Ecological thresholds and responses of stream benthic communities to heavy metals

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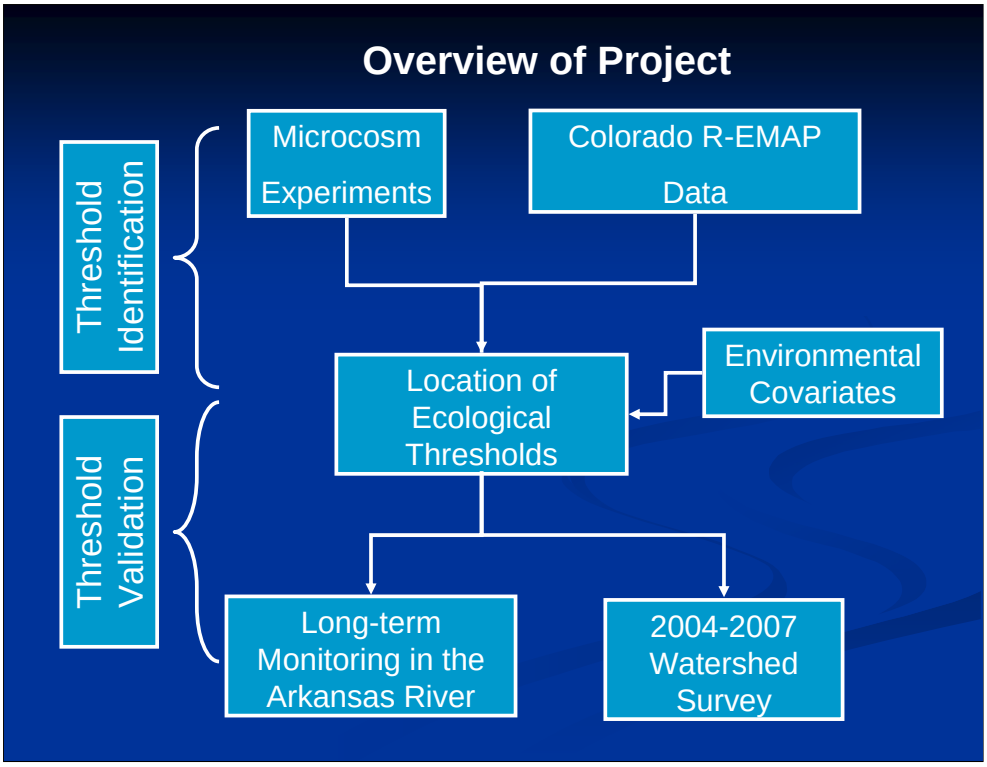
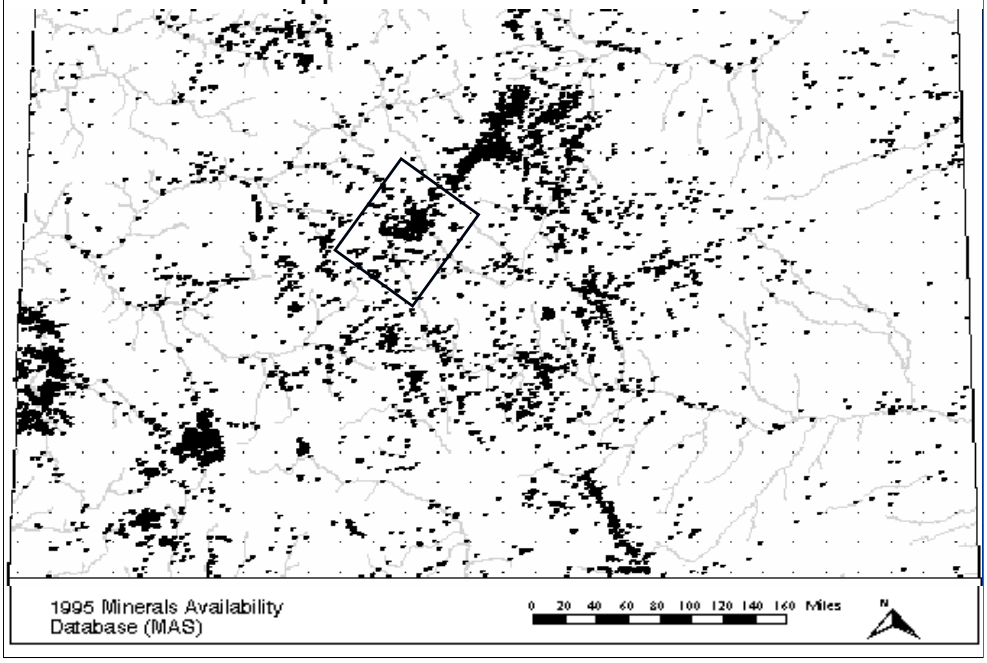
Significance of the Ecological Thresholds

- Heavy metal pollution from abandoned mines is one of the most significant environmental problems in the west
  - → 6 of 15 'Superfund' sites in Colorado
- Approximately 23% of streams in Colorado mineral belt are degraded by heavy metals
- Exceeding metal pollution thresholds has significant consequences for stream integrity and salmonid fisheries

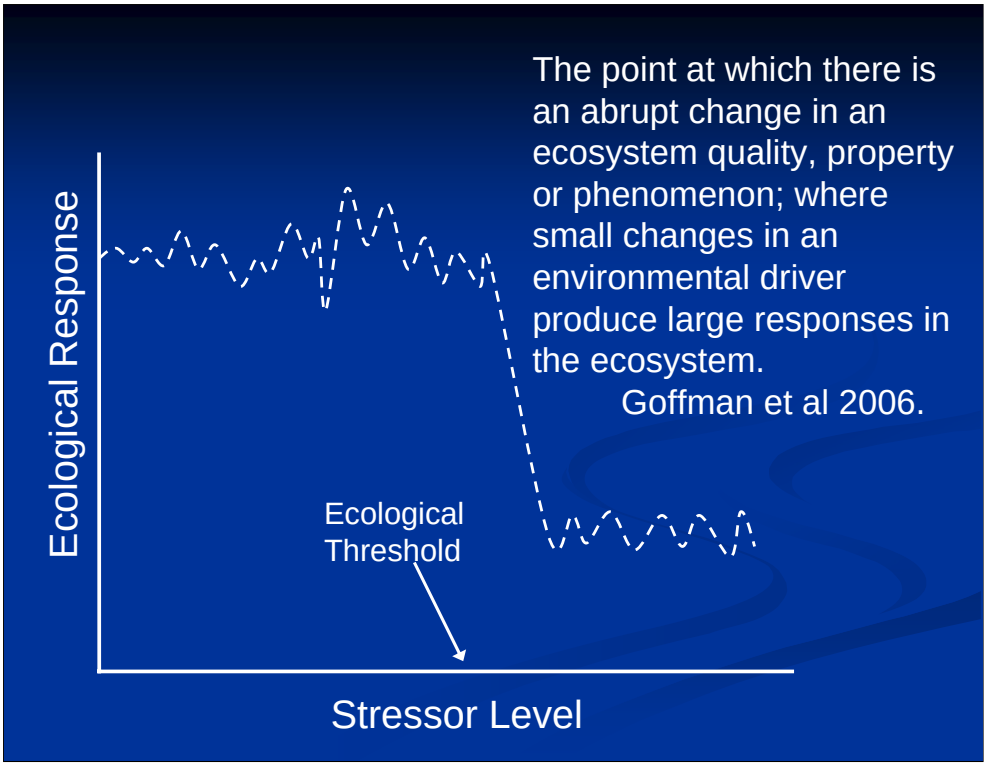


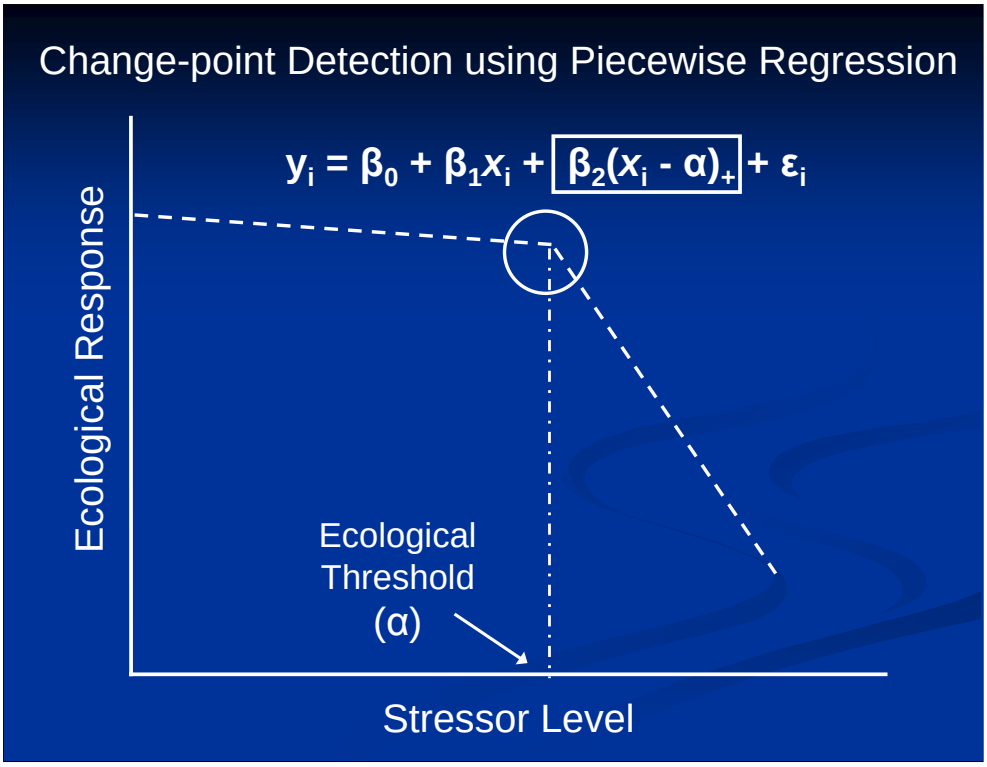
Map of Colorado Showing the Distribution of Mines and the Upper Arkansas River Watershed

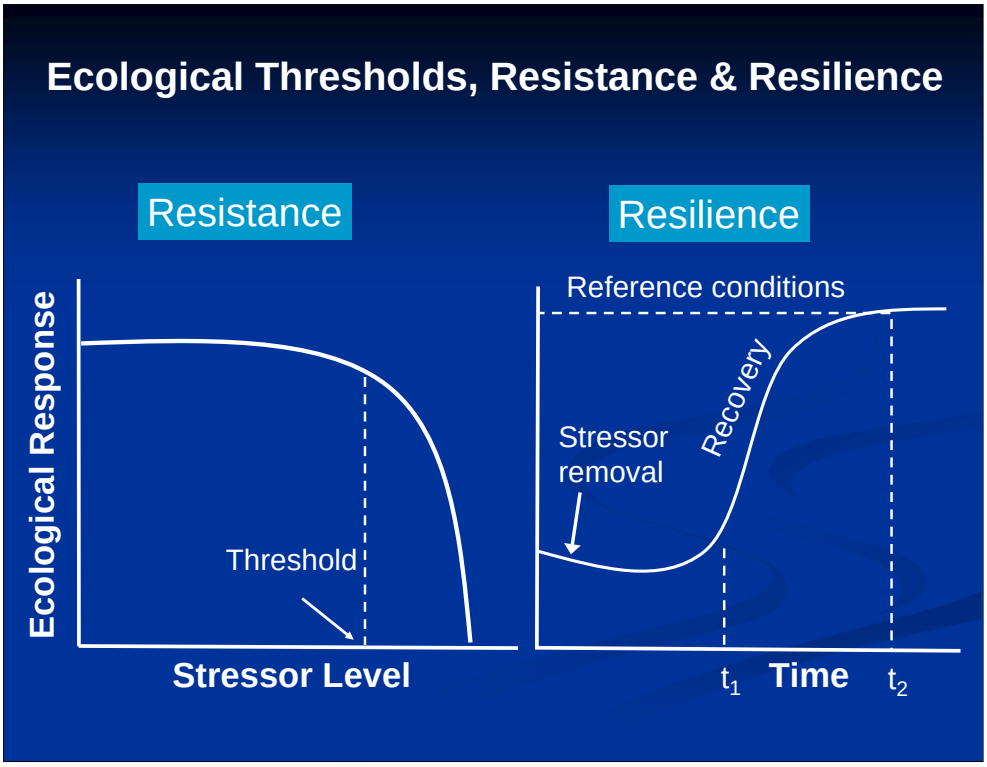


Research Questions

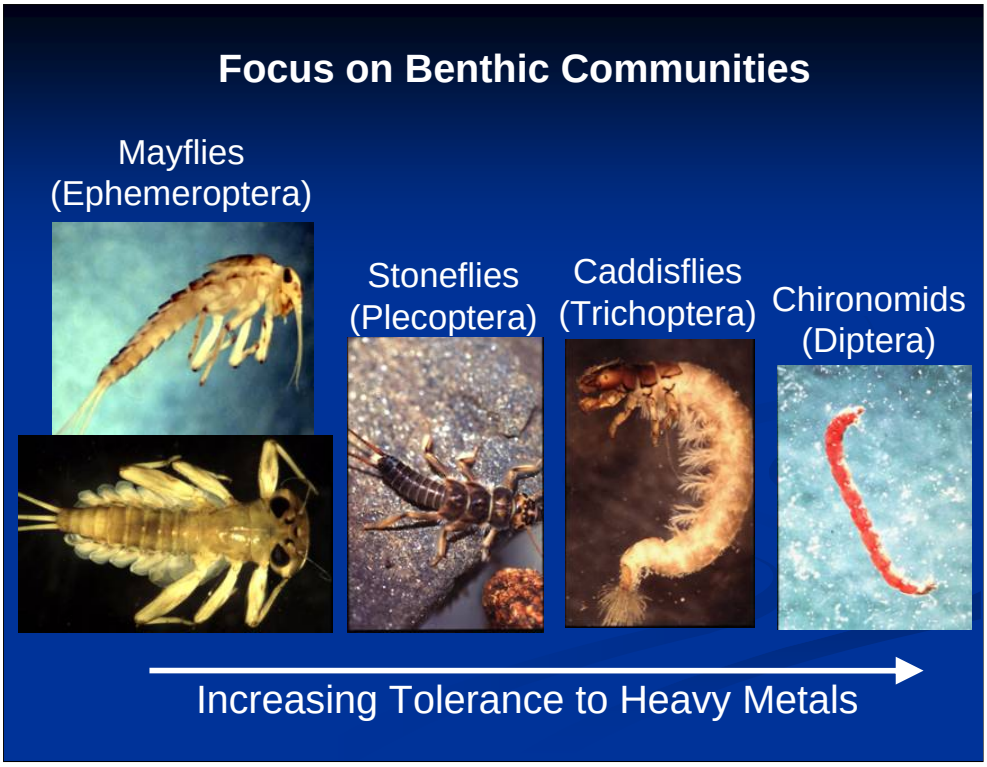
- Is there a threshold response for benthic communities exposed to heavy metals in Rocky Mountain streams?
- How do experimentally derived threshold values compare to ecological thresholds?
- Is there a “recovery threshold” for ecological responses to metals?
- Do reach-scale and landscape-level covariates influence ecological thresholds?







If a stressor is removed, what does the recovery trajectory look like? How long before recovery begins? How long is the recovery phase?



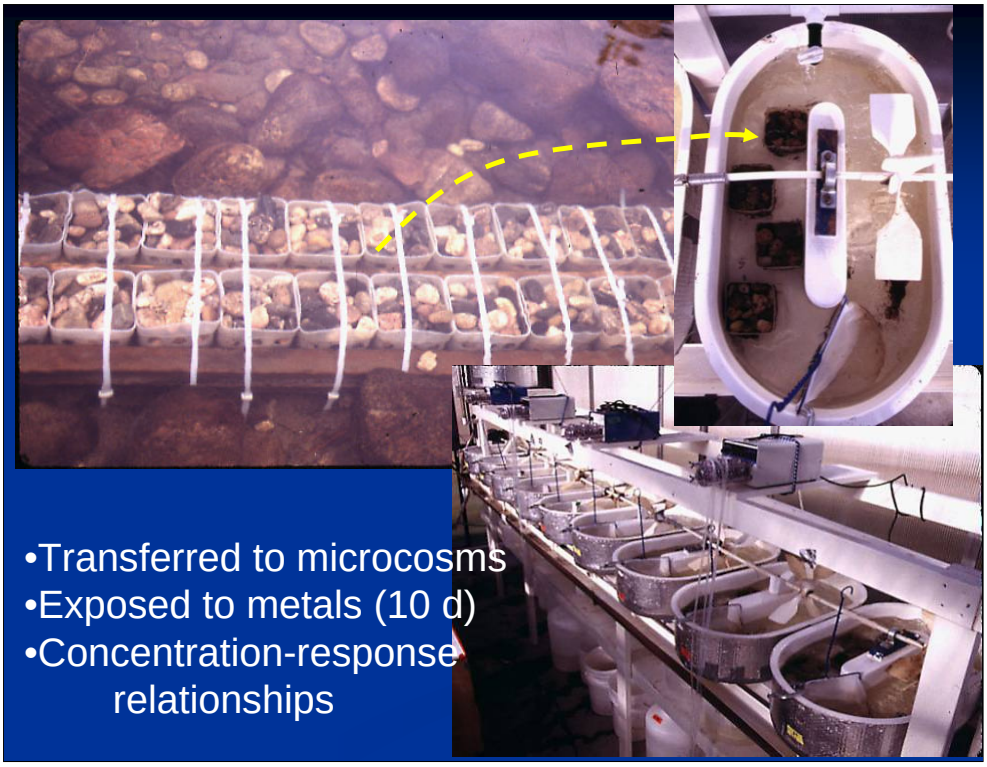
The relative sensitivity of different organisms is known.

Microcosm Experiments

Date	Metals	Reference
Oct 1991	Zn	Kiffney & Clements 1994
Jul 1992	Cd, Cu, Zn	Kiffney & Clements 1994
Sep 1992	Cd, Cu, Zn	Kiffney & Clements 1996
Nov 1993	Zn	Kiffney & Clements 1996
Aug 1996	Zn	Clements 2004
Aug 1997	Cd, Cu, Zn	Courtney & Clements 2000
Sep 1997	Cd, Cu, Zn	Clements 1999
Oct 1998	Cd, Zn	Clements 2004
Oct 1999	Cd, Cu, Zn	Clements, unpublished
Nov 1999	Cd, Cu, Zn	Clements 2004
Aug & Oct 2000	Cd, Cu, Zn	Clements, unpublished
Jul 2002 & May 2003	Cd, Cu, Zn	Clark & Clements, 2006
Sep 2003	Zn	Kashian & Clements, 2004
Aug 2003	Cd, Cu, Zn	Kashian & Clements, 2007

Microcosm experiments have been conducted looking at a range of metal combinations, but most typically the combination of copper, cadmium, and zinc.

The researchers establish benthic communities that are colonized in the field for approximately 40 days.



- Transferred to microcosms
- Exposed to metals (10 d)
- Concentration-response relationships

Cumulative Criterion Unit (CCU) used to quantify metal stressor:

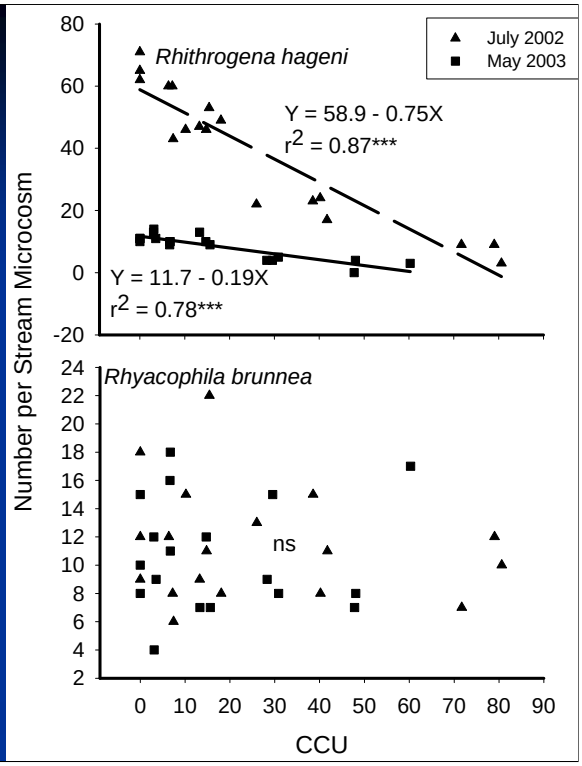
$$CCU = \Sigma\, m_i/c_i$$

where:
m_i = measured concentration
c_i = hardness-adjusted criterion value

- Assumes metal effects are additive (no interactions among metals)
- 1.0 = "safe concentration"

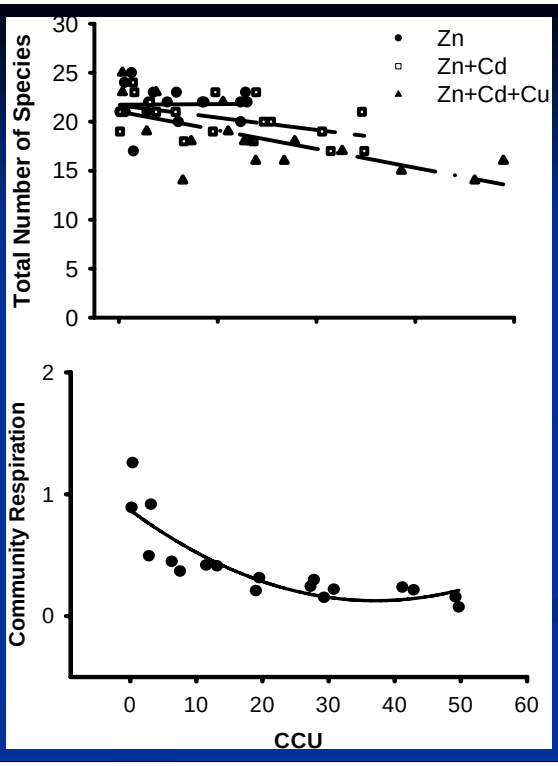
Example:

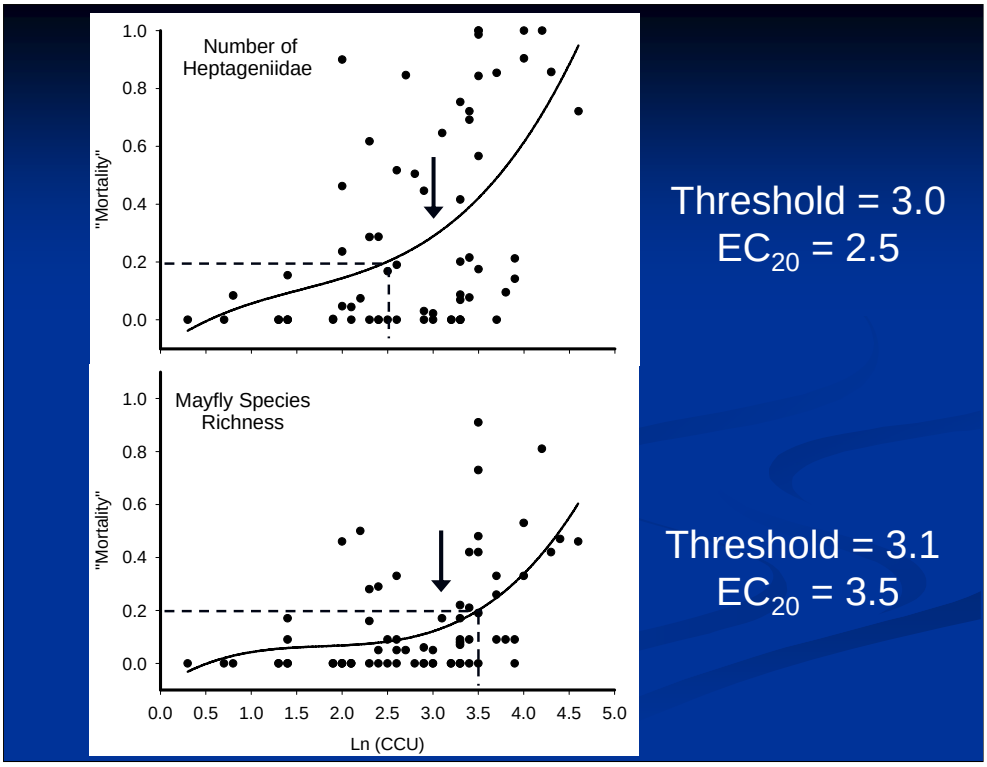
Responses of sensitive & tolerant species



Example:

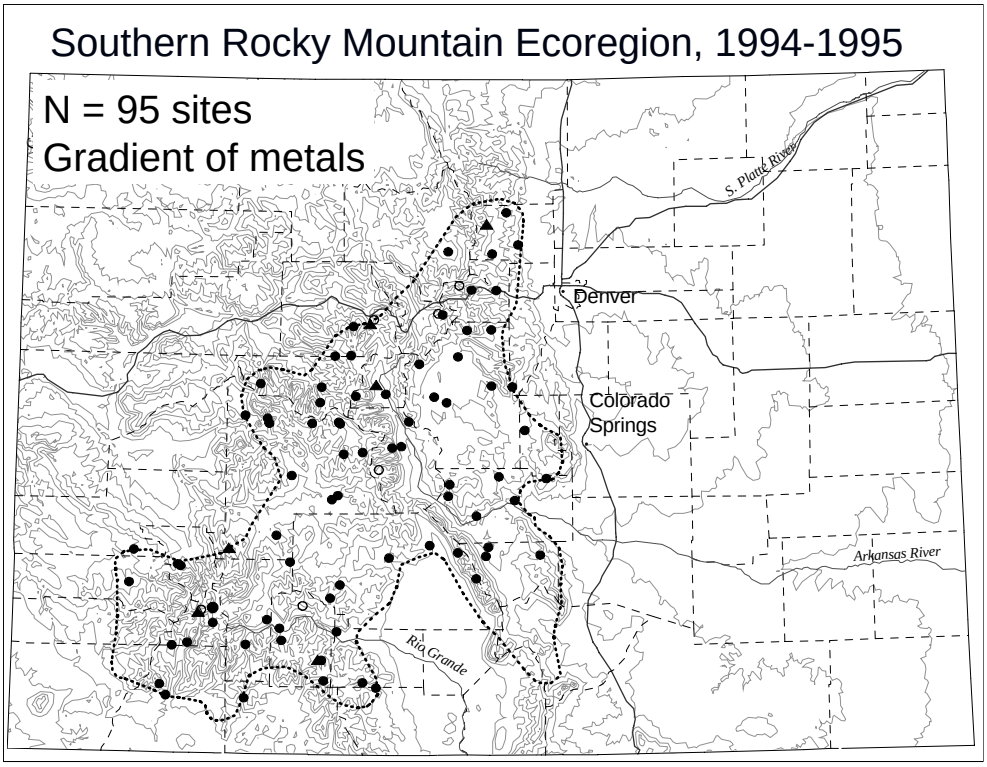
Responses of structural and functional measures

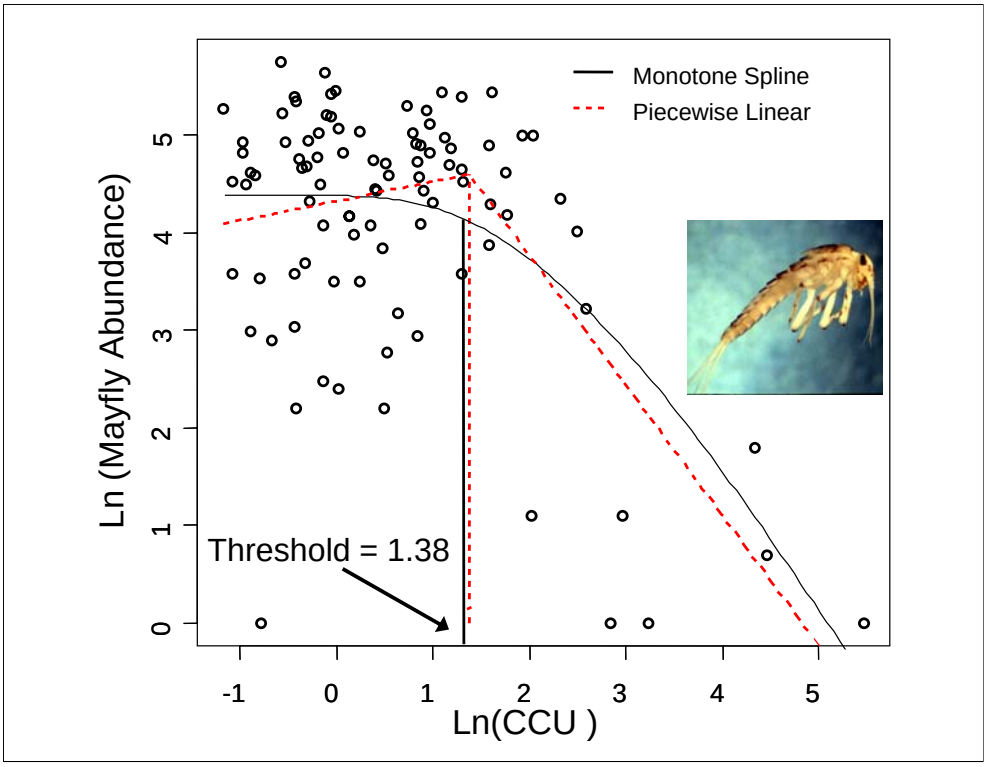




The arrows indicate the thresholds.

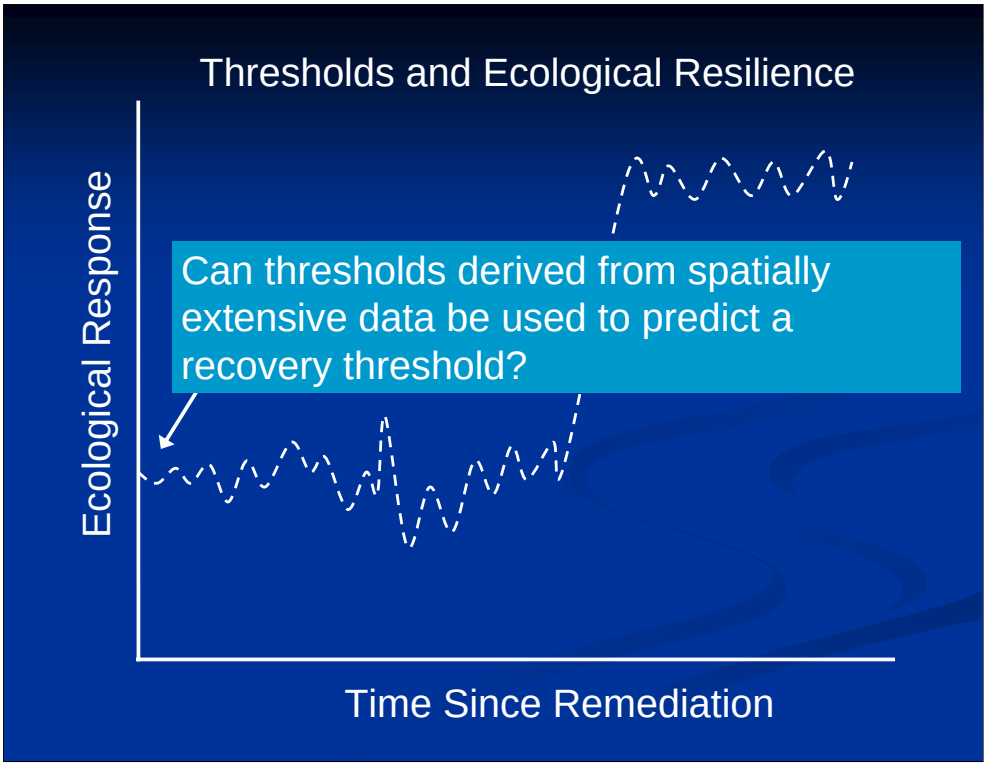
Southern Rocky Mountain Ecoregion, 1994-1995

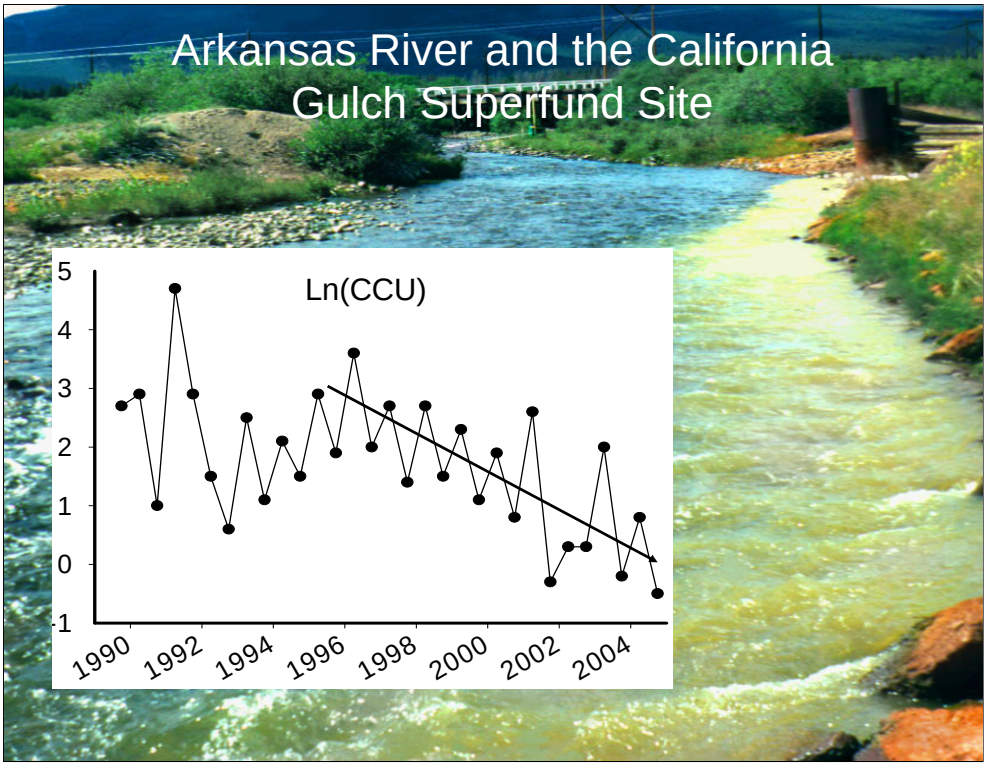




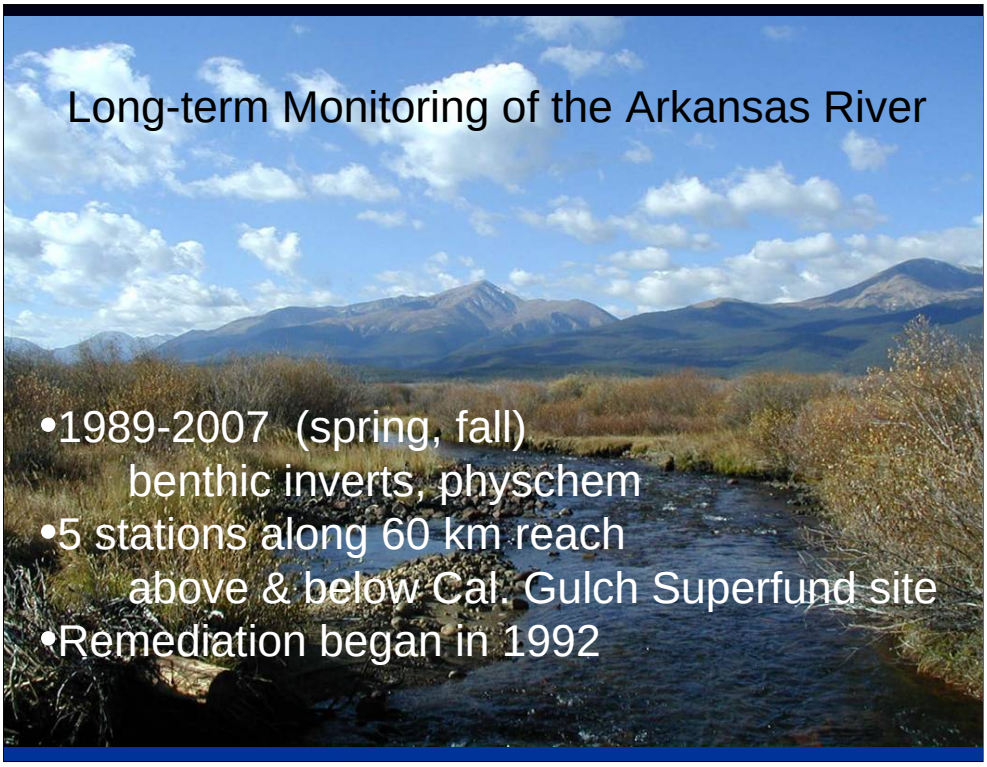
Comparison of Microcosm & R-EMAP Thresholds for Benthic Community Metrics (Ln CCU)

Metric	Microcosm EC20	Microcosm Threshold	R-EMAP Threshold
# Heptageniidae	2.5	3.0	1.7
# of mayflies	2.4	3.9	1.4
EPT abundance	3.0	3.9	1.6
Mayfly richness	3.5	3.1	1.3
EPT	3.9	3.2	0.9
Total richness	4.1	3.3	1.0

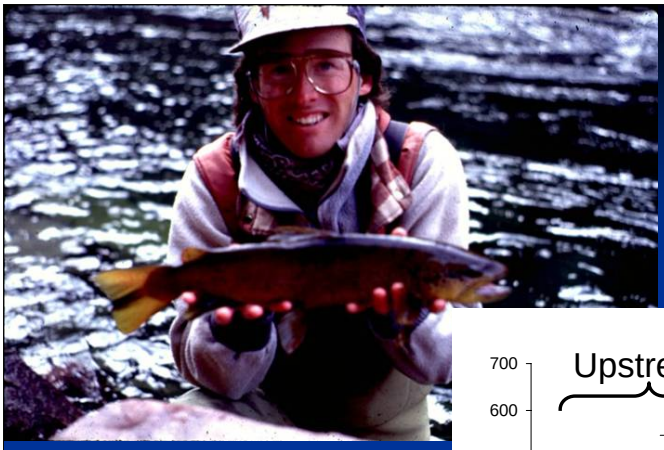




This graph shows that restoration efforts in the Arkansas River have had an effect.

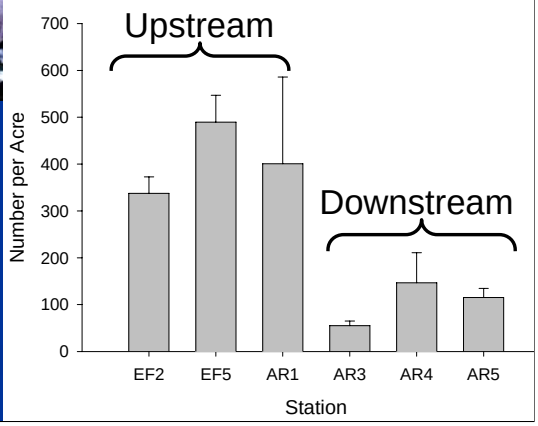


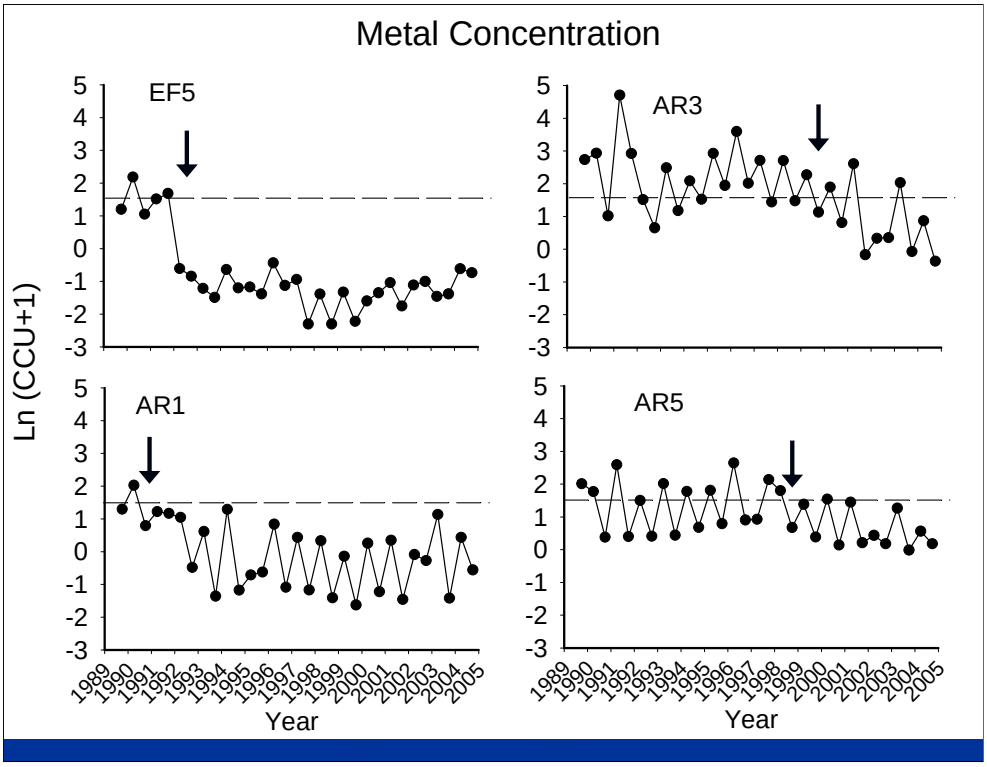
Higher metal concentrations are found during spring runoff.



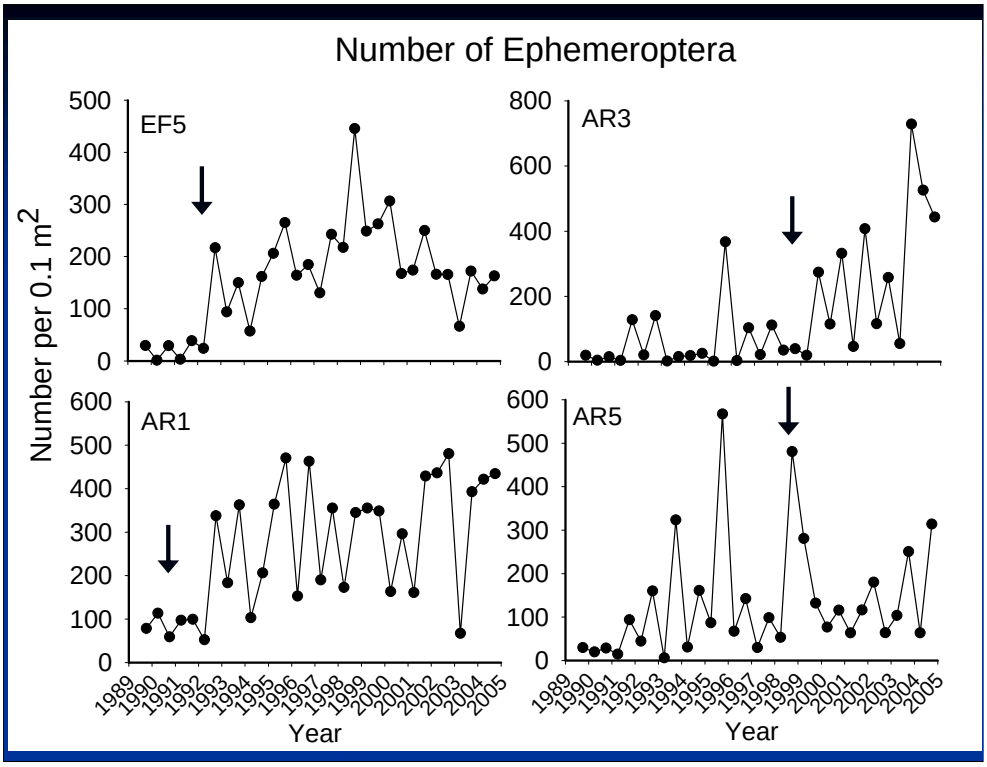
Brown Trout Abundance

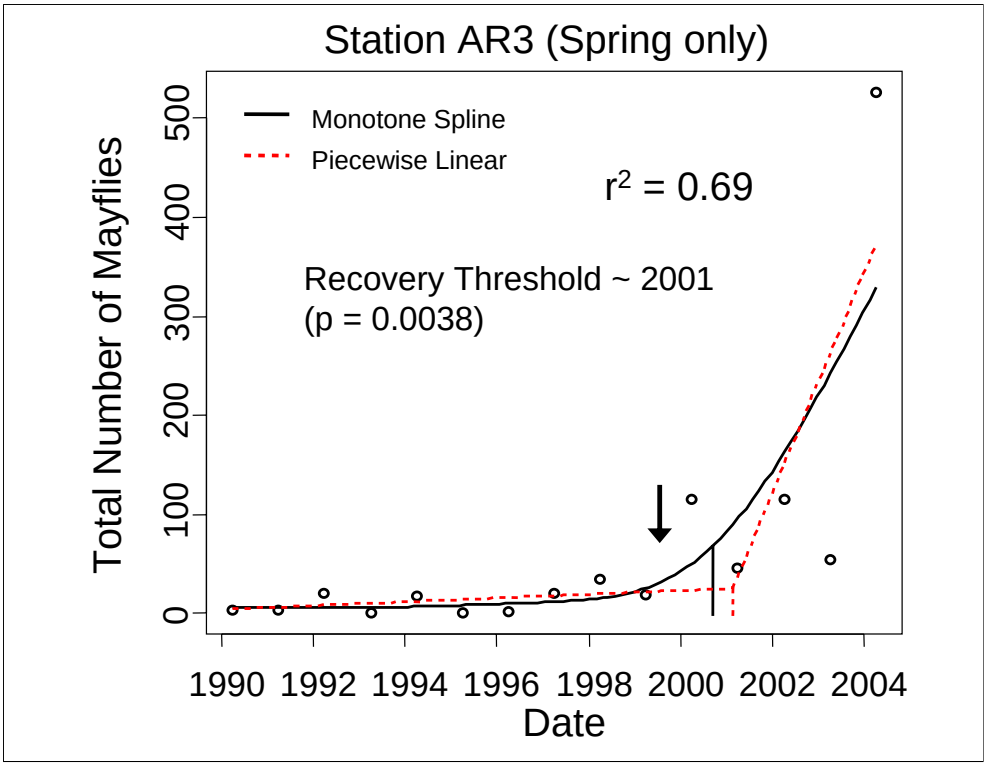
<u>Remediation Goal:</u>
"Restore a healthy and productive brown trout fishery to the Arkansas River"

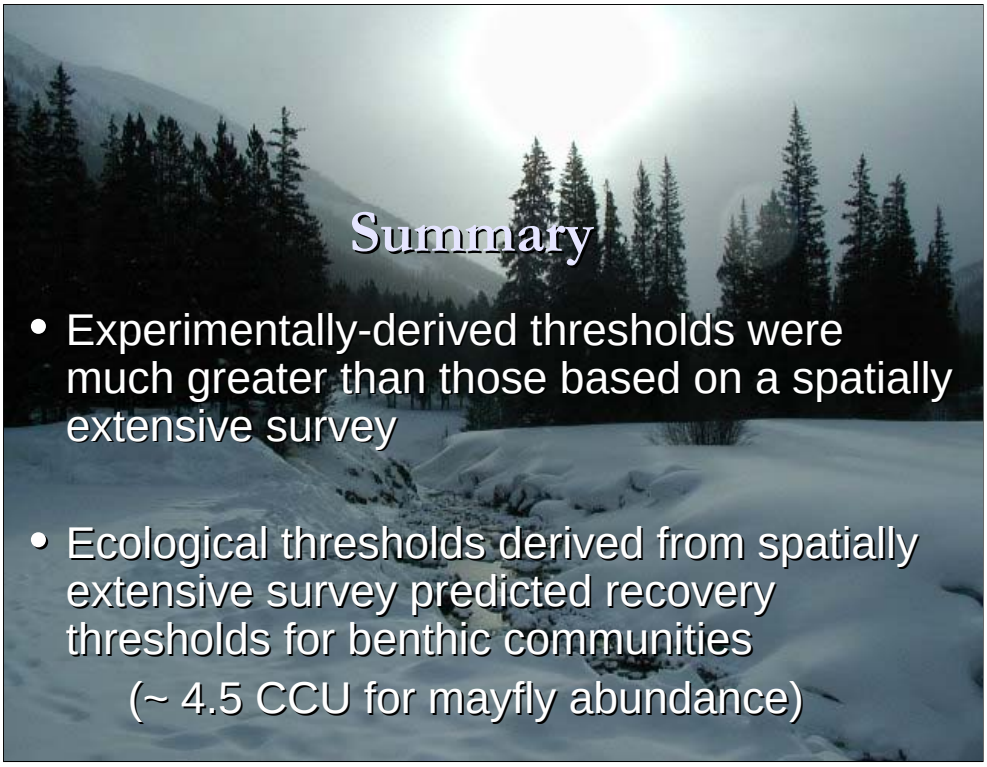


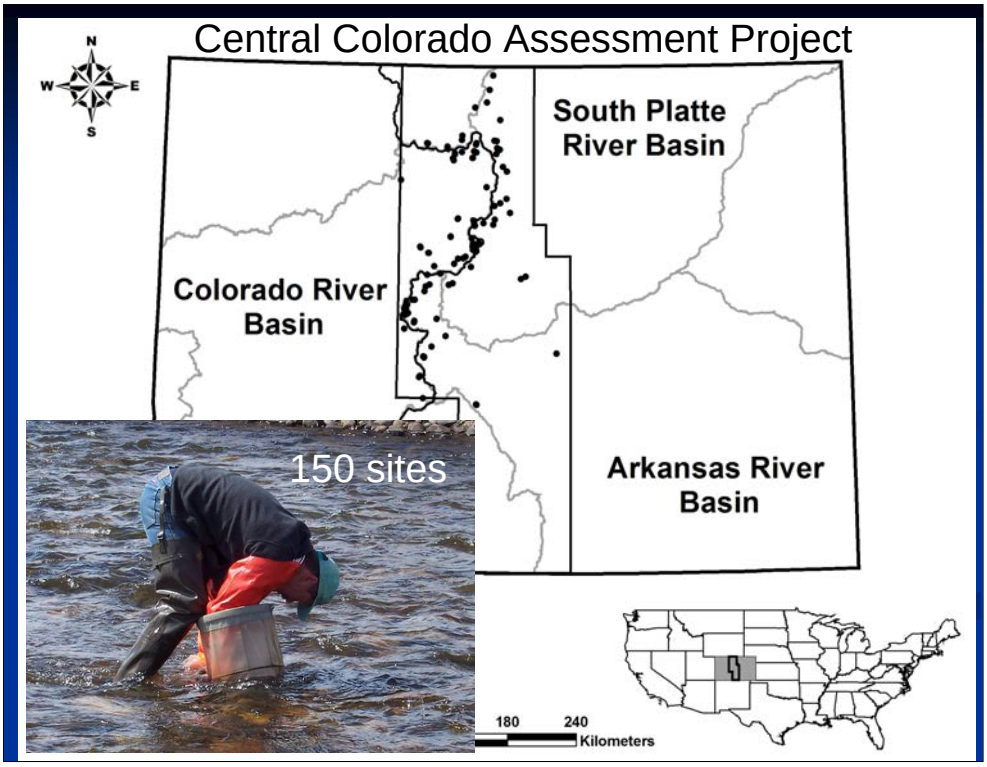


The two graphs on the left represent two upstream sites; the two graphs on the right represent two downstream sites. Remediation has occurred throughout the system. The arrows indicate the approximate start of declines in metal concentrations below the threshold of 1.5. Both upstream and downstream, there is a tremendous amount of seasonal variability in metal concentrations.

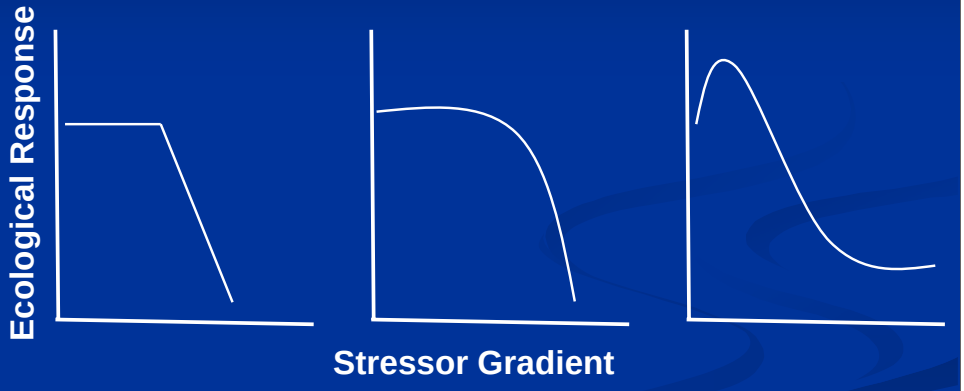






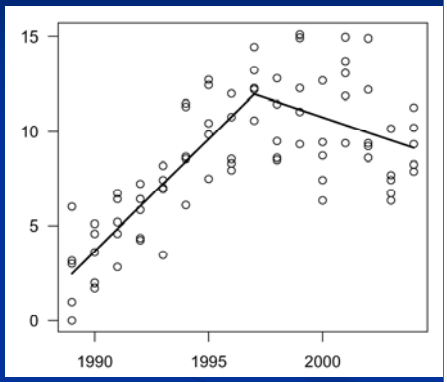


New Statistical Approaches for Detecting Ecological Thresholds



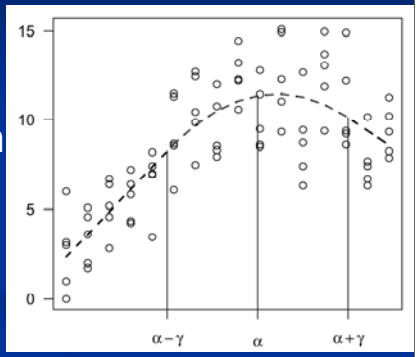
Piecewise Linear

- **Strengths**
  - Conceptually simple
  - Easy to implement
- **Limitations**
  - Correct inference on threshold is not obvious
  - Number of thresholds is limited by computational issues
  - Abrupt threshold is often unrealistic



Bent-Cable

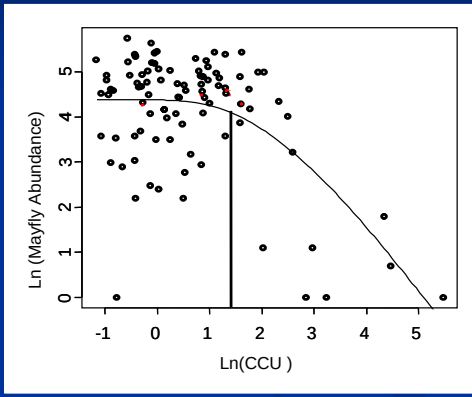
- **Strengths**
  - Smooth transition region
  - Estimate a threshold region instead of a specific point
- **Limitations**
  - Rarely sufficient data to justify bent-cable over other smooth transition models
  - Interpretation issues



The Bent-Cable analysis can inform the experimental design by showing where additional data are needed.

Monotone Spline

- **Strengths**
  - Derivative-based
  - Similar to piecewise regression
- **Limitations**
  - Assumes monotonic response
  - Single threshold



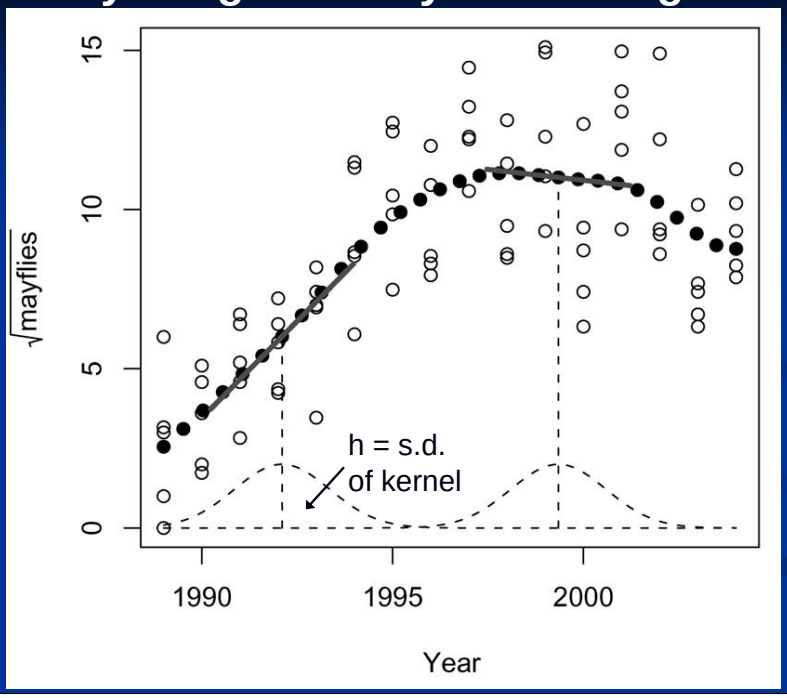
Nonparametric Smoothing Techniques (Locally Weighted Polynomial Regression)

- Obtain a smooth function
  -estimate slope and CI at any point

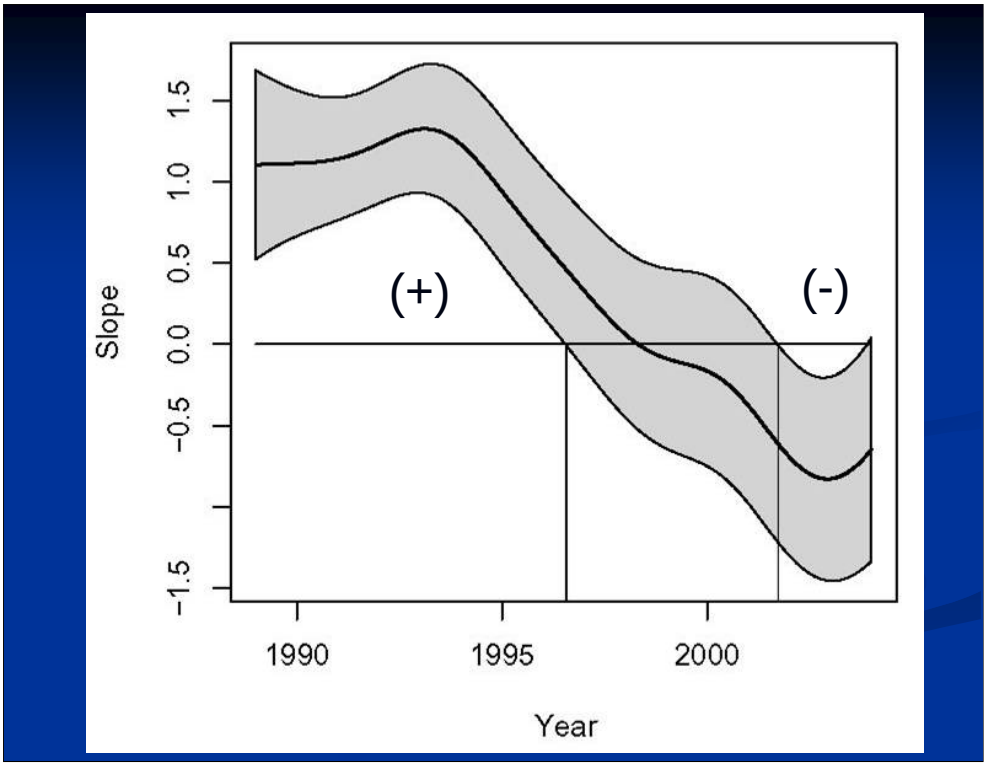
- **Threshold** = point where the derivative changes among states:

  - significantly negative
  - possibly zero
  - significantly positive

Locally Weighted Polynomial Regression



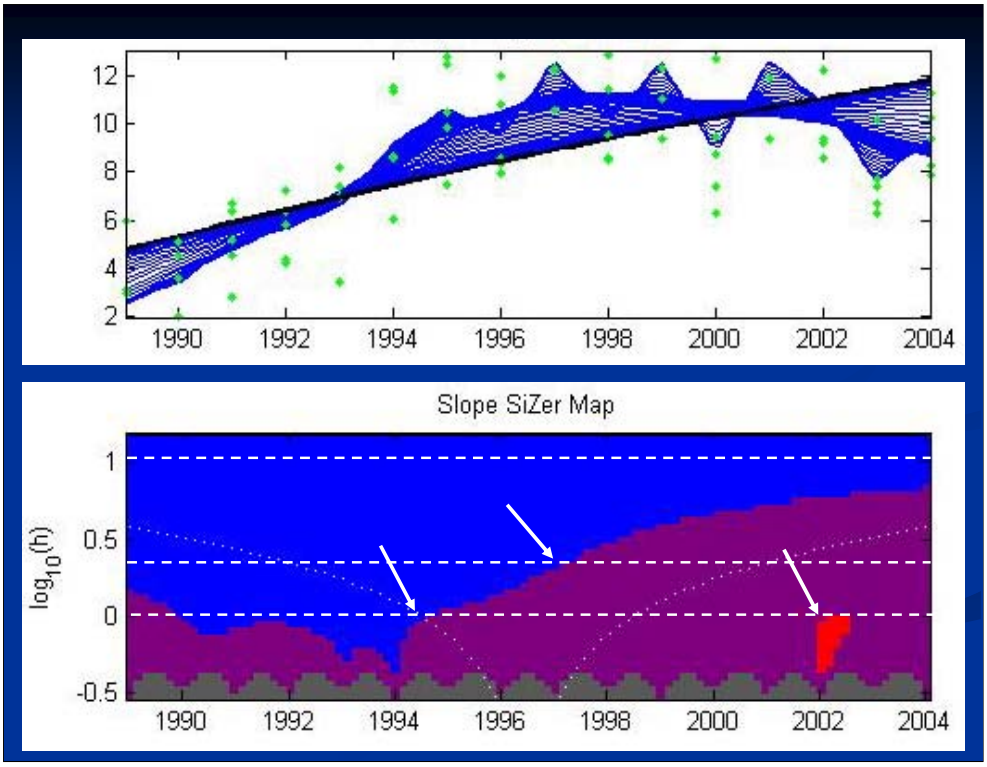
A linear regression is performed at each point along the x-axis. Points close to the line are weighted more than points far from the line. The normal distributions show the weighting kernel. At each point, a smooth function and the value of the derivative are obtained. Note the importance of the kernel width. A narrow kernel results in a wiggly graph, whereas a wide kernel underfits the data.



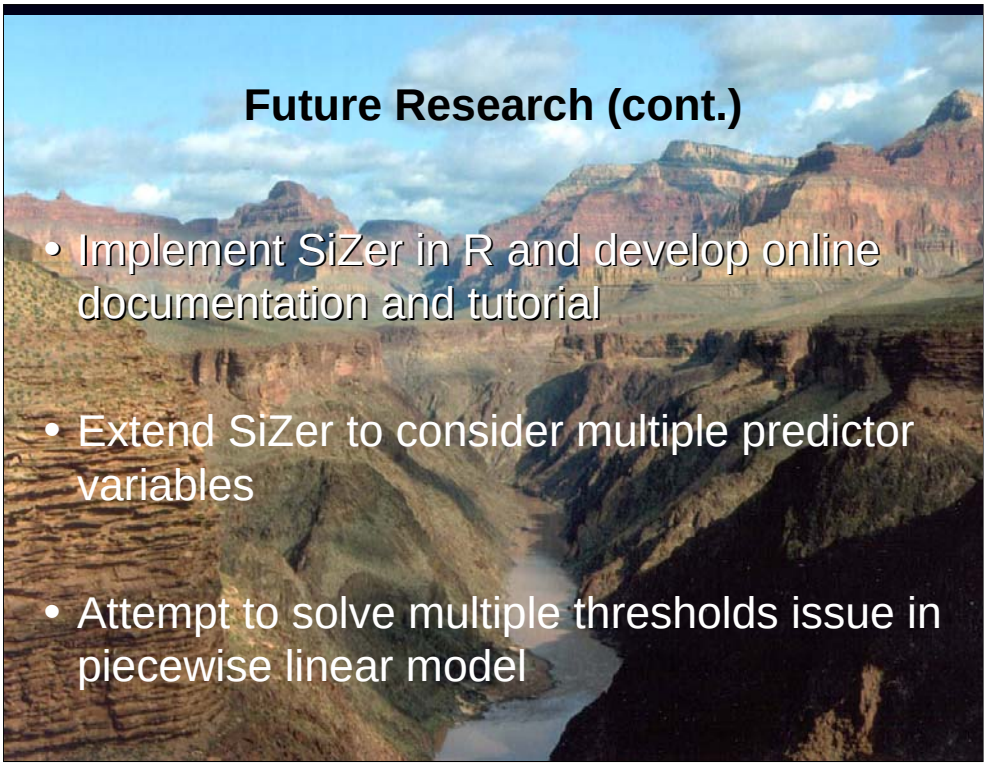
After the smoothing function is created, the researchers can partition the x-axis into three categories: significantly positive, possibly zero, and significantly negative. A threshold occurs when the first derivative changes among states. At this bandwidth there are two potential thresholds. The first is in 1996, when the derivative changes from positive to possibly zero; the second is where the derivative changes from possibly zero to significantly negative.

SiZer
Significance of Zero Crossings

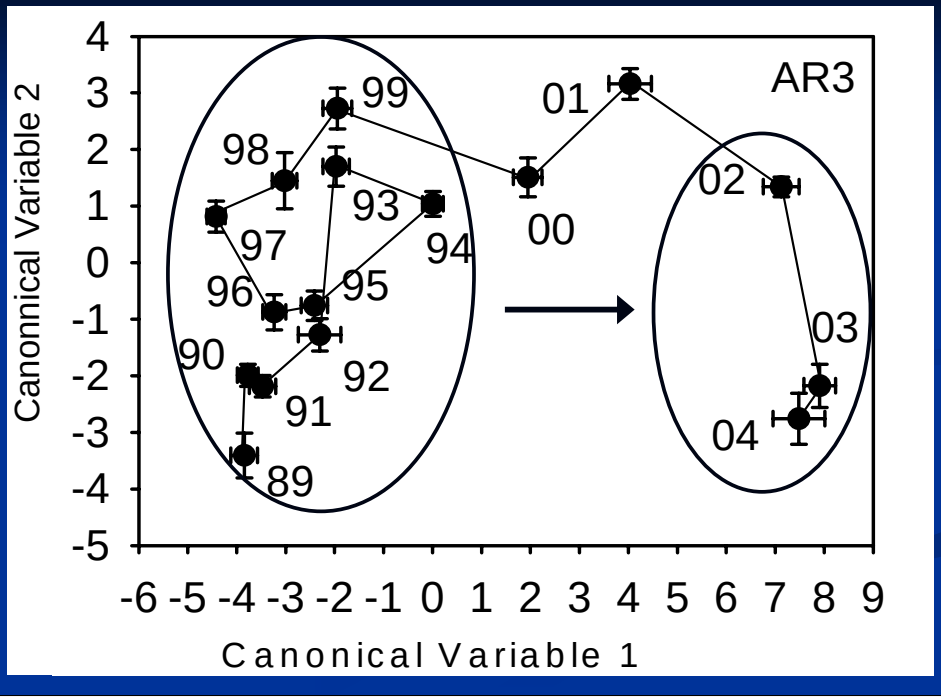
- Exploratory and visualization technique
  -determine significance of features in a smoothed function
- Nonparametric
  -minimal assumptions (smooth function)
- Determines where the derivative is non-zero
- Not constrained by number of thresholds



h = standard deviation of kernel



Multivariate Thresholds?



Lessons Learned

- Experimentally derived estimates of toxicity (e.g., EC_{20} values) were inadequate to protect stream ecosystems and predict recovery

- Ecological thresholds derived from spatially extensive data provided a good estimate of recovery thresholds for benthic communities

- A need for more sophisticated approaches to quantify location of ecological thresholds
  - -statistical issues (confidence intervals)
  - -multiple thresholds & predictors

Management Implications for Resilient Ecosystems

- Dramatic shifts in community composition occur when thresholds are exceeded

- These shifts are reversible
  Reducing metal concentrations below thresholds resulted in rapid recovery
  → need source of colonists

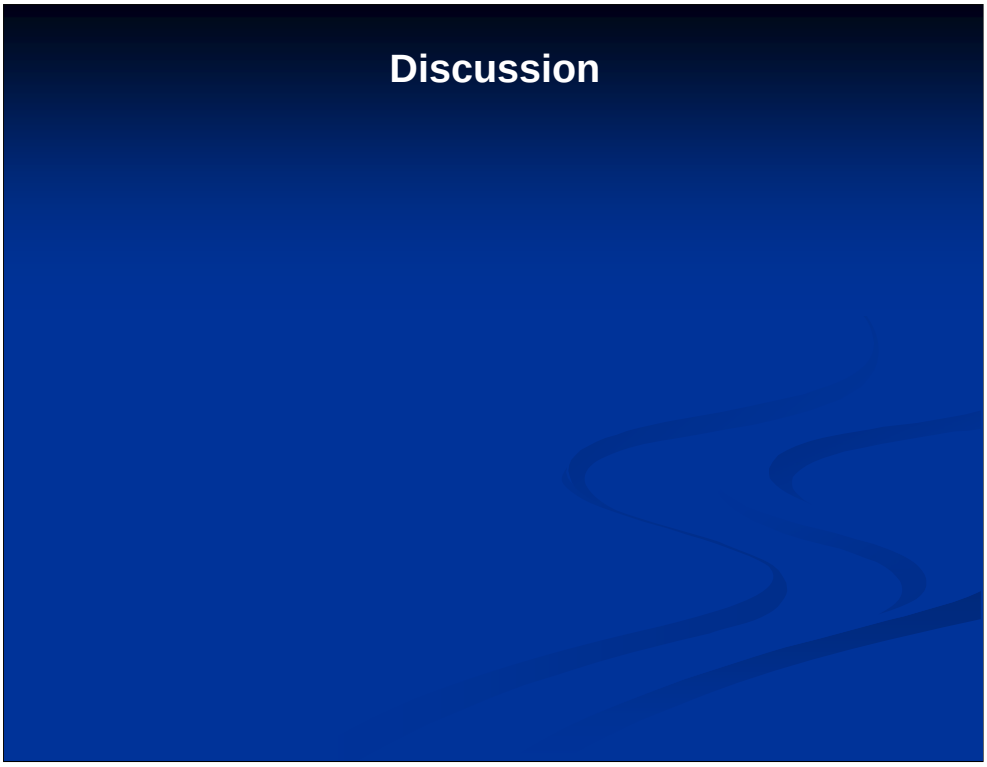
- However, recovering benthic communities are more susceptible to novel stressors
  (Kashian and Clements, 2007)

Inquiries and Outreach

- Assisted in the development of a special session on Ecological Thresholds for the National Park Service, September, 2006

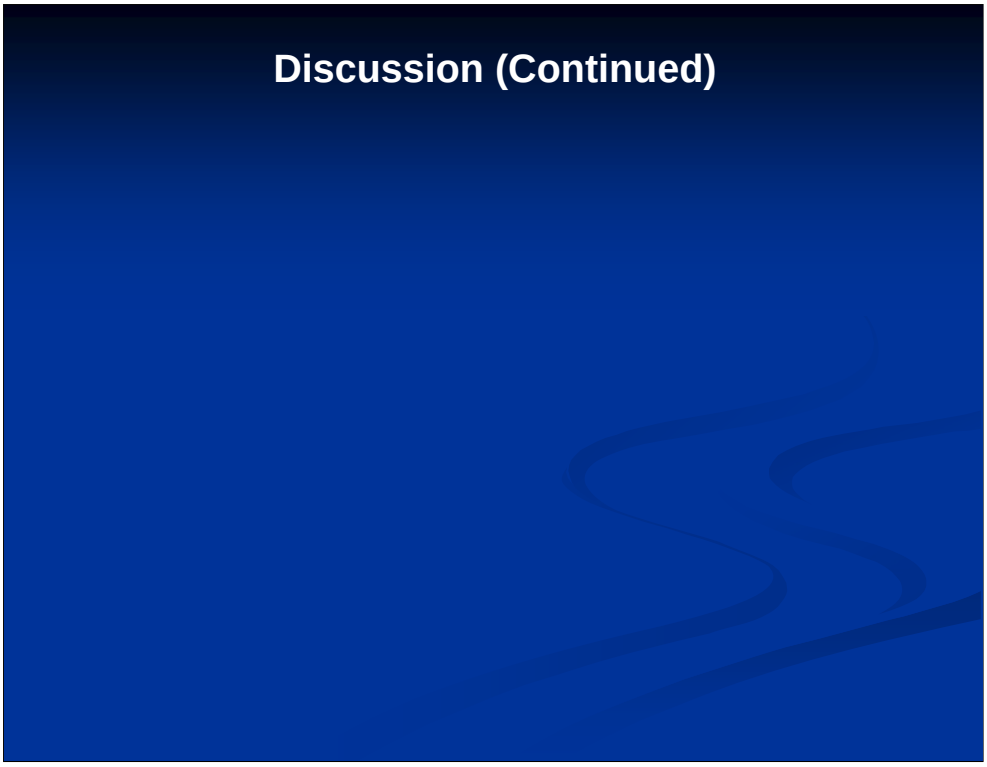
- Presented a talk to the NPS “Thresholds in aquatic and terrestrial ecosystems”

- Collaborating with the Greater Yellowstone Network to quantify spatiotemporal variation in water quality & identify ecological thresholds based on long-term monitoring of benthic communities



One participant commented on the Slope SiZer Map and the use of the change of slope sign to indicate a threshold. The participant shared another example of this type of analysis. Phosphate-based detergent was banned in 1988, so the change in the phosphate concentration would be expected to occur in 1988 or after, but not before. If a smoothing curve is fit through the time series, however, the shift appears to occur before 1988. Dr. Clements responded that modification of the tuning parameter allows for a measure of control over the smoothing curve. The participant pointed out that modifying the tuner may result in multiple thresholds, as it will pick up seasonal changes. Another participant stated that smoothing can push the threshold in either direction. Another participant added that this shows the value of ecologists and biologists working closely with statisticians.

Another participant asked how the tolerance values of aquatic insects were estimated. Dr. Clements responded that a tremendous amount of research, both in the field and in laboratory experiments, has been done on these groups and how they respond to heavy metals. The tolerance values vary for different species.



A participant asked if it is difficult to link the laboratory observations to what actually occurs in the field. In the field, there are significant perturbations with each storm, with each year's snowmelt, and so on. Dr. Clements responded that, in the laboratory, researchers tend to use higher concentrations than what is seen in the field. The challenge for researchers is to determine the meaning of a lab experiment in the field. The study sites represent a wide range of metal contamination levels. A participant commented that it would seem to be difficult to accurately determine the water quality in the different sites. Dr. Clements stated that he and his colleagues have taken multiple samples at each site.

A participant asked if the researchers had any difficulty interpreting the data, given the use of the multivariate threshold. Dr. Clements responded that the analysis will be driven by the species that respond to that separation.