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Development of a Statistical Modeling Methodology for the Detection and Quantification of Ecological Thresholds

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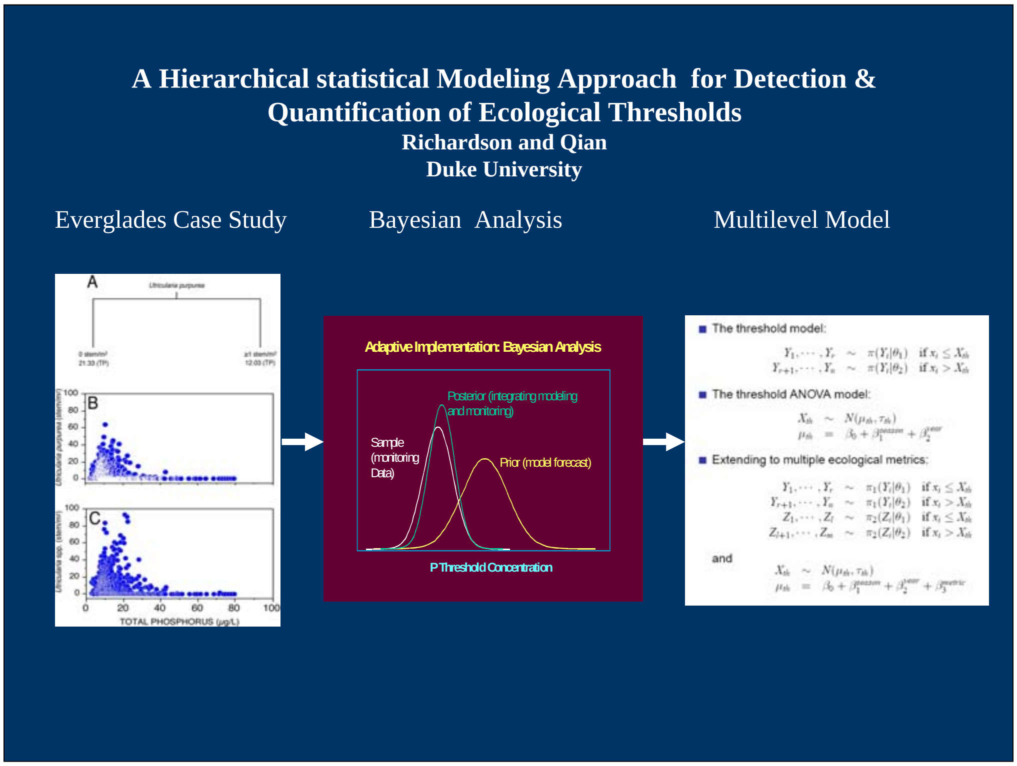
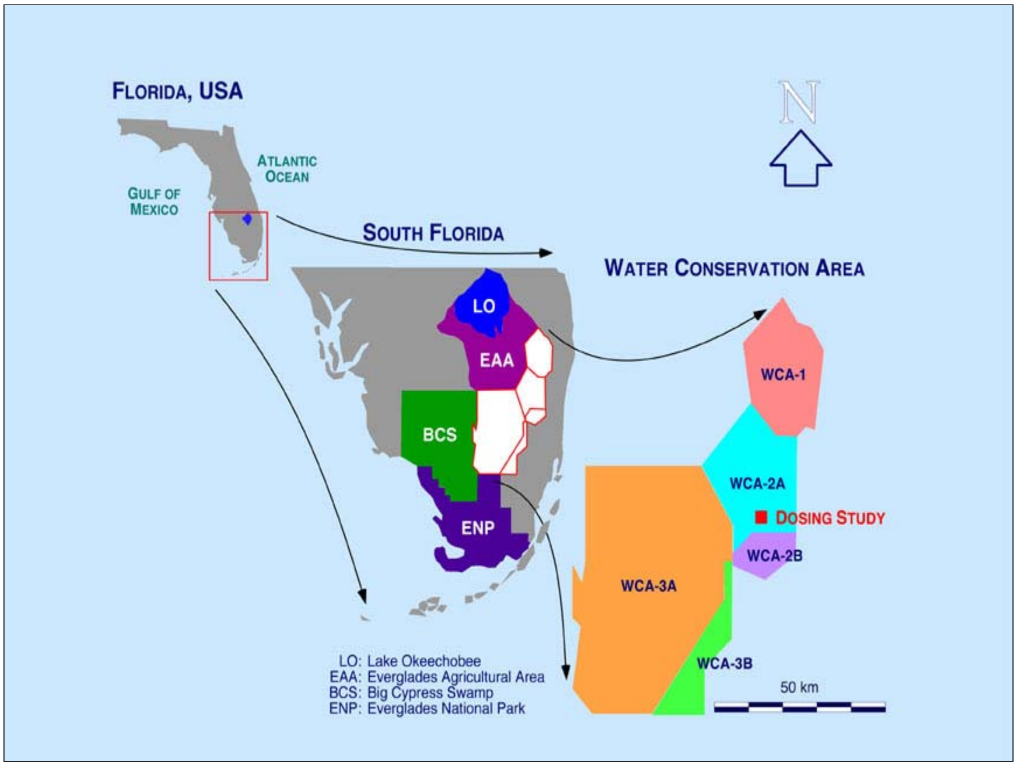
Ecological Significance

- Provide scientifically defensible methods for quantifying an ecosystem threshold.
- Introduce and validate a new and novel quantitative modeling approach to evaluate interactions between species-specific thresholds.
- Illustrate the applicability of a hierarchical change point model as a tool supporting applied adaptive management and environmental decision-making.
- Understanding how a freshwater wetland ecosystem responds to increased nutrient inputs will lead to better resource management strategies.
- Develop methods for quantifying ecological thresholds and interactions among various ecological metrics.
- Utilize a test case of Everglades where high nutrient (P) concentrations lead to a shift in species, excessive growth of non-native species and loss of habitat.



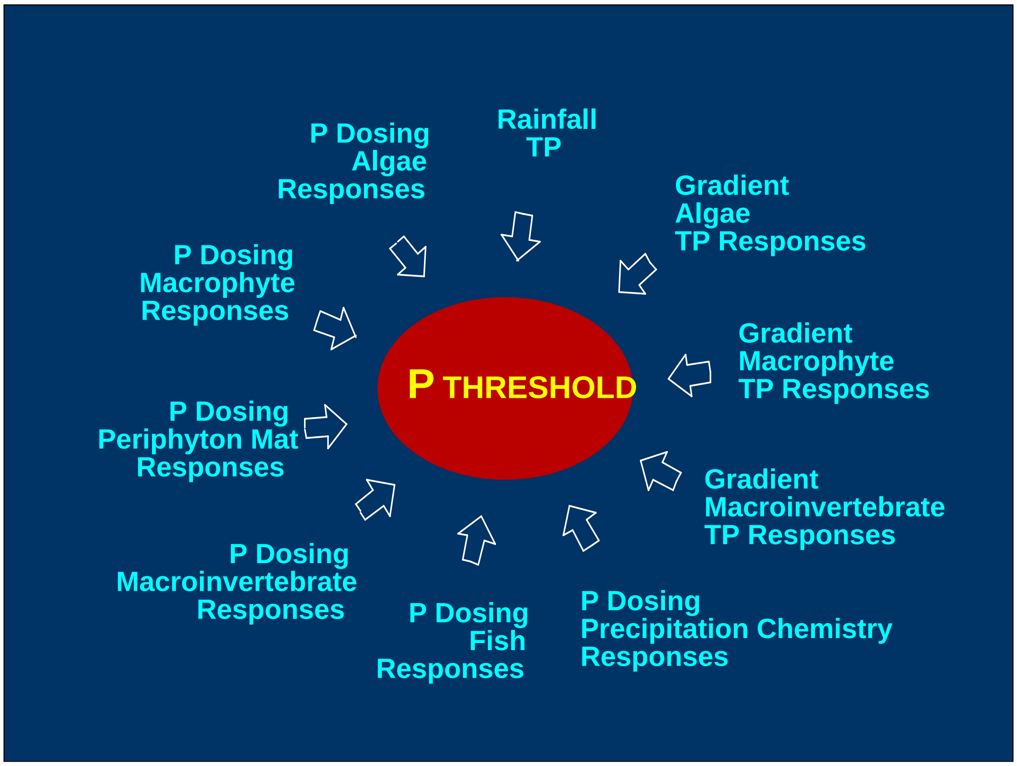
There is much data from the past 35 years on the gradients going into the Everglades, but until the early 1990s very little biological response data were collected. The gradients coming in from agricultural runoff had high sulfate, sodium, and calcium concentrations. This research project was developed to identify the phosphorus threshold in the Everglades.



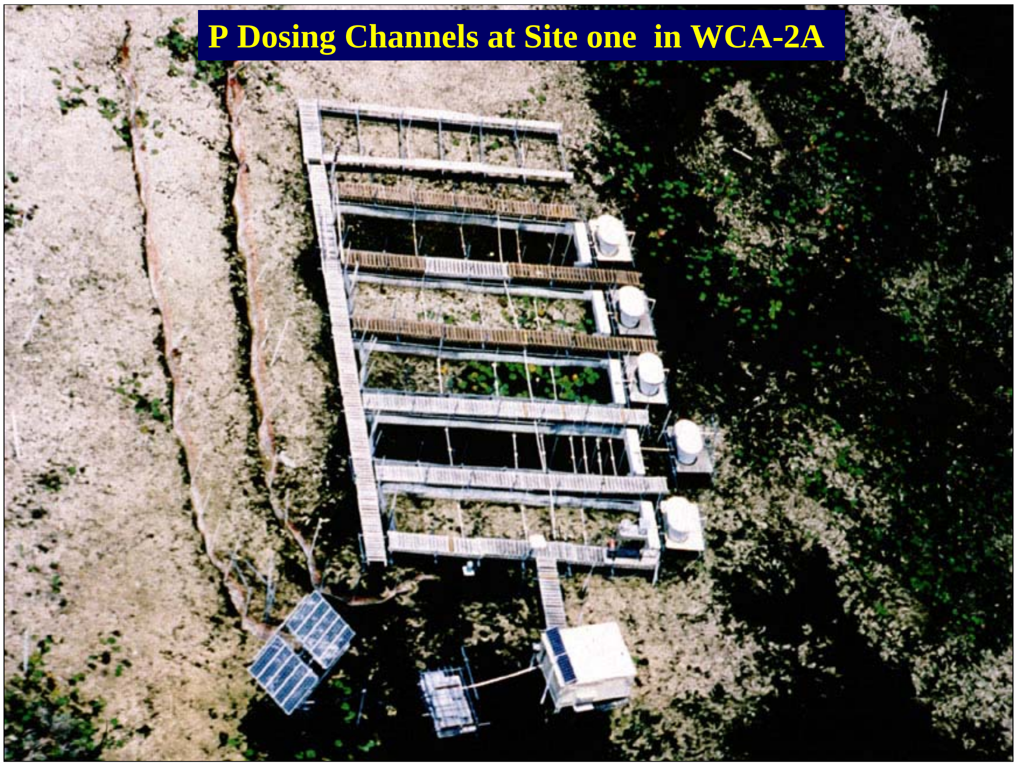
Agricultural areas (EAA) have a major effect on the Everglades (white area). When this research project began, it was determined that 60 metric tons of phosphorus had been going into the Northern Everglades for more than 30 years. This has had a dramatic effect on the system.

Project Overview

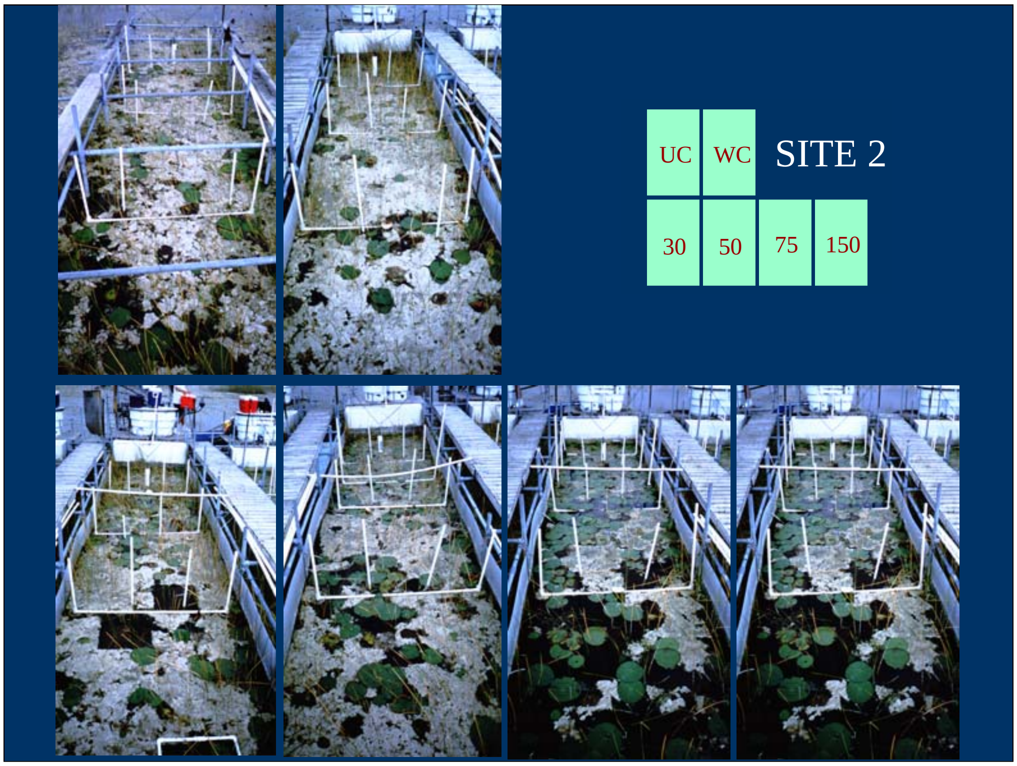
- Experimental design and data collection
  - Everglades Wetlands
  - Ecological responses to elevated SRP in a mesocosm P dosing experiment
  - Ecological metric selection at multiple trophic levels
- Statistical representation of ecological thresholds
- Statistical modeling of ecological thresholds
- Statistical presentation of multilevel ANOVA
- A Bayesian hierarchical modeling approach for combining spatial/temporal data from multiple metrics


P Dosing
Algae
Responses
Rainfall
TP
Gradient
Algae
TP Responses
P Dosing
Macrophyte
Responses
P THRESHOLD
Gradient
Macrophyte
TP Responses
P Dosing
Periphyton Mat
Responses
Gradient
Macroinvertebrate
TP Responses
P Dosing
Macroinvertebrate
Responses
P Dosing
Fish
Responses
P Dosing
Precipitation Chemistry
Responses

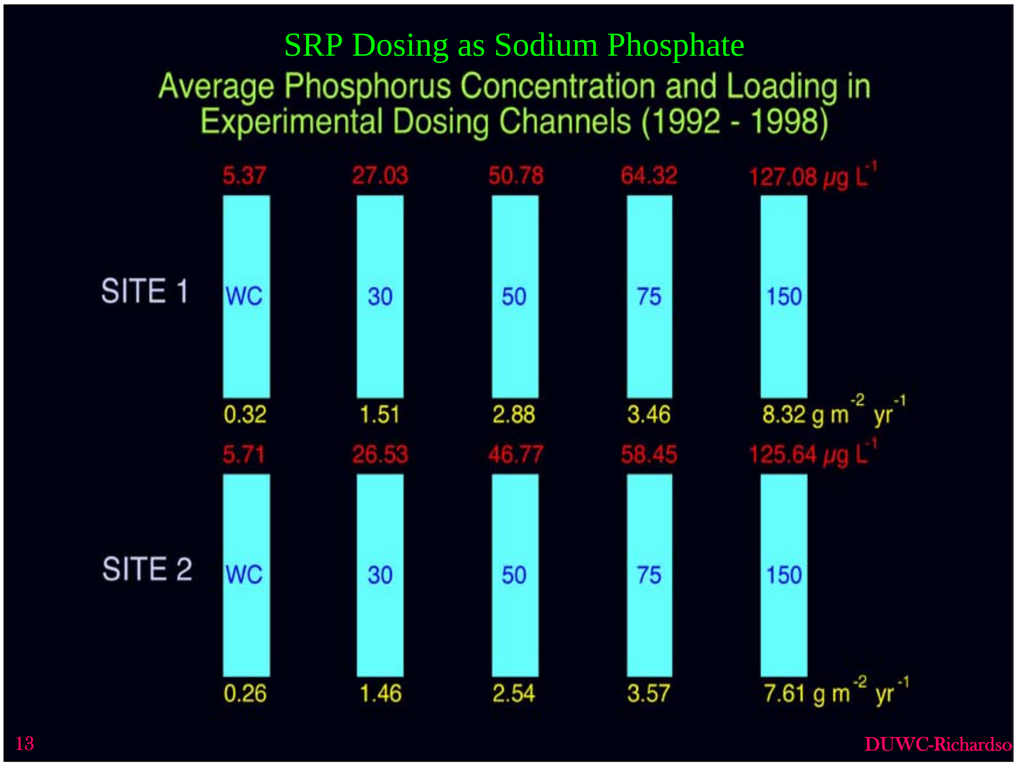
The researchers added different amounts of phosphorus to these channels over a 6-year time period.

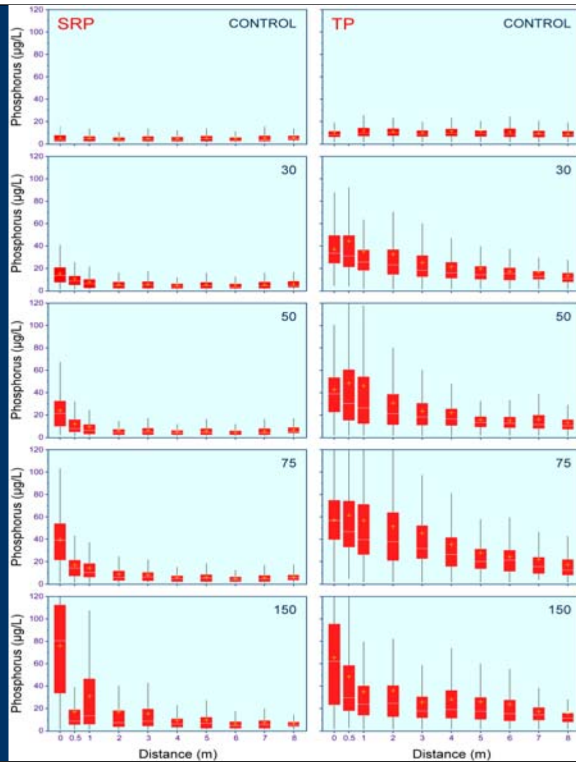


There are 36 channels in total, all with different levels of phosphorus.

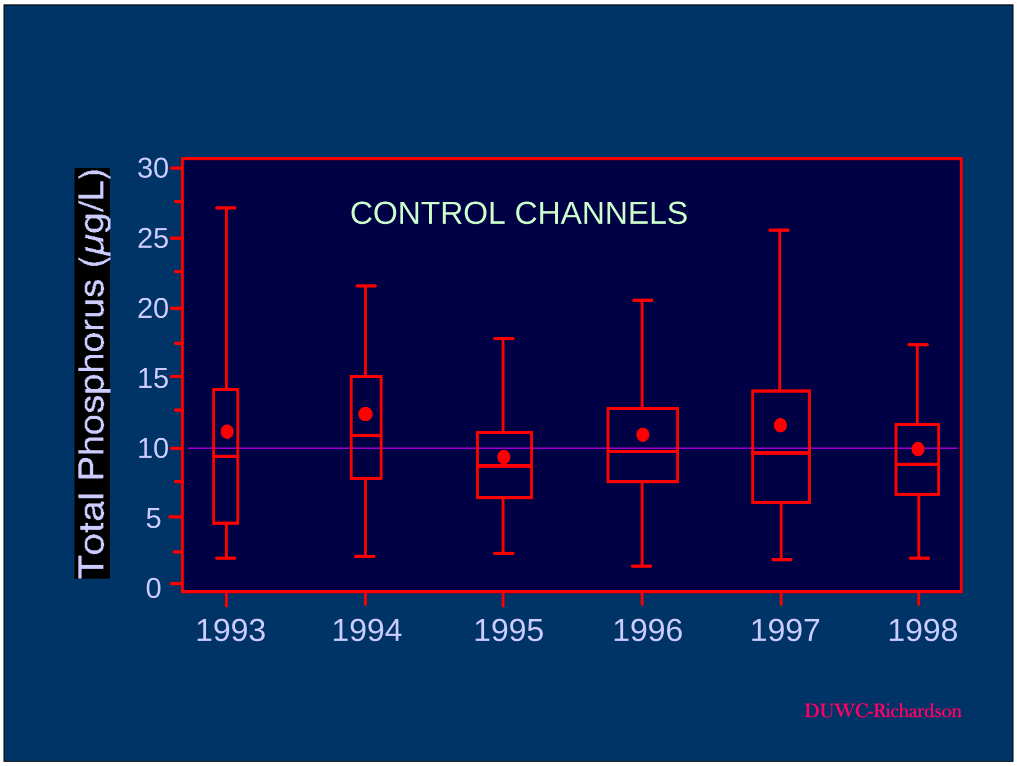


Higher levels of phosphorus result in more significant changes.


SRP Dosing as Sodium Phosphate
Average Phosphorus Concentration and Loading in Experimental Dosing Channels (1992 - 1998)
5.37
27.03
50.78
64.32
127.08 µg L-1
SITE 1
WC
30
50
75
150
0.32
1.51
2.88
3.46
8.32 g m-2 yr-1
5.71
26.53
46.77
58.45
125.64 µg L-1
SITE 2
WC
30
50
75
150
0.26
1.46
2.54
3.57
7.61 g m-2 yr-1
13
DUWC-Richardso



(Richardson et. al., 2007, in Press)



CONTROL CHANNELS
Total Phosphorus (μg/L)
0
5
10
15
20
25
30
1993
1994
1995
1996
1997
1998
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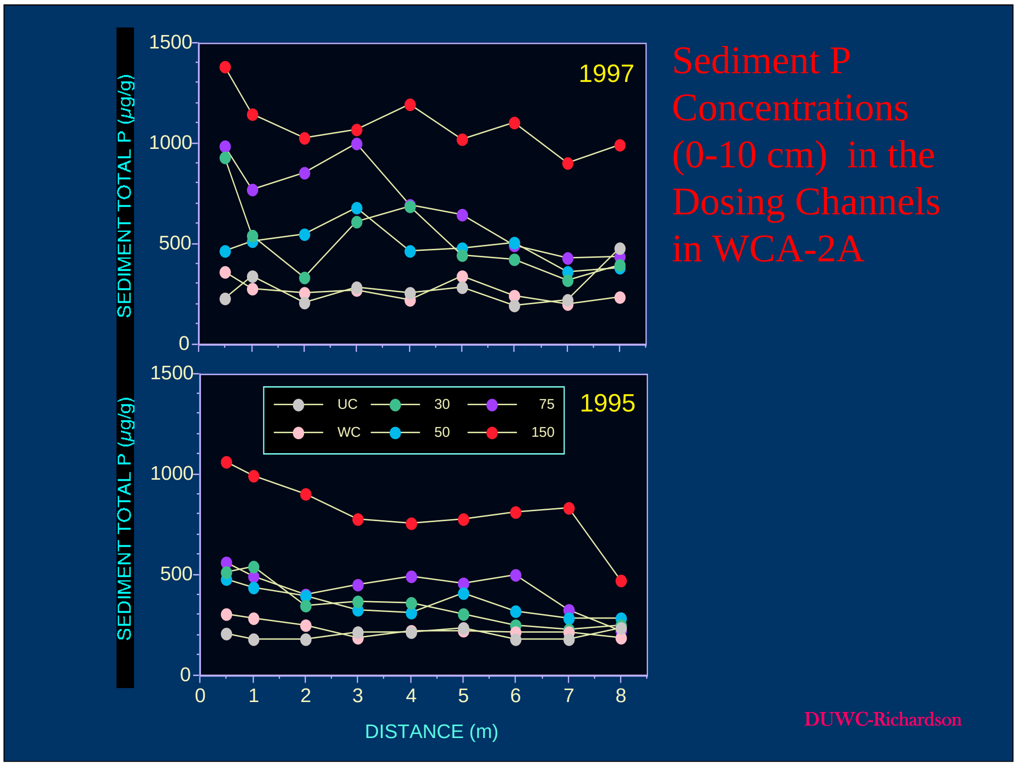
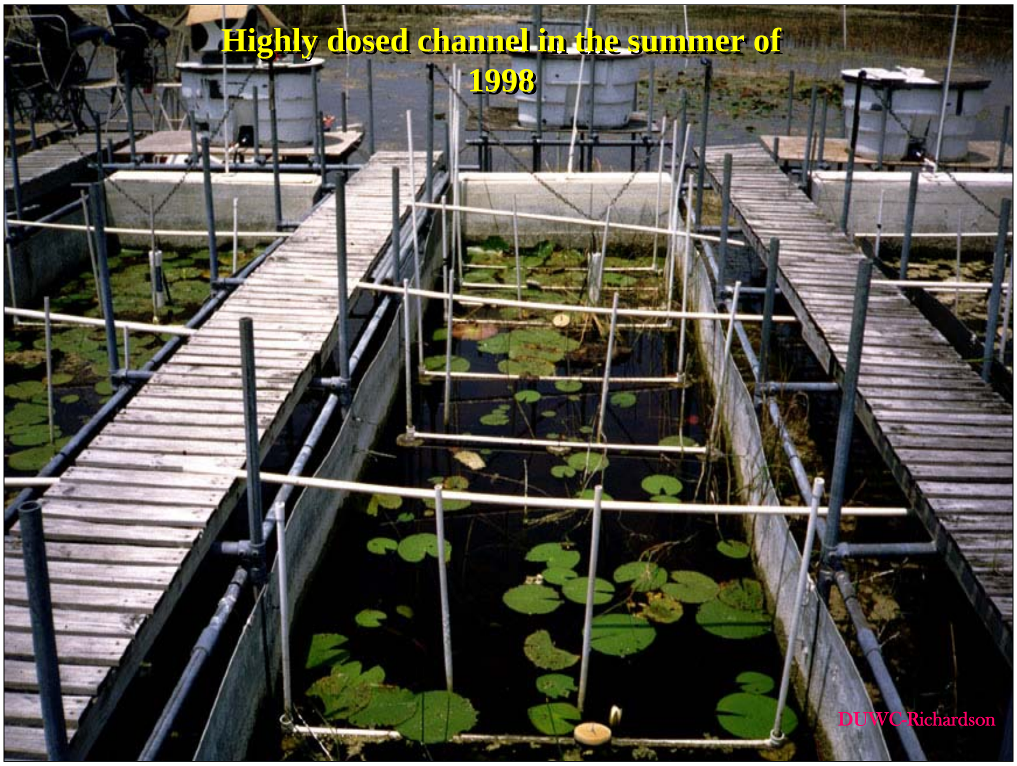


Most phosphorus goes into the sediment soil in a short time and then refluxes back out.

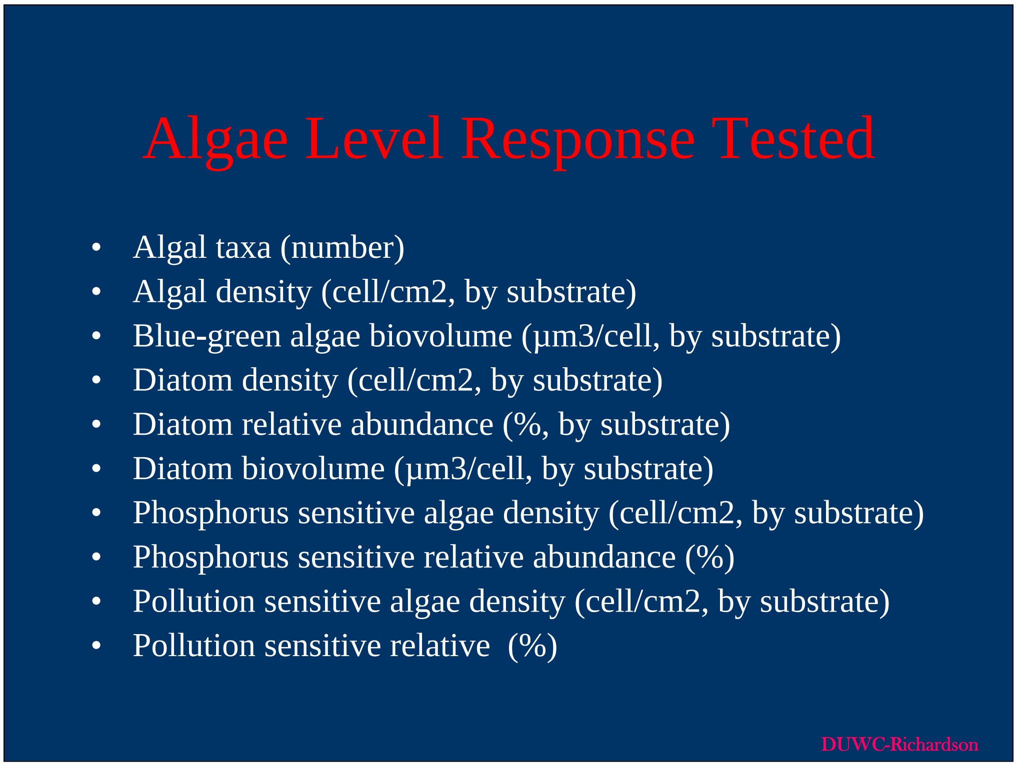

Highly dosed channel in the summer of 1998
DUWC-Richardson


Control channel in the summer of 1998
DUWC-Richardson

How do we define an Ecological P Threshold ?

- EPA -- a condition beyond which there is an abrupt change in a quality, property, or phenomenon of the ecosystem.
- Significant alteration in distribution (e.g., mean and/or variance) of the biological response variable (attribute) found above versus below a gradient changepoint

DUWC-Richardson



More than 50 algal metrics were collected. Metrics initially were tested at the algal trophic level.

Macroinvertebrate Level Responses

- Total macroinvertebrate (abundance)
- Total biomass (mg per H-D composite sample)
- Microcrustacea (abundance)
- Oligochaeta (number)
- Naididae (abundance)
- Taxa (number)
- Predators (%)
- Gastropoda (%)
- (CV Temporal Abundance)
- Sensitive species (FDEP) (%)

DUWC-Richardson

Community Level Responses

- Calcareous periphyton mat Cover (%)
- Community similarity (%)
- Community dissimilarity (%)
- Shannon-Weiner diversity (scaled index)
- Bray-Curtis dissimilarity

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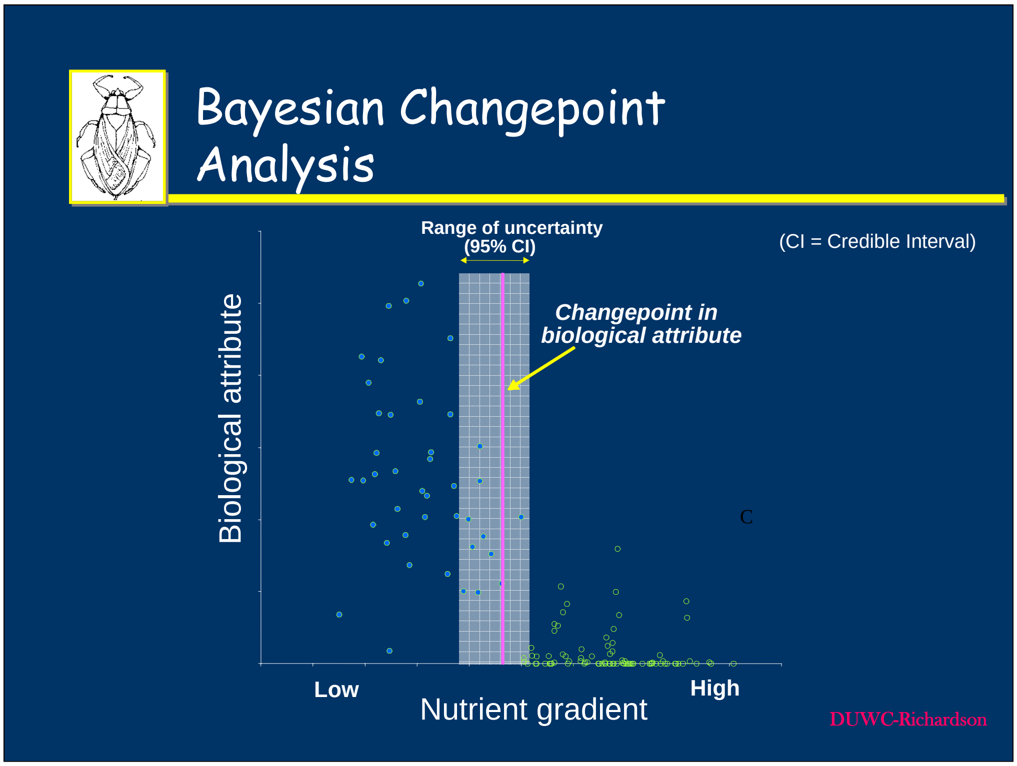
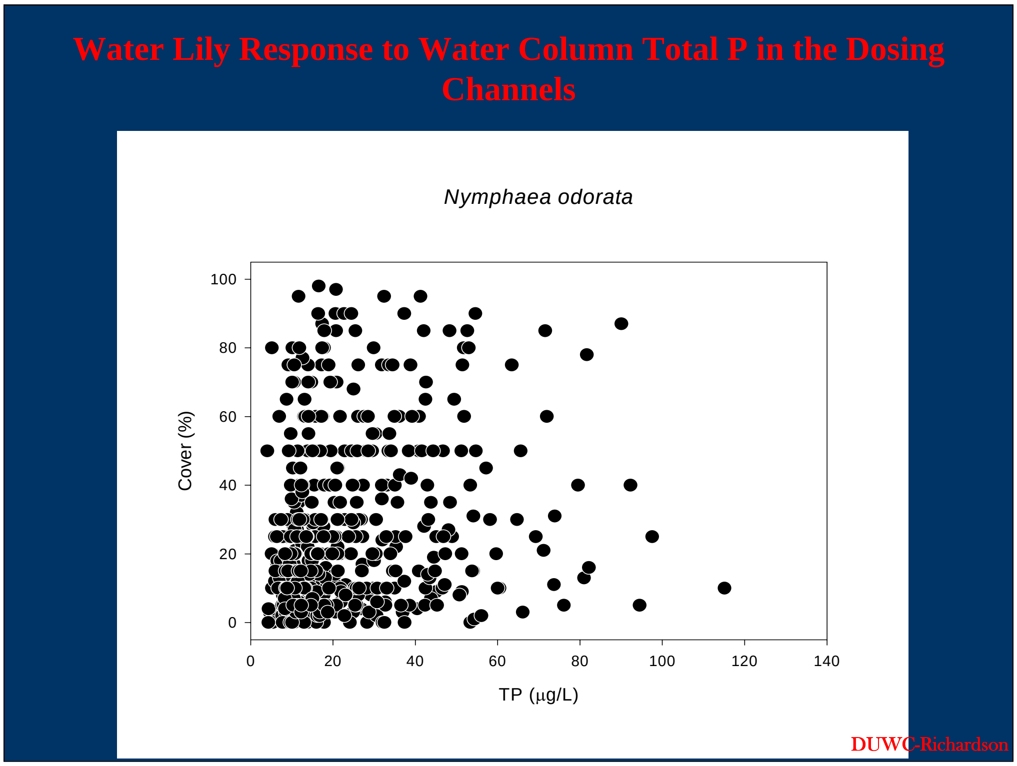
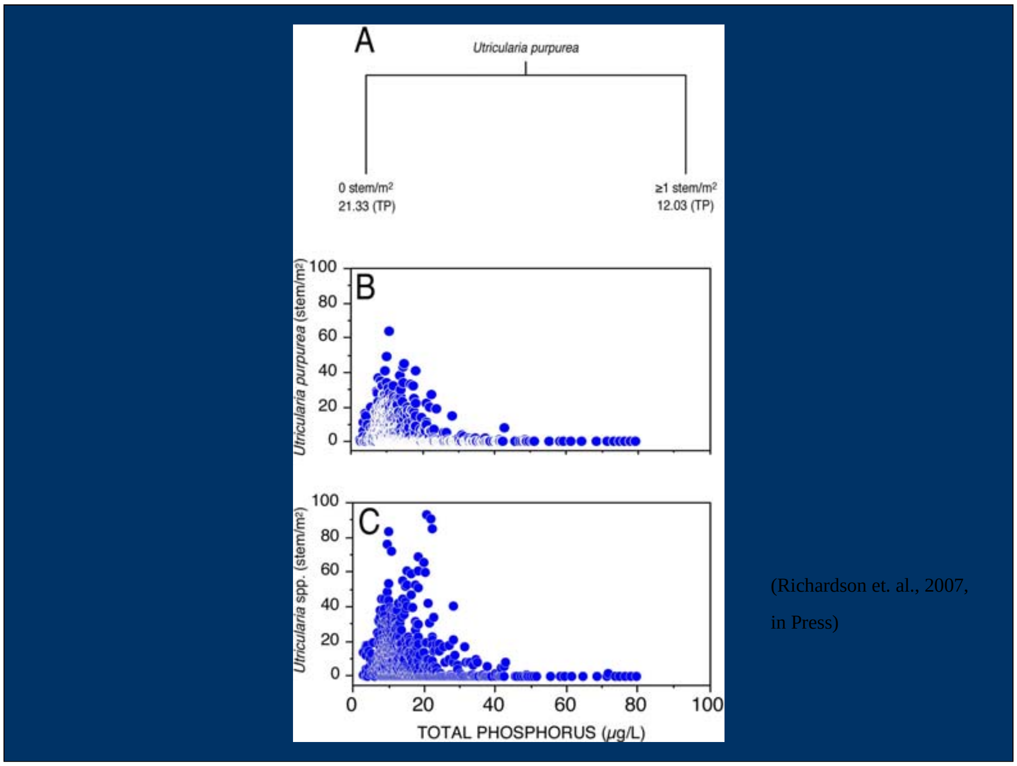


This graph depicts the changepoint developed by the Bayesian analysis along with the 95% confidence intervals for this metric.

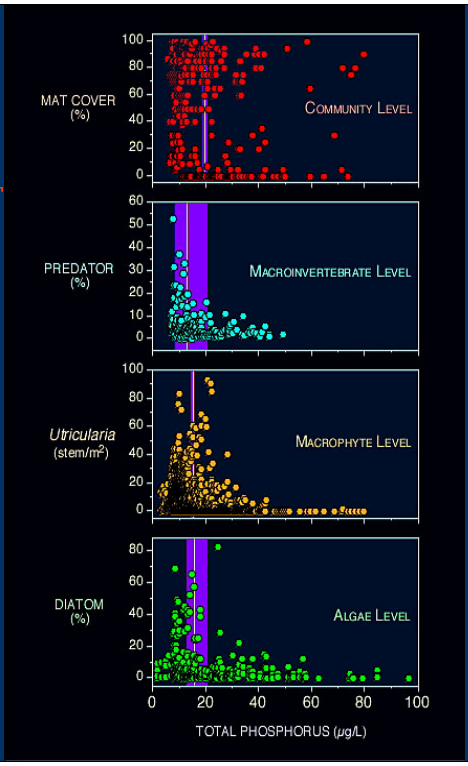


For this species, there is no threshold.

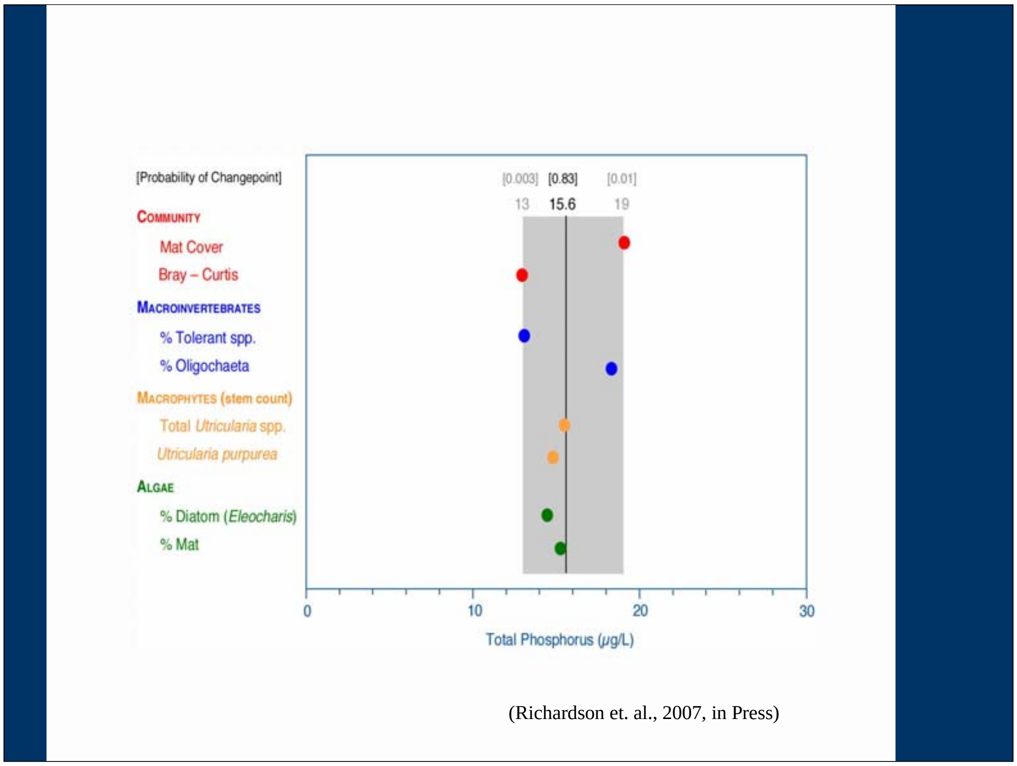


Utricularia purpurea show a response to added phosphorus. This species uses only CO_2 to photosynthesize. When phosphorus is added to the water, the pH increases from 7.5 to more than 9, depleting the CO_2 in the water. This species is dying during full sunlight because it no longer can photosynthesize.

Biological Metrics Across All Trophic Levels with the Highest Ecological Predictor Value Based on Both CART Predictor Selection and Bayesian Analyses of Changepoints with 95% CI's.



DUWC-Richardson



Combining these data results in a threshold range.

The next research questions are:
How should we account for the interactions of these components?
How should we account for the variation between the wet and dry seasons?

Why ANOVA is Relevant?

- Easy to use and easy to understand
- Conceptually appealing, representing an important scientific model: imagine ecology without ANOVA
- Properly conducted ANOVA is a basis for causal inference
- Multiple factors affecting an ecological threshold, the ANOVA concept is directly relevant

Factors affecting an ecological threshold include different species, different time frames, different locations, and so on.

Why ANOVA is Difficult?

- Charles McCulloch (2005), Repeated Measures ANOVA, RIP?, Chance, 18(3), 29-33
- The question of the article: Should we quit using repeated measures ANOVA?
- Multiple and nested sources of variability – main effects of each source calculated based on residuals from different levels:
  - Plot effect: main plot residual MSS
  - Sub-plot effect: sub-plot residual MSS
  - Imbalanced sampling: ambiguous interpretation of ANOVA results

A common theme
(bad news for ANOVA)

- Multiple factors (both categorical and continuous) affecting the response
- Imbalanced data
- Repeated measures
- Observational data
- Non-normal or unobserved variables

A Simple Solution

- Multilevel ANOVA using Bayesian hierarchical regression
  - ANOVA the model: partitioning the total variance
  - ANOVA the calculus: residual sum of squares and F-test
- Multilevel ANOVA -- A generalization of classical ANOVA
  - Keep the ANOVA model
  - Change the ANOVA calculus -- Bayesian hierarchical regression
- The ANOVA model can be applied to non-normal responses
- For a threshold problem, we use multilevel ANOVA to quantify the effects multiple predictors and interactions of the predictors

The Change Point Problem

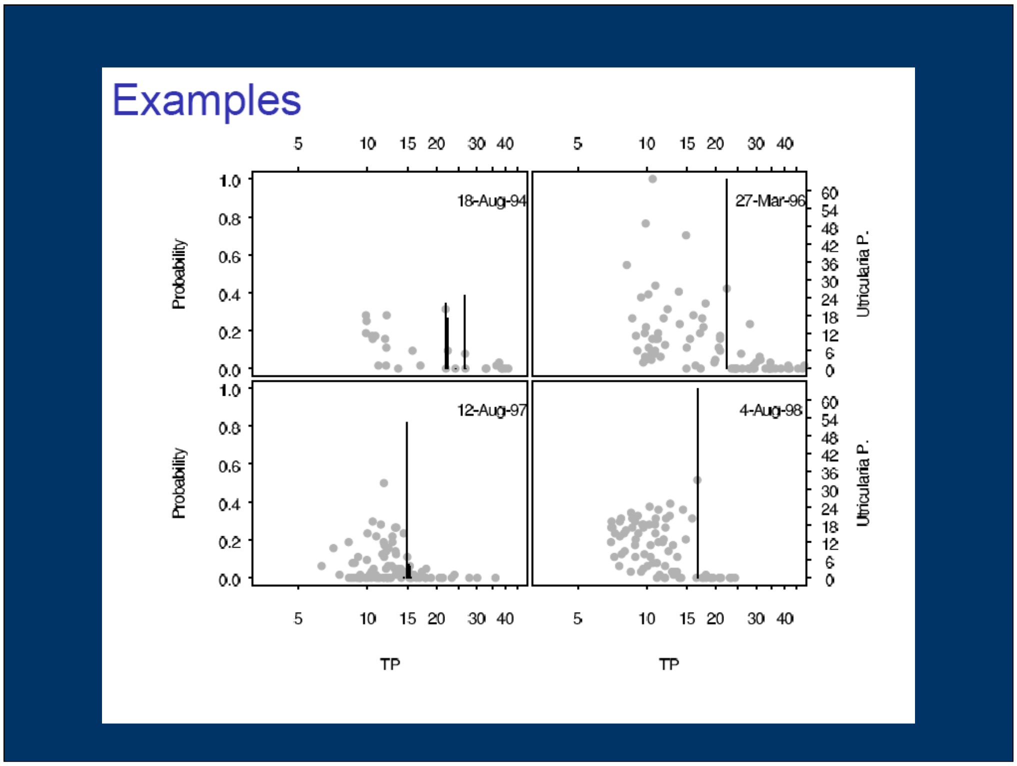
- Statistical interpretation of a threshold:

$$\begin{aligned} Y_1, \cdots, Y_r &\sim \pi(Y_i|\theta_1) \quad \text{if } x_i \leq X_{th} \\ Y_{r+1}, \cdots, Y_n &\sim \pi(Y_i|\theta_2) \quad \text{if } x_i > X_{th} \end{aligned}$$

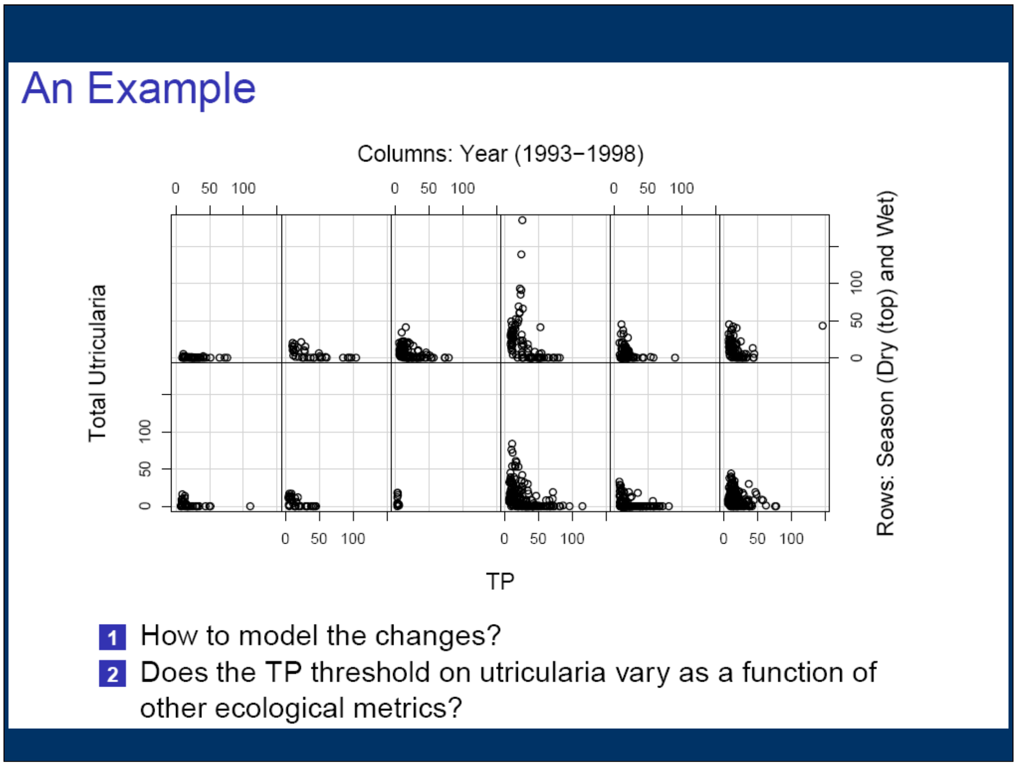
- Analytical solutions exist, assuming an uniform distribution of the threshold
- Different Y will lead to a different model:
  1. $Y = \log(Concentration) \sim N(\mu, \sigma^2)$
  2. $Y = \#of\ animals \sim Poisson(\lambda)$
- We have worked out analytical solutions for distributions commonly seen in ecological studies

An Example

- Response -- stem count of utricularia in the dosing study
- Environmental Factor -- Total phosphorus
- When TP exceeds a threshold, utricularia will disappear
- But the TP threshold varies -- year, season, location, ...



The vertical lines represent the estimated thresholds. Each plot represents a different sample base.



The data are plotted together in this graph, showing changes from year to year and season to season.

An Example

- The threshold model:

$$\begin{array}{rcll} Y_1, \cdots, Y_r & \sim & \pi(Y_i|\theta_1) & \text{if } x_i \leq X_{th} \\ Y_{r+1}, \cdots, Y_n & \sim & \pi(Y_i|\theta_2) & \text{if } x_i > X_{th} \end{array}$$

- The threshold ANOVA model:

$$\begin{array}{rcl} X_{th} & \sim & N(\mu_{th}, \tau_{th}) \\ \mu_{th} & = & \beta_0 + \beta_1^{season} + \beta_2^{year} \end{array}$$

- Extending to multiple ecological metrics:

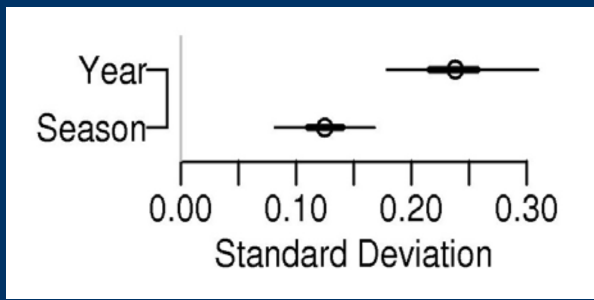
$$\begin{array}{rcll} Y_1, \cdots, Y_r & \sim & \pi_1(Y_i|\theta_1) & \text{if } x_i \leq X_{th} \\ Y_{r+1}, \cdots, Y_n & \sim & \pi_1(Y_i|\theta_2) & \text{if } x_i > X_{th} \\ Z_1, \cdots, Z_l & \sim & \pi_2(Z_i|\theta_1) & \text{if } x_i \leq X_{th} \\ Z_{l+1}, \cdots, Z_m & \sim & \pi_2(Z_i|\theta_2) & \text{if } x_i > X_{th} \end{array}$$

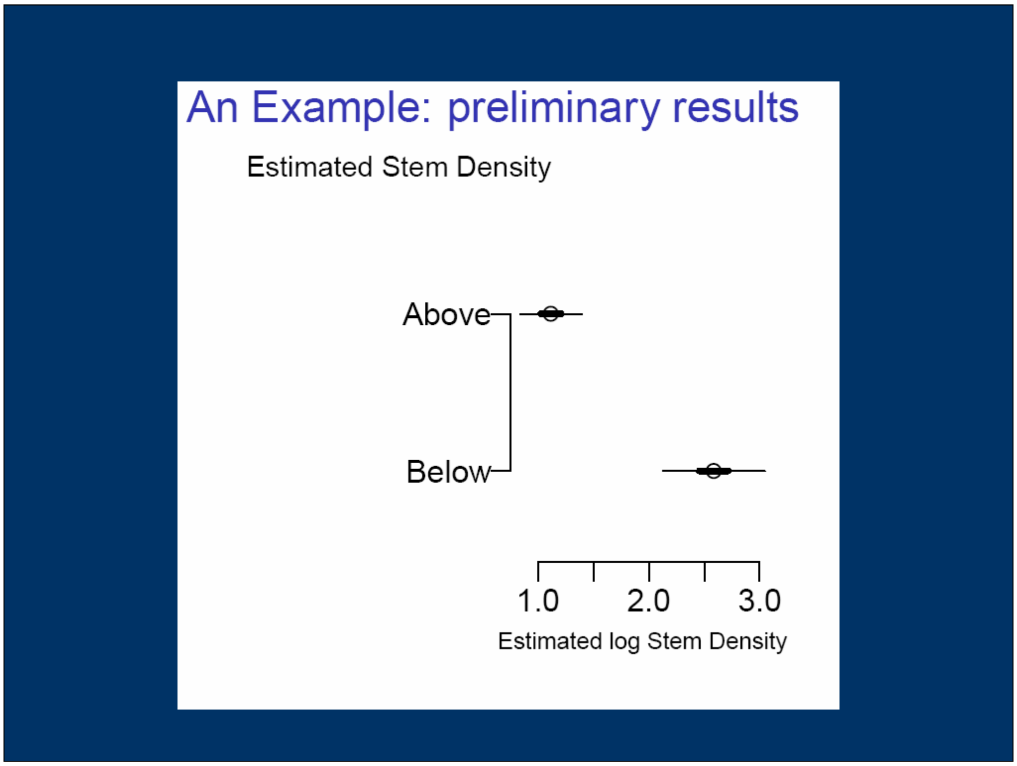
and

$$\begin{array}{rcl} X_{th} & \sim & N(\mu_{th}, \tau_{th}) \\ \mu_{th} & = & \beta_0 + \beta_1^{season} + \beta_2^{year} + \beta_3^{metric} \end{array}$$

An Example: preliminary results

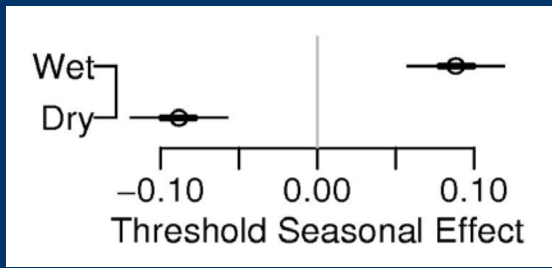
- Factors affecting the threshold -- year, season




An Example: preliminary results
Estimated Stem Density
Above
Below
1.0
2.0
3.0
Estimated log Stem Density

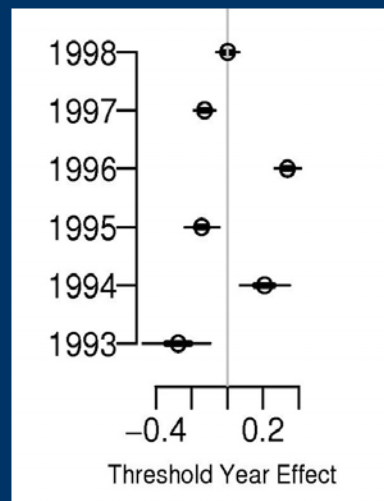
Preliminary Results

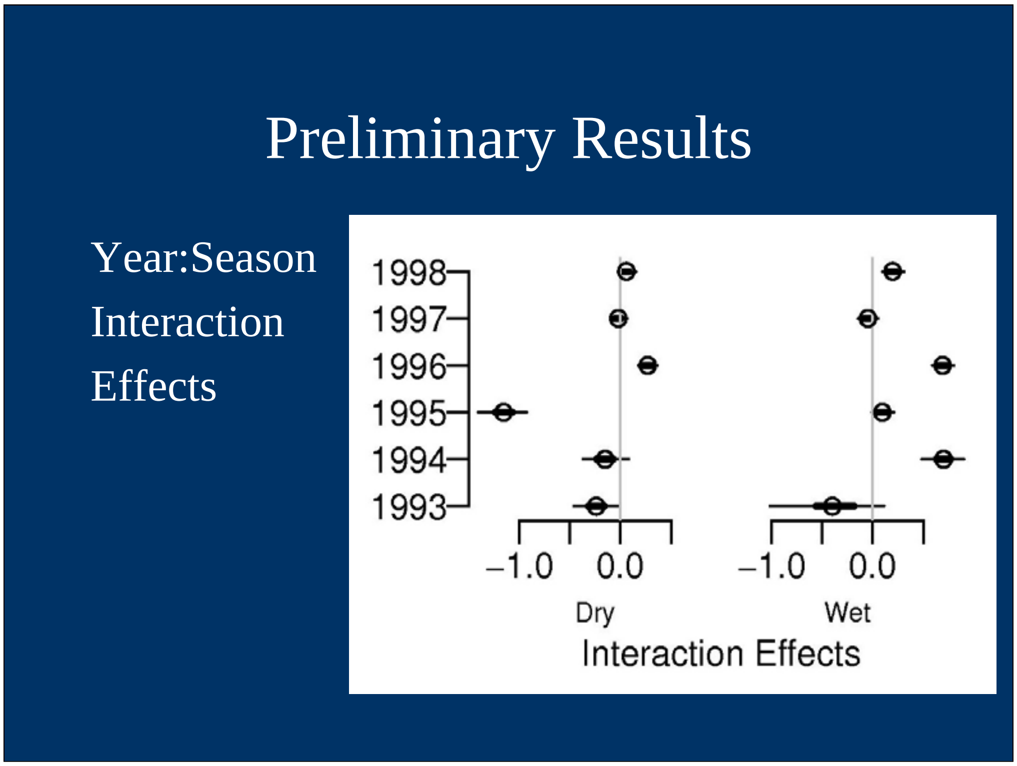
- Seasonal Effects



Preliminary Results

- Year Effects:
  - A dampening amplitude





The analysis showed that higher mat coverage resulted in a higher threshold.

Lesson Learned

- Hierarchical modeling (Bayesian and multilevel ANOVA) provide new approaches to quantify ecological thresholds.
- Sensitivity of threshold responses to disturbance, seasons and wet vs dry seasons in wetlands.
- P thresholds in Everglades varied over the 6 year experiment but converged to a stable state after 4 years.
- Interactions between ecological metrics at different trophic levels are important: *Utricularia* spp.plant density was effected by the % calcareous mat cover,where a higher mat cover results in a higher TP threshold.
- When the word threshold is used we should be specific on what ecological metric is being used and more importantly we should utilize a more integrated hierarchical approach to threshold analysis, i.e., threshold metrics interact.
- Multilevel ANOVA is a versatile and powerful new approach to threshold analysis.

In the Best of All Worlds

- Funding will be available in the future to refine our selection of ecological threshold metrics and test if " sentinel species" metrics can be developed to better predict shifts in ecosystem processes.
- Appreciation of the sensitivity of threshold responses to disturbance, seasons, wet vs. dry conditions and trophic level interactions in wetlands.
- Bayesian statistics and Multilevel modeling will be accepted as a powerful approach to threshold analysis.
- Understanding the interaction among multiple ecological metrics will improve communications between ecologists and resource managers.
- Quantifying the interaction among multiple ecological metrics can lead to a better management strategy.

A Broad Interest

- International interest –collaborations with Peking University, Potsdam Institute for Climate Impact Research, Finnish Environmental Institute, University of Liverpool, University of Utrecht, and Eurolimpacs Climate Change Program.
- Presentations- Ecological Society of America, Society of Wetland Scientists, INTECOL meeting in Holland, and Australia, numerous academic institutions and over 10 presentations to state government officials and Everglades restoration review panels in south Florida.
- Reprint requests from government agencies (USGS, NOAA, Environment Canada, Michigan, North Carolina) and academic institutions.
- Incorporation of the threshold approach into the State of Florida's environmental planning process.

Key Publications and Presentations

- Poulter, B., N. Christensen, and S. S. Qian. 2007 Tolerance of two pine species to low-salinity and flooding: Implications for equilibrium vegetation dynamics,. Journal of Vegettion Science (in press).
- Qian, S.S., and Z. Shen. 2007. Ecological applications of multilevel analysis of variants. *Ecology* (in press).
- Richardson, C.J., R.S. King, S.S. Qian, P. Vaithiyanathan,. 2007. Ecological Basis for Establishment of a Phosphorus Threshold for the Everglades Ecosystem. In (Richardson, C.J.). The Everglades Experiments: Lessons for Restoration. Chapter 25. (in press Springer-Verlag).
- Richardson, C.J., R.S. King, S.S. Qian, P. Vaithiyanathan, R.G. Qualls, and C.A. Stow. 2007. Estimating ecological thresholds for phosphorus in the Everglades. *Environmental Science & Technology* (in revision).
- Qian, S. S., and V. Hickey. 2006. A multilevel model for analyzing zero-inflated count data, ESA 91st Annual Meeting, August 6-11, 2006, Memphis, TN.

Questions ?

Everglades
Snail Kite

Visit our website at:
WWW.env.duke.edu/wetland

for a listing of research papers and a tour of the Everglades

A participant asked if there are other species with different turnover rates that might affect the threshold. Dr. Richardson responded that it is possible.

Another participant asked if it were not possible to measure all six or seven variables, is there one that is particularly sensitive? What approach would you use to identify the best variable to study? Dr. Richardson reiterated that the first part of the study involved testing the different variables to determine which would be the best indicator. The *Utricularia purpurea* showed the biggest response to added phosphorus.