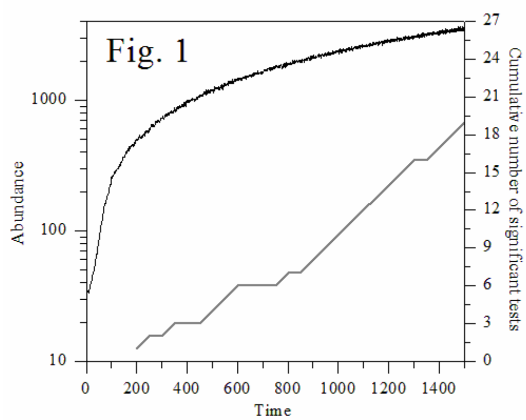
Forecasting regime shifts in ecosystems

Introduction: Regime shifts are rapid, often irreversible, re-arrangements of non-linear ecological feedback mechanisms that occur when a system passes a critical transition point (Biggs et al. 2009; Scheffer et al. 2009). Ecological regime shifts sometimes have severe consequences for human well-being including irreversible eutrophication in lakes, irreversible desertification and fisheries collapses (Scheffer et al. 2009). Recent theoretical (Scheffer et al. 2009) and laboratory evidence (Drake and Griffen 2010) suggests that ecological time series from systems approaching critical transition points contain statistical anomalies such as increased autocorrelation and increased variance that warn of an impending regime shift. These indicators may make it possible to foresee and even avert catastrophic regime shifts by warning that adaptive management is necessary (Biggs et al. 2009). There is concern that popular leading indicators such as increased variance 1) may not be powerful enough to forecast regime shifts with enough time to adapt management strategies, 2) return a large number of false positives, and 3) require a pristine reference system to compare leading indicators from the perturbed systems (Biggs et al. 2009; Scheffer et al. 2009; Drake and Griffen 2010). These concerns must be resolved before recent progress in leading indicators of regime shifts can successfully be applied in ecological management. **Hypothesis:** Conditional heteroskedasticity is persistence in the error variance of time series models. This is a distinct concept from autocorrelation and increasing variance. In time series conditional heteroskedasticity appears as clustered volatility such as that seen in plots of stock market returns. I hypothesize that evaluating ecological time series for conditional heteroskedasticity will provide a powerful means for early forecasts of impending regime shifts. Simple statistical tests for conditional heteroskedasticity will minimize detecting false positives and may eliminate the need for pristine reference systems by associating probability values with the leading indicator. **Research plan:** My research plan involves conducting both theoretical and empirical investigations of the potential of conditional heteroskedasticity as a leading indicator of regime shifts. *Theoretical Analysis* – I will first establish a theoretical basis for conditional heteroskedasticity as a leading indicator of ecological regime shifts through heuristic derivation from general dynamic models that exhibit critical slowing down. Critical slowing down is a generic phenomena that occurs prior to ecological regime shifts where returns to equilibrium from perturbation progressively slow down before the system reaches a critical transition point. I will apply conditional heteroskedasticity tests to simulated data from simple and complex ecological models comprised as systems of stochastic differential equations and stochastic difference equations. Each model will be calibrated to real ecological systems using statistical techniques (e.g., Ives et al. 2008). Simulated data allow for evaluation of leading indicators because the number of and locations of regime shifts are known exactly. The power of conditional heteroskedasticity as a leading indicator can be assessed at different distances preceding the simulated regime shift and the indicator can be applied to simulated time series without regime shifts to evaluate its susceptibility to returning false positives. *Empirical Analysis* – My involvement with an experimental lakes research group gives me a unique opportunity for empirical application of conditional heteroskedasticity as a leading indicator of regime shifts. The research team is currently conducting a whole-system manipulation of a heavily instrumented experimental lake aimed at causing a regime shift to evaluate leading indicators in a whole-system setting. The experimental lake is adjacent to a similar heavily instrumented reference lake. This existing NSF funded project gives me the opportunity to apply the conditional heteroskedasticity approach to a unique whole-system experimental manipulation where a variety of high frequency data are being collected. Other leading indicator studies rely on simulations (Scheffer et al. 2009) or simple laboratory experiments (Drake and Griffen 2010) that do not capture the complexity of whole-ecosystems where processes may dampen or exaggerate leading indicators of regime shifts. The lake experimental regime shift now underway is based on increasing predation pressure from top predators in the experimental lake over time and shifting the food web to dominance by predators with corresponding cascading effects. I will apply the conditional heteroskedasticity indicator to data collected from the experimental and reference lakes over the course of this project. In the experimental lake conditional heteroskedasticity should increase prior to the regime shift and decrease after the shift. Throughout the study, there should be no significant conditional heteroskedasticity in the reference lake. **Preliminary Results:** In preliminary simulations, conditional heteroskedasticity consistently forecasts regime shifts hundreds of time steps before hitting the critical transition point. For example, Fig. 1 displays a stochastic Ricker population model approaching (black line), but not crossing, a critical transition point to a period-doubling bifurcation. The model was calibrated to data from laboratory cultures of *E. coli* using maximum likelihood methods. The gray line indicates the cumulative number of significant moving window statistical tests for conditional heteroskedasticity. Using a Bernoulli expansion to evaluate the probability of returning an observed number of significant tests, the conditional heteroskedasticity leading indicator forecasted the impending regime shift long before it occurred. There is no significant conditional heteroskedasticity in simulations without regime shifts. No pristine reference system is needed to compare the perturbed simulation to as would be necessary to evaluate increased variance or increase autocorrelation because of the power and specificity of the conditional heteroskedasticity indicator. The **intellectual merit** of this project is developing a new method for detecting impending regime shifts while avoiding false positives, even when the exact mechanism of the regime shift is unknown. False positives could cause expensive and unnecessary changes in management or may undermine public confidence in managers. **Broader Impacts:** The societal impacts of this project stem from the utility of the conditional heteroskedasticity indicator in ecosystem management because it eliminates the problems that have prevented practical application of other indicators. I will contribute a module on conditional heteroskedasticity to a planned manual on leading indicators of regime shifts. This descriptive workbook aimed at ecologists and ecosystem managers will contribute to the scientific and technical outreach of my project and the overall lake manipulation research project. I will also develop an on-line education module on ecological regime shifts for environmental science undergraduates at the University of Virginia using the *webMathematica* program. *webMathematica* provides interactive calculations and graphing online in a user friendly graphical environment based on same engine as the popular *Mathematica* symbolic calculus software.



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