Chinook salmon





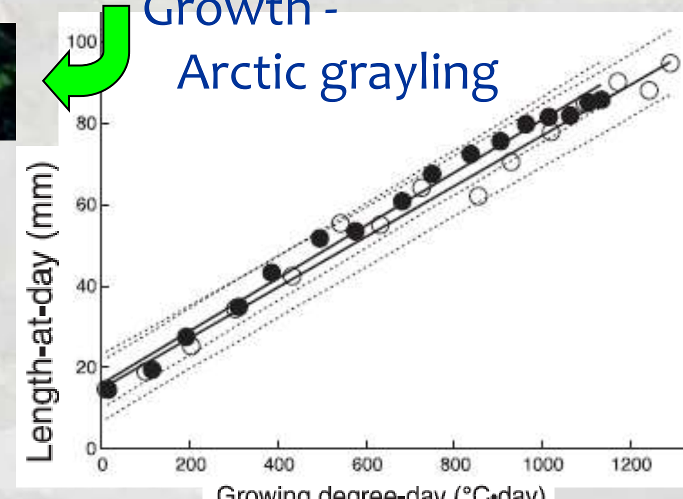
Brannon et al. 2004

Migration timing - sockeye salmon



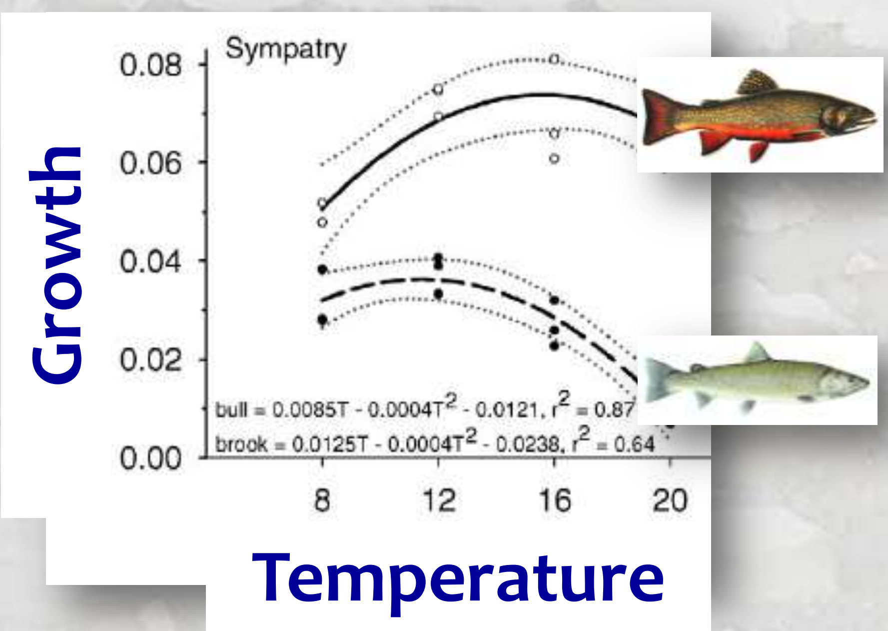
Crozier et al. 2008

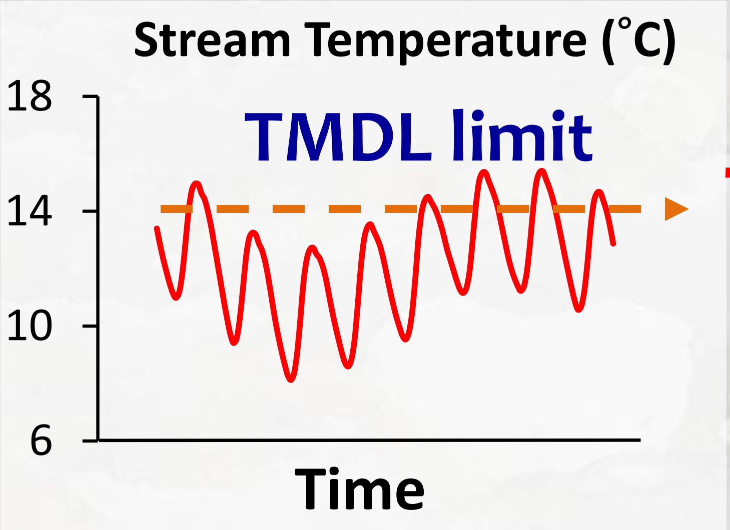
Growth - Arctic grayling



Dion and Hughes 1994

Concern About "Climate" Led to Temperature TMDL Standards

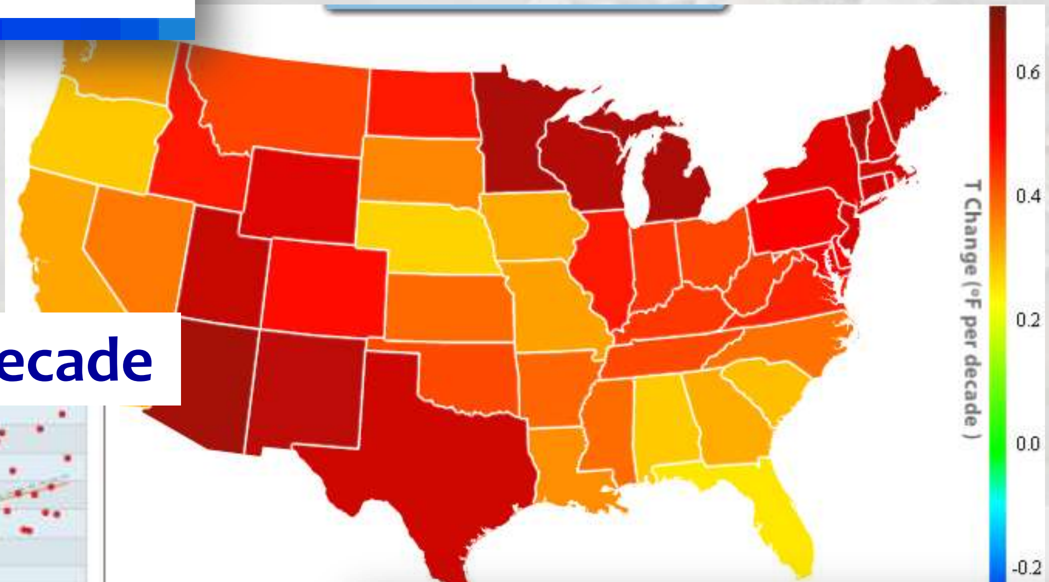


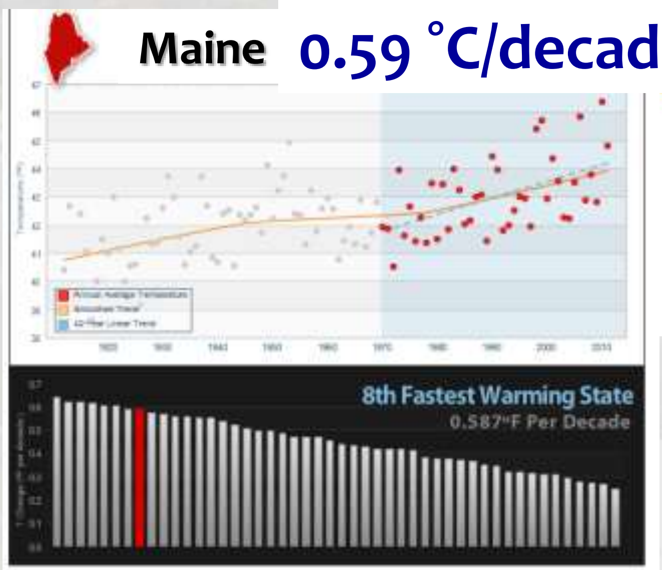


Too Hot!

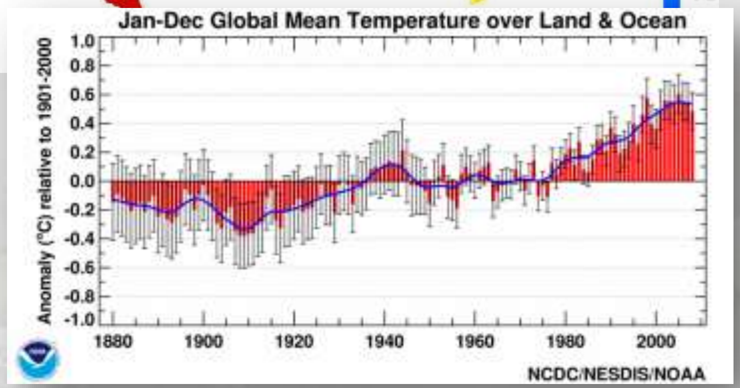
New Concerns About “Climate *Change*”

Air Temperature Warming Rates (1970 – 2011)





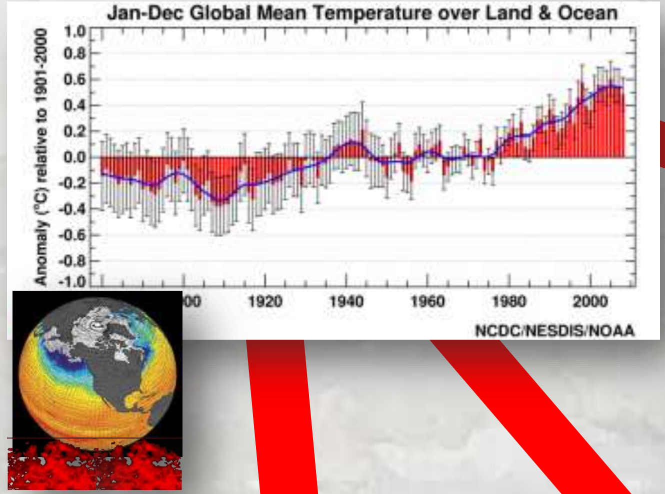
“Heat is on report” Tebaldi 2012

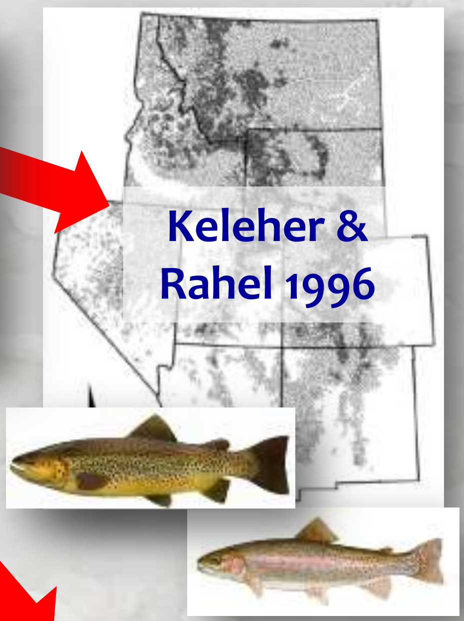


http://www.climatecentral.org/news/the-heat-is-on/

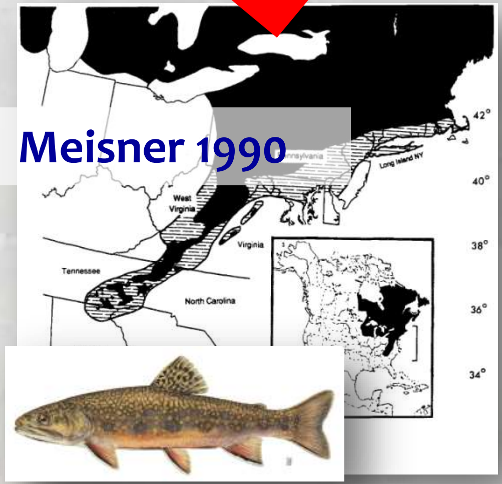
Concern About "Climate *Change*" Drives Biological Vulnerability Assessments

Air Temp trends

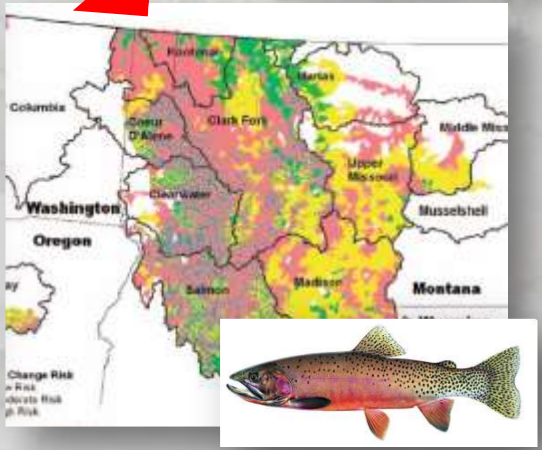




Keleher & Rahel 1996

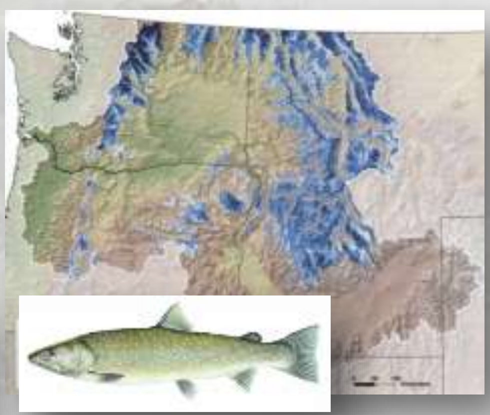


Meisner 1990



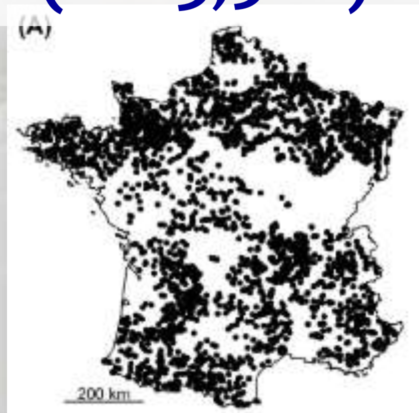
Many Others…

- Isaak et al. 2010
- Eaton & Schaller 1996
- Reusch et al. 2012
- 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

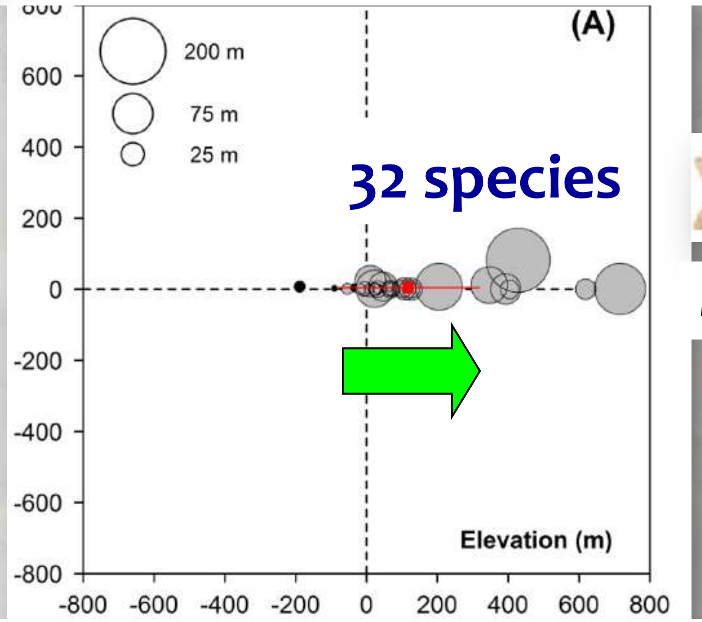


French Study Documents Biological Response

Survey sites (n = 3,500)



Difference in stream fish distributions (1980's vs 2000's)



32 species

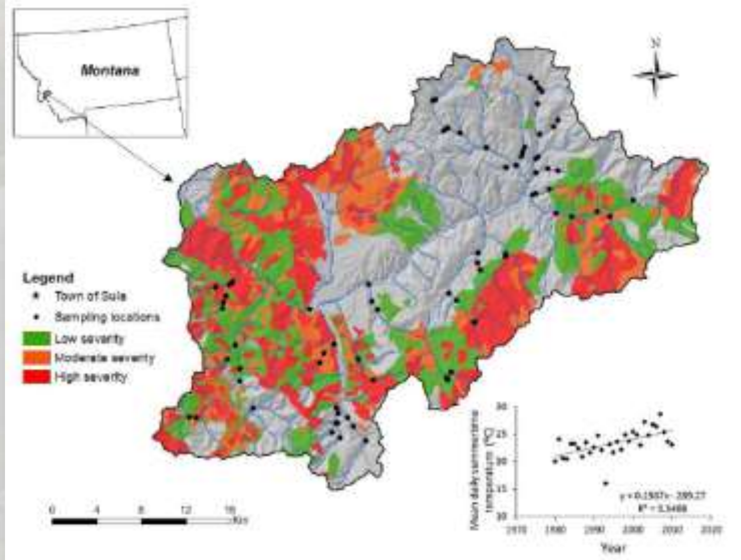
Change in Elevation (m)

March of the fishes…

Comte & Grenouillet. 2013. Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography* **36**:1236-1246.

Distribution Shifts in Montana Bull Trout Populations

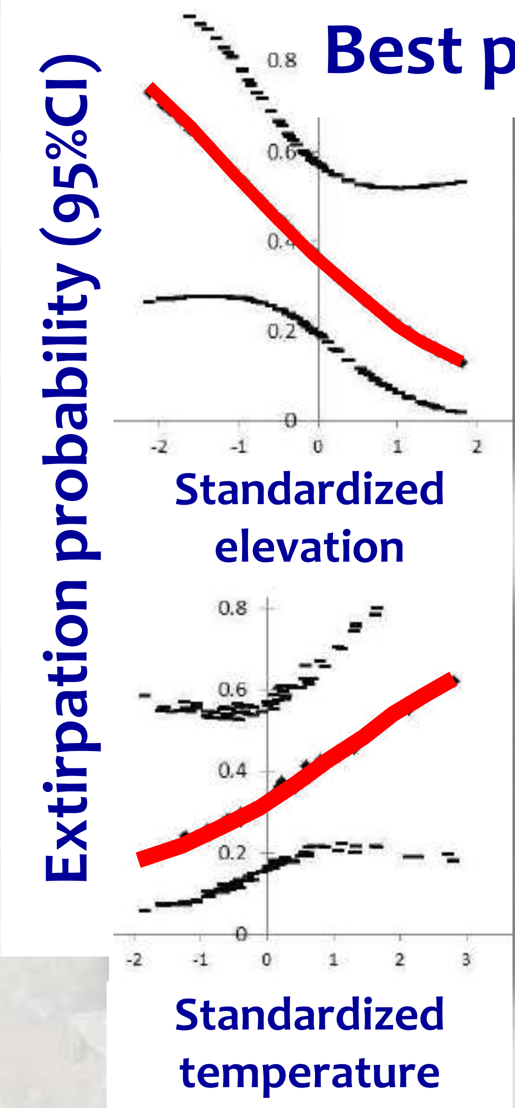
- Resurveyed Rich et al. 2003 sites 20 years later
- 77 sites, 500 m in length
- Modeled extirpations/colonizations accounting for detection efficiency

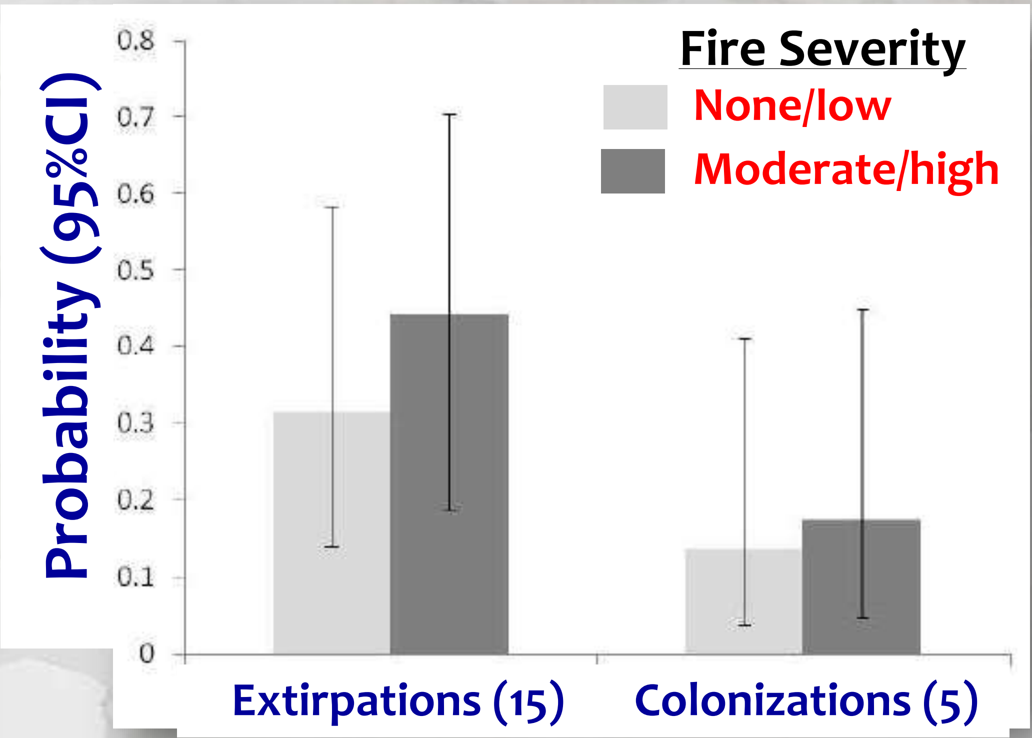


Eby et al. In Review. Evidence of climate-induced range contractions for bull trout to cooler, higher elevation sites in a Rocky Mountain watershed, U.S.A. *Conservation Biology*

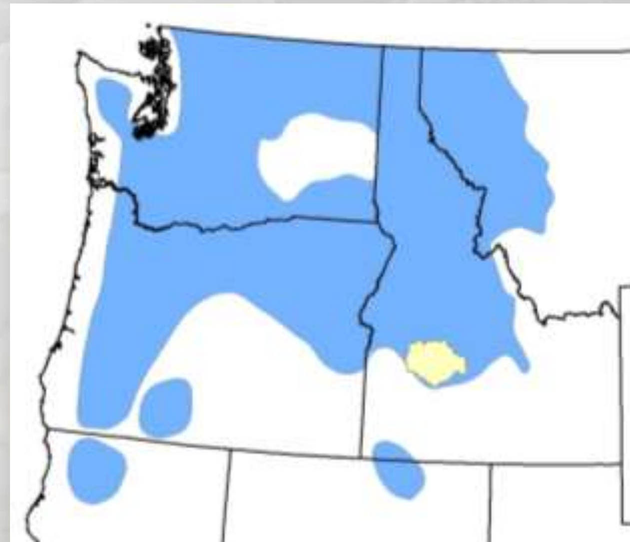
Distribution Shifts in Montana Bull Trout Populations

Best predictors

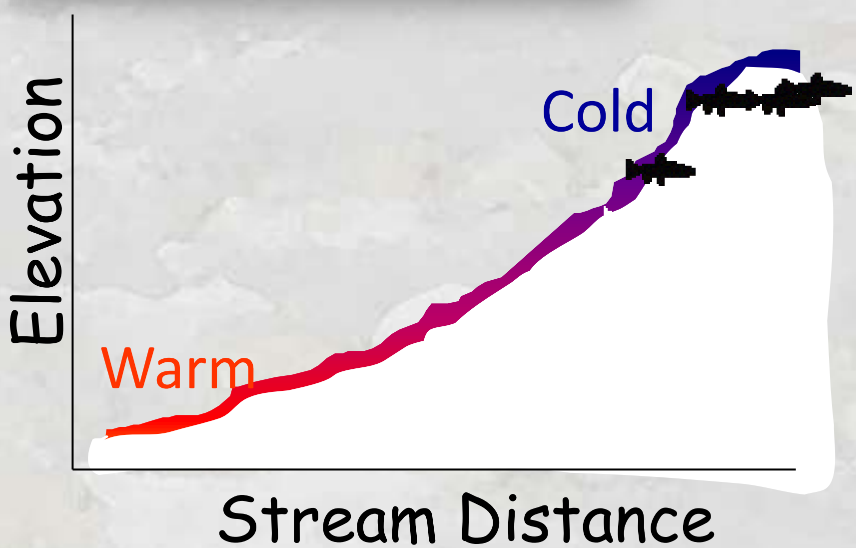


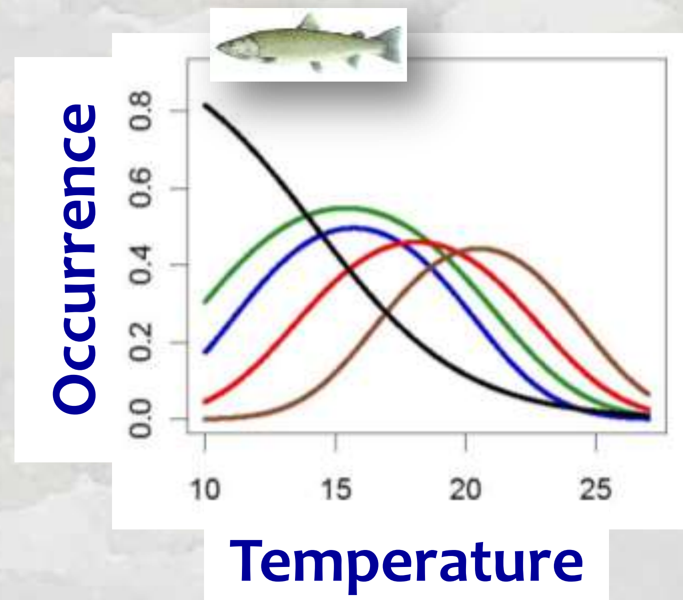


Why That's a Problem…



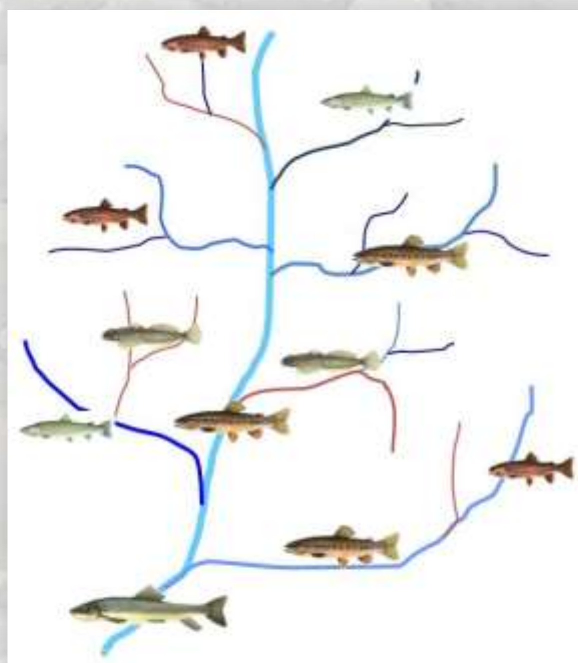
- Occur throughout Pacific Northwest
- ESA Listed as Threatened in 1998
- Cold thermal niche
- Exist on "mountain-top islands"





The 21st-Century will Be a Transitional One

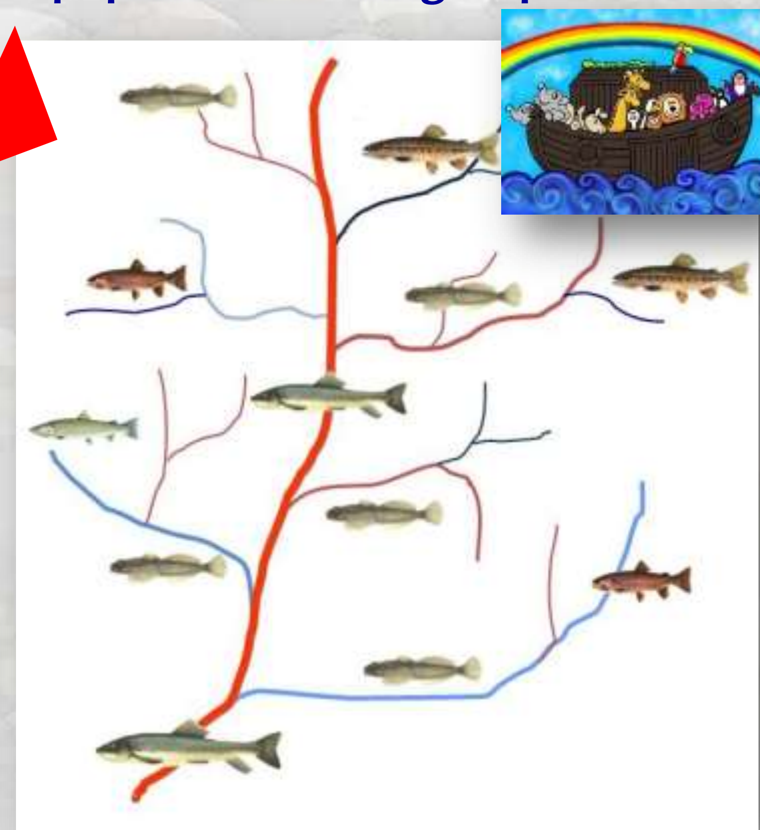
Current Status



What are our Goals?

Desired Future Status

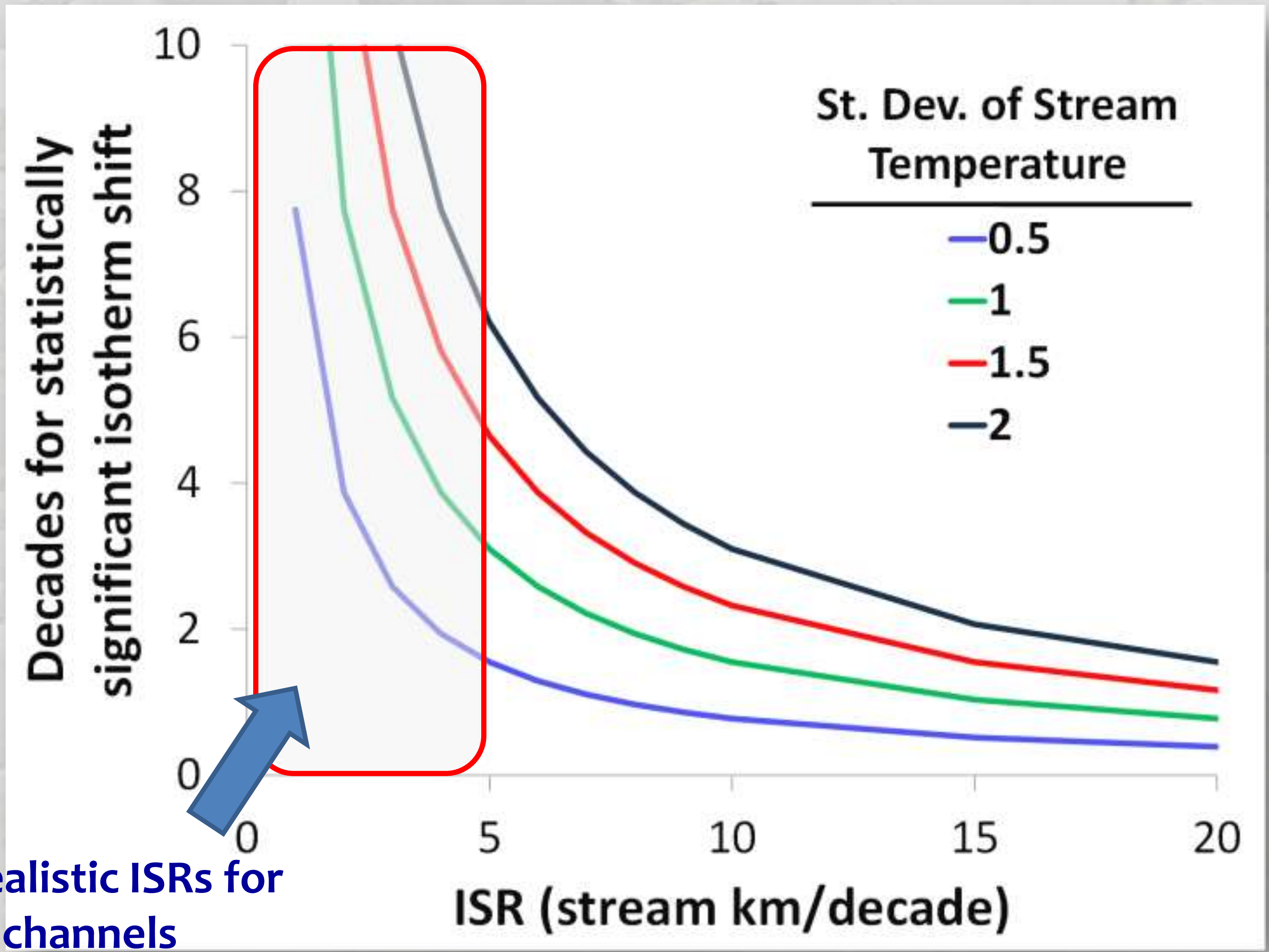
Perhaps fewer, but happy & stable populations of target species



Perhaps some new invaders, but nightmare invasion scenarios avoided

Changes Will Happen Slowly

20 – 60 years for significant isotherm shifts



Realistic ISRs for 1% channels

Isaak & Rieman. 2013. *Global Change Biology* **19**:742-751.

Changes Will Happen Slowly

20 – 60 years for significant isotherm shifts

Occur Over The Span of Careers

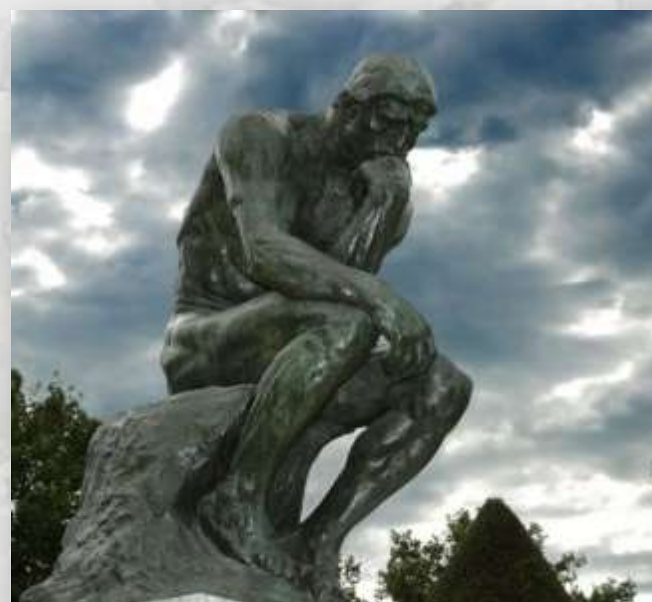
Future fish squeezer

Emeritus fish squeezer

Isaak & Rieman. 2013. *Global Change Biology* **19**:742-751.

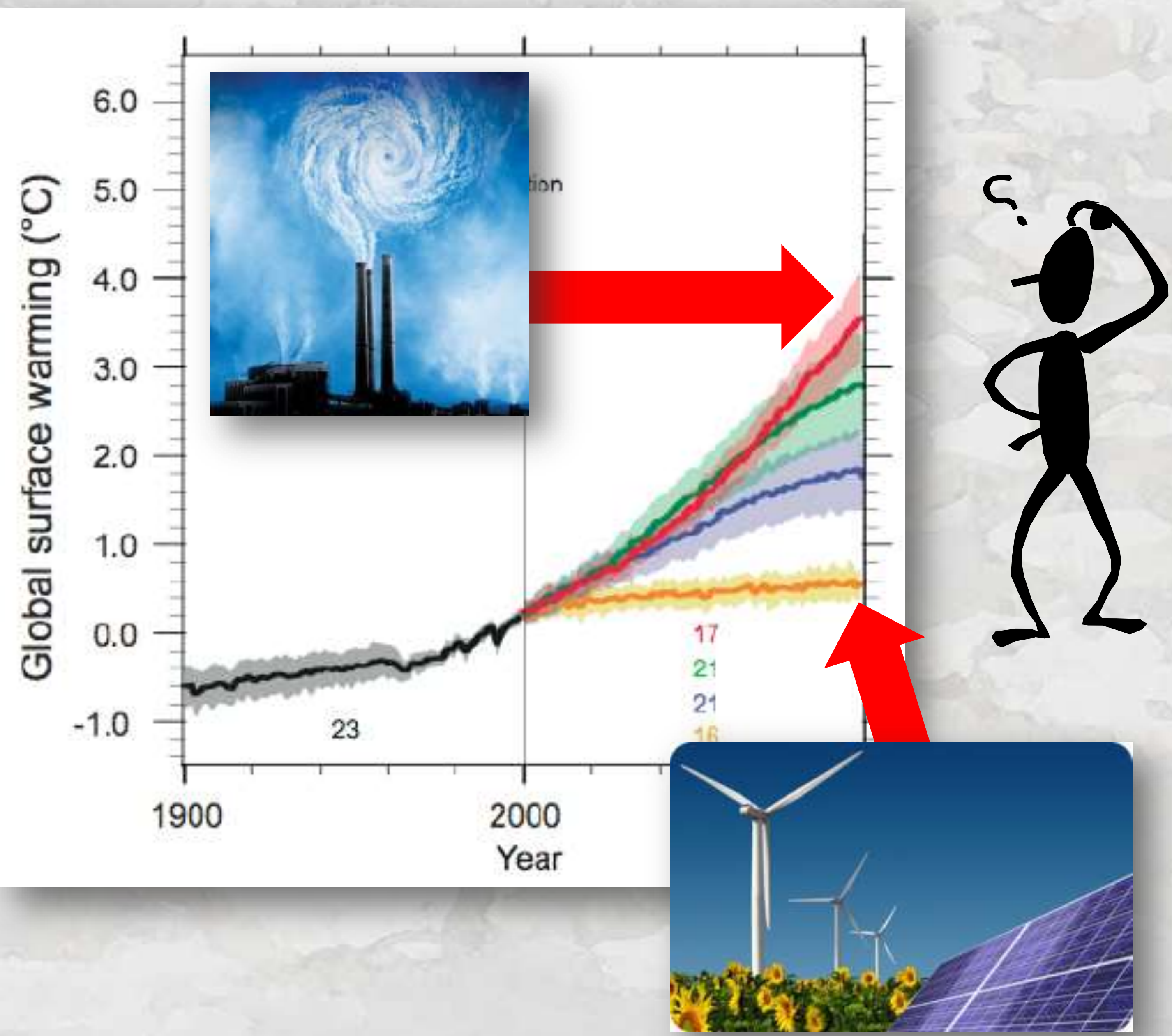
Time is a Double-Edged Sword

Strategic planning is possible, but…



… urgency may be lacking

Current Choices Set Future Trajectories



Current Choices Set Future Trajectories

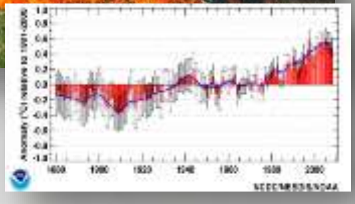
Choice A: Coexistence (accept change passively &/or shape transition to more desirable communities)


OR?


Choice B: Resistance (protect native biodiversity & other currently valued resources)



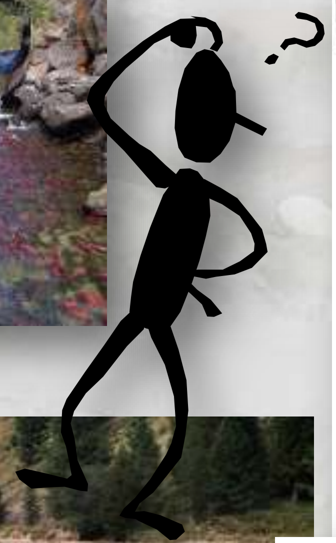
Conservation reserves, important fisheries

Climate-Smart Prioritization of Habitat Restoration

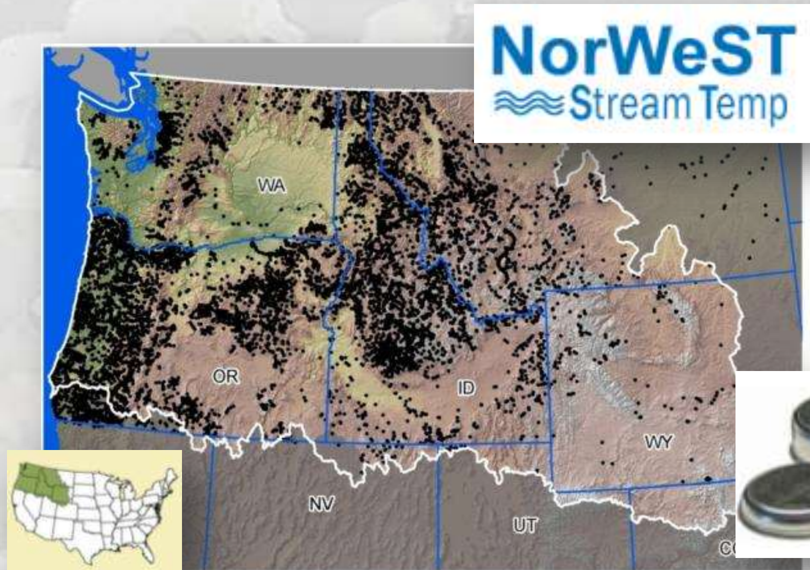
Lots of things we can do…

- •Maintaining/restoring flow…
- •Maintaining/restoring riparian…
- •Restoring channel form/function…
- •Prescribed burns limit wildfire risks…
- •Non-native species control…
- •Improve/impede fish passage…



… but where to do them?

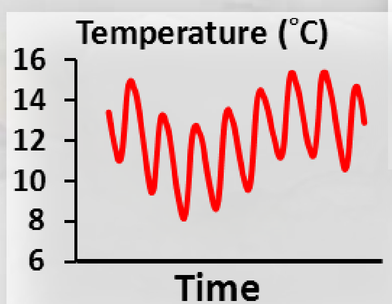
Existing Data Can be Mined to Create Massive Amounts of Useful Information

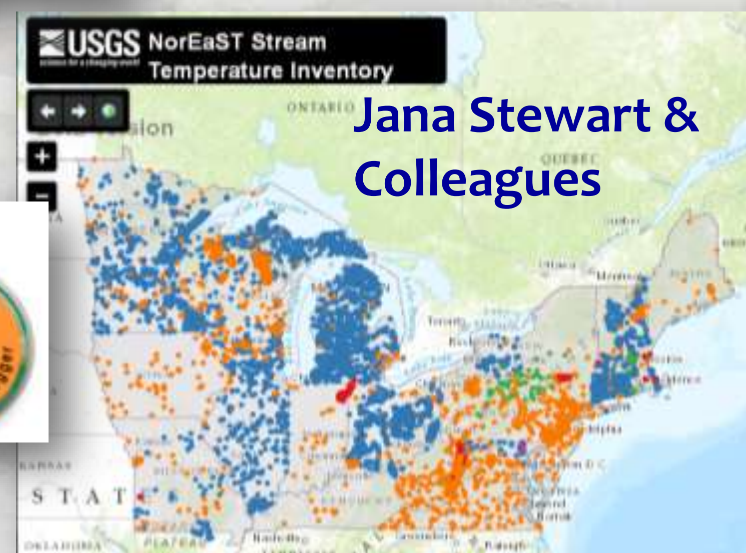


Free

millions!

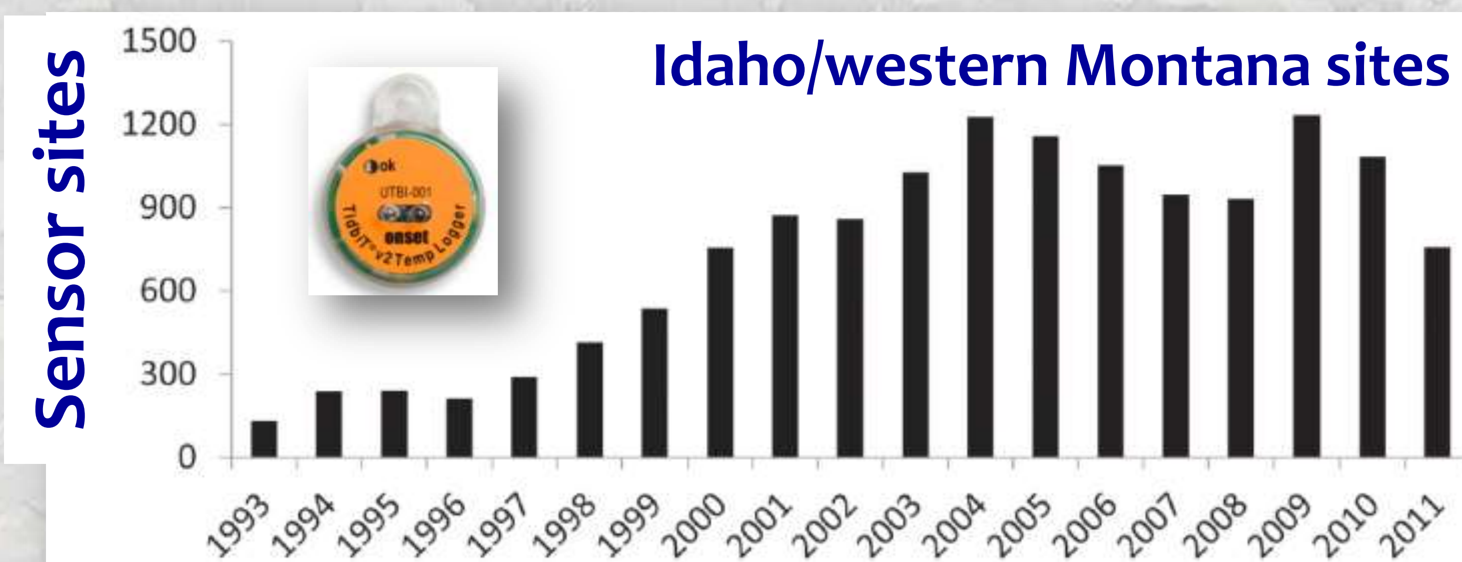
>60 agencies
>45,000,000 hourly records
>15,000 unique sites



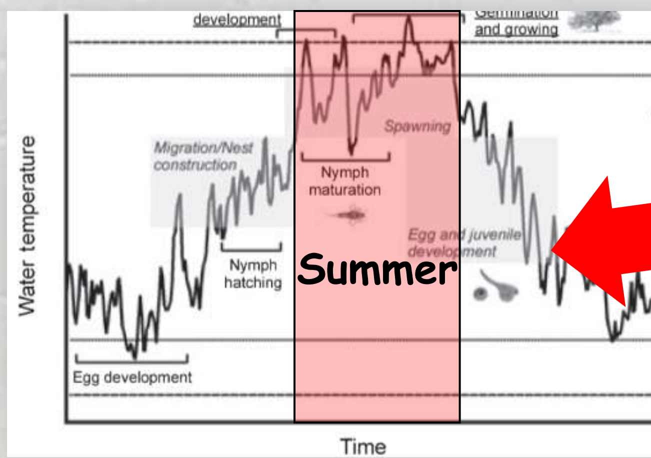


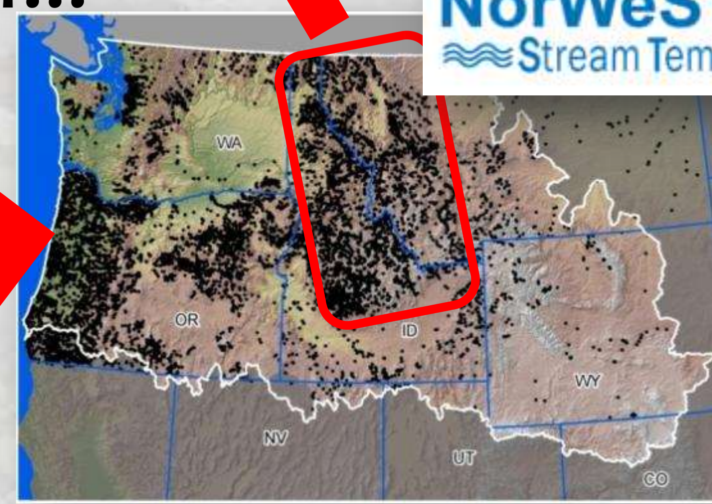
Jana Stewart & Colleagues

How Do We Monitor? Many sites, but…



usually only in the summer…

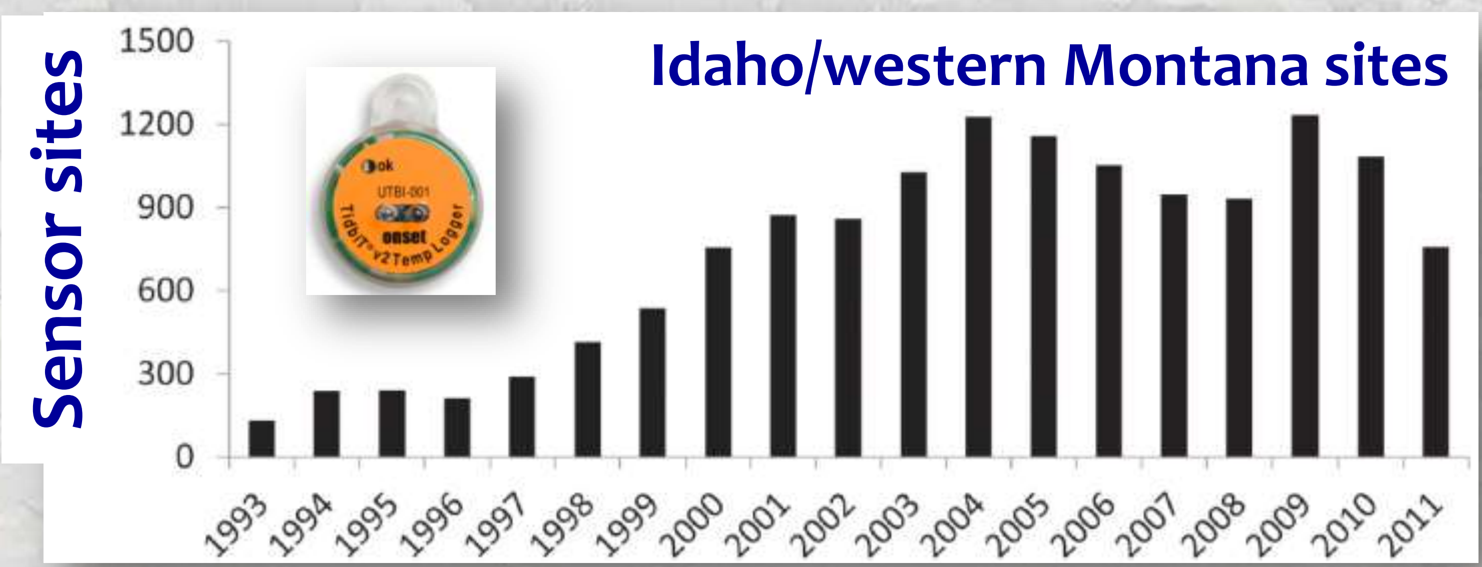




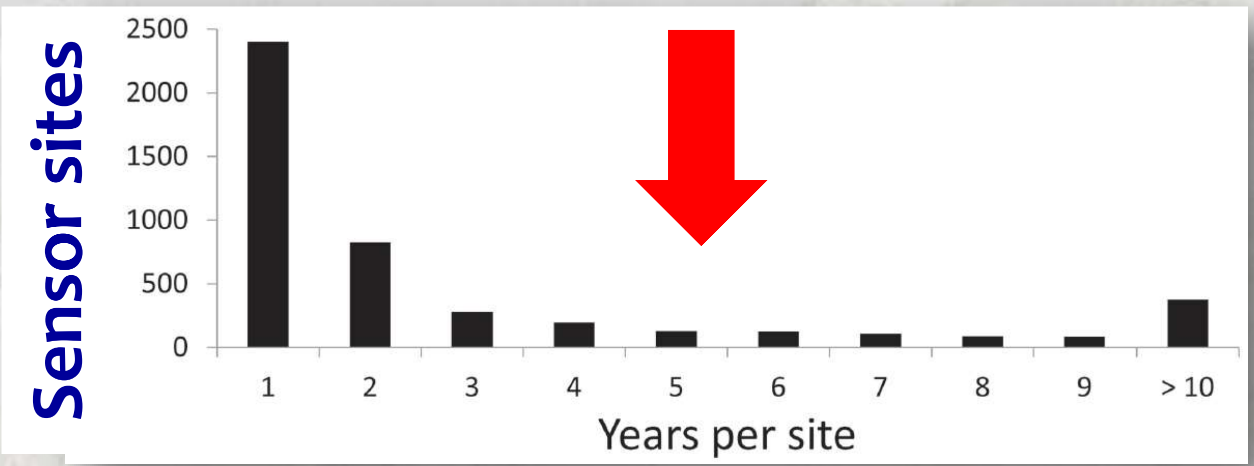
NorWeST Stream Temp

Isaak et al. 2013. A simple protocol using underwater epoxy to install annual temperature monitoring sites in rivers and streams. USFS General Technical Report, 314.

How Do We Monitor? Many sites, but…

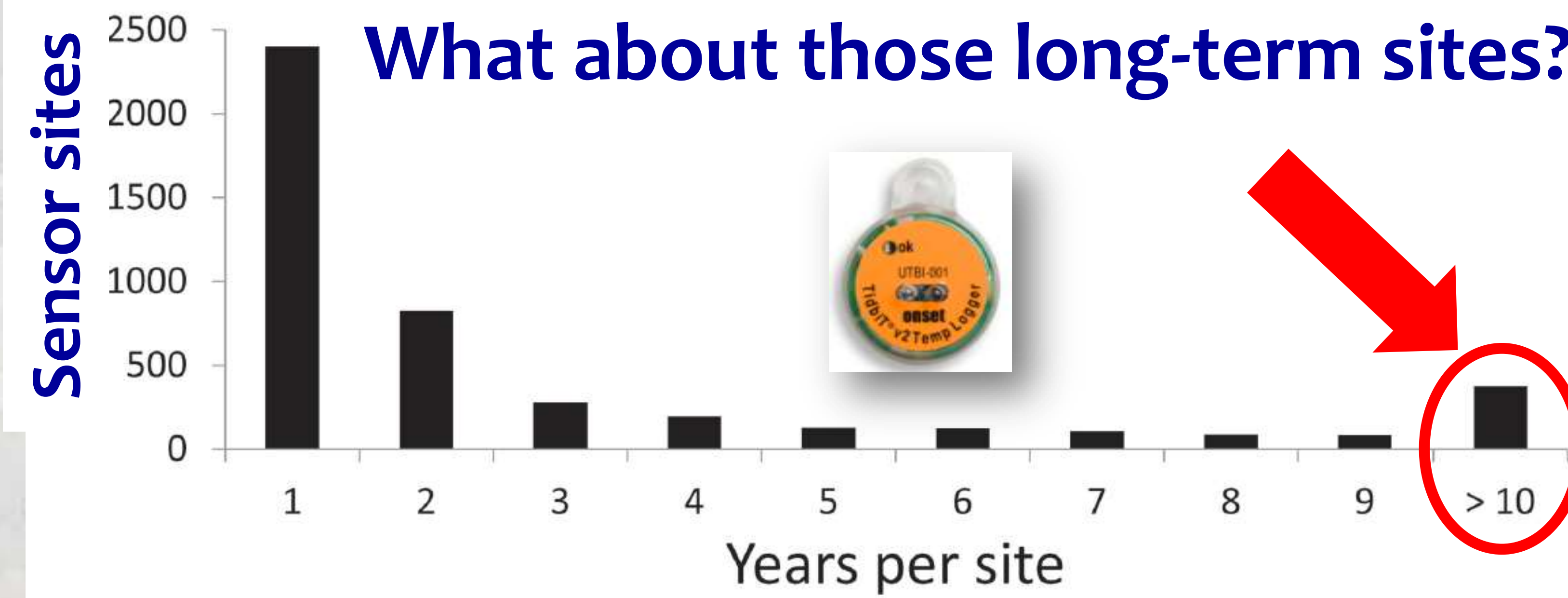


& not for very long

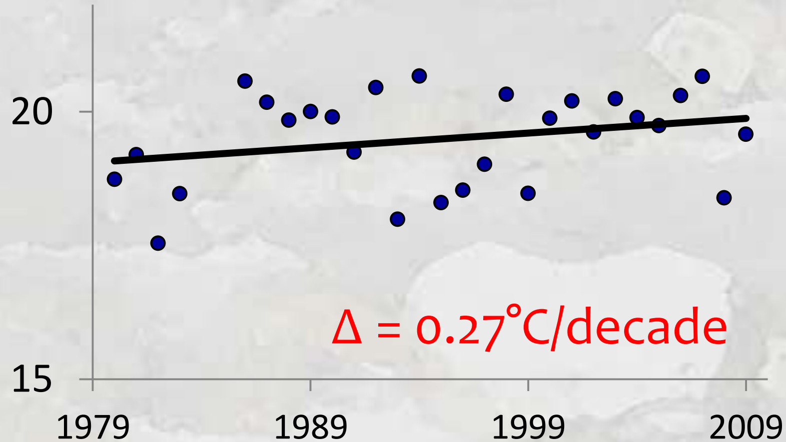


Isaak et al. 2013. [A simple protocol using underwater epoxy to install annual temperature monitoring sites in rivers and streams](). USFS General Technical Report, 314.

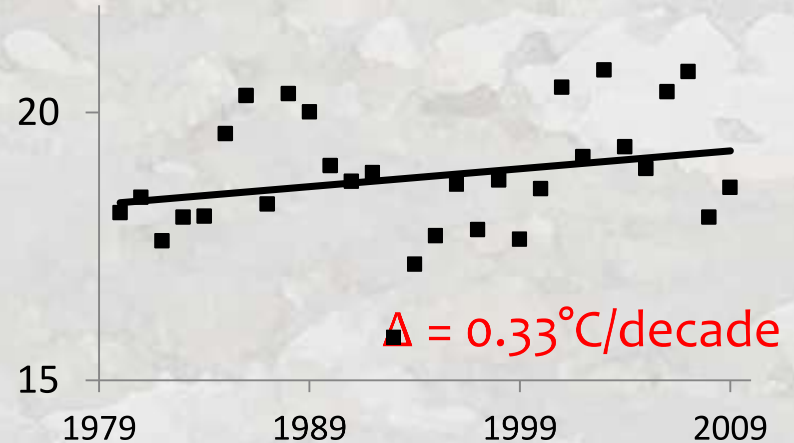
What about those long-term sites?



Snake River, ID - Summer

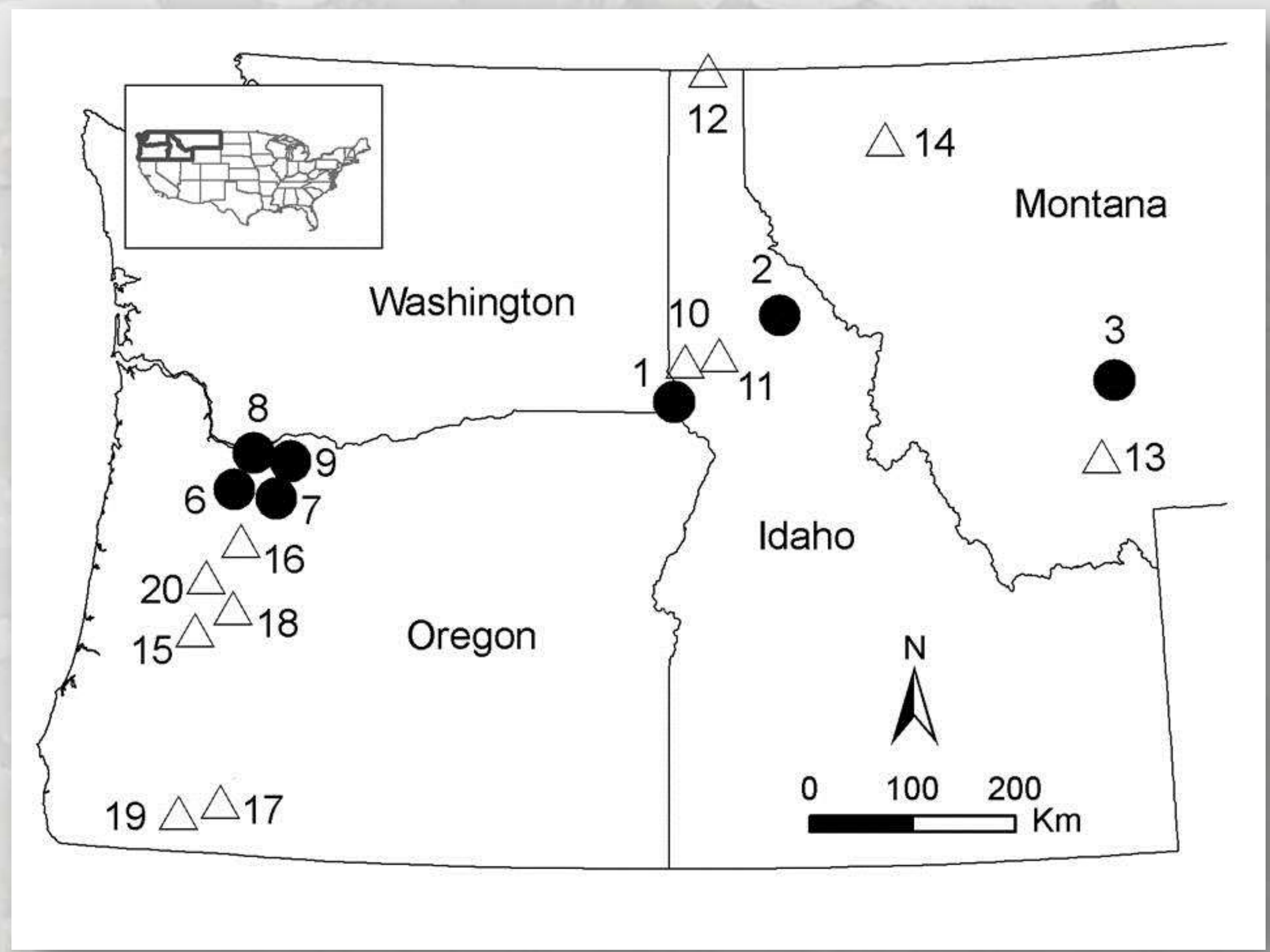


Missouri River, MT - Summer



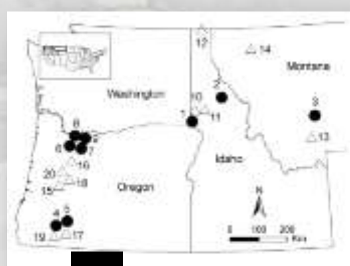
Unregulated Sites With >25 Years Data

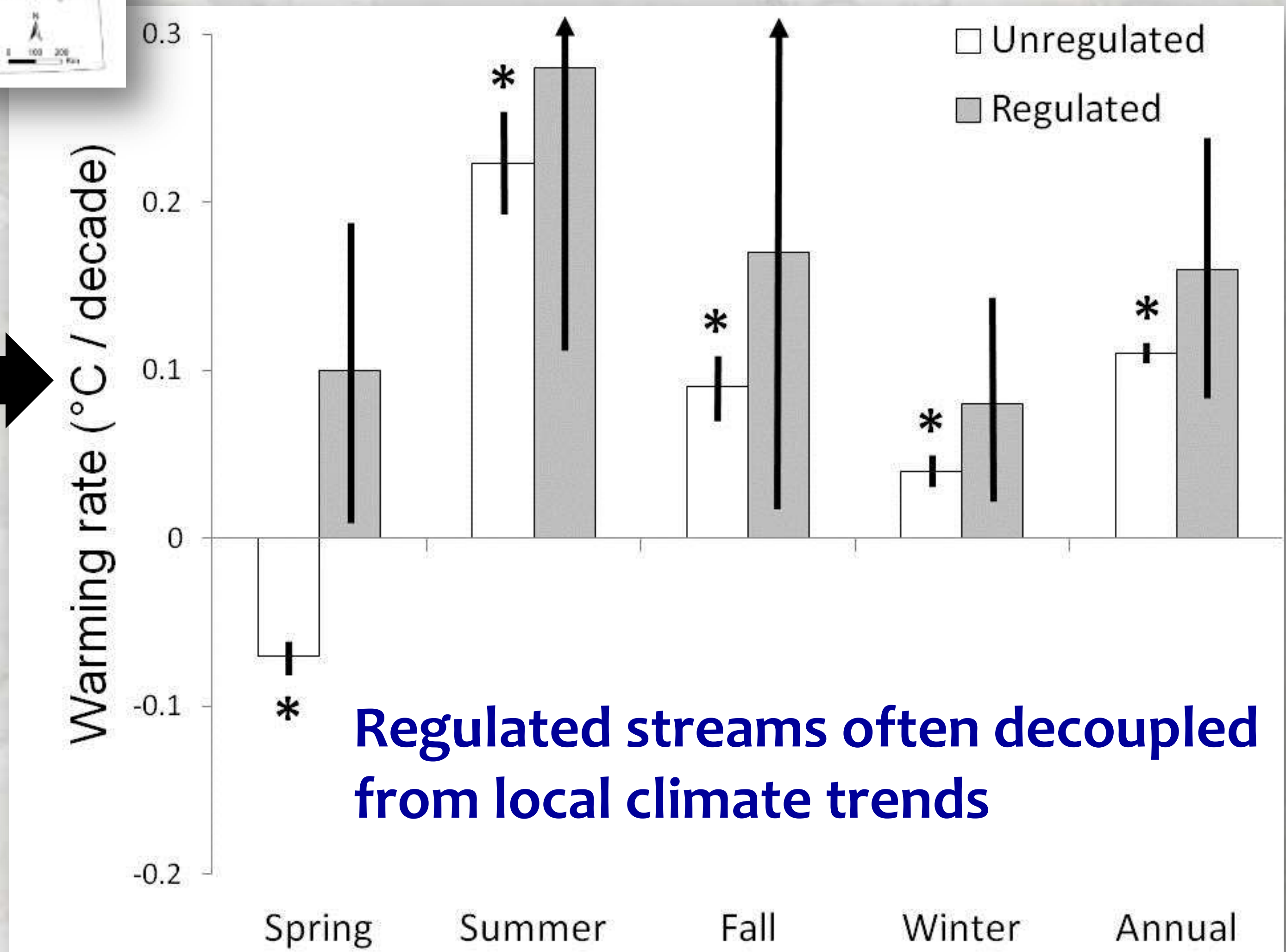
△ = regulated (11) ● = unregulated (7)



Data Source: USGS NWIS

Seasonal Trends In Stream Temperatures (1980-2009)



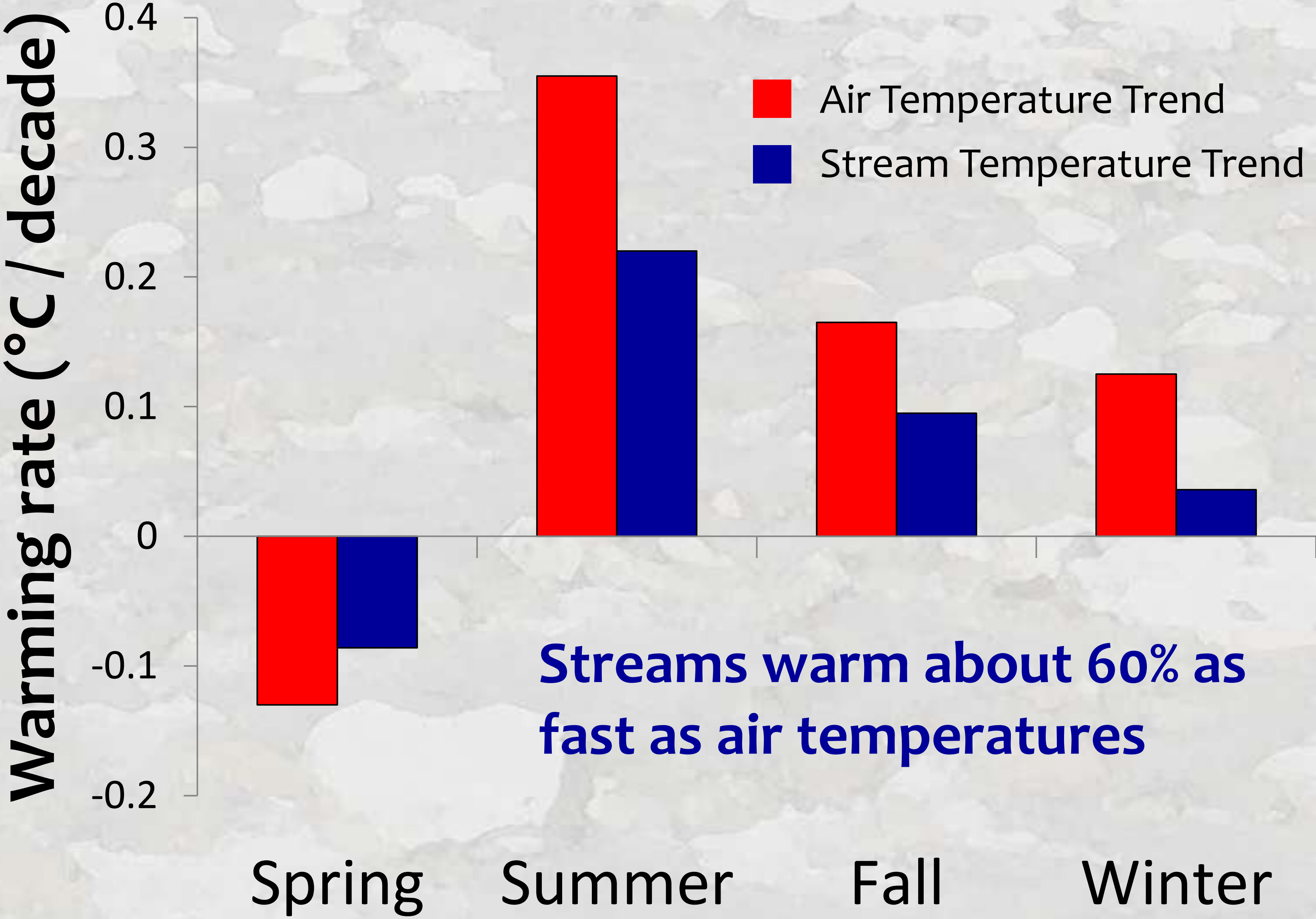


Regulated streams often decoupled from local climate trends

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

Stream Temperatures Track Air Temps

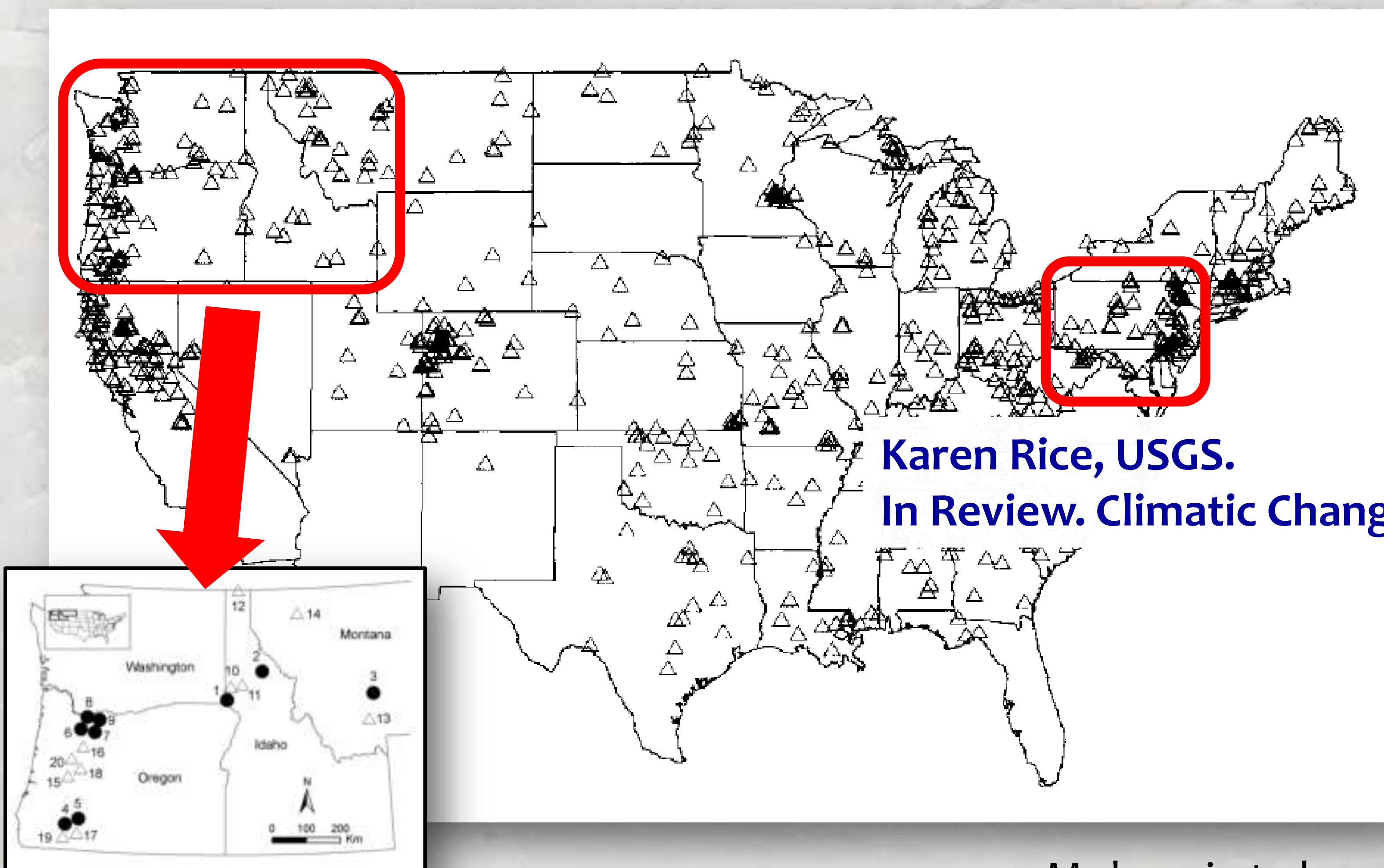
Trends at 7 Unregulated Sites



Sites with Long-term Monitoring Data?

764 gage sites have some temperature data

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

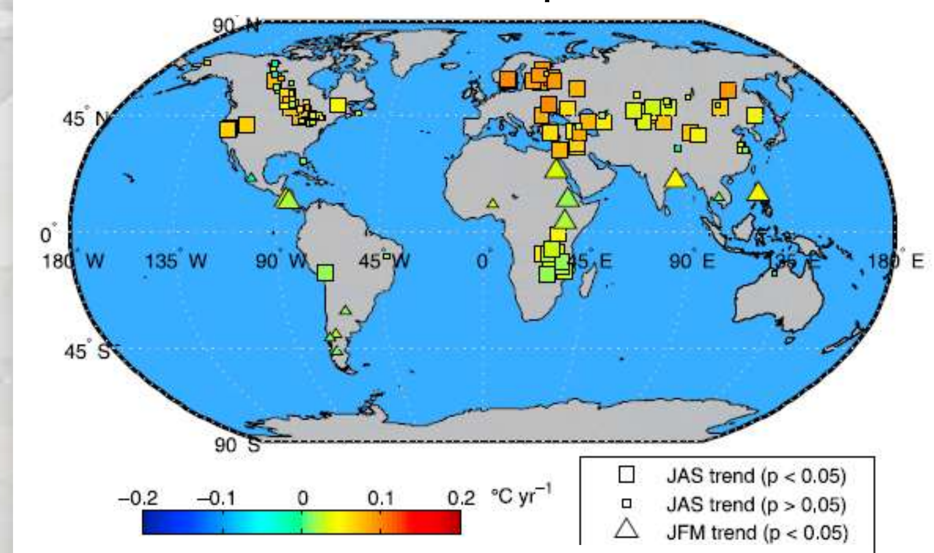


Karen Rice, USGS.
In Review. Climatic Change

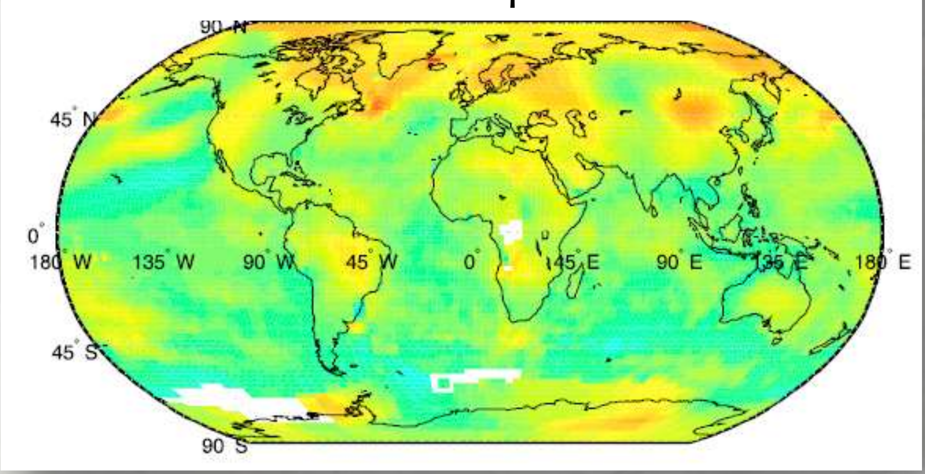
Mohseni et al. 2003

Global Lake Temperatures Increasing also...

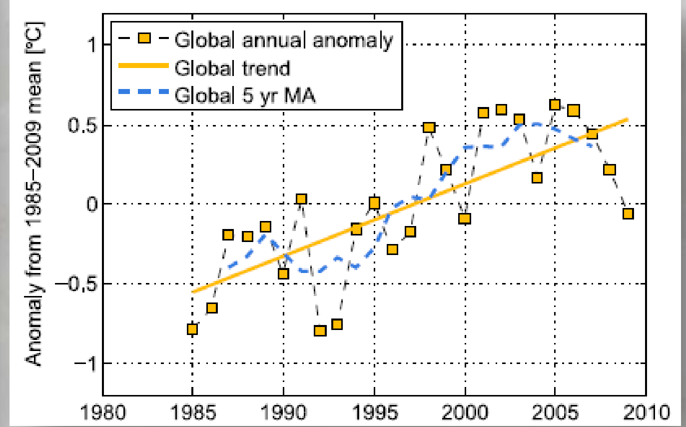
Individual Lake Temperature Trends



Concurrent Air Temperature Trends



Global Lake Temperature Trend



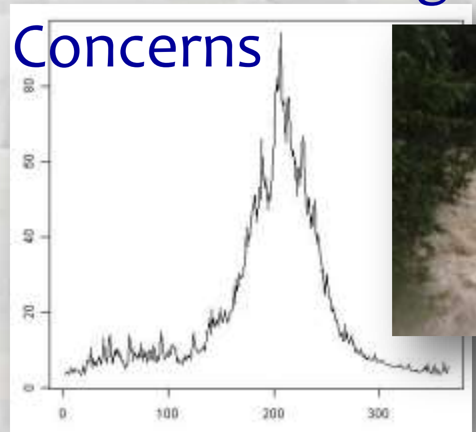
+0.45°C/decade from 1985-2009

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

More Longterm, Annual Monitoring Needed

Inexpensive, reliable "epoxy protocol"

Annual Flooding Concerns



Underwater epoxy cement

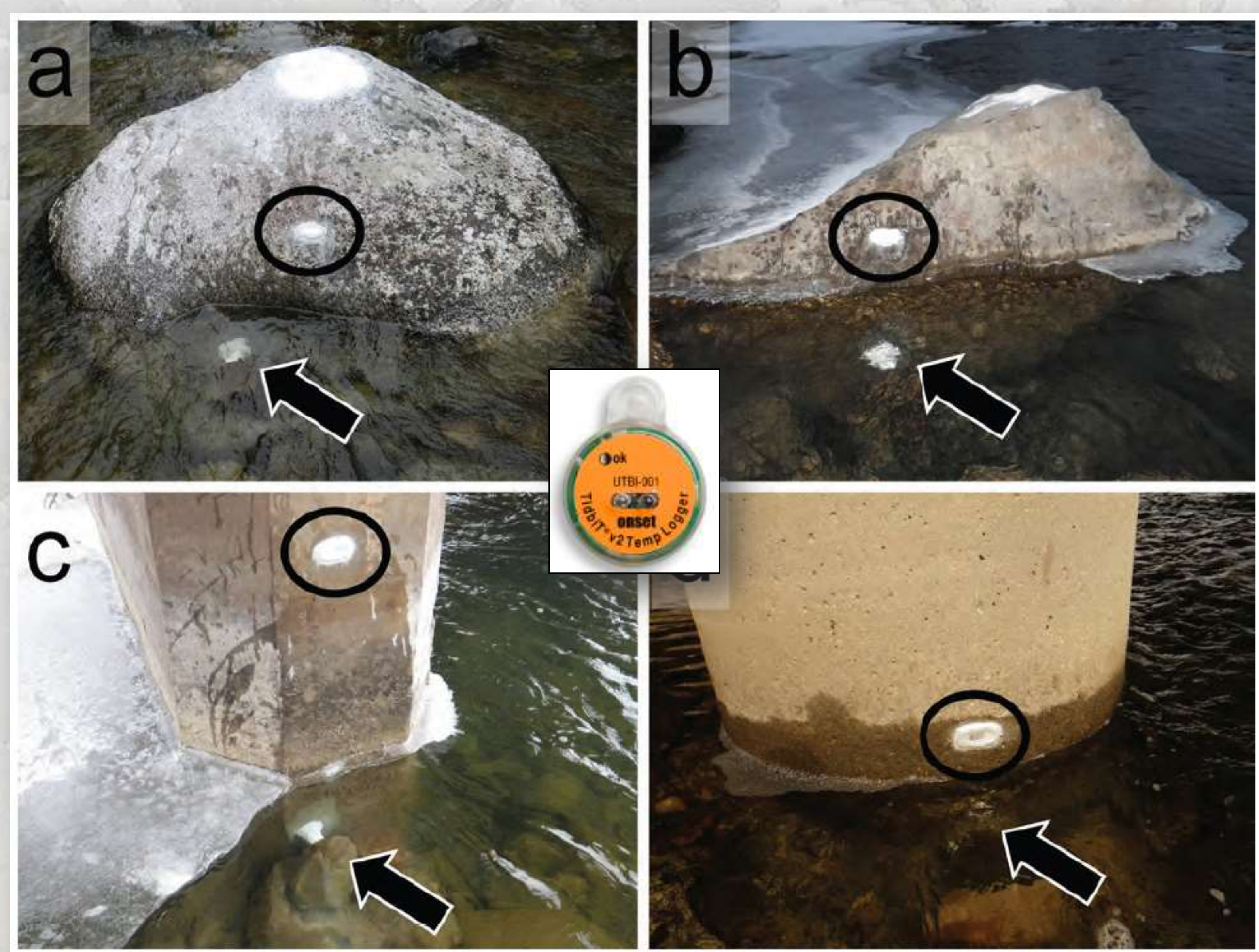
$130 = 5 years of data

Sensors glued to large boulders & bridges

Data retrieved from underwater

Isaak et al. 2013. USFS Report;
Isaak & Horan 2011. ***NAJFM*** 31:134-137

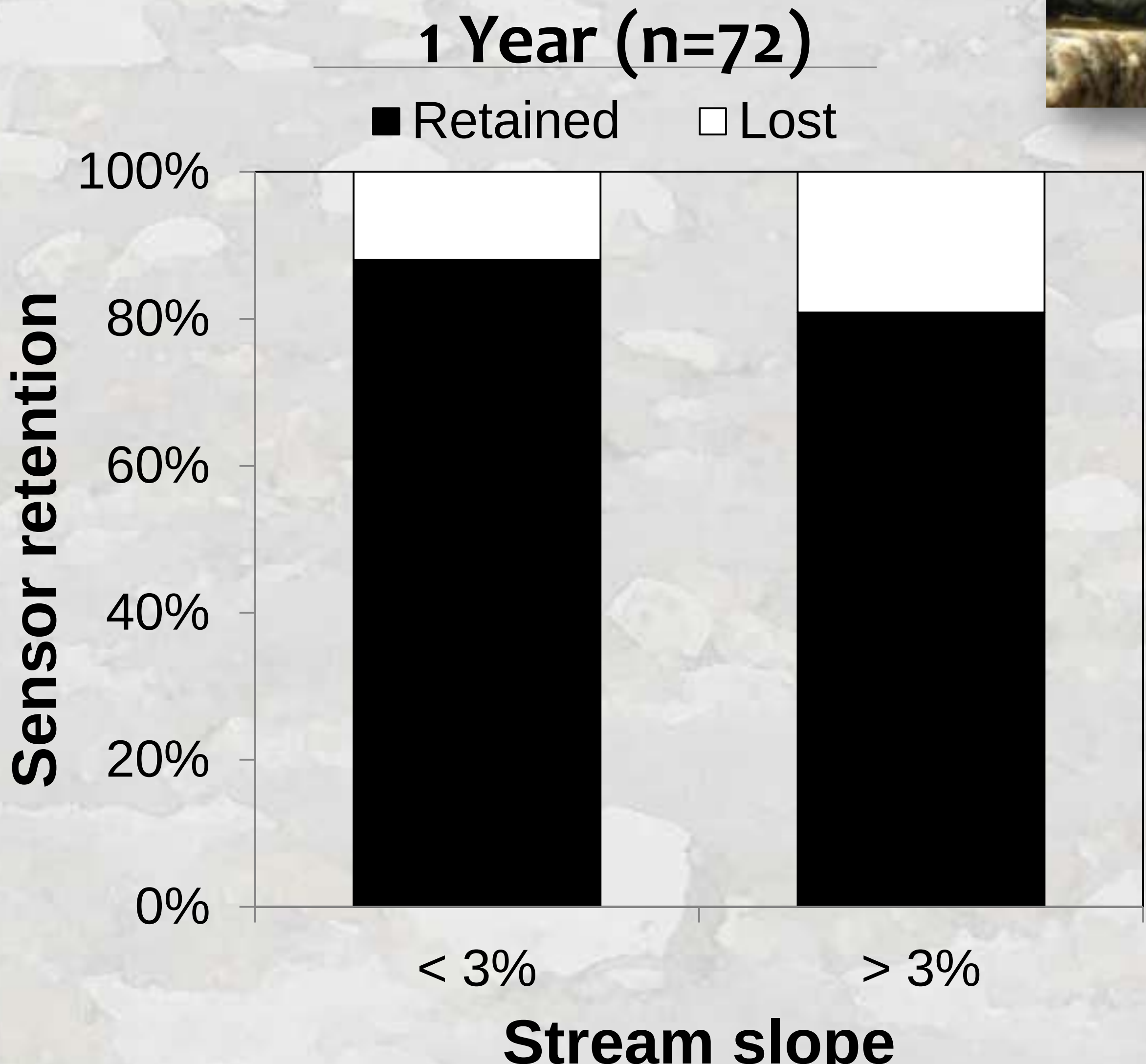
Small Sensors & Immobile Objects

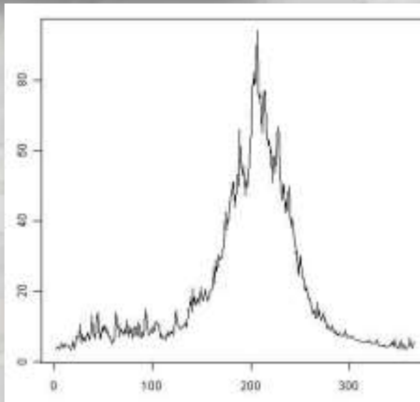


Small Sensors & Immobile Objects

Does it Work?

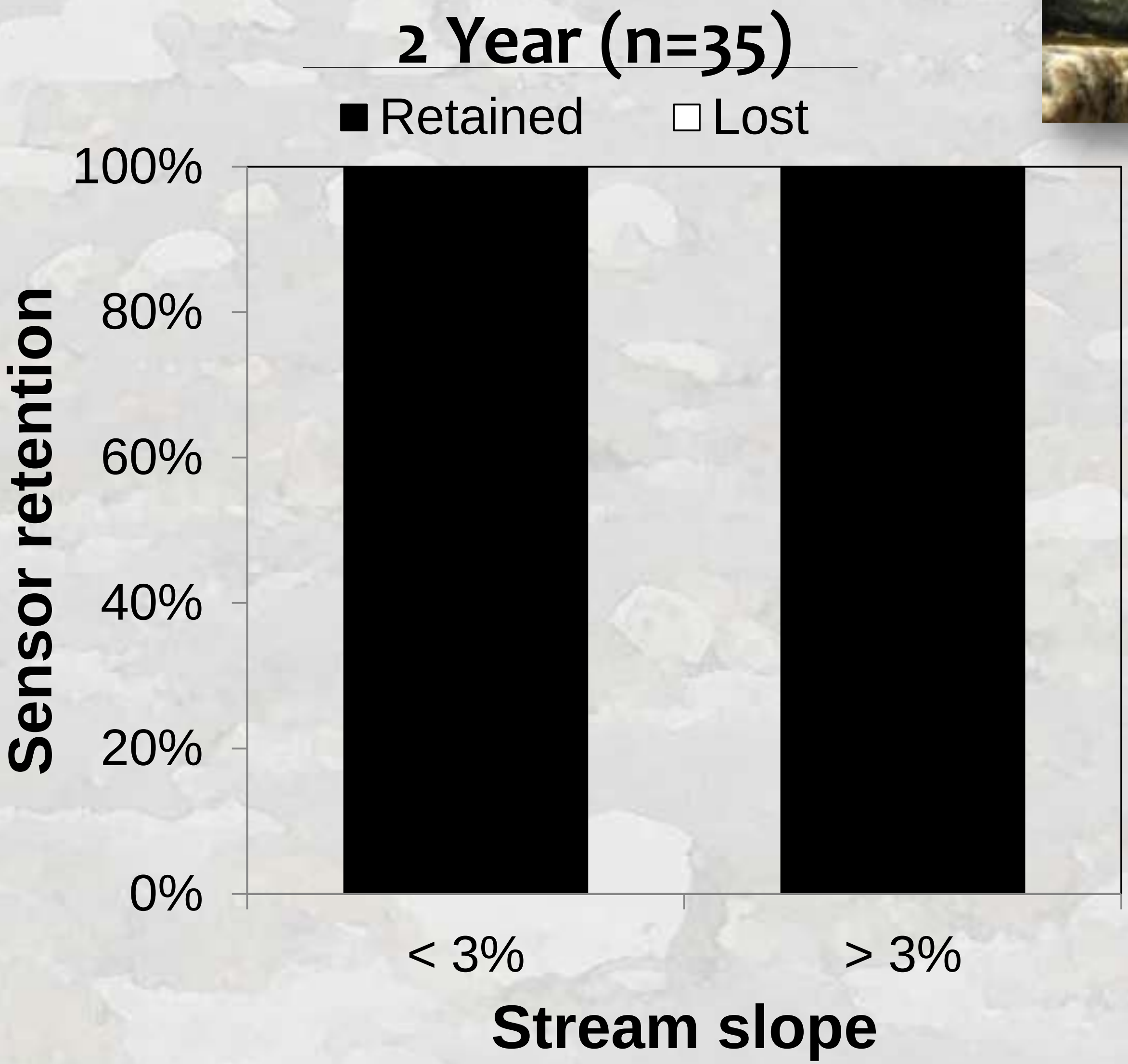
Retention success at…

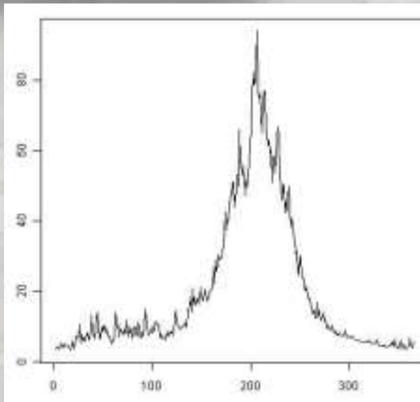




Does it Work?

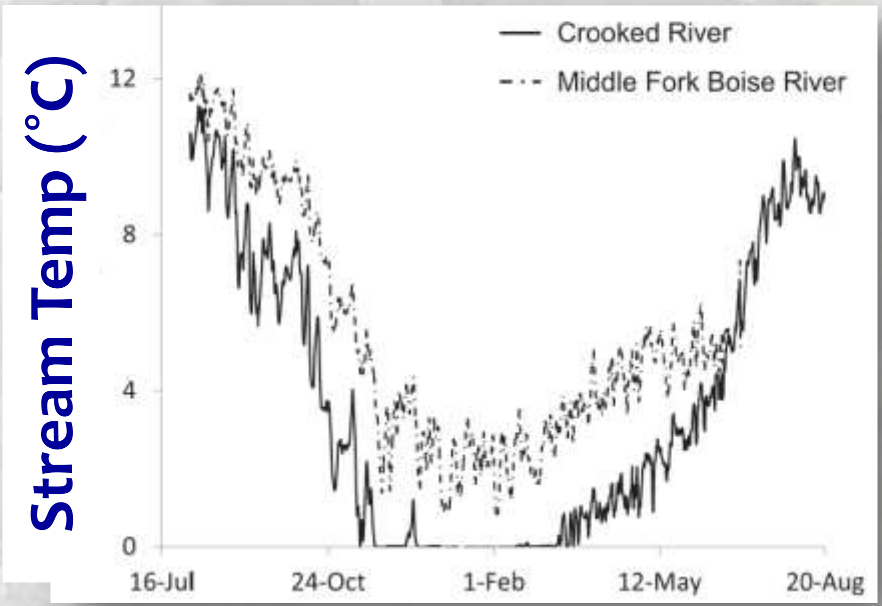
Retention success at…



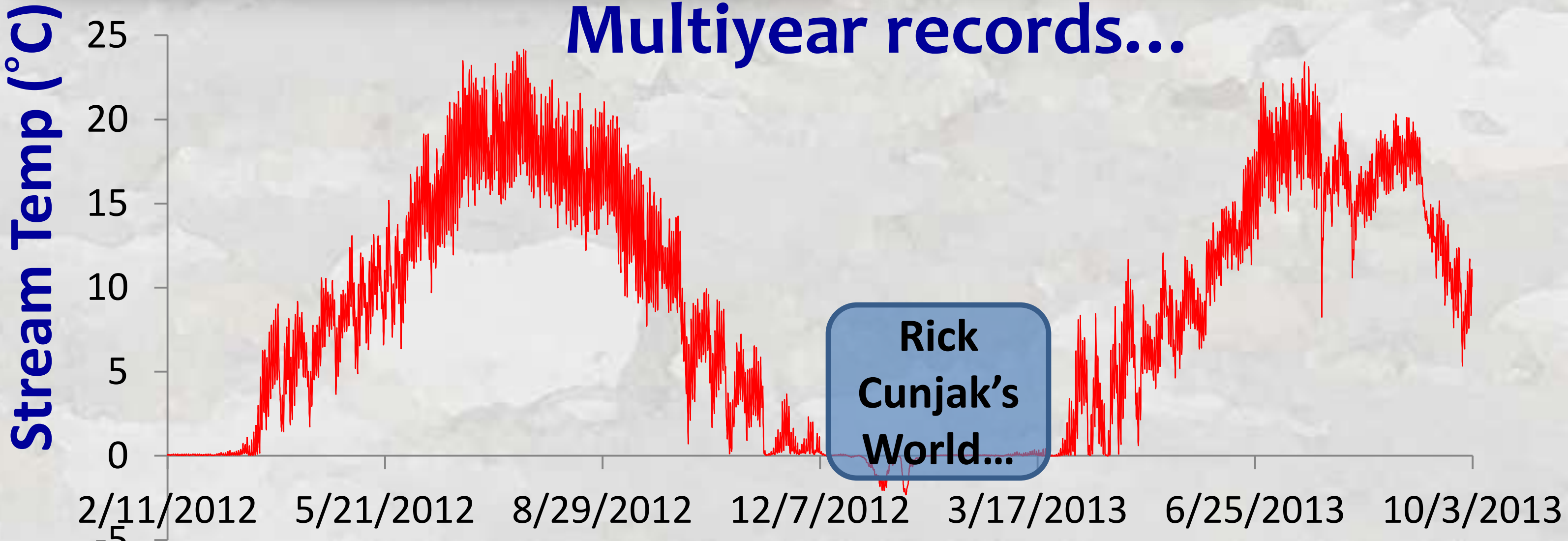


It's a Win-Win

More data, more hunting!



Multiyear records…



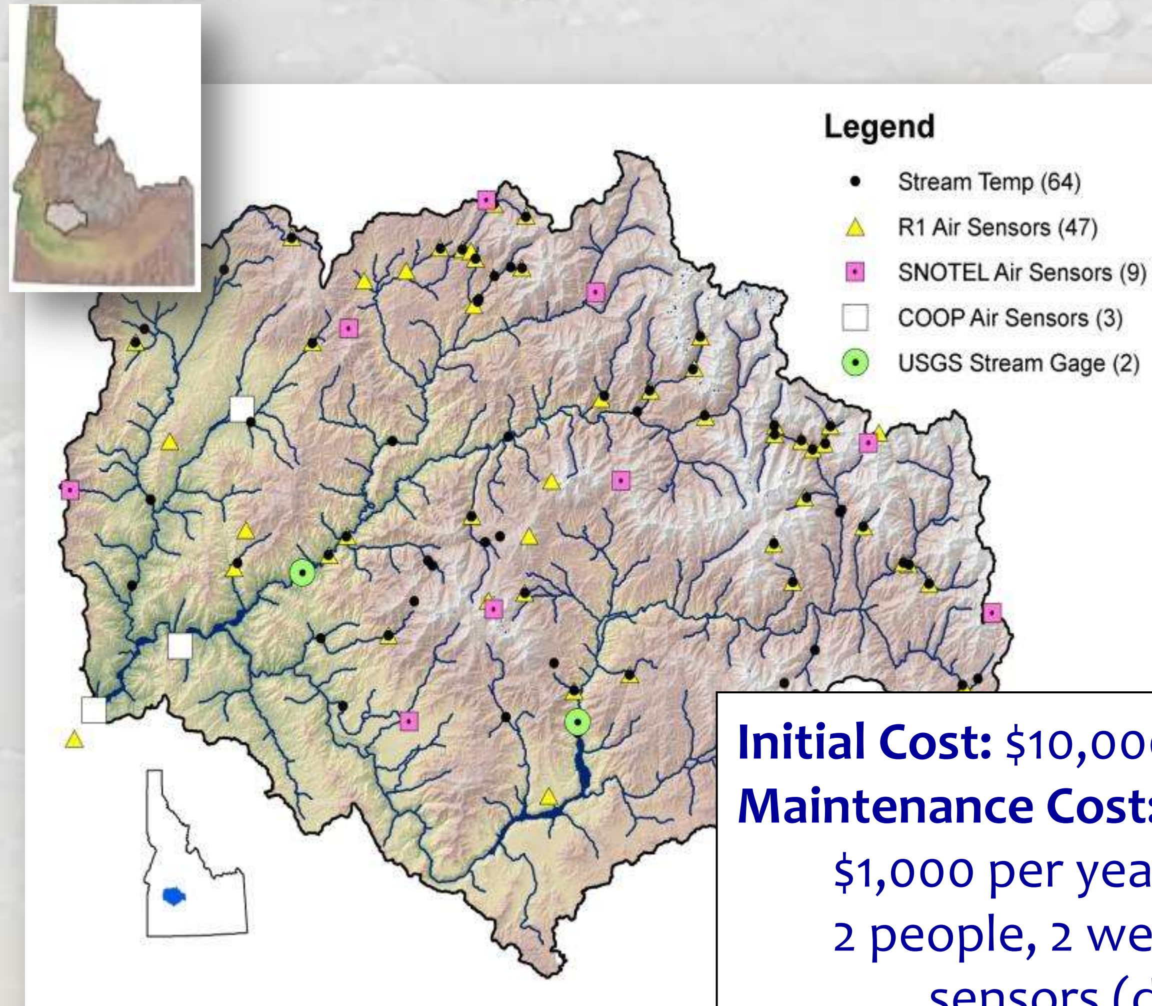
Flexible Protocol Works with Miniature Sensors

Sensor model	Accuracy	Battery life & memory	Cost
Hobo Pro v2	+/-0.2°C	6 years	$123
Tidbit v2	+/-0.2°C	5 years	$133
iButton	+/-0.5°C	1 year	$20 – 40
Tinytag Aquatic 2	+/-0.5°C	1 year	$170

Example Annual Monitoring Networks…

Dense sensor arrays for landscape analysis

Boise River Basin – 7,000 hectares, 2,500 stream kilometers

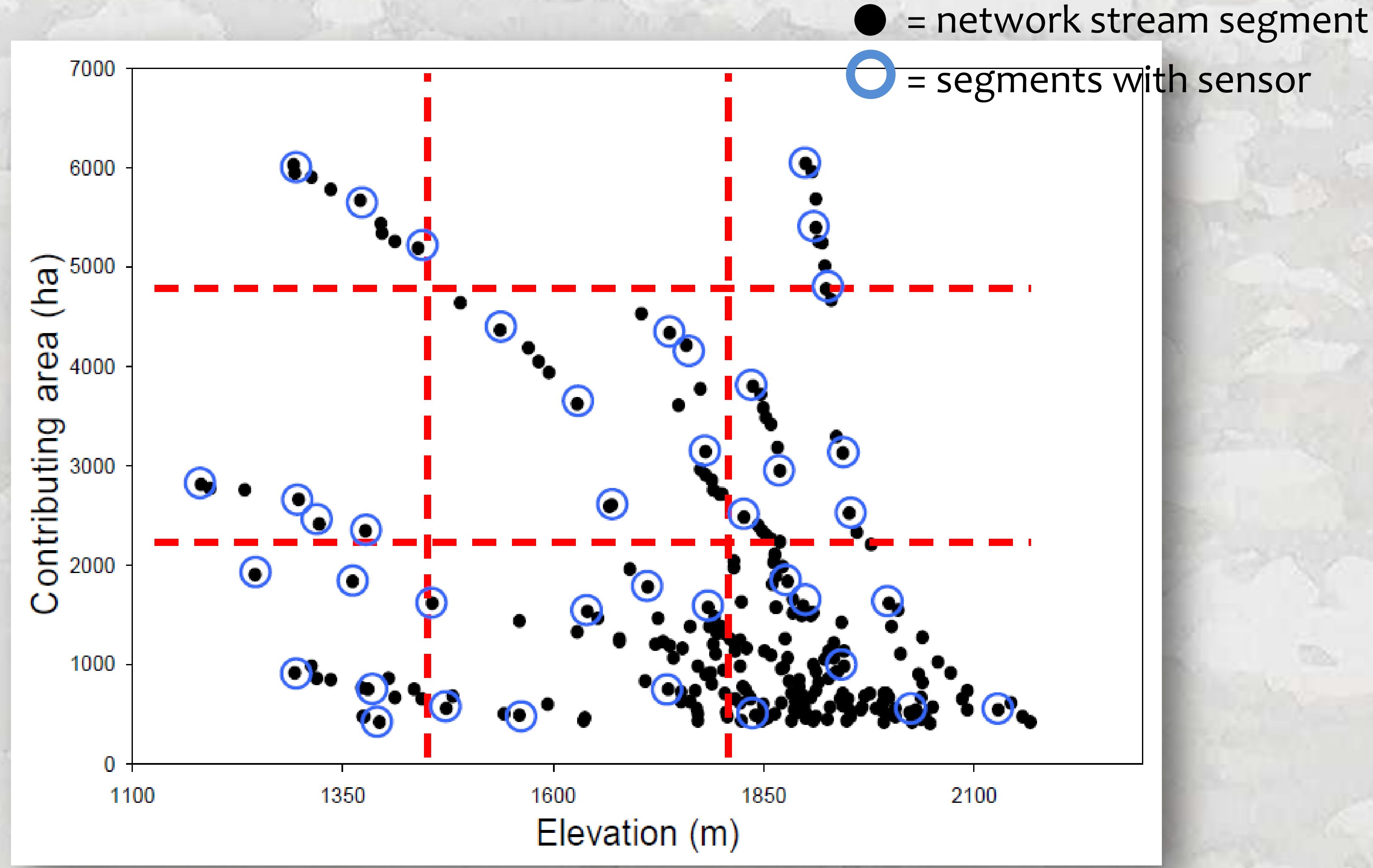


Stream sensors

Air sensors

Initial Cost: $10,000
Maintenance Cost:
$1,000 per year
2 people, 2 weeks to visit sensors (download & replace)

Sample Sites Representative of Full Network Gradients



Plots easily developed from reach descriptors already linked to NHDPlus hydrography layer

"Bracket" Important Local Features

Sensors above & below measure the effect

Lakes/Reservoirs/Bogs

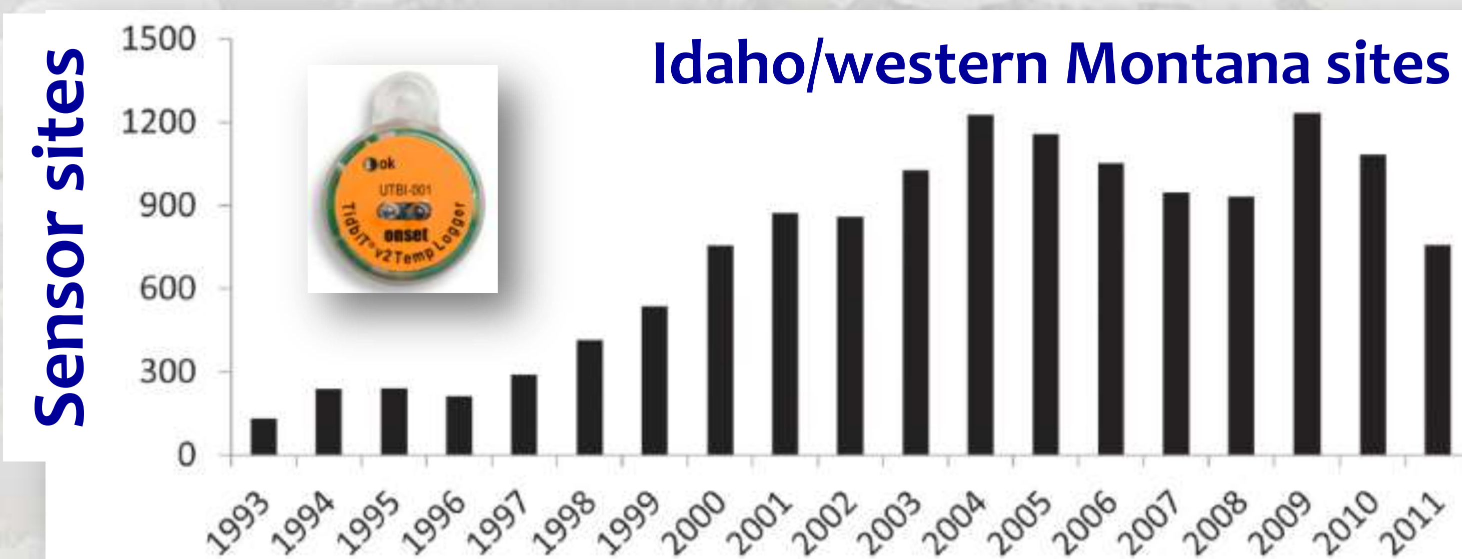
Hot Springs

Degraded Riparian Areas

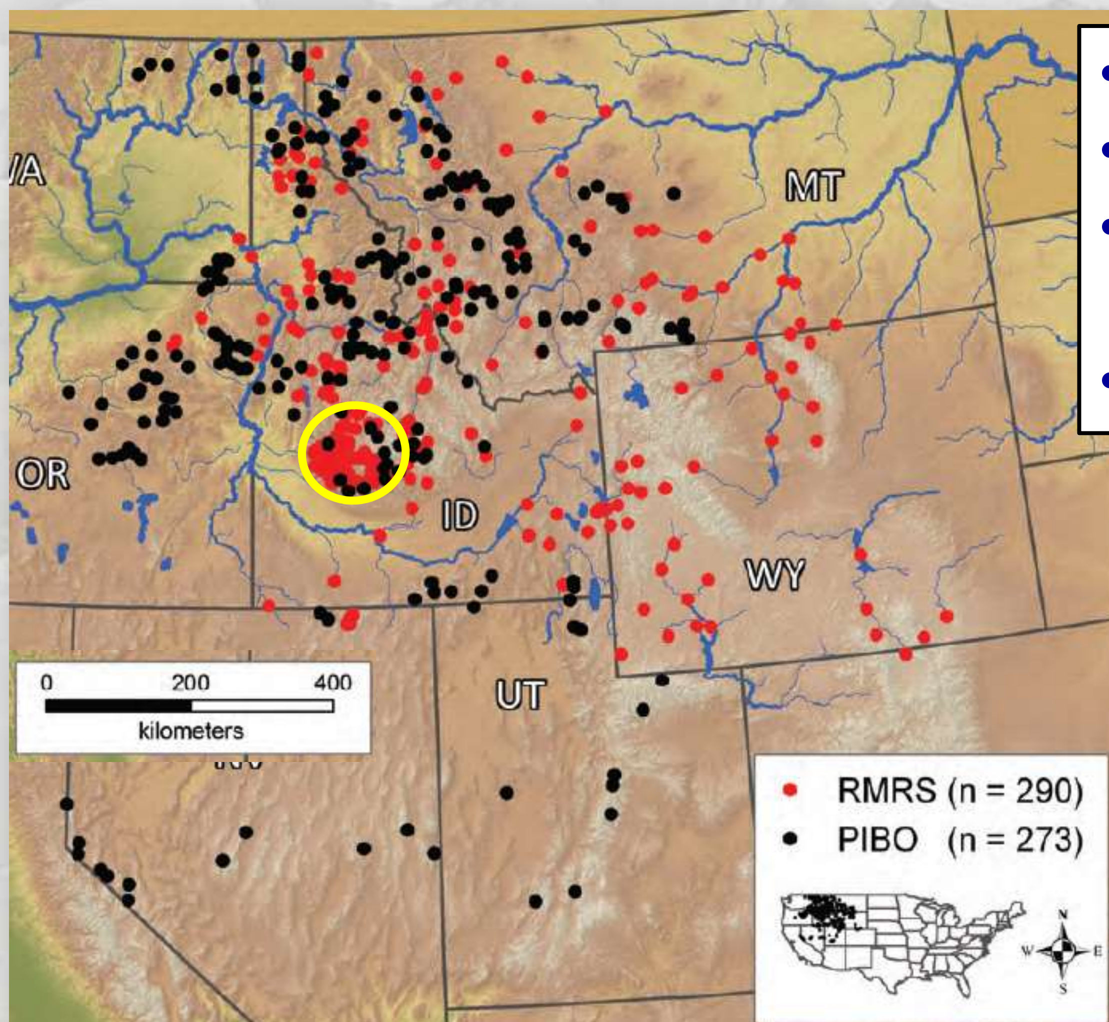
Clearcuts

Wildfires

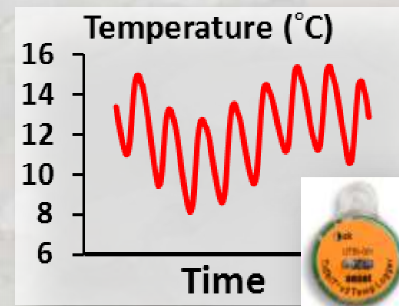
Monitoring GAP = unregulated rivers with important fisheries



NoRRTN: Northern Rockies River Temperature Network



- n = 563 sites;
- Cost = $100,000;
- 3 months time for 2 technicians;
- 2,500 years data

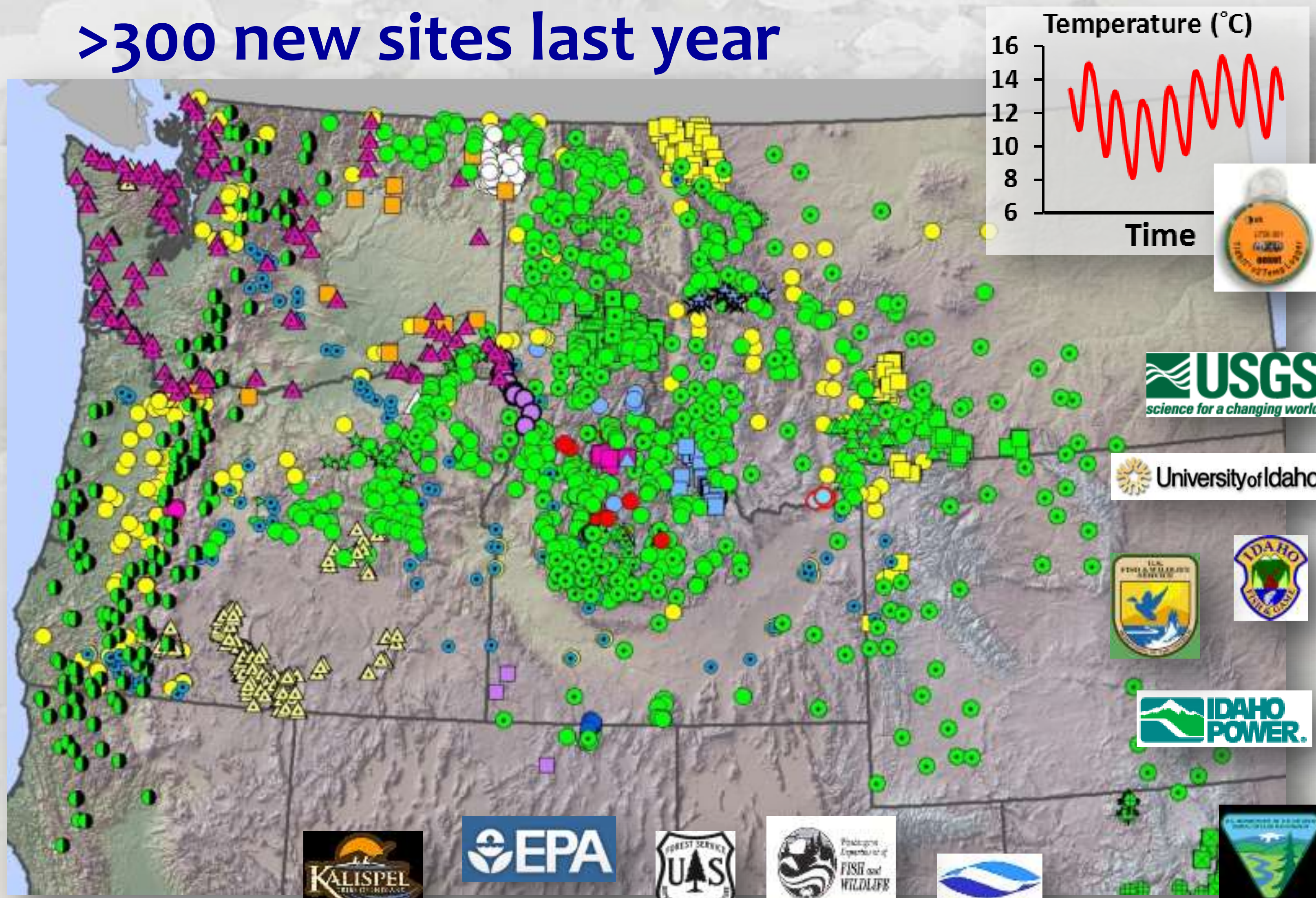


During today's meeting, NoRRTN recorded 3,378 stream temperatures (that's 3,698,910 annually…)

Annual Temperature Monitoring is Increasing

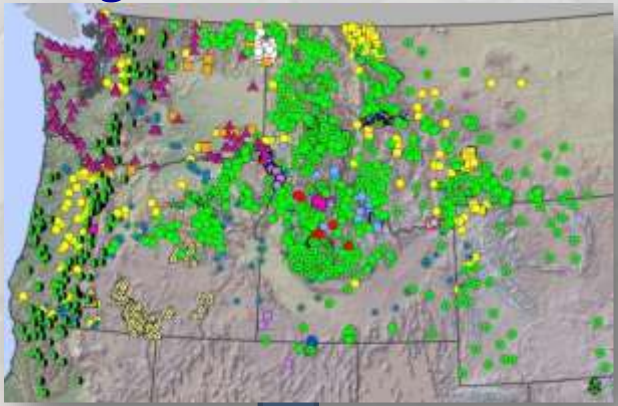
>3,000 sites in Pacific Northwest

>300 new sites last year



A GoogleMap Tool for Dynamic Queries of Temperature Monitoring Sites

Regional Sensor Network

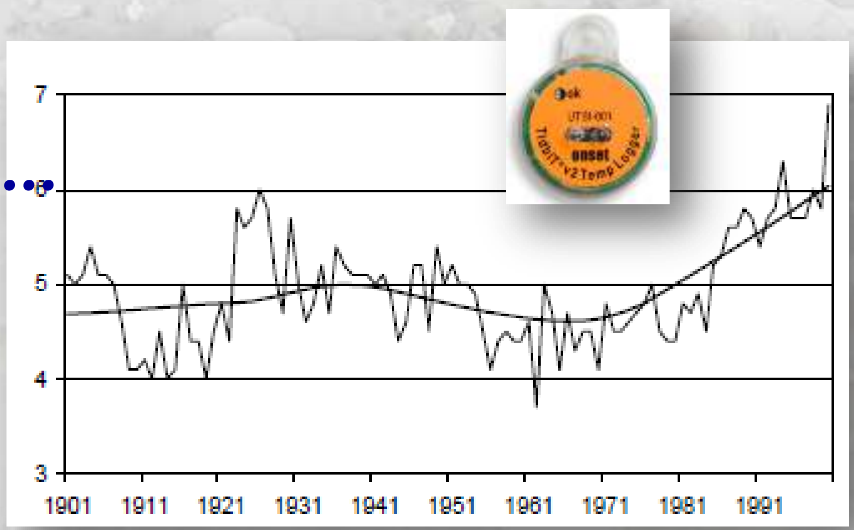


Site Information
- Stream name
- Data steward contact information
- Agency
- Site Initiation Date

Query Individual Sites

GoogleMap Tool at "Stream Temperature Monitoring and Modeling" website

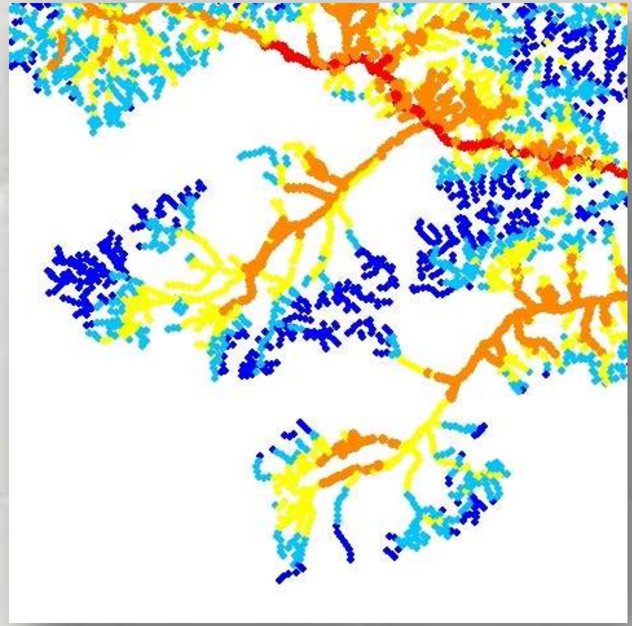
How Long Should Temperatures be Monitored?



Webb and Nobilus 2007

Long-term records are rare…

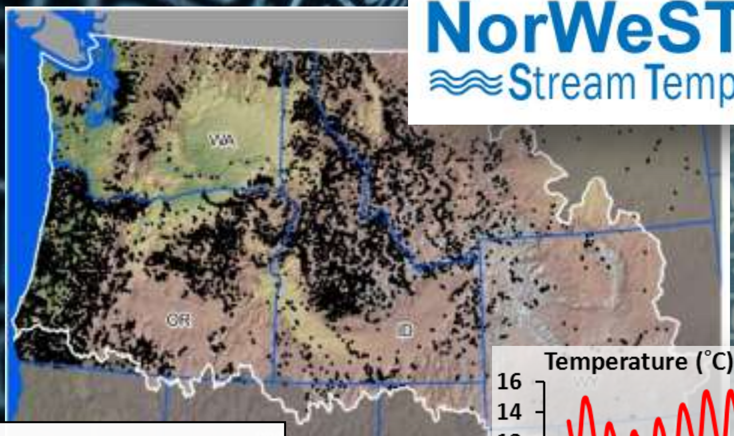
So some sites should be monitored indefinitely



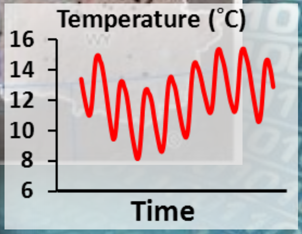
…but spatial variation among sites contains most "information" about thermal regimes

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

So What About All That Summer Data?



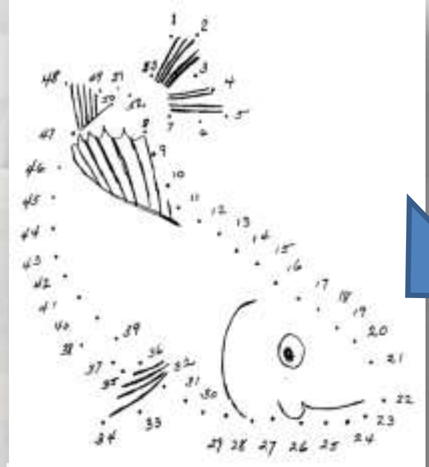
~45,000,000 hourly records



BIG DATA = BIG INFORMATION?

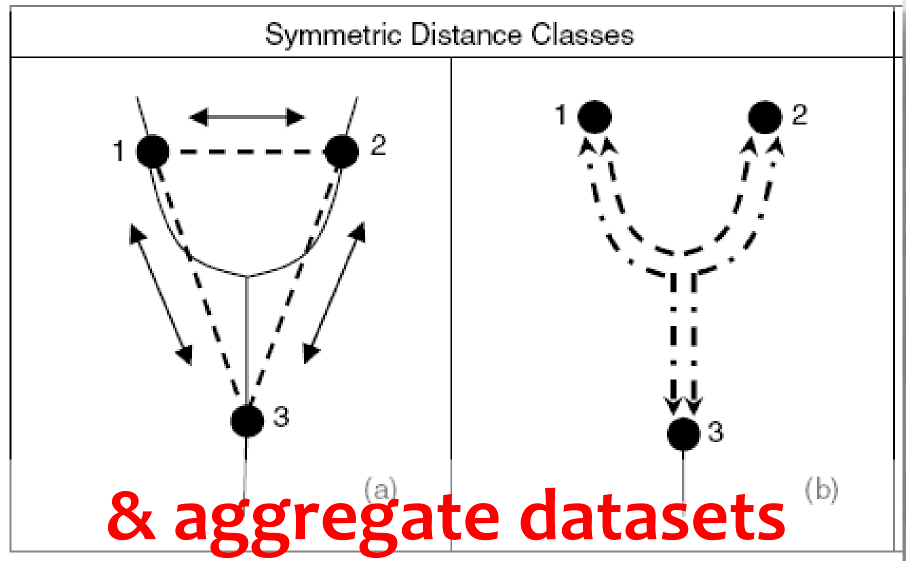
BIG DATA are often Autocorrelated

Spatial Statistical Network Models



Let's us connect the dots…

Valid interpolation on networks



& aggregate datasets

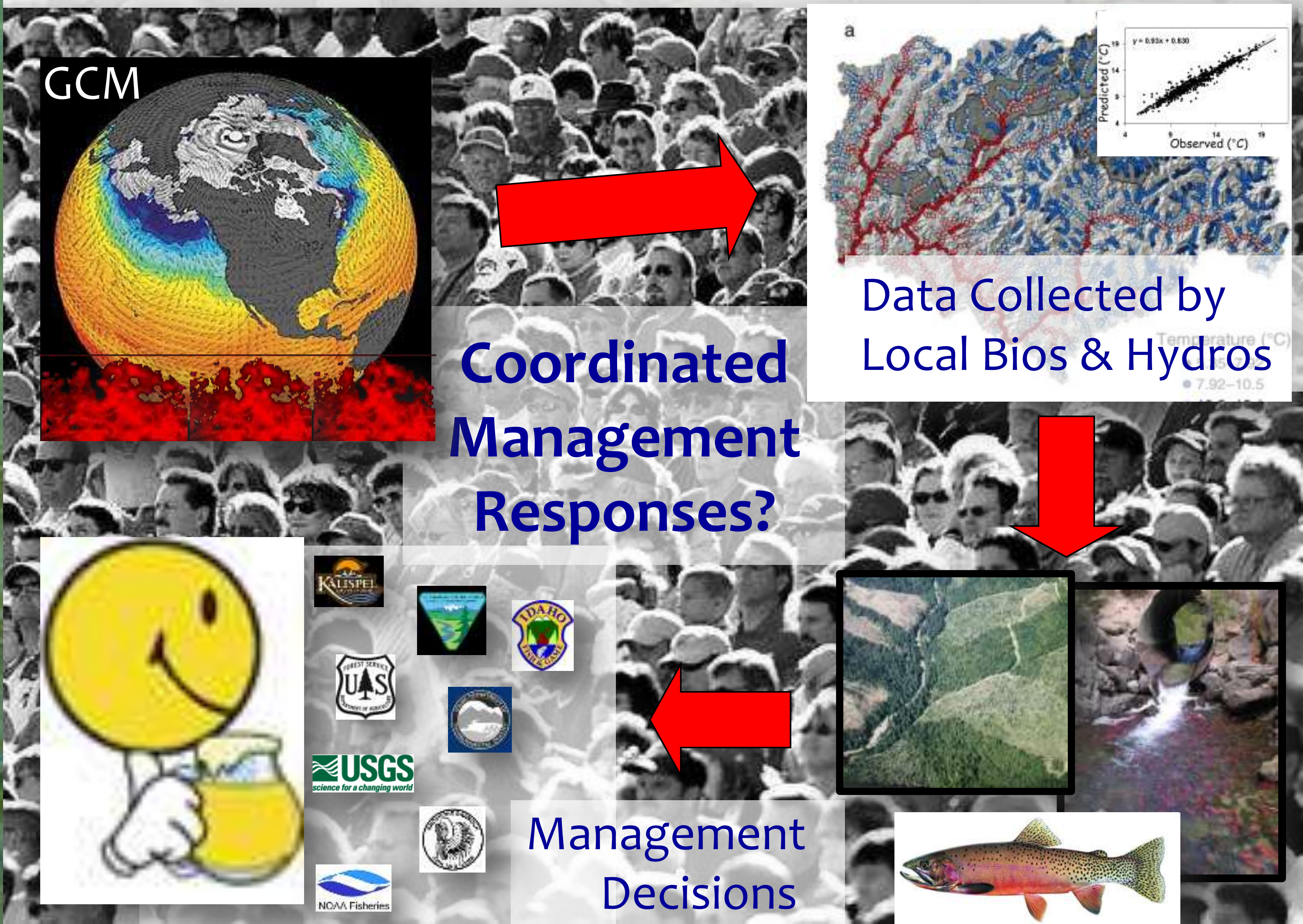
Advantages:

-flexible & valid autocovariance structures that accommodate network topology & non-independence among observations

-improved predictive ability & parameter estimates relative to non-spatial models

Ver Hoef et al. 2006; Ver Hoef & Peterson 2010; Peterson & Ver Hoef 2013

Spatial Models Enable "Crowd-Sourcing" so Everyone's Data is Used



The NorWeST Stream Temperature Database, Model, & Climate Scenarios

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, Colete Breshares, Neal Bernklau

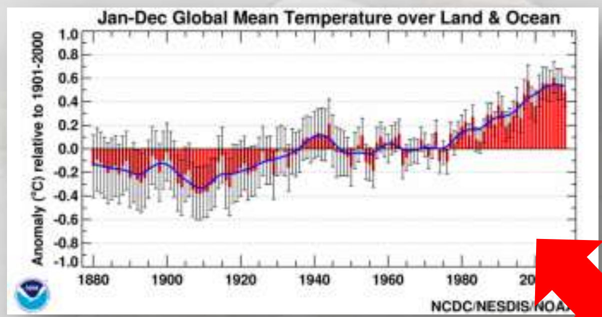
U.S. Forest Service

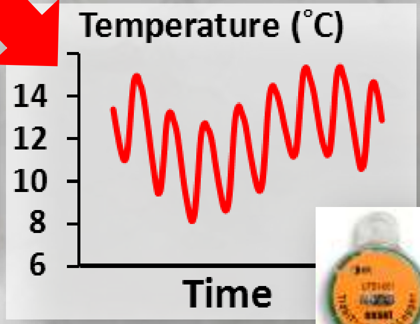
[1]Trout Unlimited

[2]CSIRO

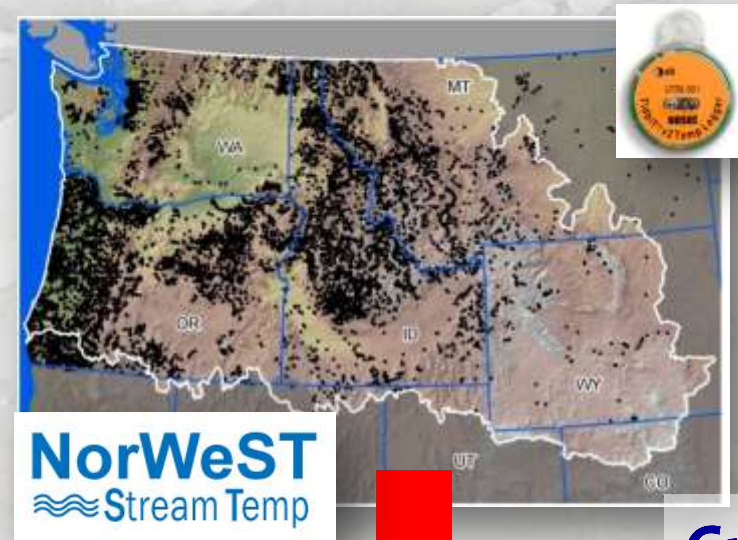
[3]NOAA

[4]USGS

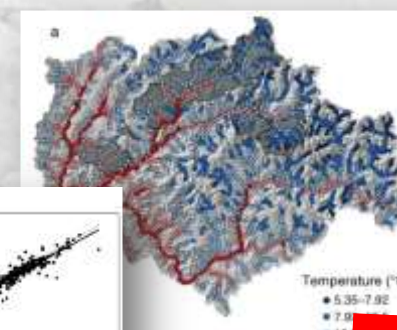


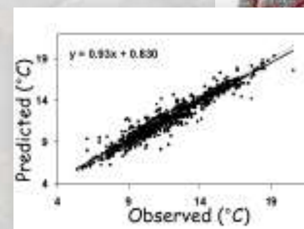


Regional Temperature Model



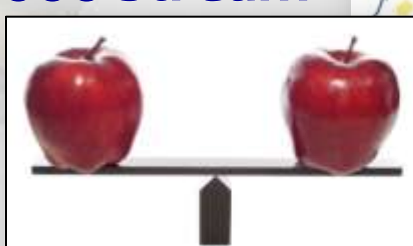
Accurate stream temp model



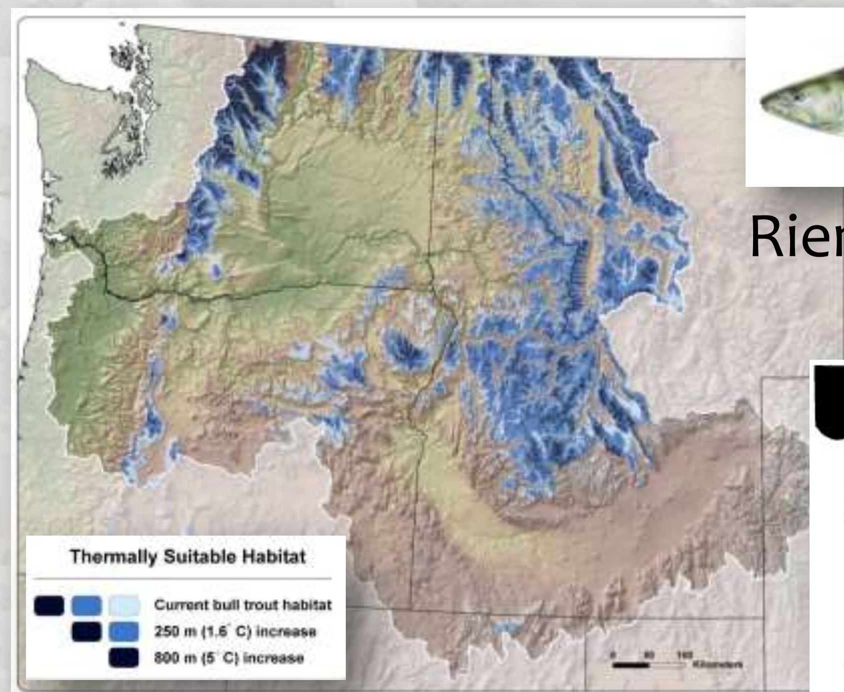


Cross-jurisdictional "maps" of stream climate scenarios

Consistent datum for strategic planning across 500,000 stream kilometers



Improve Resolution of Climate Vulnerability Models



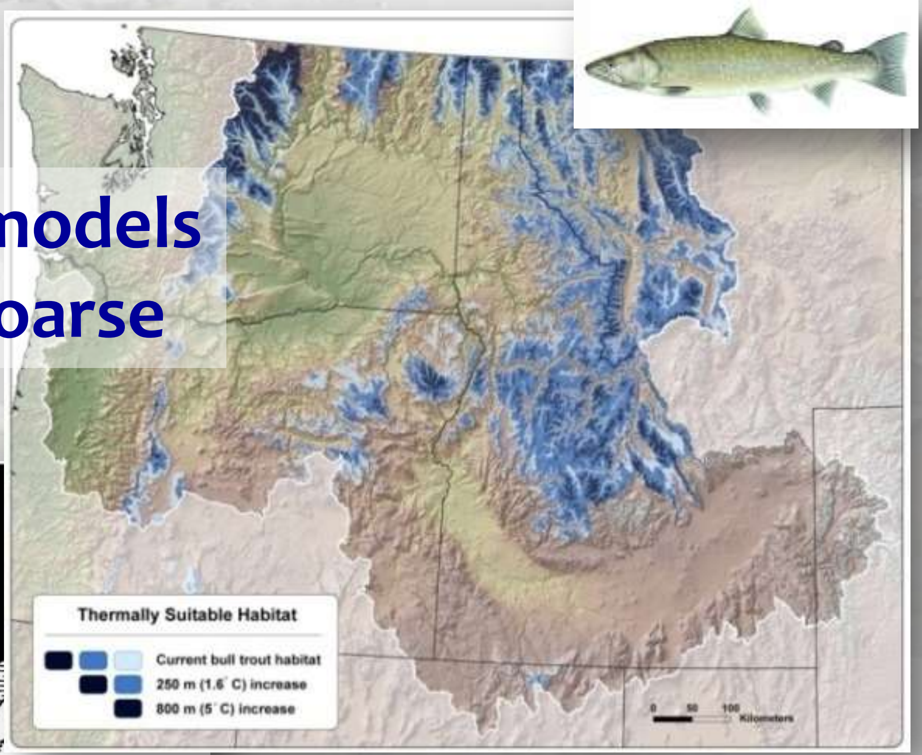
Rieman et al. 2007

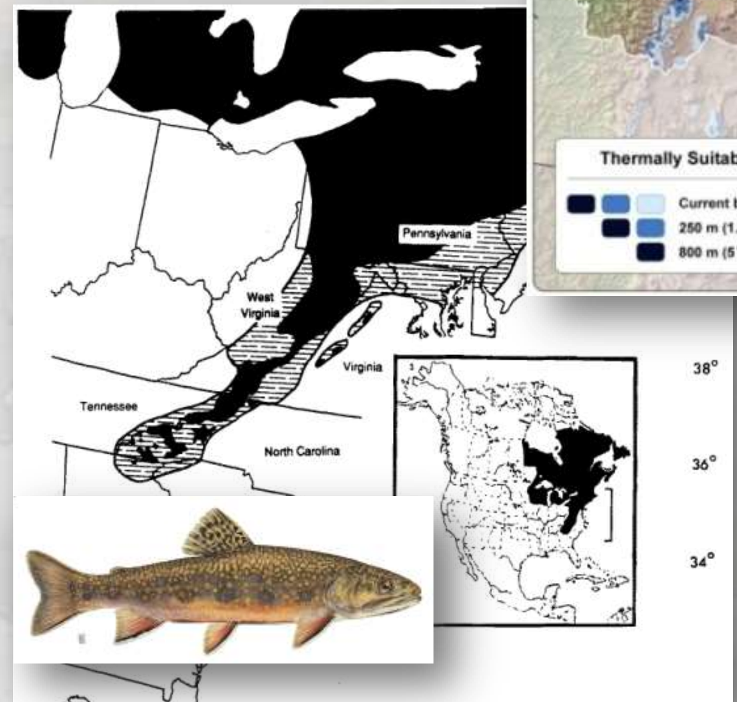
Meisner 1990

Create "actionable intelligence"

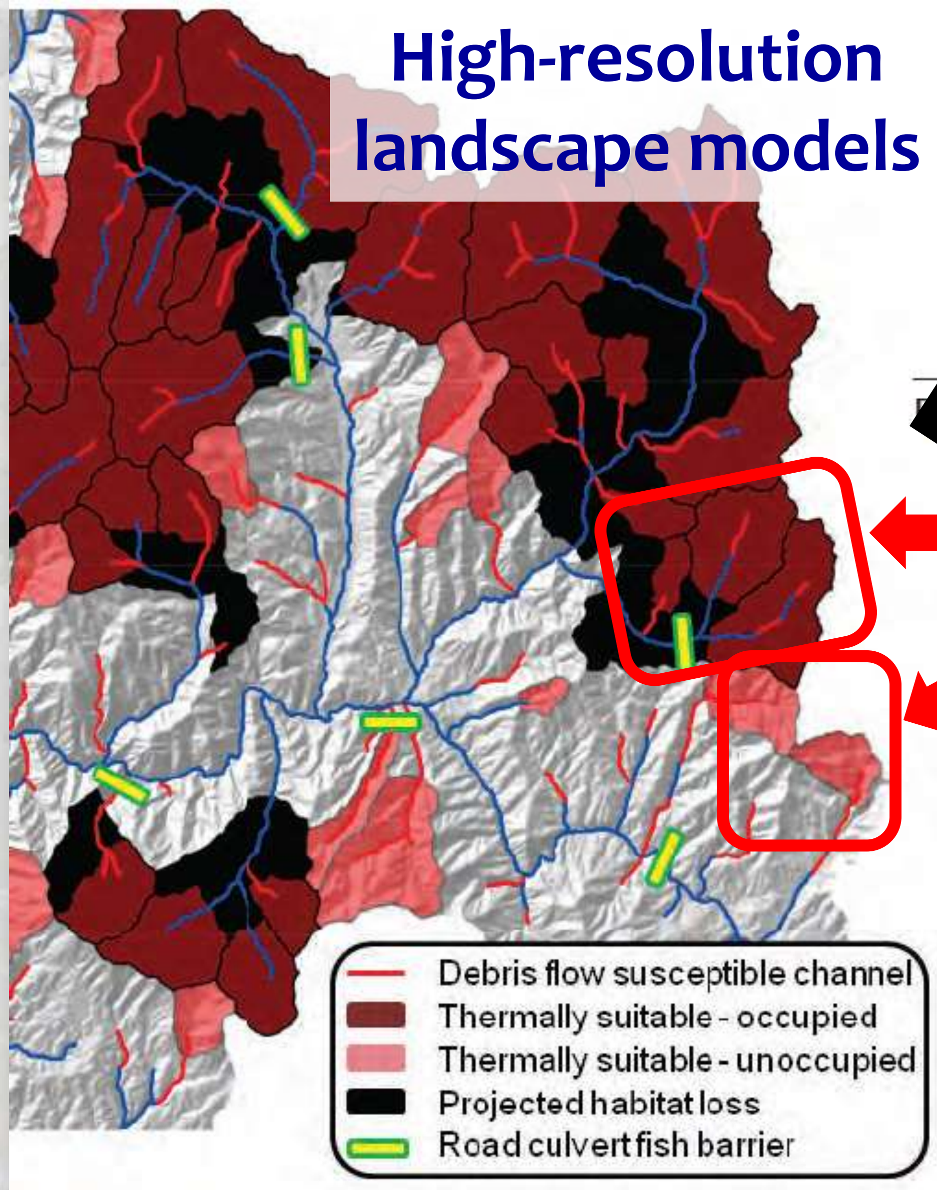
Precise Information Needed to Facilitate Strategic Decision Making & Empower Local Decision Makers

Regional models are too coarse





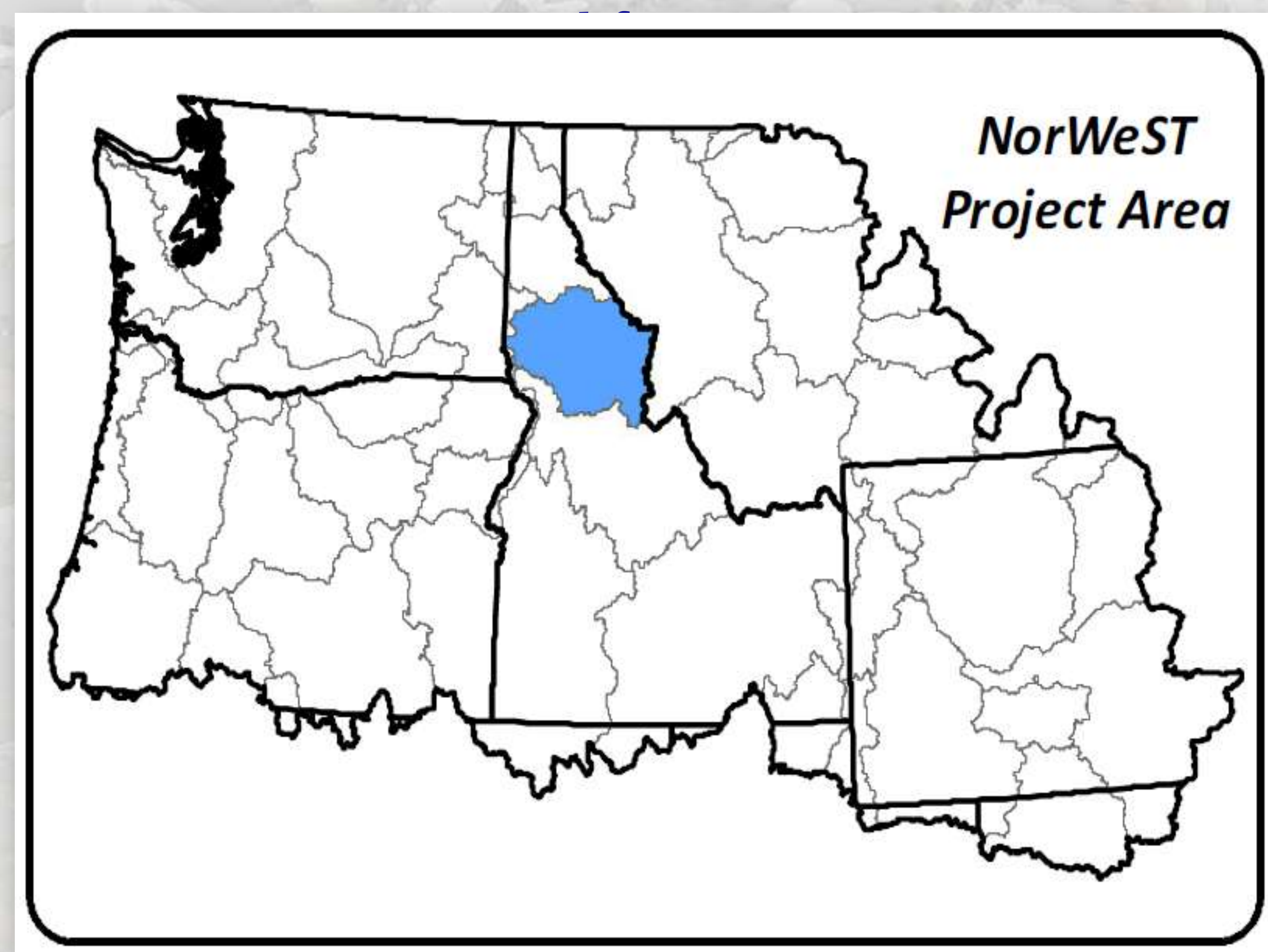
Precise Information Needed to Facilitate Strategic Decision Making & Empower Local



I'm going to invest here…

… instead of here

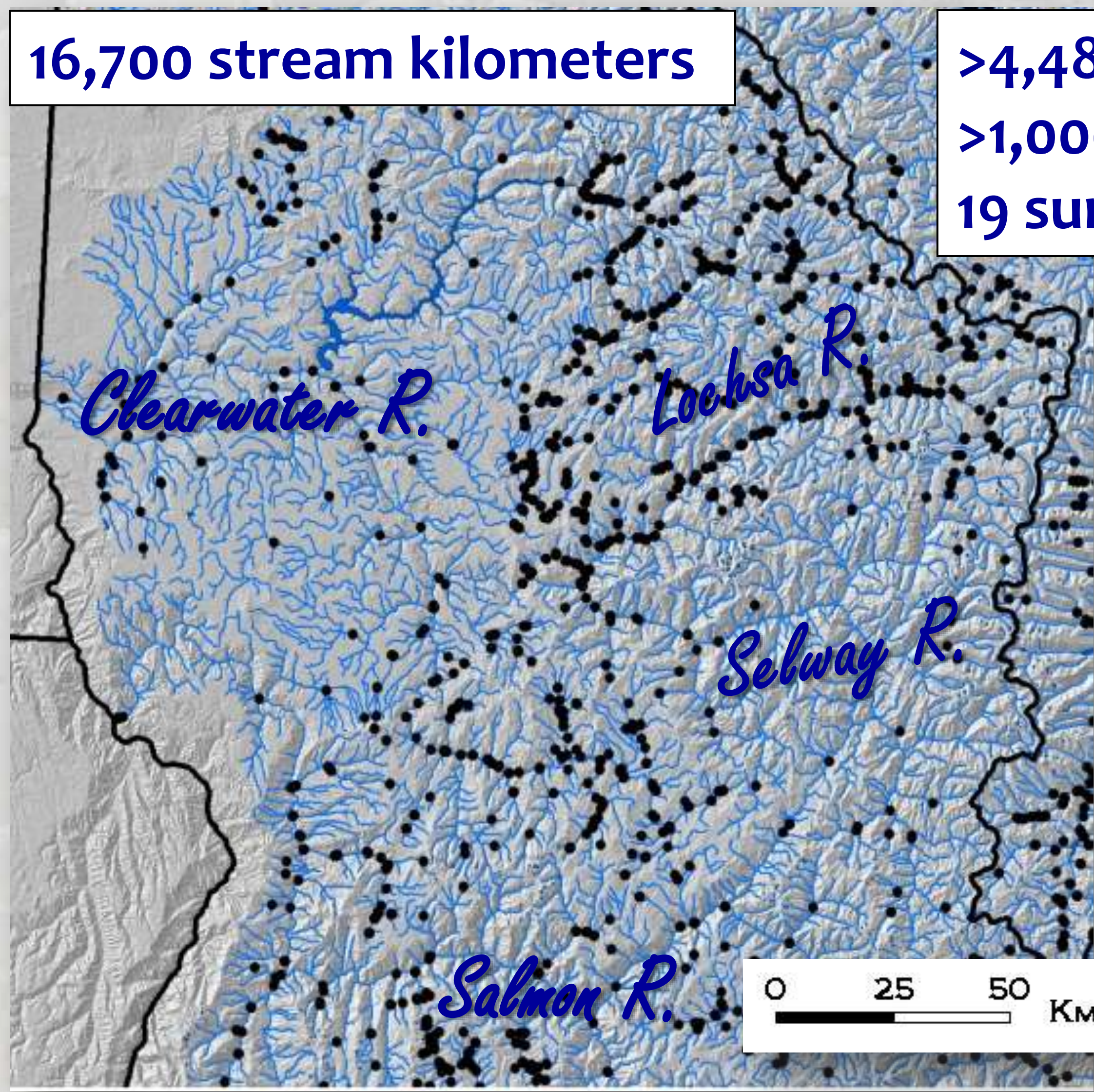
Example: Clearwater River Basin



Example: Clearwater River Basin

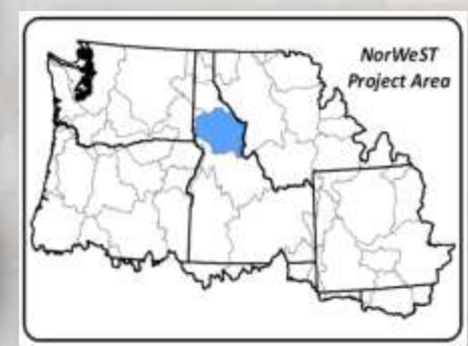
Data extracted from NorWeST

16,700 stream kilometers



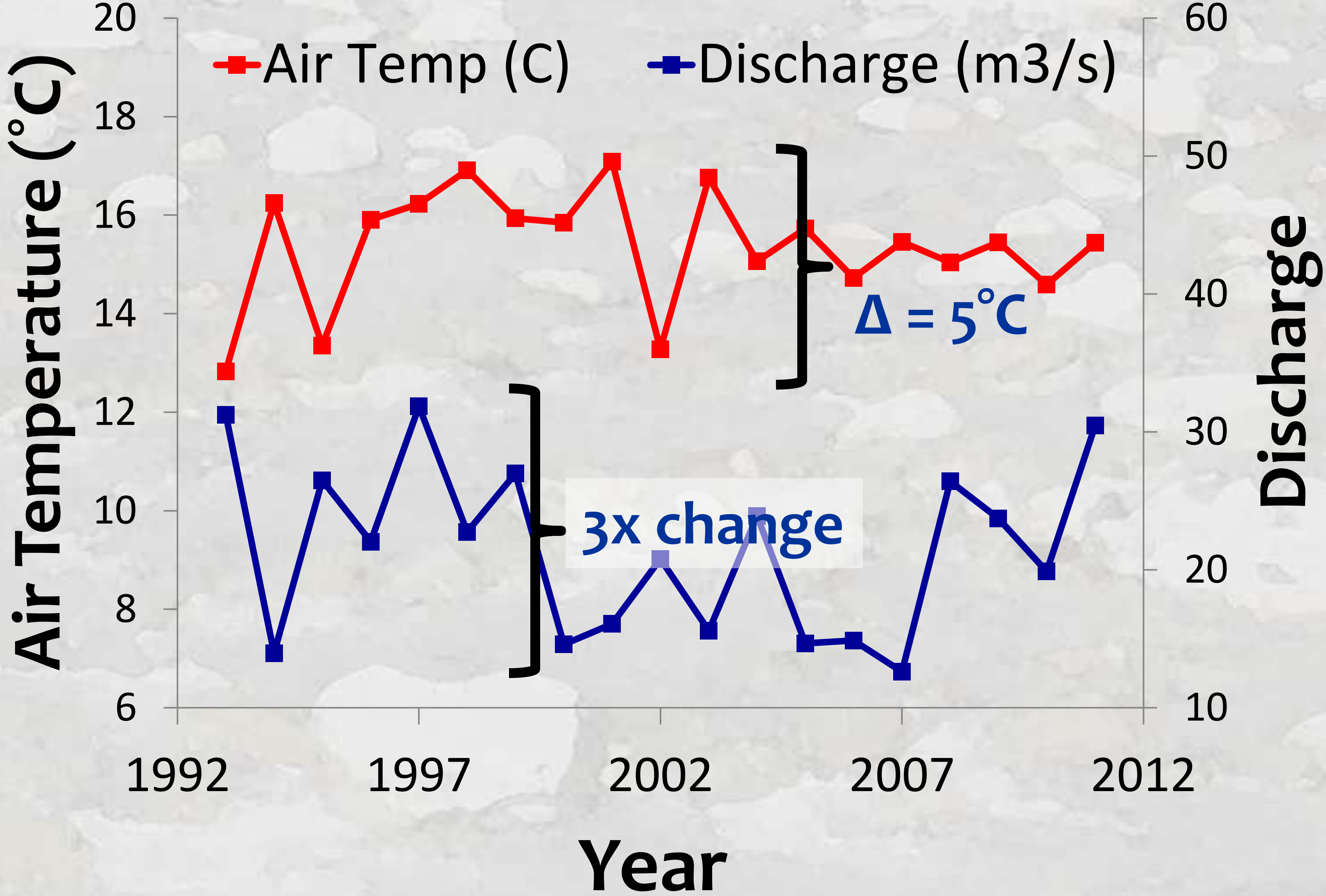
>4,487 August means
>1,000 stream sites
19 summers (1993-2011)

•Temperature site



Climatic Variability in Historical Record

Extreme years include mid-21st-Century "averages"



Clearwater River Temp Model

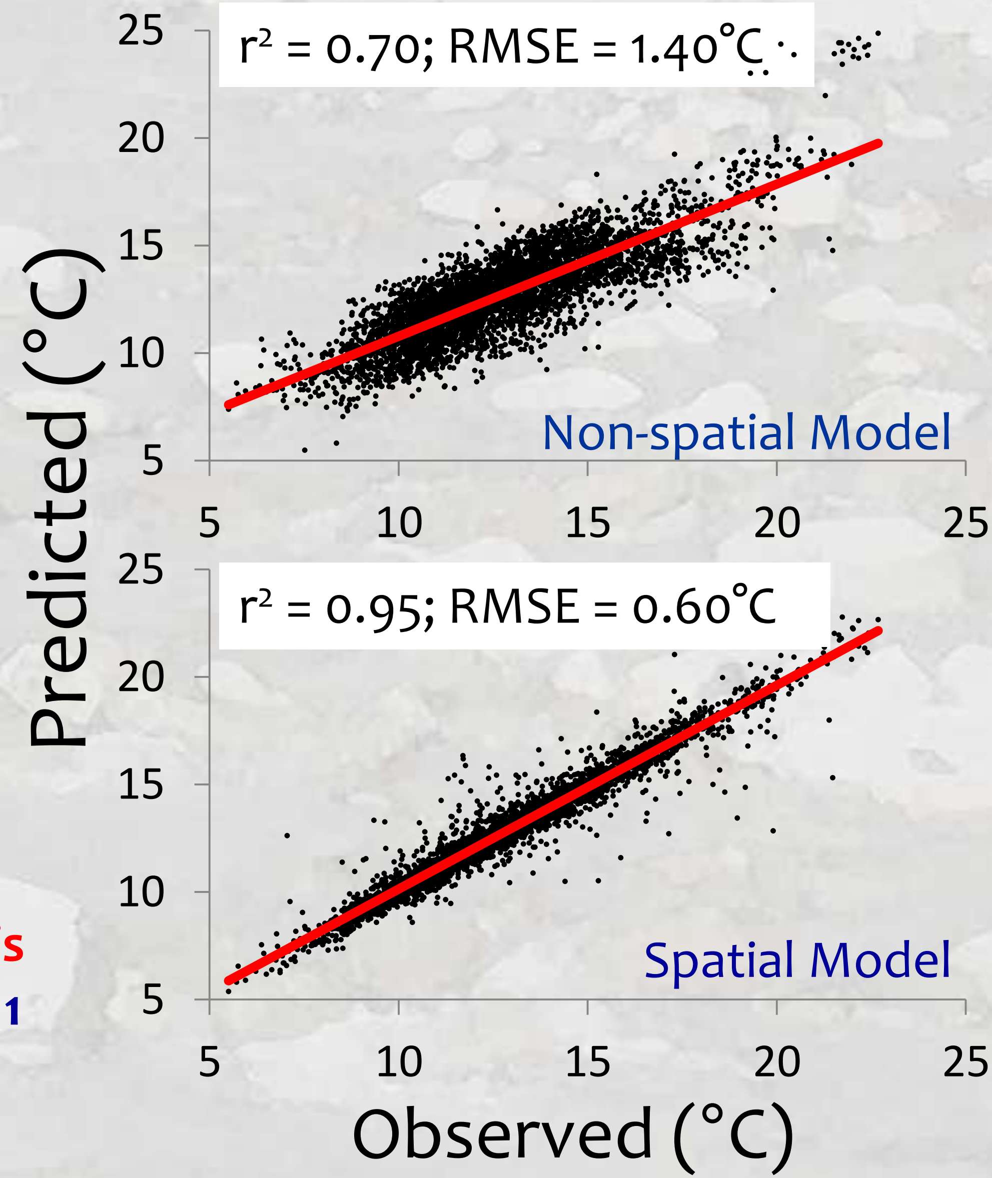
n = 4,487

<u>Covariate Predictors</u>

1. Elevation (m)
2. Canopy (%)
3. Stream slope (%)
4. Ave Precipitation (mm)
5. Latitude (km)
6. Lakes upstream (%)
7. Baseflow Index
8. Watershed size (km^2)

9. Discharge (m^3/s)
   USGS gage data
10. Air Temperature (°C)
    RegCM3 NCEP reanalysis
    Hostetler et al. 2011

Mean August Temperature



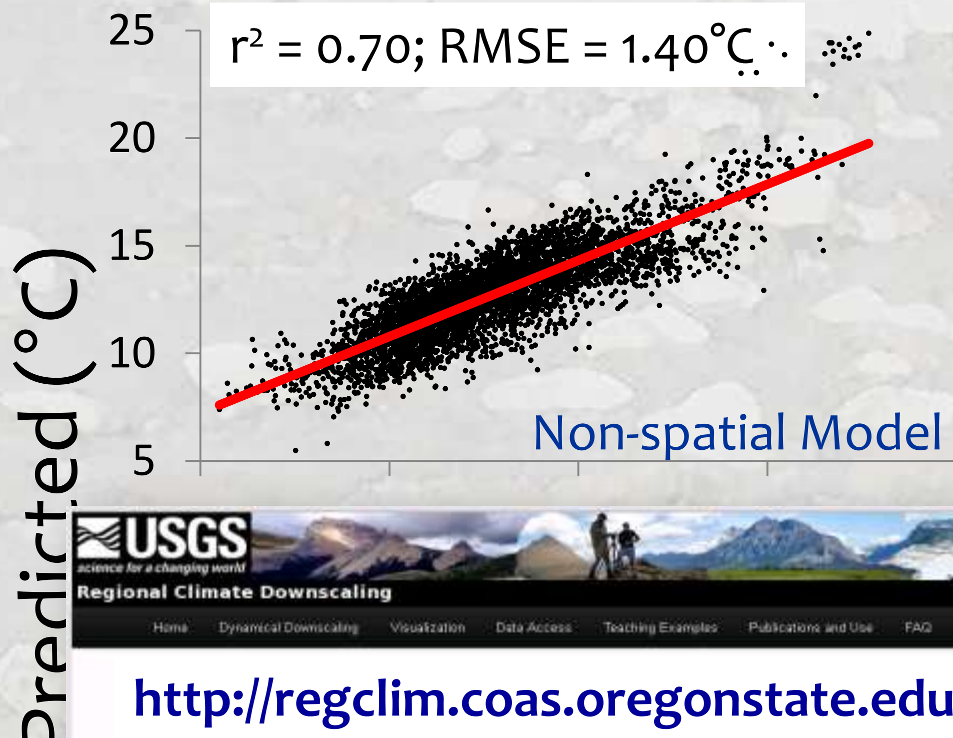
Clearwater River Temp Model

n = 4,487

Covariate Predictors

1. Elevation (m)
2. Canopy (%)
3. Stream slope (%)
4. Ave Precipitation (mm)
5. Latitude (km)
6. Lakes upstream (%)
7. Baseflow Index
8. Watershed size (km²)

9. Discharge (m³/s)
   USGS gage data
10. Air Temperature (°C)
   RegCM3 NCEP reanalysi
   Hostetler et



Why August Mean Temperature?

- 95% of temperature data are summer only
- All summer metrics are strongly correlated
- Monthly mean is easily linked to regional climate model

MWAT ~ **Maximum** ~ **Minimum**

MDAT ~ **AWAT** ~ **Degree-days** ~ Mean

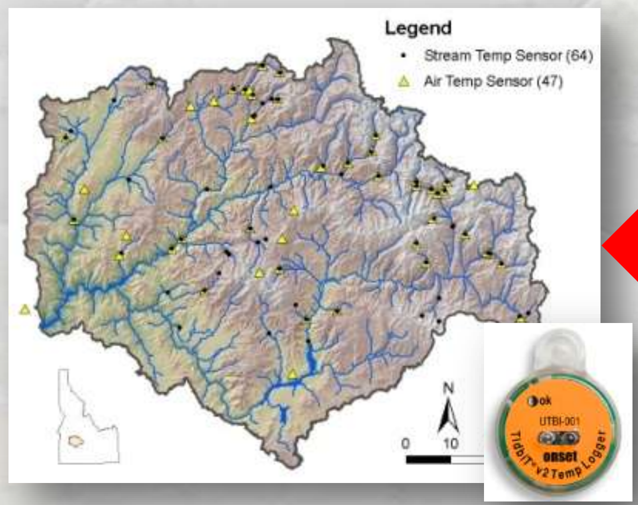
	Summer_mn	*Mwmt*	*Mwat*	*awat_mn*	*awmt_mn*	***August Mean***
Summer_mn						
Mwmt	0.93					
Mwat	0.98	0.94				
awat_mn	1.00	0.93	0.97			
awmt_mn	0.96	0.98	0.94	0.96		
August Mean	**0.99**	**0.92**	**0.96**	**0.99**	**0.95**	
August MWMT	0.92	0.99	0.92	0.92	0.98	**0.92**

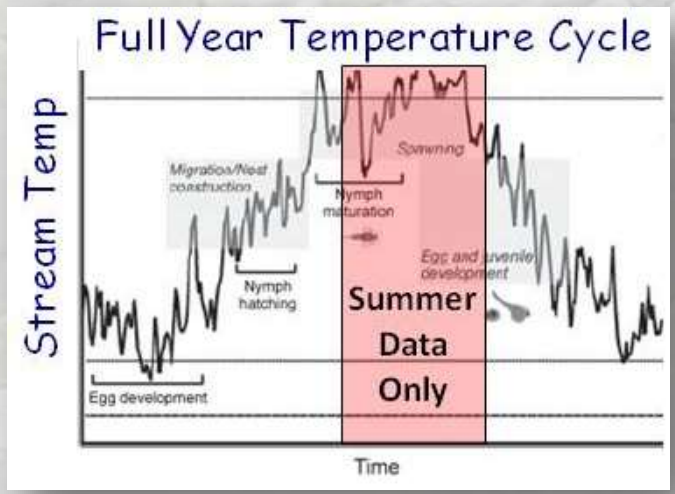
***Modeling each additional metric doubles computational time**

***Conversion factors can facilitate metric translation**

Summer Temperatures ~ Other Seasons

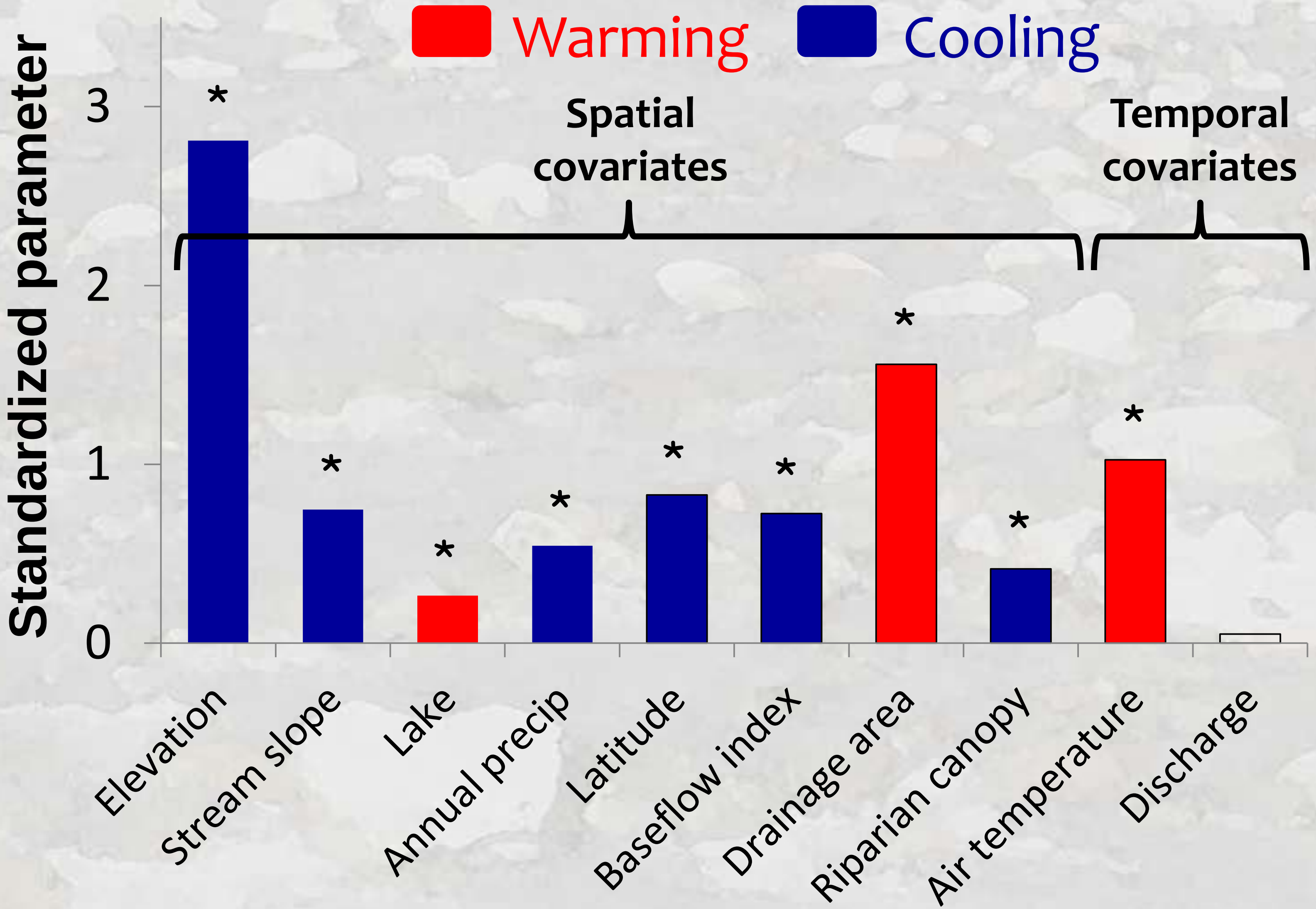
	Fall mean	Fall SD	Winter Mean	Winter SD	Spring mean	Spring SD	Summer Mean
Fall SD	0.87	---					
Winter Mean	0.50	0.02	---				
Winter SD	0.70	0.35	0.83	---			
Spring mean	0.95	0.76	0.51	0.78	---		
Spring SD	0.69	0.77	-0.05	0.29	0.74	---	
Summer Mean	**0.91**	**0.92**	**0.23**	**0.45**	**0.88**	**0.87**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





Relative Effects of Predictors

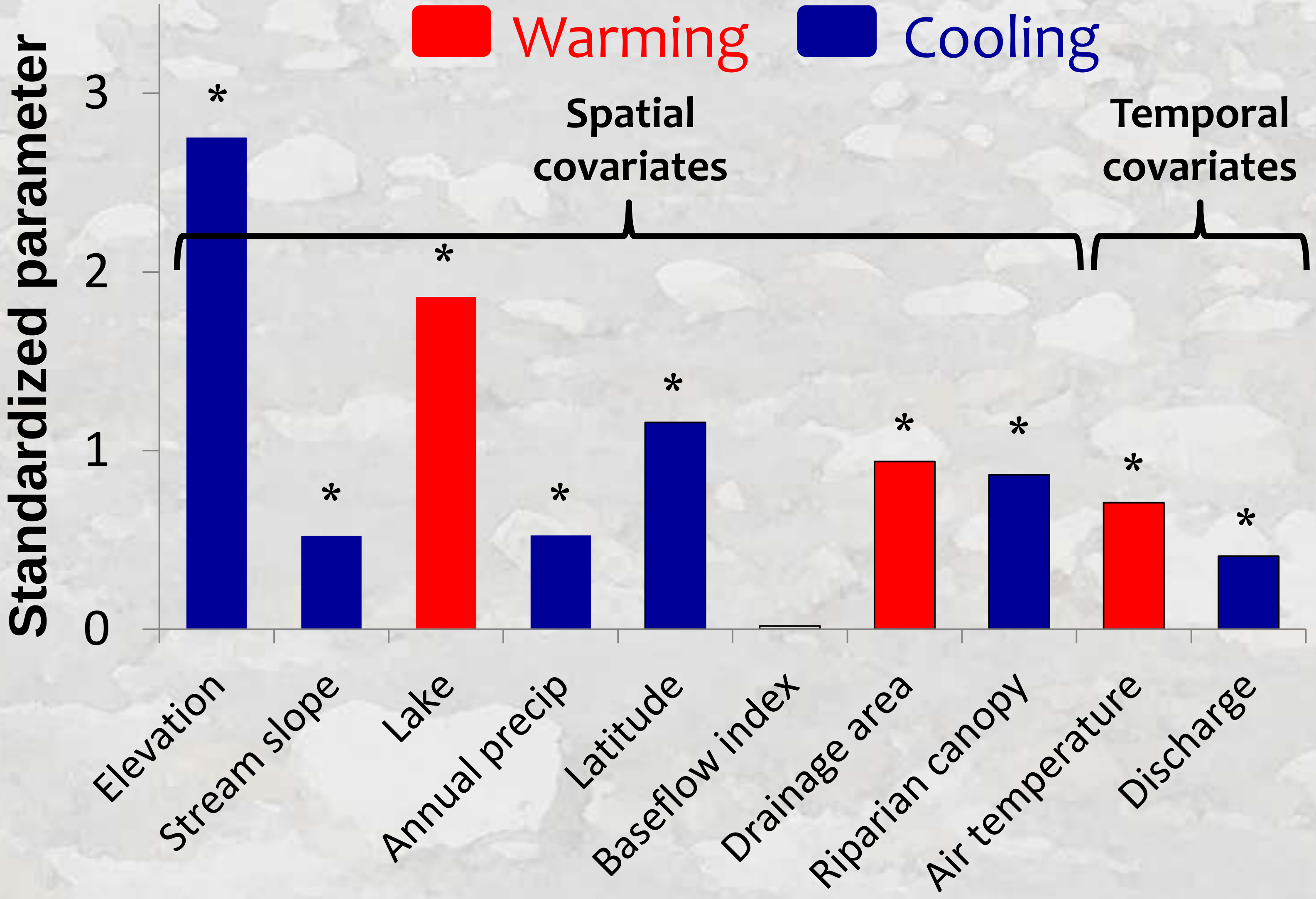
Clearwater Temperature Model



* = statistically significant at $p < 0.01$

Relative Effects of Predictors

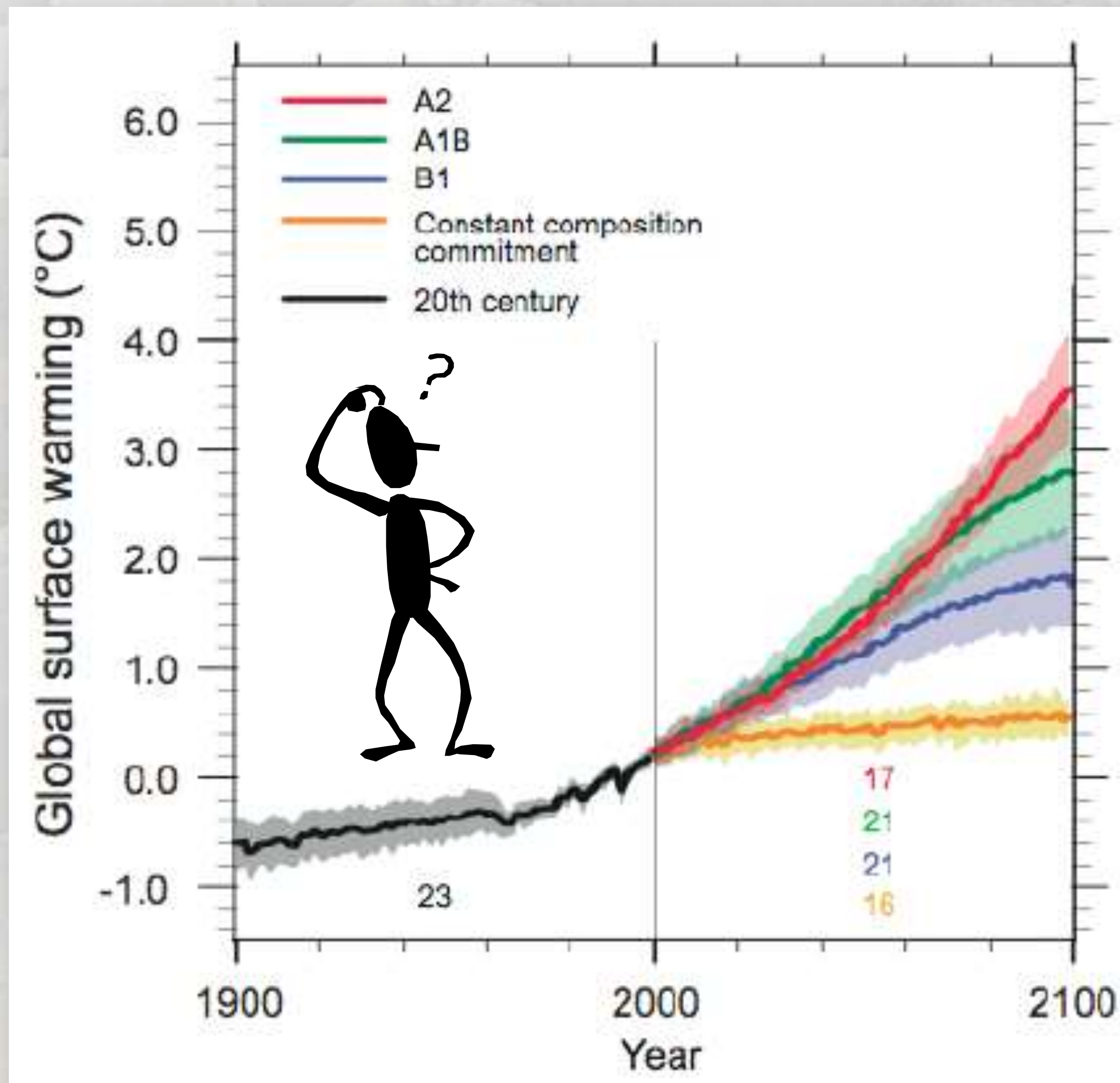
SpoKoot Temperature Model



* = statistically significant at $p < 0.01$

Models Enable Climate Scenario Maps

Many possibilities exist…



Adjust…

- Air
- Discharge
- %Canopy

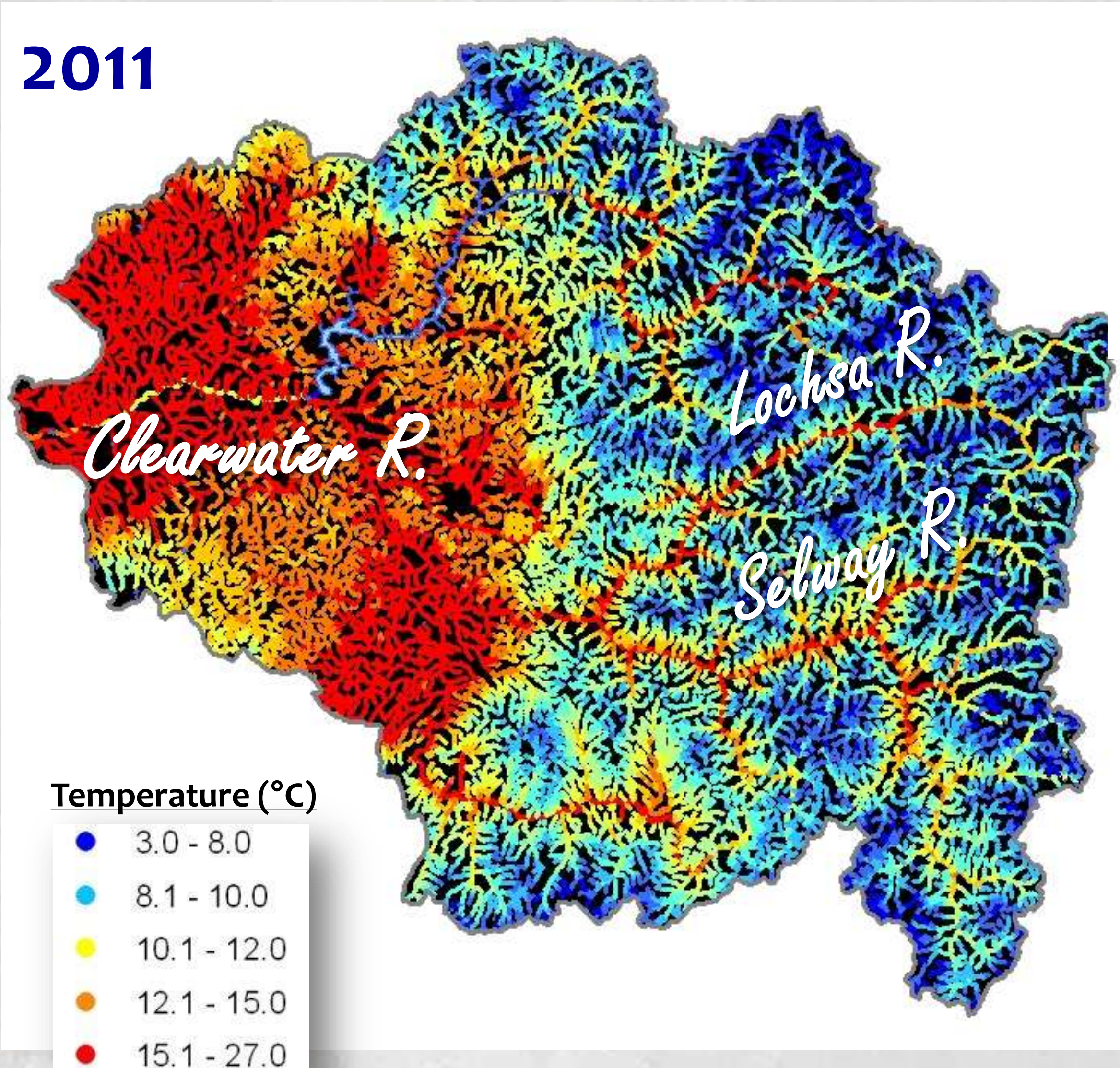
…values to create scenarios

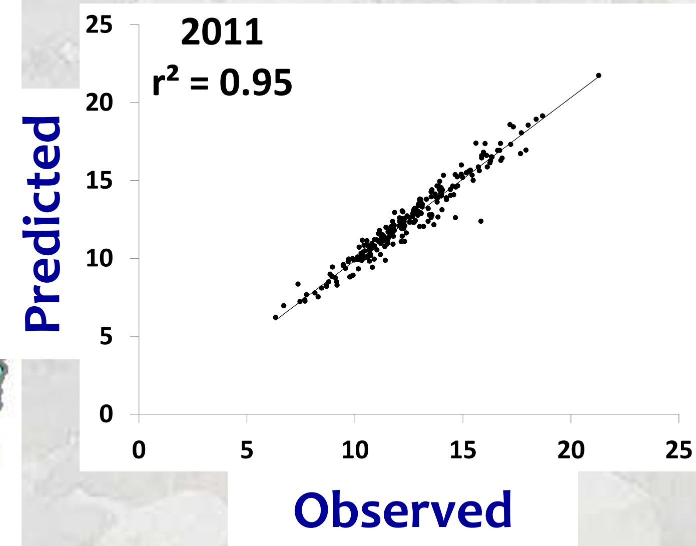
NorWeST Scenario Descriptions

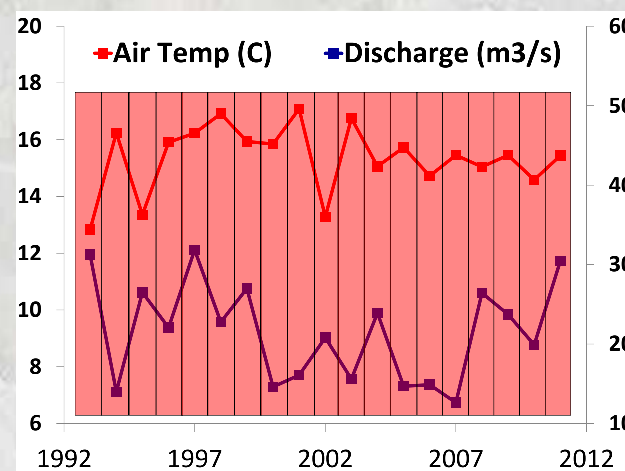
Scenario	Description
S1_93_11	Historical scenario representing 19 year average August mean stream temperatures for 1993-2011
S2_02_11	Historical scenario representing 10 year average August mean stream temperatures for 2002-2011
S3_1993	Historical scenario representing August mean stream temperatures for 1993
S4_1994	Historical scenario representing August mean stream temperatures for 1994
Etc…	
S22+…	Futures: 1) A1B scenarios for 2040s and 2080s; 2) “scenario free (e.g., +1˚C, +2C, etc.)

Historical Scenarios (1993-2011)

Mean August Temperature - Clearwater Basin

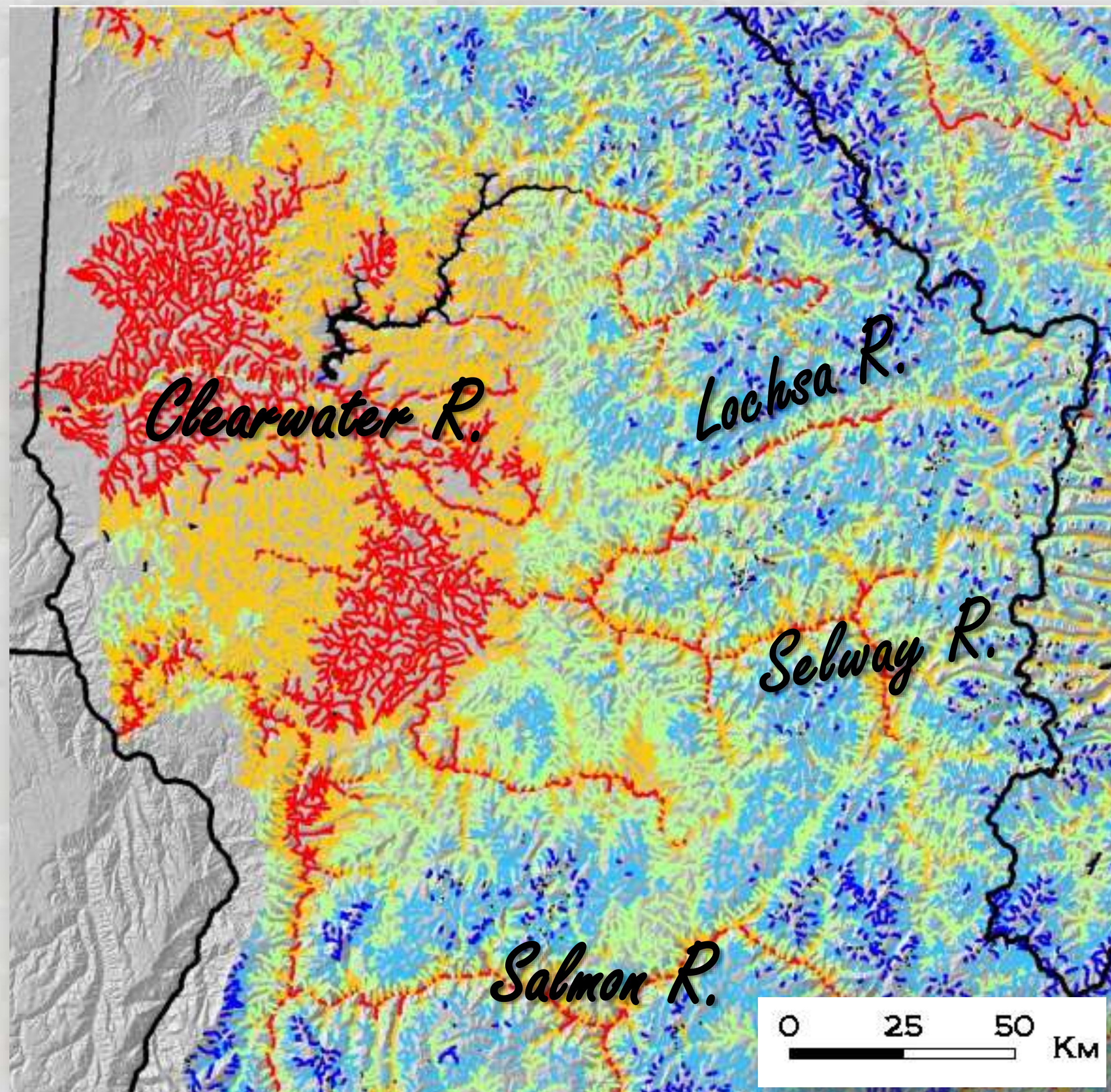






Clearwater Stream Temperature Scenario

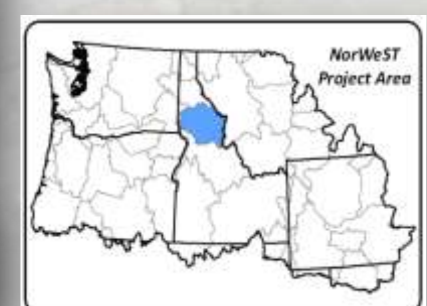
Historic (1993-2011 Average August)



Temperature (°C)

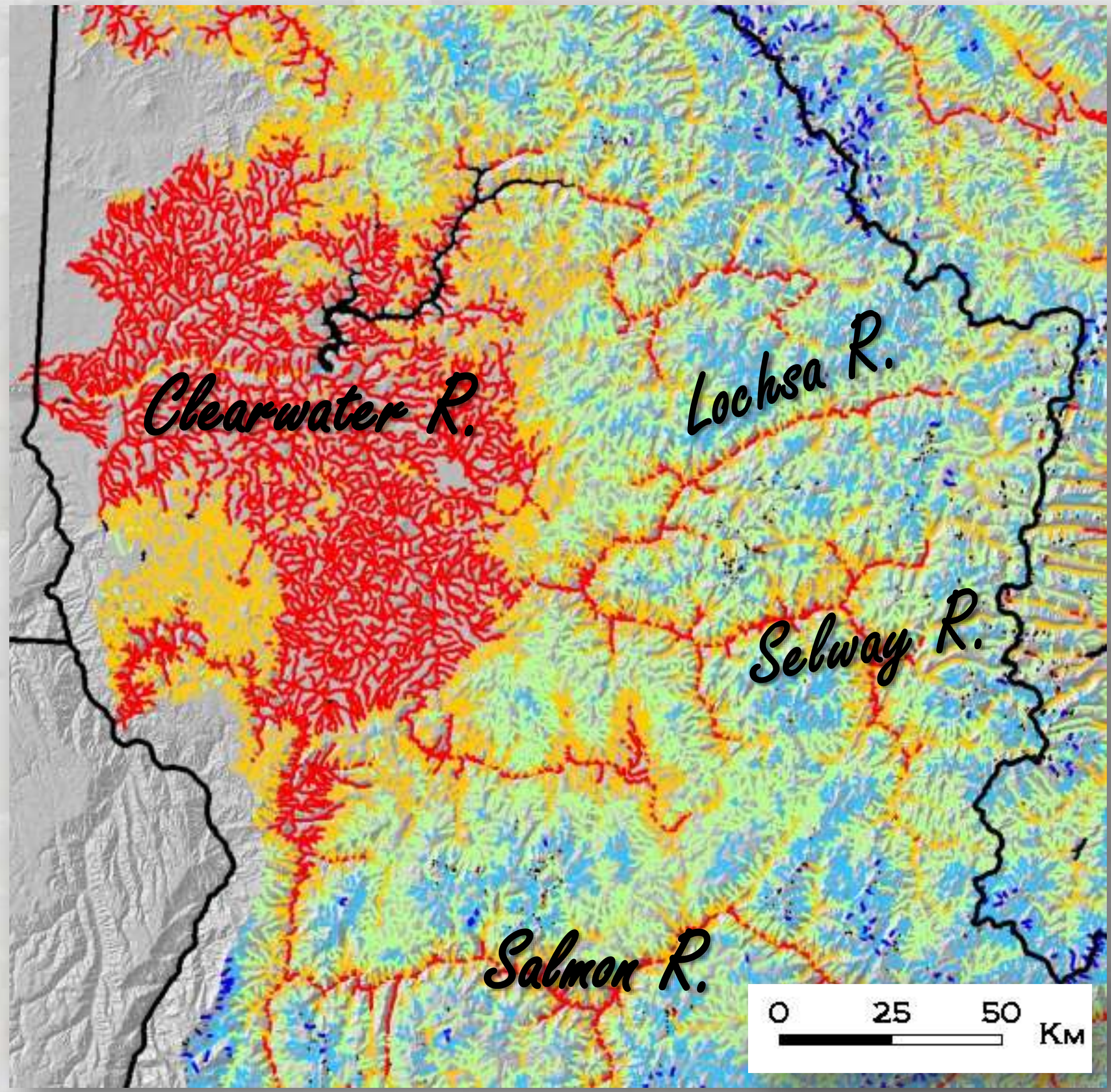
- 0.0 - 8.0
- 8.1 - 10.0
- 10.1 - 12.5
- 12.6 - 15.0
- > 15

1 kilometer resolution



Clearwater Stream Temperature Scenario

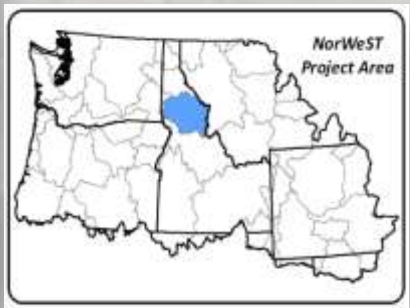
+1.50°C Stream Temp (A1B, 2040s)



Temperature (°C)

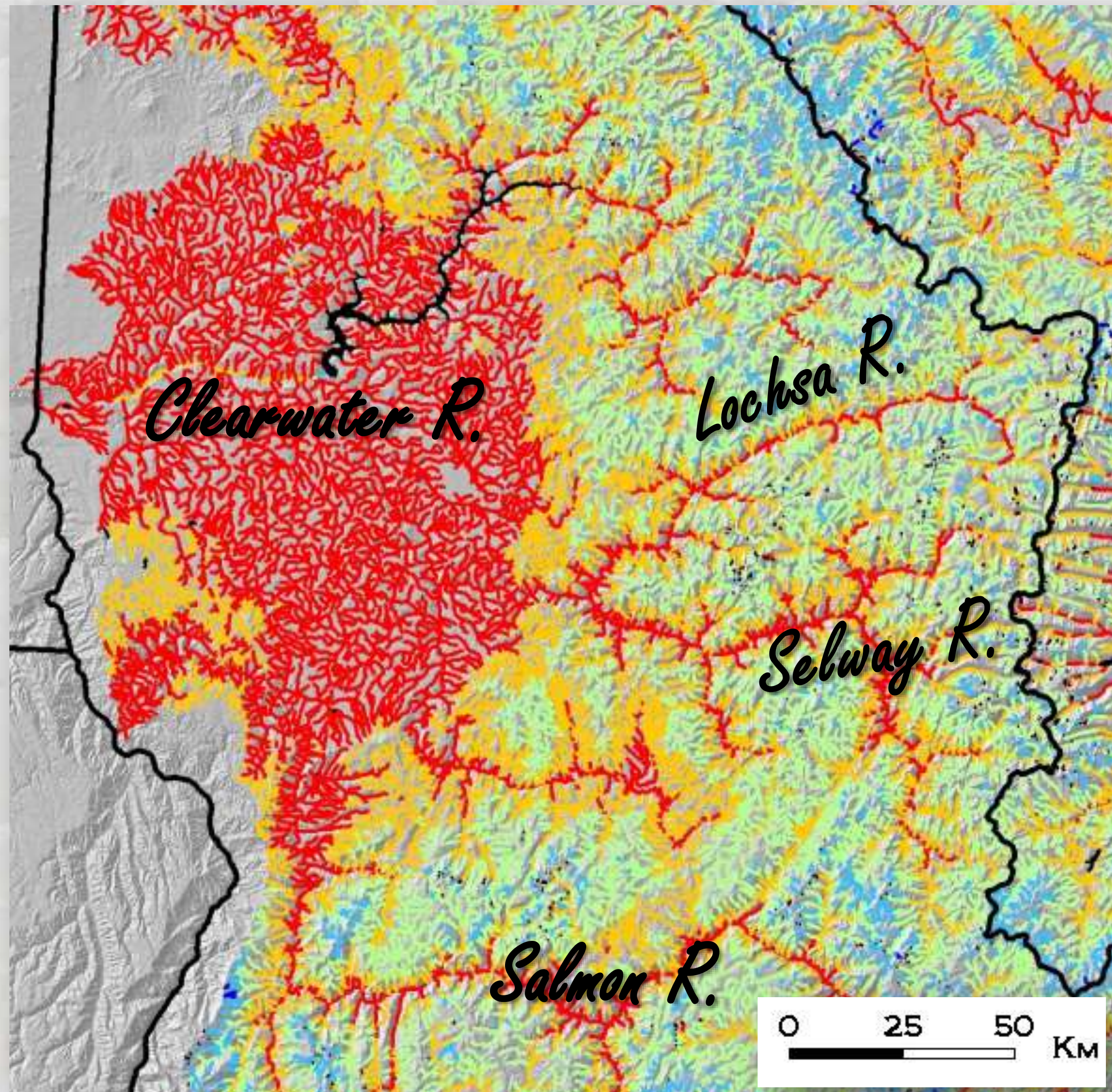
- 0.0 - 8.0
- 8.1 - 10.0
- 10.1 - 12.5
- 12.6 - 15.0
- > 15

1 kilometer resolution



Clearwater Stream Temperature Scenario

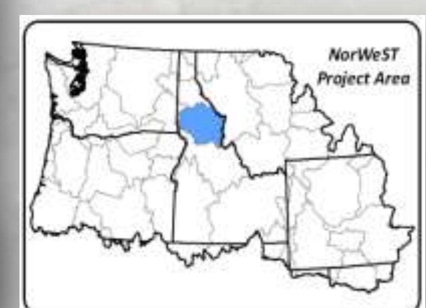
+3.00°C Stream Temp (A1B, 2080s)



Temperature (°C)

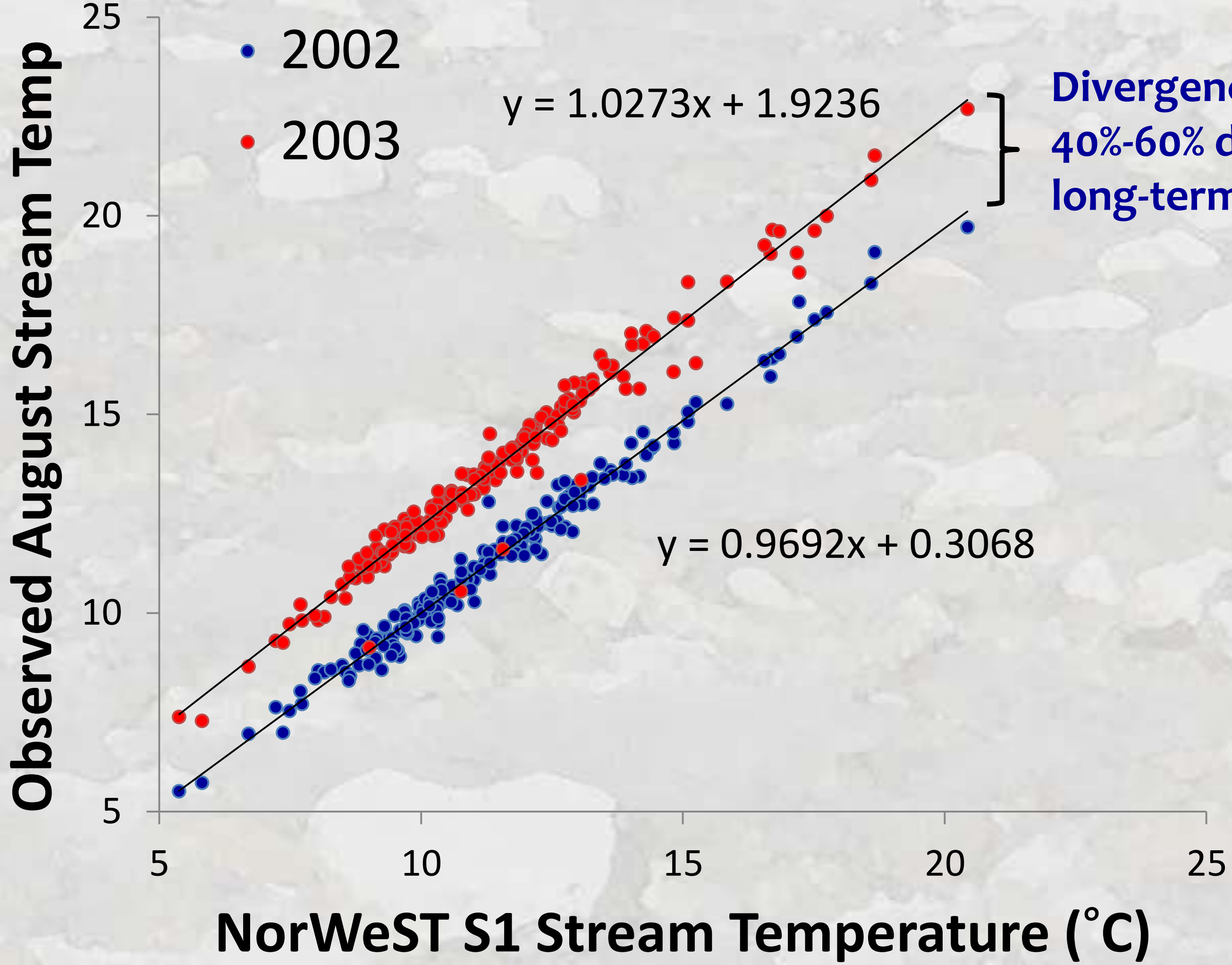
0.0 - 8.0
8.1 - 10.0
10.1 - 12.5
12.6 - 15.0
> 15

1 kilometer resolution



Future Scenarios Include Intrabasin Differential Sensitivity

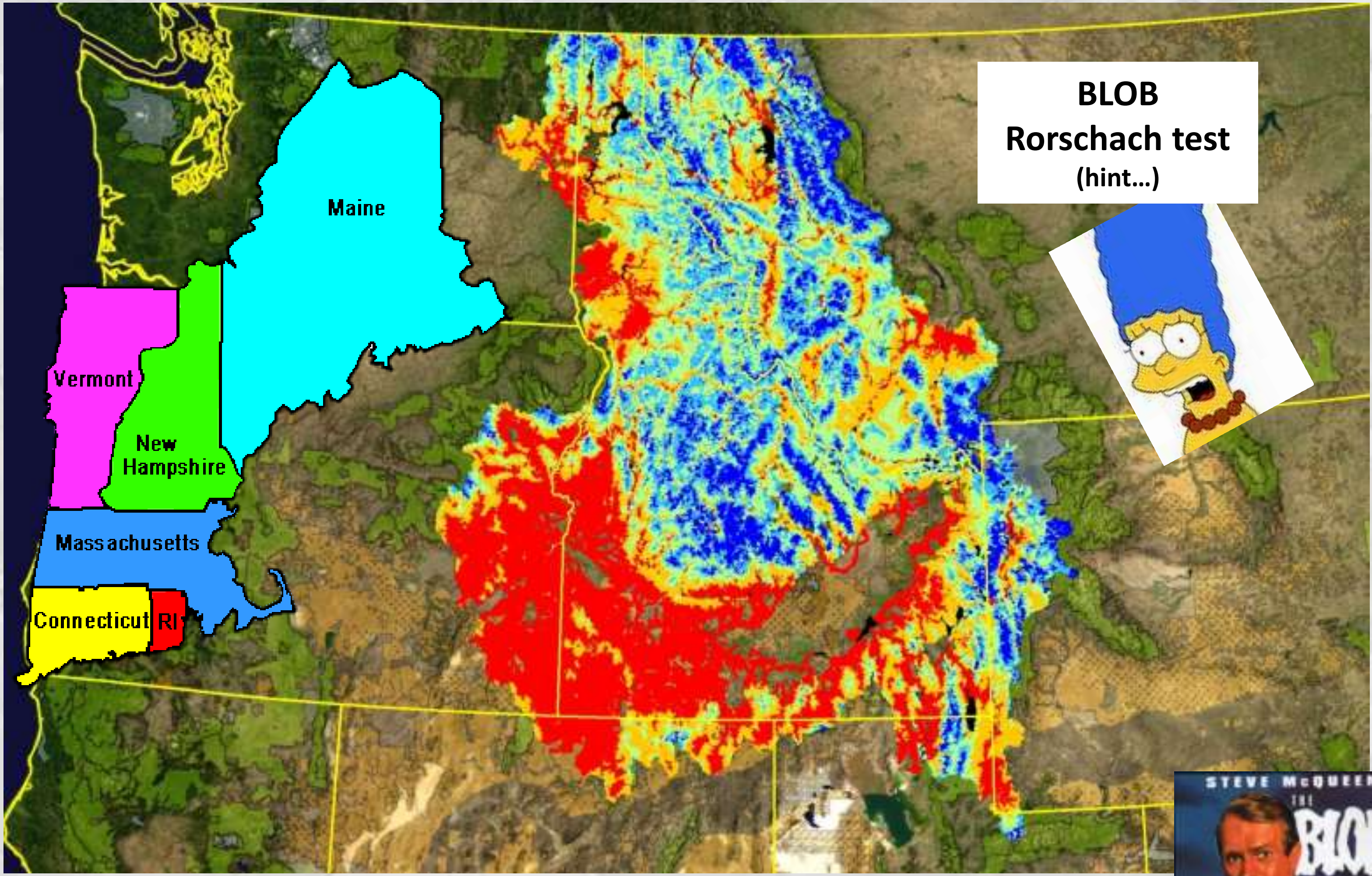
Warm streams warm more than cold streams



Divergence suggests 40%-60% difference in long-term warming

Luce et al. In Press. *Water Resources Research*

Stream Thermalscape so Far…

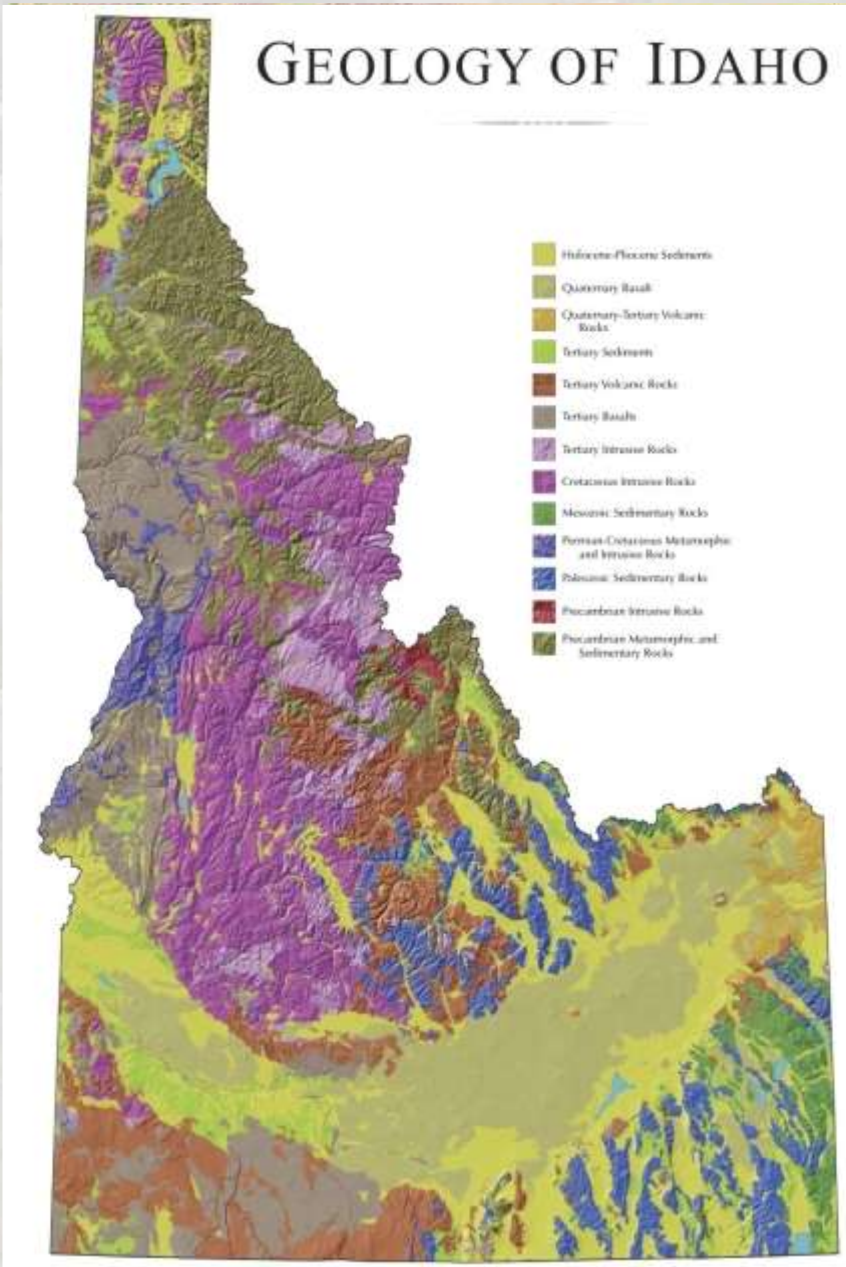


BLOB
Rorschach test
(hint…)

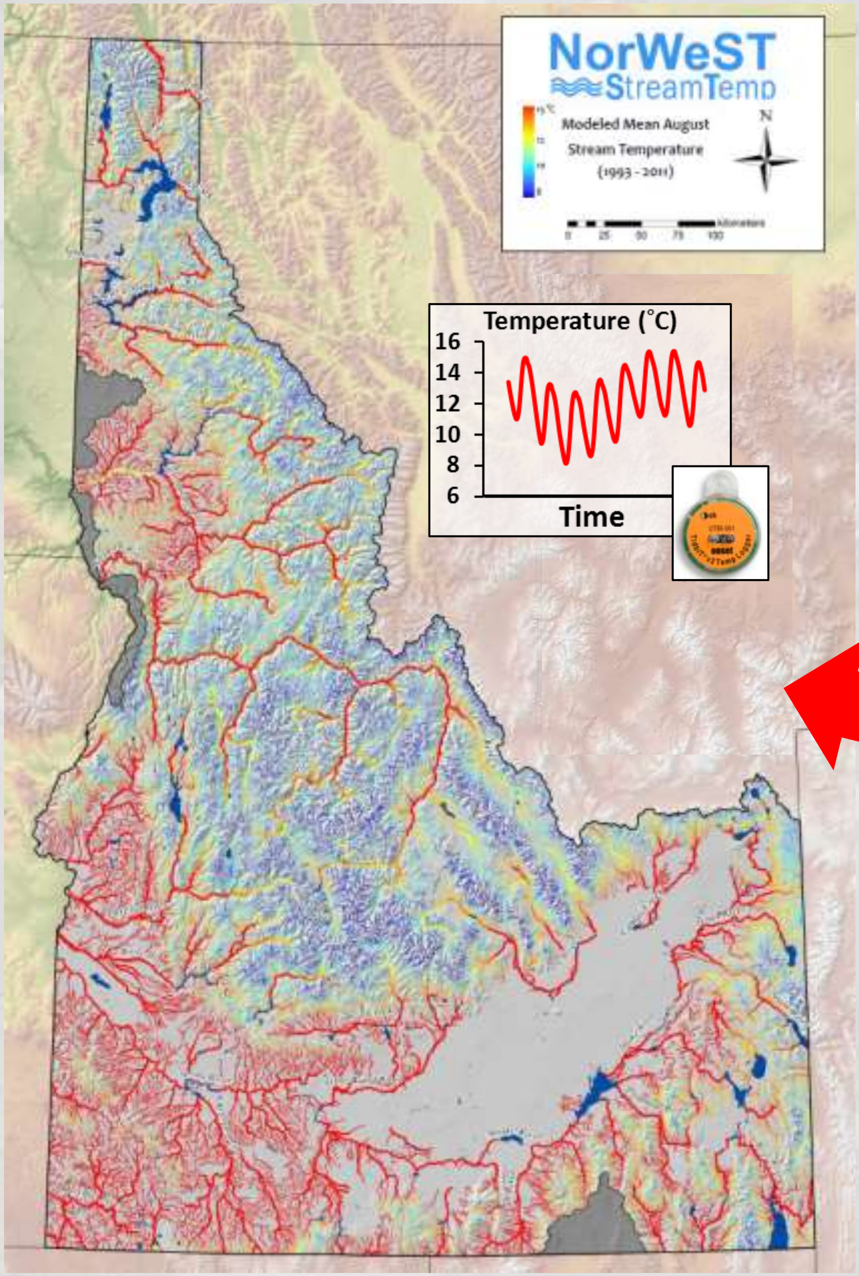
The BLOB… it just keeps growing…

- 234,000 stream kilometers of thermal ooze
- 20,072 summers of data swallowed

We have State Geologic Maps…



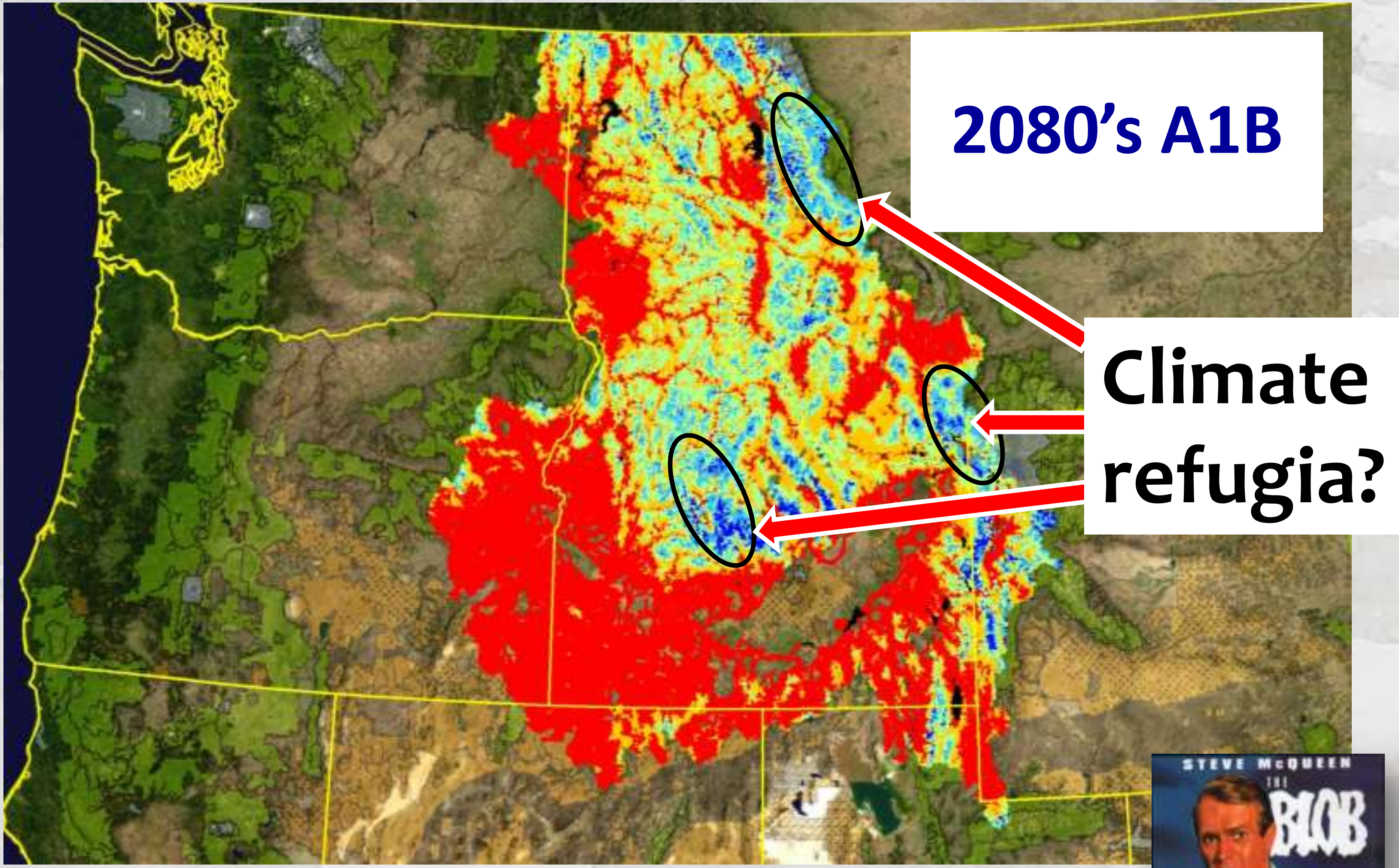
Why not Stream Thermalscape Maps?



Built From…

- 4,888 stream sites
- 12,755 summers of data
- Dozens of contributing individuals
- all agencies

BLOB Space, but BLOB time too…

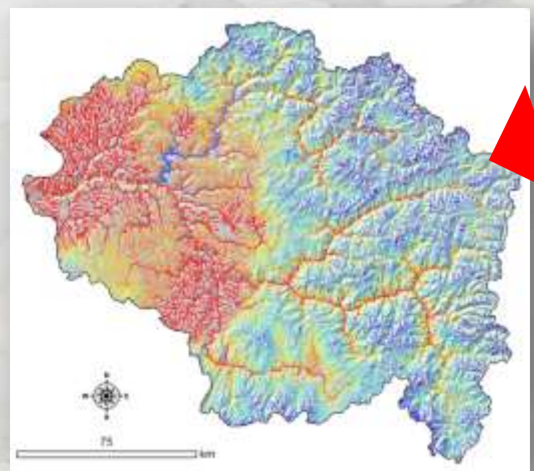


The BLOB… it just keeps growing…

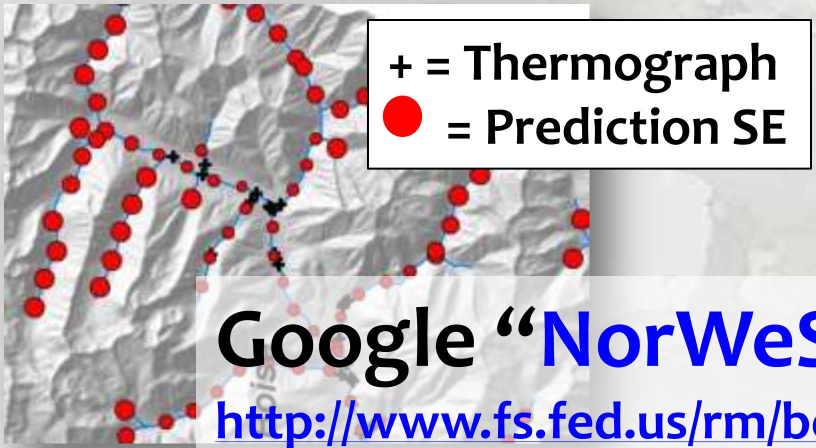
- 234,000 stream kilometers of thermal ooze
- 20,072 summers of data swallowed

Website Distributes BLOB Scenarios & Temperature Data as GIS Layers

1) GIS shapefiles of stream temperature scenarios



2) GIS shapefiles of stream temperature model prediction precision



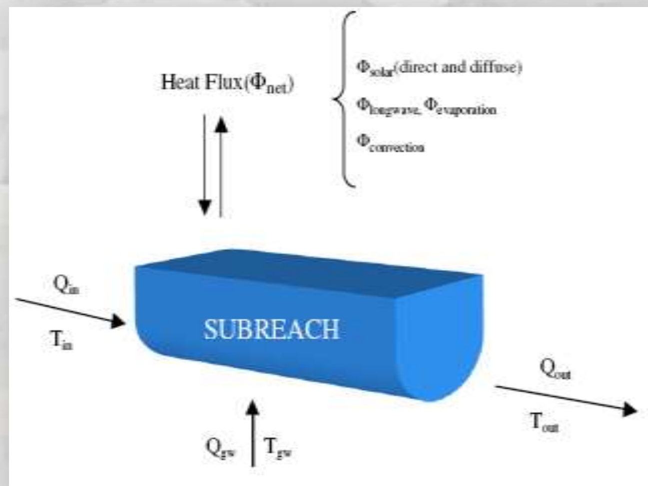
3) Temperature data summaries

Google "NorWeST" or go here…

http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.shtml

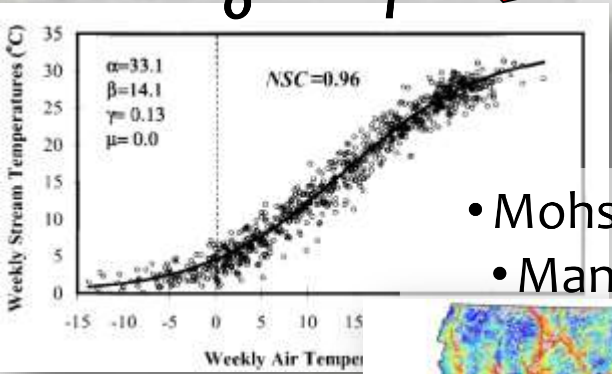
Empirical Data feeds All Models…

Mechanistic & Statistical



NorWeST
Stream Temp

$$Y = b_o + b_1x$$

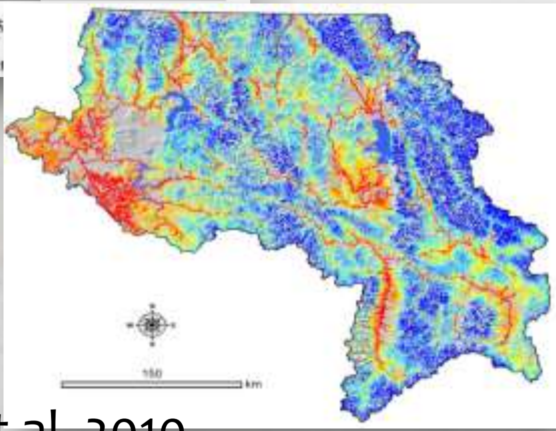


For example…

- QUAL2Kw
- SSTEMP/SNTEMP
- BasinTemp
- Heat Source
- WET-Temp

Site

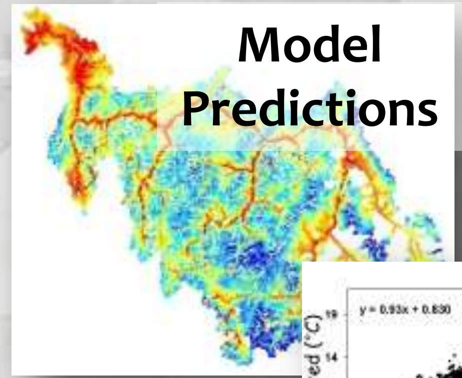
- Mohseni et al. 1998
- Mantua et al. 2010

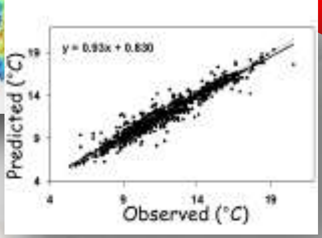


Network

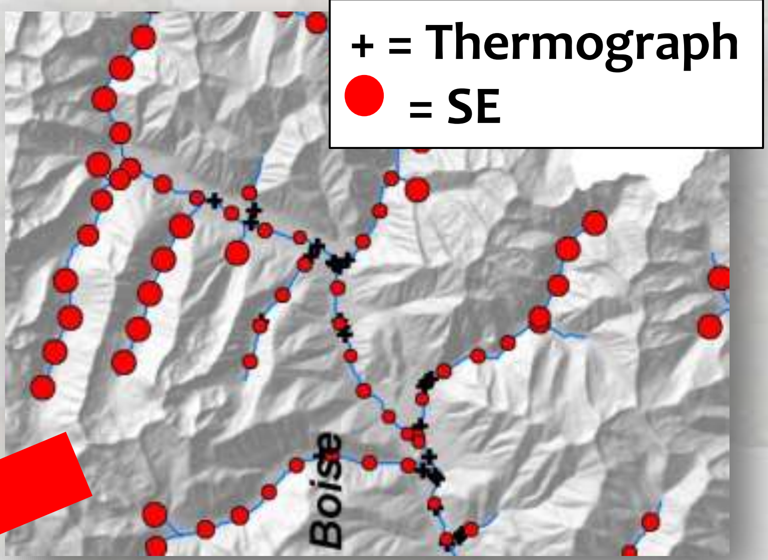
Isaak et al. 2010

S34_PredSE = Spatially Explicit Maps of Model Prediction Uncertainty

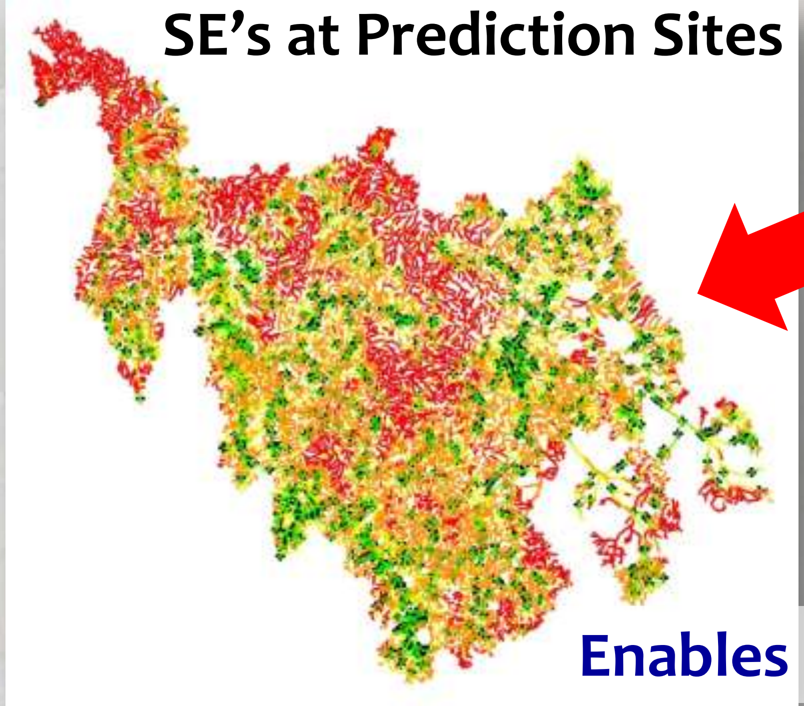




Temperature Prediction SE's



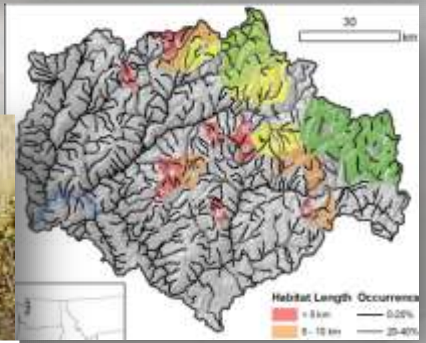
SE's are small near sites with temperature measurements



Enables efficient monitoring designs

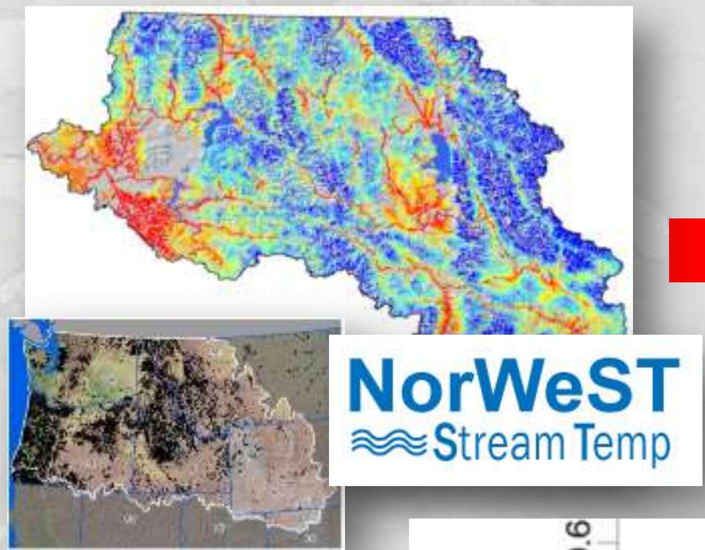
Good Stream Temperature Information Creates Many Synergies…

- Efficient temperature monitoring
- Better understand thermal ecology of aquatic species
- Precise bioclimatic models & vulnerability assessments
- Consistent application of climate decision support tools
- Regionally consistent thermal criteria using BIG FISH data

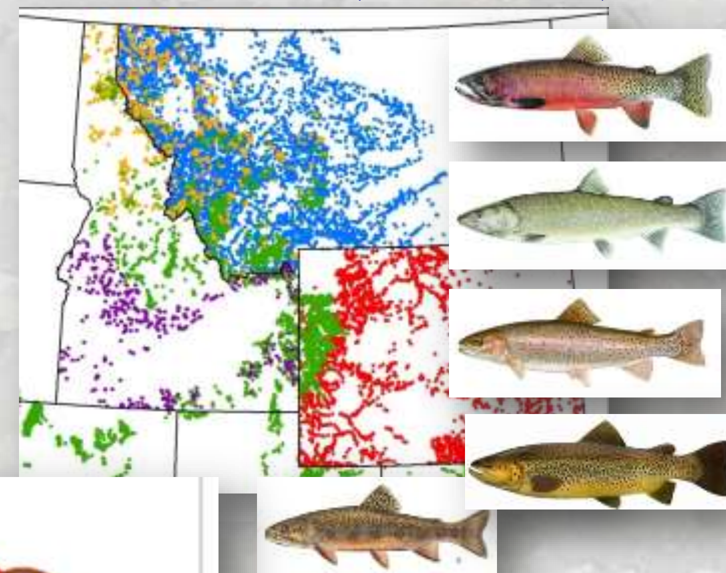


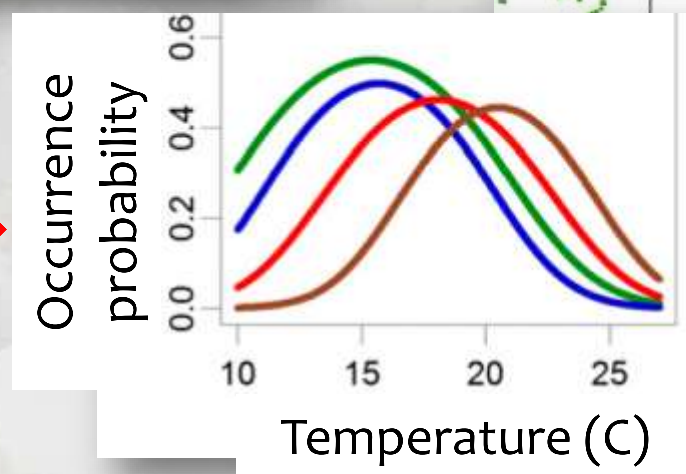
Regionally Consistent Thermal Criteria

Stream temperature maps



Regional fish survey databases (n ~ 20,000)



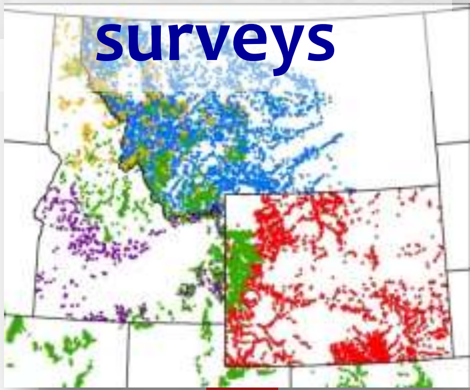


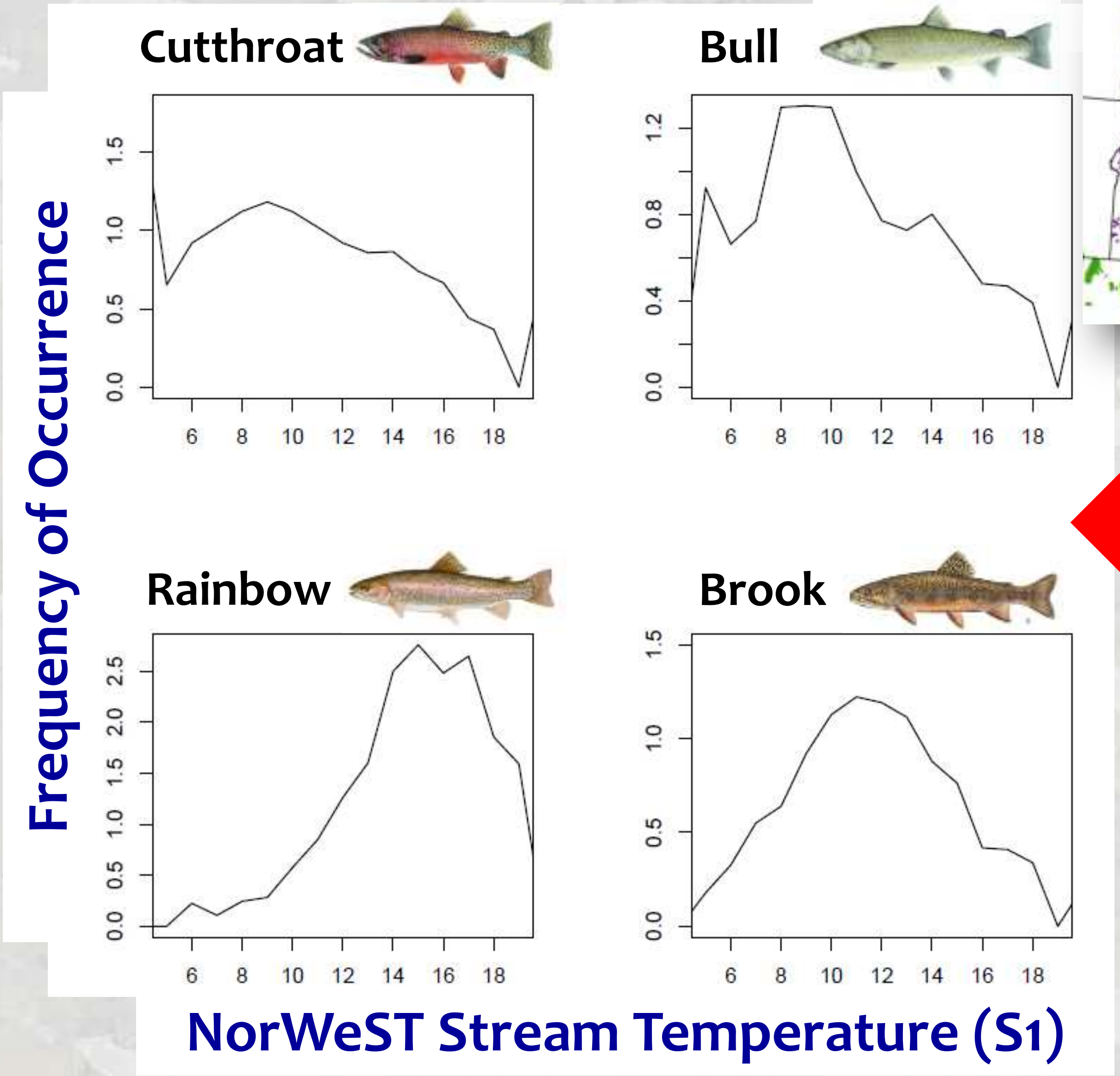
Wenger et al. 2011a. *PNAS* **108**:14175-14180

Wenger et al. 2011b. *CJFAS* **68**:988-1008; Wenger et al., *In Preparation*

Trout…

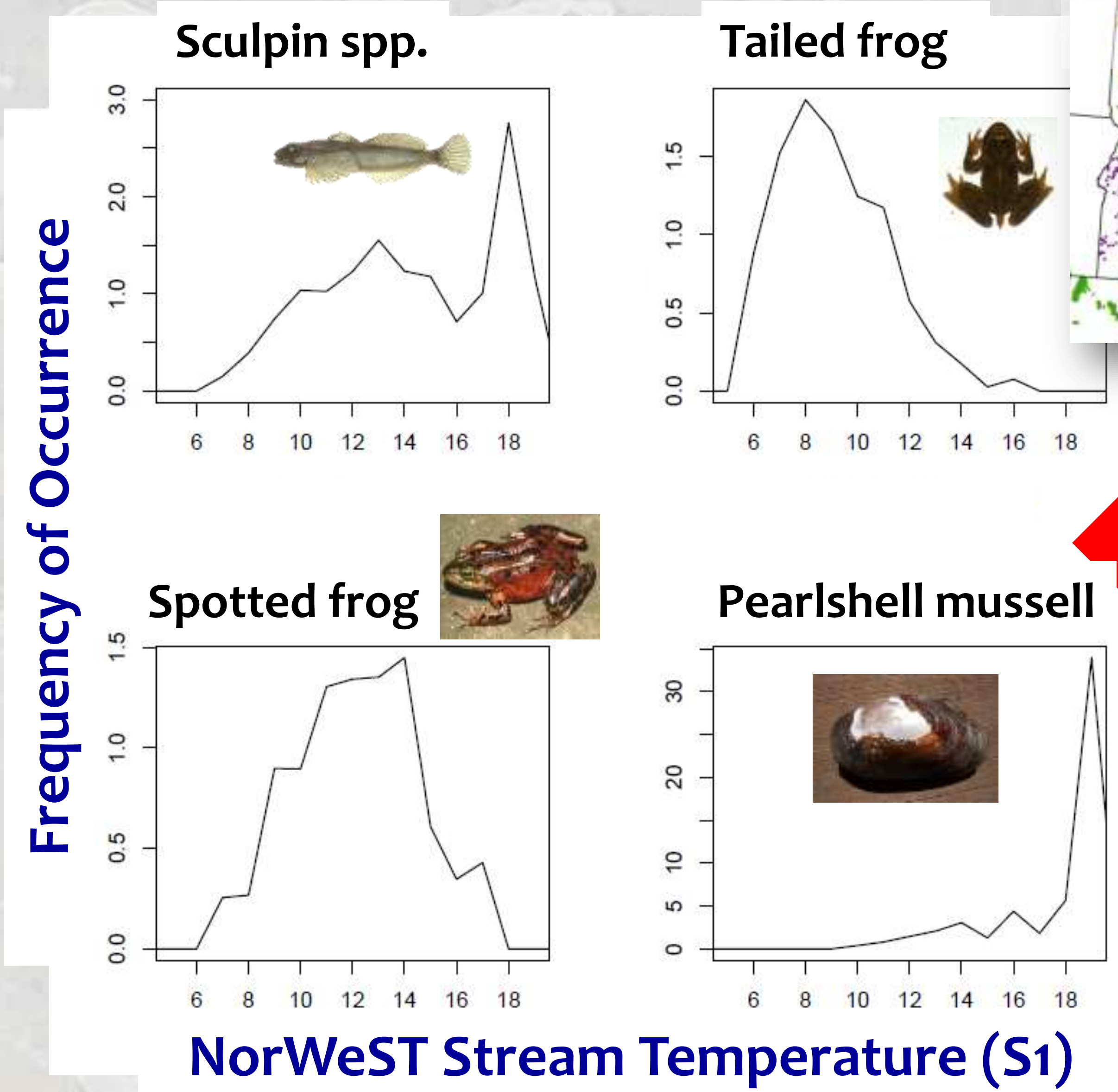
~20,000 fish surveys

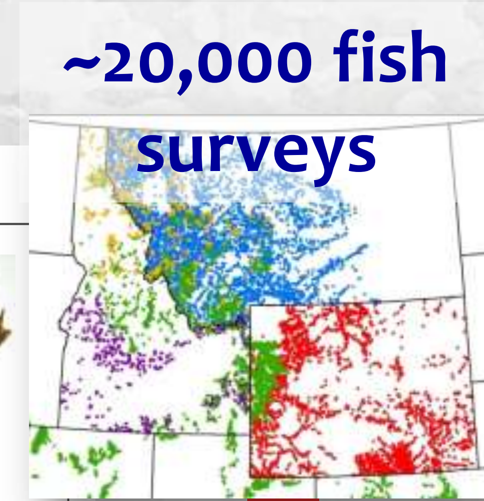




Wenger et al., *In Preparation*

Other Critters…

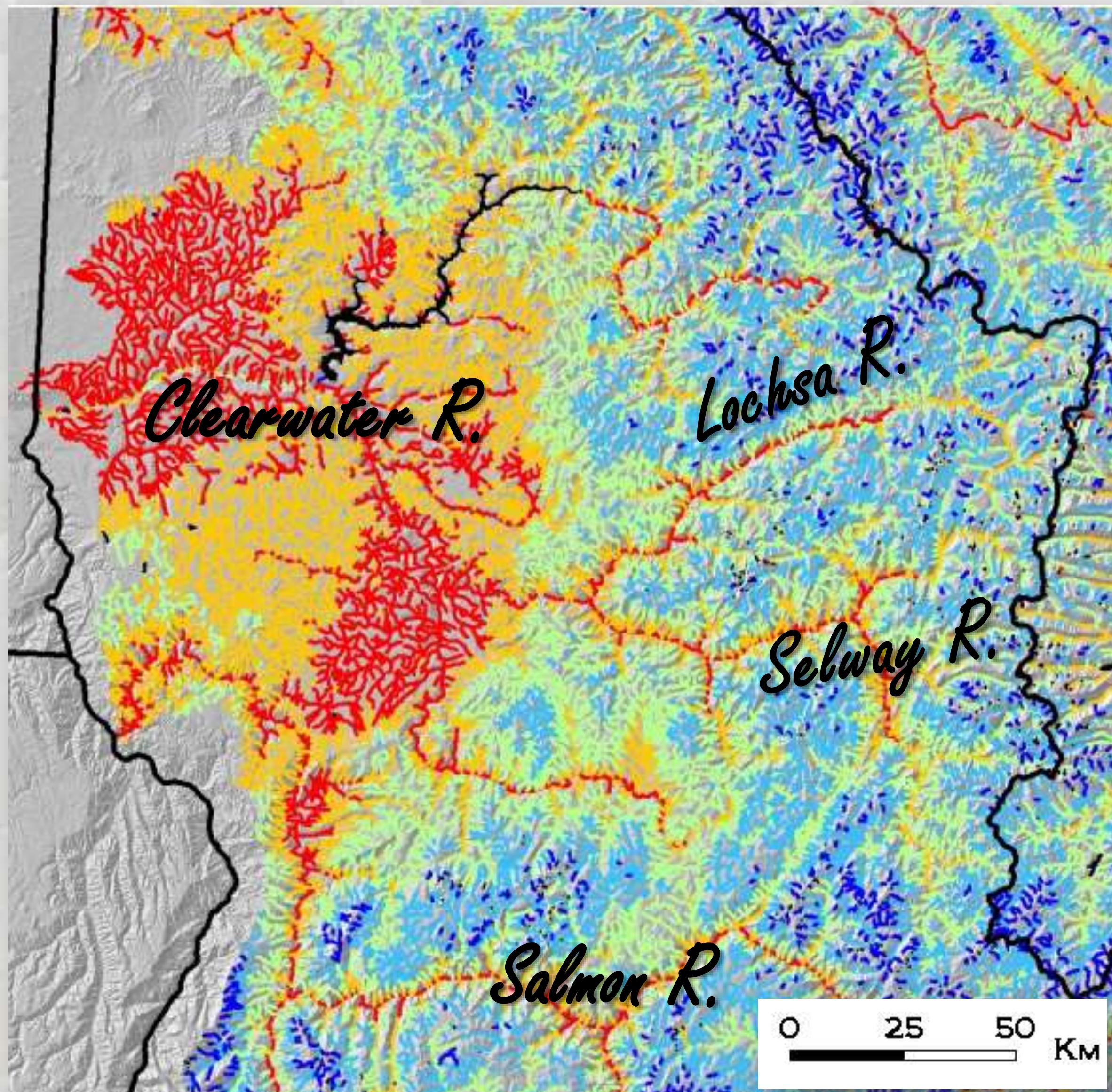




Wenger et al., *In Preparation*

Clearwater Stream Temperature Scenario

Historic (1993-2011 Average August)



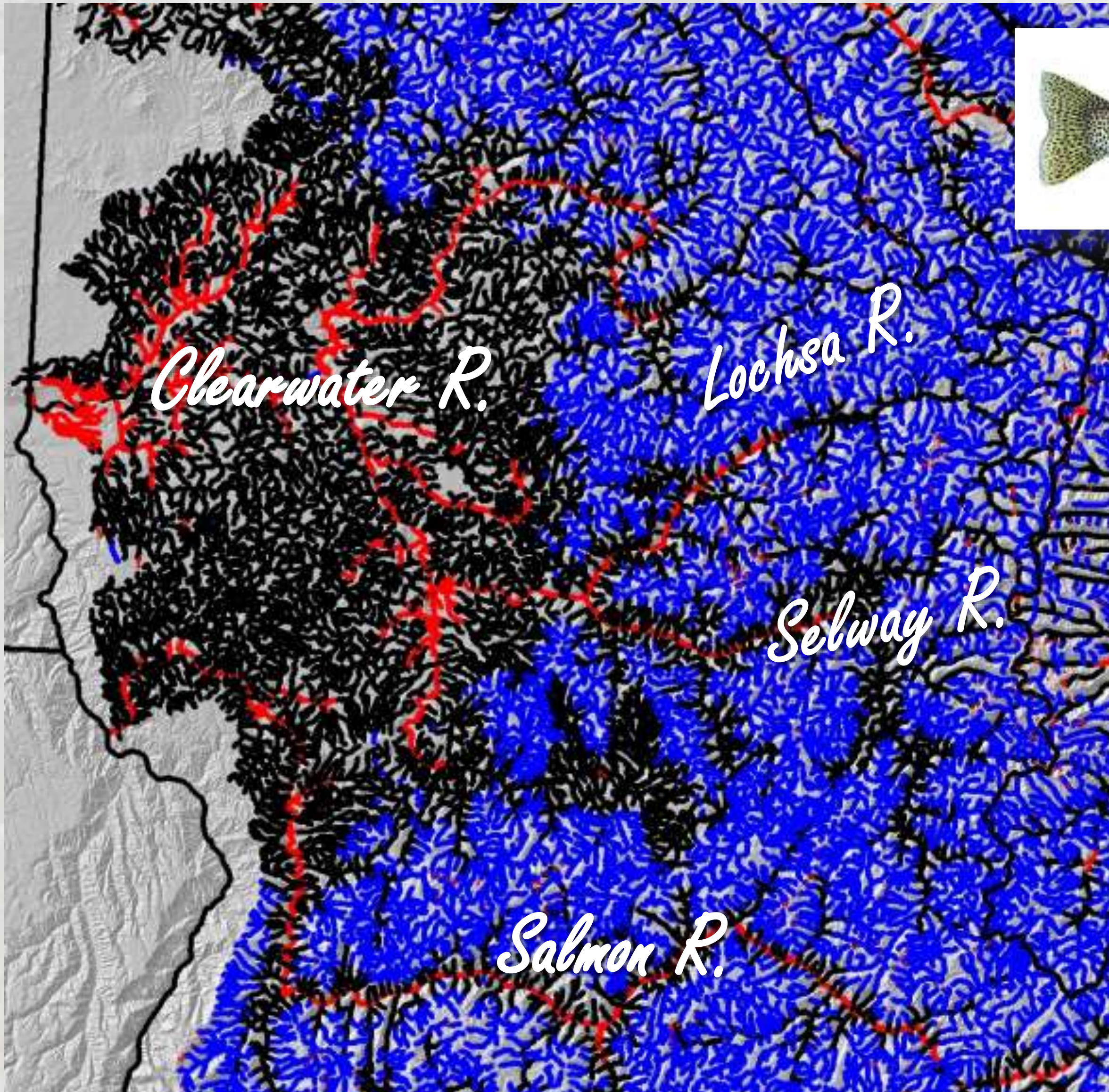
Temperature (°C)

	0.0 - 8.0
	8.1 - 10.0
	10.1 - 12.5
	12.6 - 15.0
	> 15

1 kilometer resolution

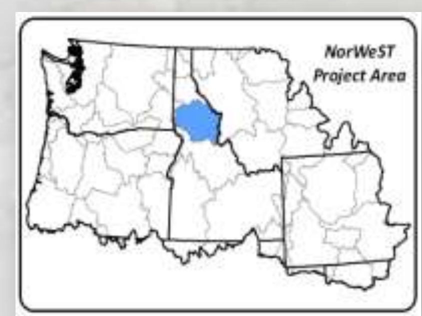
Climate Effects on Cutthroat Thermal Habitat

Historic (1993-2011 Average August)



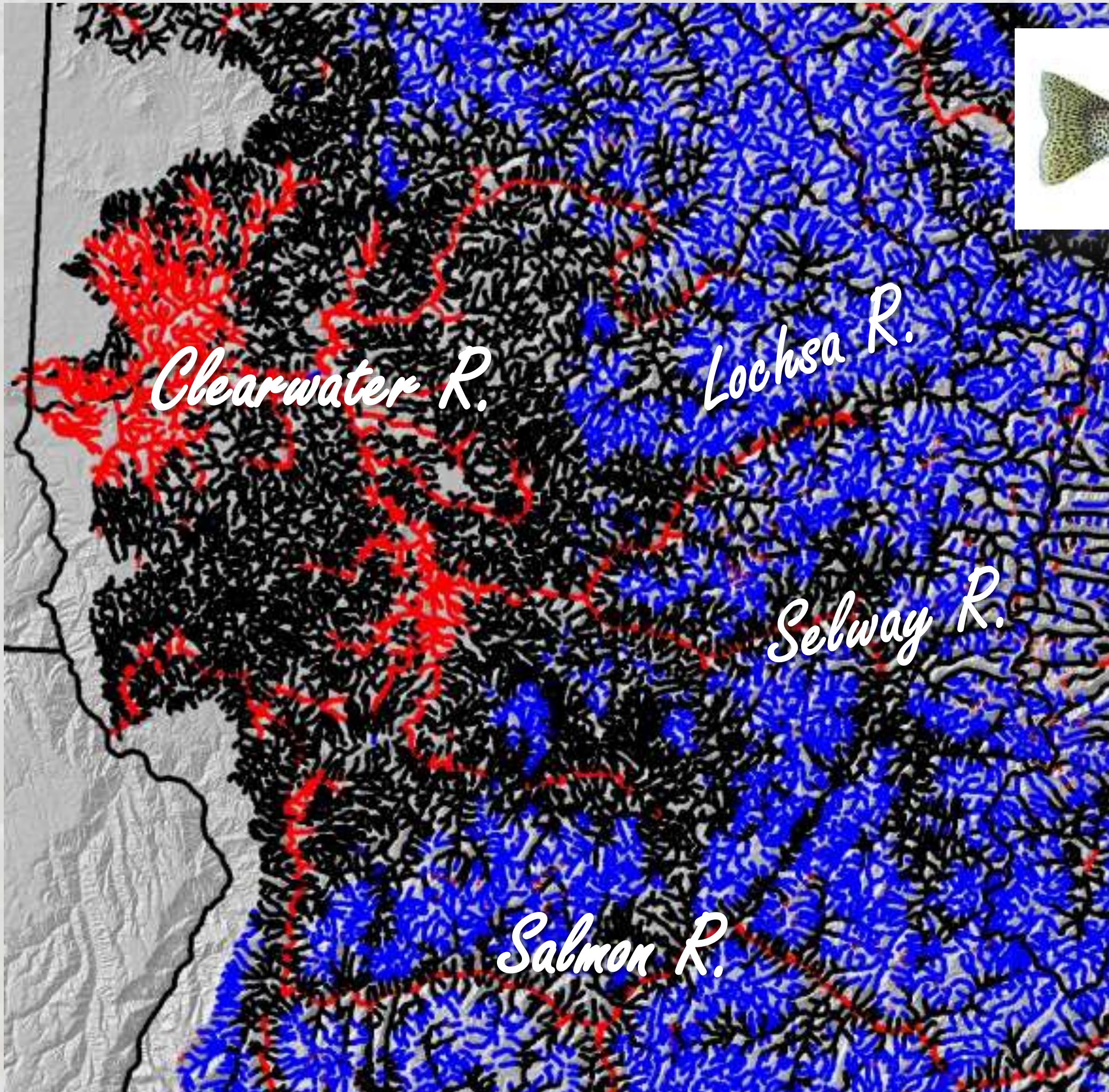
- Suitable
- Too Hot
- Too Cold

<17.0°C & >11.0 °C



Climate Effects on Cutthroat Thermal Habitat

+1.50°C Stream Temp (~2040s)

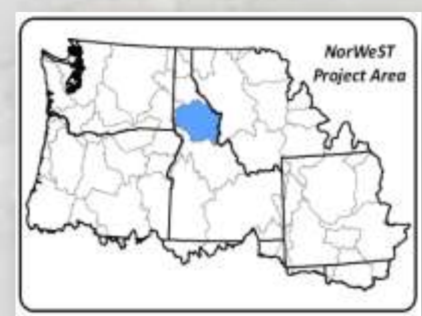


Suitable

Too Hot

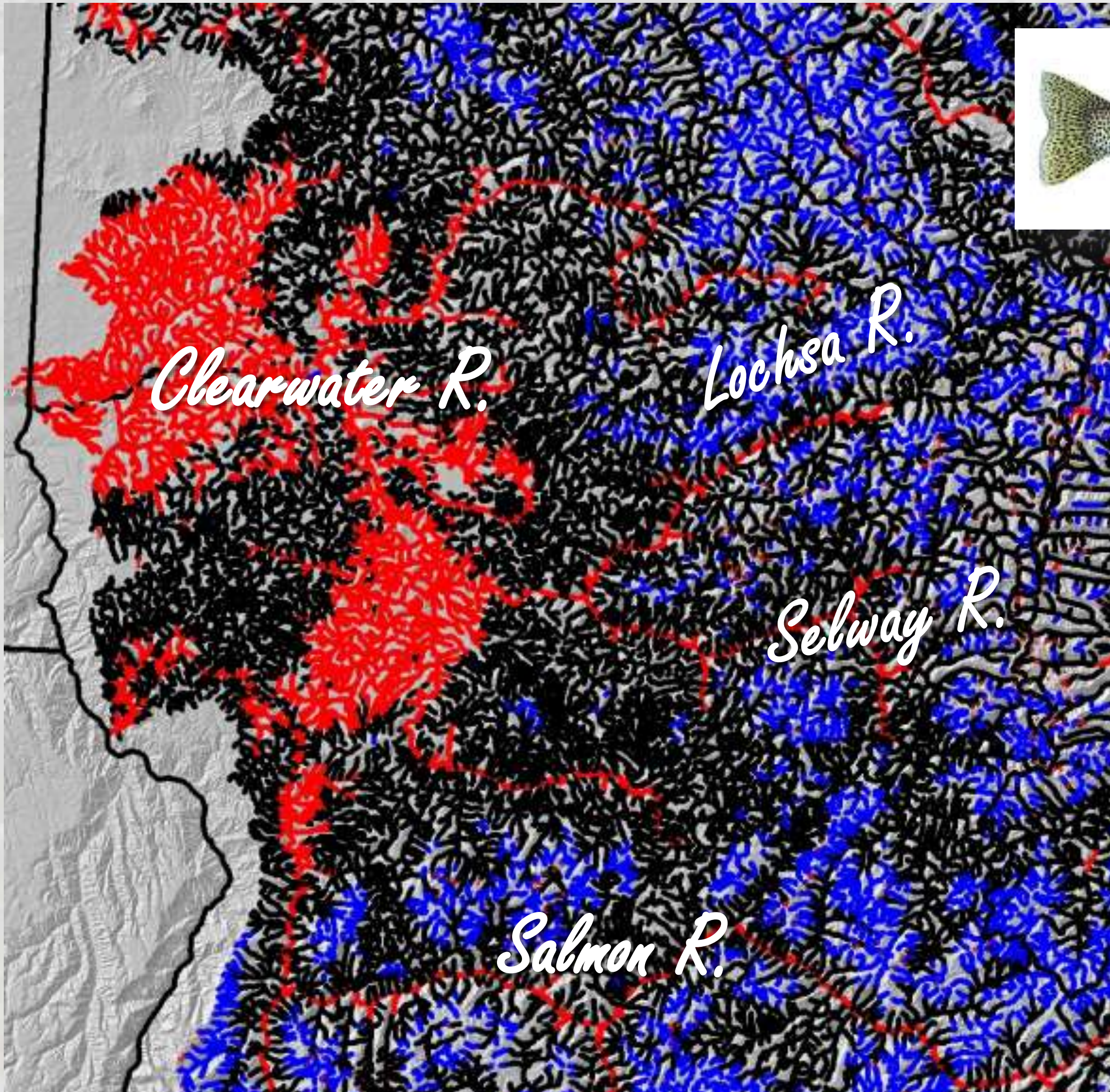
Too Cold

<17.0°C & >11.0 °C



Climate Effects on Cutthroat Thermal Habitat

+3.00°C Stream Temp (~2080s)

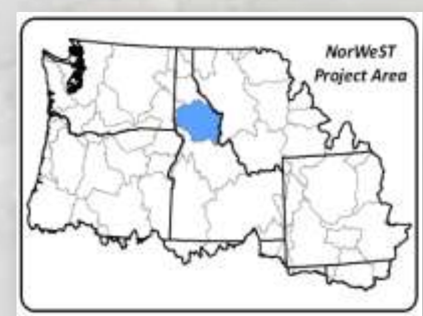


Suitable

Too Hot

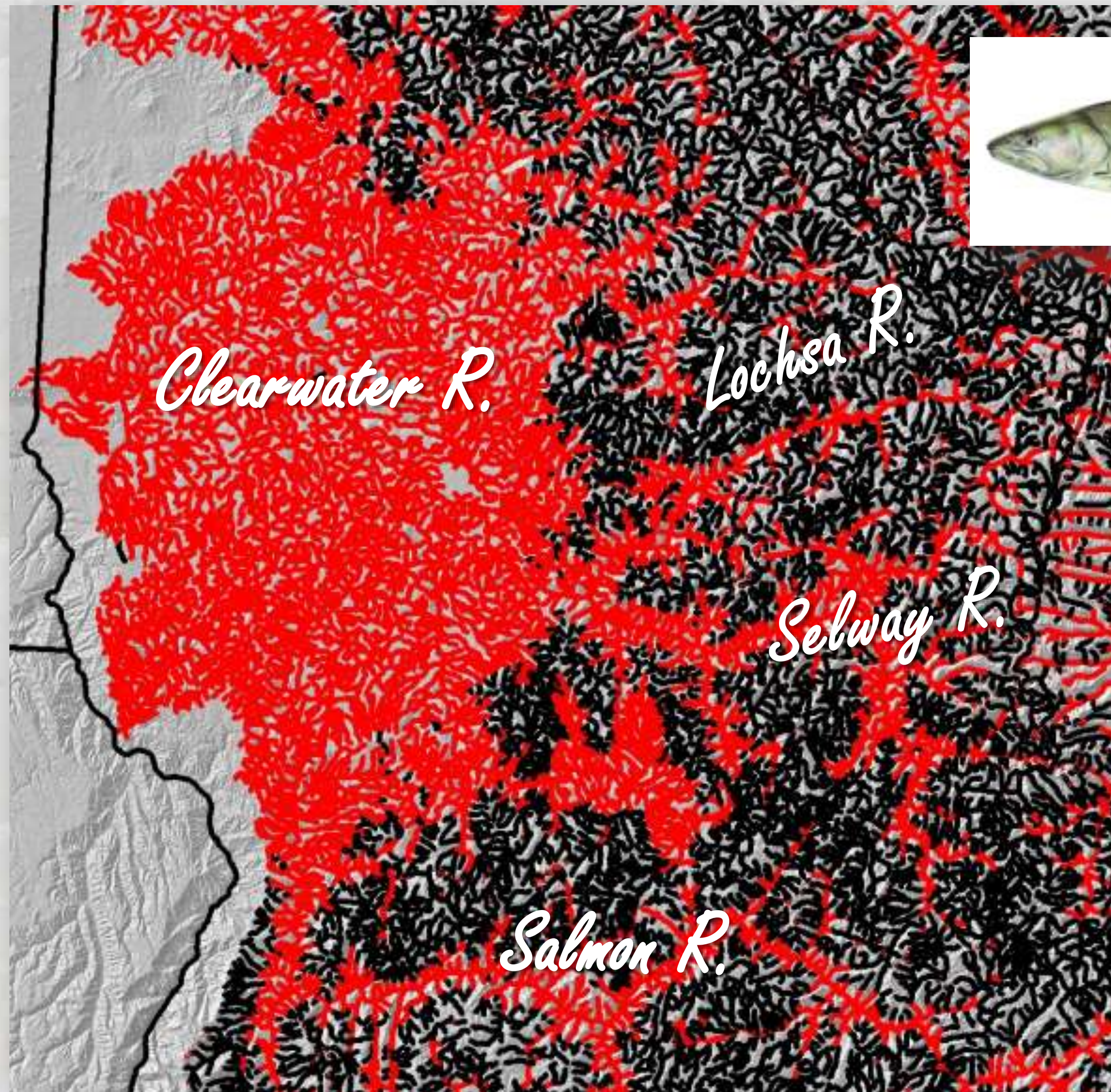
Too Cold

<17.0°C & >11.0 °C



Climate Effects on Bull Trout Thermal Habitat

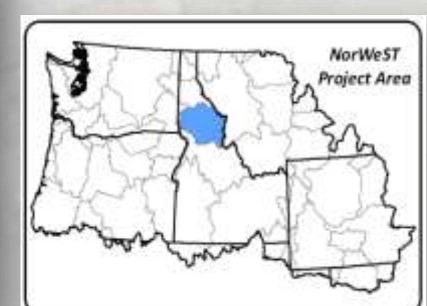
Historic (1993-2011 Average August)



Suitable

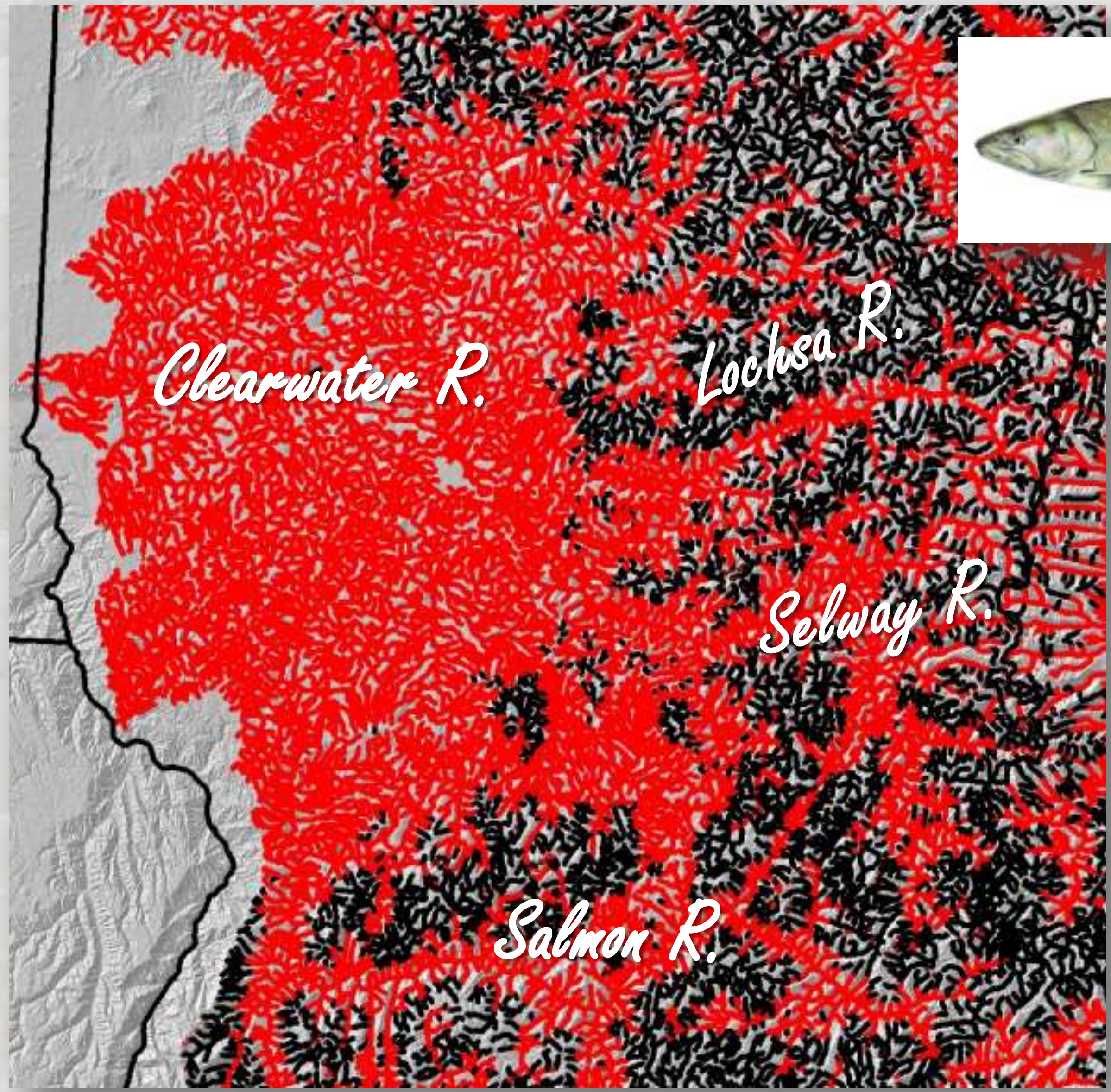
Unsuitable

< 11.0°C



Climate Effects on Bull Trout Thermal Habitat

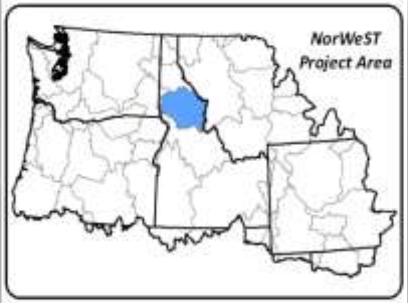
+1.50°C Stream Temp (~2040s)



Suitable

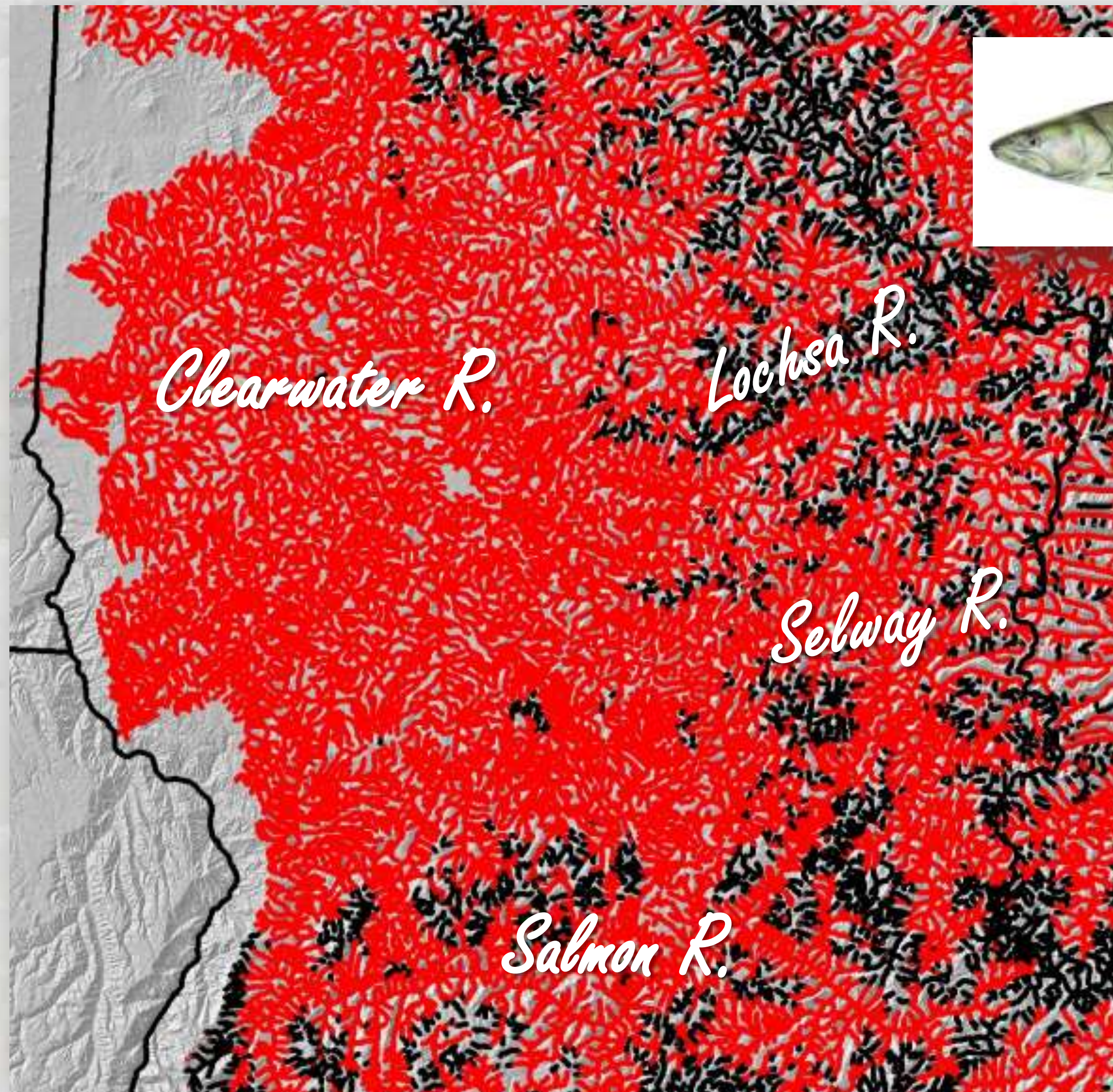
Unsuitable

< 11.0°C



Climate Effects on Bull Trout Thermal Habitat

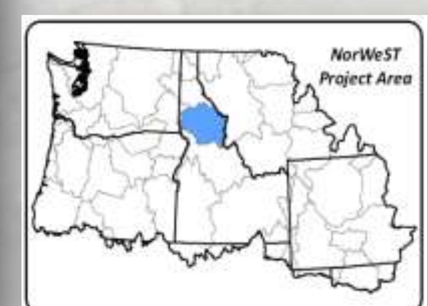
+3.00°C Stream Temp (~2080s)



Suitable

Unsuitable

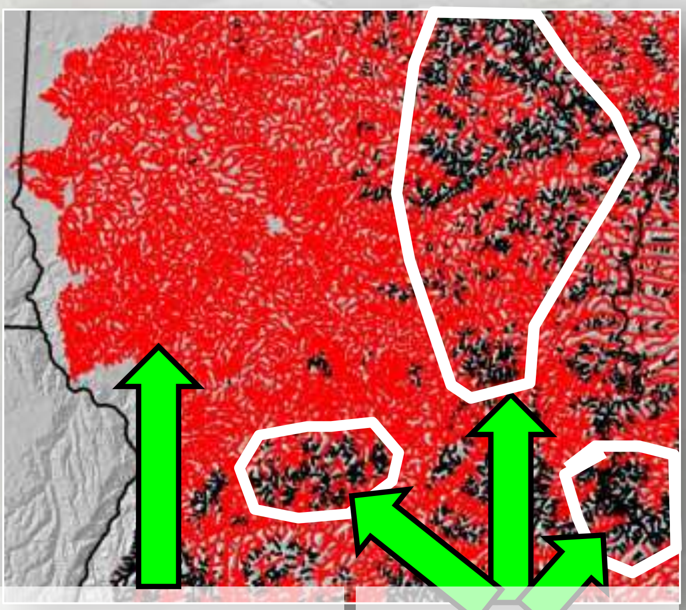
< 11.0°C



Climate-Smart Prioritization of Habitat Restoration

Lots of things we can do…

- Maintaining/restoring flow…
- Maintaining/restoring riparian…
- Restoring channel form/function…
- Prescribed burns limit wildfire risks…
- Non-native species control…
- Improve/impede fish passage…



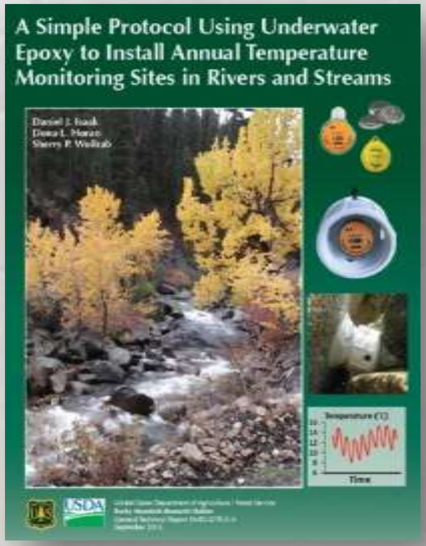
Low Priority | **High Priority**

Additional Resources…

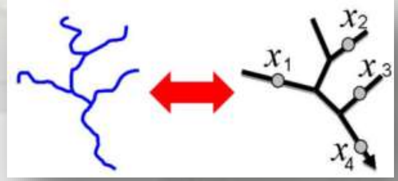
Websites (Google Search On…)

1) ***SSN/STARS*** – statistical modeling of data on networks
2) ***NorWeST*** – regional stream temperature database & climate scenarios
3) **Stream Temperature Modeling & Monitoring**

Publications…



Software…



Data…