A dissertation

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The Division of
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Doctor of Philosophy

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Craig R. Allen

Dirac Twidwell

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To my partner of eight years–Schultzie–thank you for everything. Just kidding, thank you, Nat Price.

Preface

Supplemental published materials include: [1] DOD White paper on Fisher Information (include reference and post onto Zenodo, if not available via DOD webpage) [2] Packages [3] IIASA report

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Dedication

Something snarky to mike moulton – maybe a limerick

Chapter 1

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Placeholder

Preliminary Content

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Acknowledgements

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Preface

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Dedication

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Abstract

Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo. Nemo enim ipsam voluptatem quia voluptas sit aspernatur aut odit aut fugit, sed quia consequuntur magni dolores eos qui ratione voluptatem sequi nesciunt. Neque porro quisquam est, qui dolorem ipsum quia dolor sit amet, consectetur, adipisci velit, sed quia non numquam eius modi tempora incidunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim ad minima veniam, quis nostrum exercitationem ullam corporis suscipit laboriosam, nisi ut aliquid ex ea commodi consequatur? Quis autem vel eum iure reprehenderit qui in ea voluptate velit esse quam nihil molestiae consequatur, vel illum qui dolorem eum fugiat quo voluptas nulla pariatur?

Chapter 2

Introduction

If a regime shift occurs and no one detects it–is it a regime shift at all?

Anthropogenic activity in the last few decades will continue to influence the interactions within and among ecological systems worldwide. The complexity of and drivers of changes in coupled human-natural systems is consequently altered, further limiting our ability to detect and predict change and impacts of change (Liu et al., 2007; Scheffer, 2009). Early warning systems are developed to detect, and in some cases predict, abrupt changes in disparate systems [e.g. cyber security [@], infrastructure [@], banking crises (Davis & Karim, 2008), and agricultural systems]. The need to develop and improve early warning systems for natural and coupled human-natural systems is exacerbated by the consequences of climate change and globalization, especially when the human-related stakes are high.

Forecasting change is, arguably, the holy grail of ecology. Paired with an understanding of system interactions, forecasting change is ideal if it provides information with sufficient time to prevent or mitigate unwanted systemic change.

Despite the quantitative methods proposed as early warning systems for ecological data, they are currently of limited practical utility. This paradox may be a consequence of existing ecological early warning systems (or quantitative methods for identifying systemic change) having one or more of the quailities below. Research focusing on these areas will contribute to the advancement and improvement of existing early warning systems, and ideally rule out or highlight those that are or are not useful to practitioners and decision makers.

1. not generalizable across systems or system types (especially when it requires a model or a determinsitic function to describe the system)
2. require a large number of observations
3. difficult to implement
4. difficult or to interpret
5. requires an understanding of the drivers of change

6. performs poorly under uncertainty
7. give no uncertaintiy around estimates (tying into interpretation issues)

8. cannot handle noisy data
9. ignores or does not sufficiently account for observation error

10. no baseline with which to compare results
11. no application/testing on empirical systems data

The overarching aim of this work is to advance our understanding of the utility and limitations of select early warning systems (a.k.a. regime detection metrics; RDMs). Specifically, herein I focus on RDMs which are designed for or capable of analyzing multi-varaible data, including temporally- and spatially-explicit. Although the most widely-applied RDMs proposed in the ecological literature are those deveoped for and tested on single-variable time series (e.g., temperature or fisheries stock time series), the utility of these methods in multi-variable systems (data) is limited. Regime detection metrics for tracking and identifying changes in multivariable systems data are of greater use than single-variable RDMs in systems within which a change manifests dynamically and across multiple variables (e.g., species). Multivariable RDMs may also prove advantageous when the drivers of systemic change are unknown. Further, ecological systems are noisy, and ecological systems data are messy.

2.0.1 Dissertation structure

The chapters hereain are written as separate, publishable manuscripts. Where applicable, co-authors are listed in the front matter of the chapter. The dissertation comprises an introduction to the dissertation (Chapter 2}), a brief overview of early warning systems (or regime detection measures) for ecological systems data (Chapter 3), a detailed guide to Fisher Information as a RDM written for ecologists (Chapter 4), an application of Fisher Information to spatially-explicit data (Chapter 5), introduction of 'new' RDM, Distance Travelled (Chapter **??**), a study of data quality and data loss on select RDMs including Distance Travelled and Fisher Information (Chapter **??**), and conclusions (Chapter **??**).

Chapter 3

A brief overview of ecological regime detection methods methods

3.1 Introduction

Long-lasting changes in the underlying structure or functioning of natural systems due to exogeneous forcings (also called regime shifts) is of interest to ecologists. The ability to identify and predict these shifts is particularly useful for systems which are actively managed, provide ecosystem services, or provide benefit to societiy. There exists a disparity among the number of methods proposed for detecting abrupt changes in ecological, oceanographic, and climatological systems and the studies evaluating these methods using empircal data. Despite the already large number of existing methods and models, new methods continue to permeate the literature. Although reviews of regime shift detection methods exist (Rodionov (2005), Andersen, Carstensen, Hern??ndez-Garc??a, & Duarte (2009), Perretti & Munch (2012), Roberts et al. (2018)), the most comprehensive presentation of available methods is outdated (Rodionov (2005)).

There is currently not a single, current resource to which ecologists can refer for quantitative RDMs. Past reviews (Rodionov (2005), Andersen et al. (2009), Perretti & Munch (2012)) of RDMs vary in both the number and detail of the methods presented. This chapter is meant to serve as an addendum, of sorts, to previous reviews. Rather than discussing in detail each method, I follow the style of (**???**) in that I present a brief overview of RDMs and point the reader to original sources for detailed descriptions of the methods.

3.2 Identifying new methods

Methods proposed as RSDMs are not easily identified using systematic literature review techniques for a few reasons. First, the terminology associated with regime shift detection methodologies is highly variable within and among fields. For example, the terms, *regime shifts, regime changes and tipping points* are variably used in studies of ecological systems, whereas *change point* is often used in oceanography and climatology and *structural change* is largely used in econometrics. Although the definition of a regime shift and change point are different (the former describing a change in system structure and the latter the point at which a variable of interest changes), the methods used to identify these changes are shared.

Second, papers introducing a new method or approach to identifying regime shifts are not often proposed in publications that focus primarily on quantitative methodologies (e.g., *Ecological Modelling*, *Methods in Ecology and Evolution*) or in general ecology journals (e.g., *Ecology*). Instead, they are often published in journals with audiences that may not necessarily overlap with typical searches of the ecological litearture (e.g., *Entropy*, *Progress in Oceanography*).

I used three 'methods' to identify articles proposing 'new' RSDMs: 1. prior knowledge, 1. snowball method baded on past RDM reviews, and 1. systematic literature review

It is worth noting that the latter 'method', although designed to identify all possible RDMs, does not fully overlap with the methods identified using the first two. The reasons for this will be discussed further in discussion.

3.2.1 Systematic literature review using Web of Science

To identify potential methods of which I was not previously aware, I conducted a systematic literature review using the database Web of Science. I used the following boolean to identify original methodological papers.

> (TS=("regime shift" OR "regime change" OR "abrupt shift" OR "abrupt change" OR "break point" OR "change point" OR "change-point" OR "tipping point" OR "structural change" OR "observational inhomogeneity") AND TS=("new method" OR "new approach" OR "novel method" OR "novel approach" OR "we introduce" OR "I introduce") AND WC=(Agronomy OR Fisheries OR Ecology OR "Biodiversity Conservation" OR "Environmental Sciences" OR Biology OR "Meteorology & Atmospheric Sciences" OR Oceanography OR "Geosciences, Multidisciplinary")) AND DOCUMENT TYPES: (Article)

Including the term *threshold* increased the search yield approximately ten-fold, but yielded aticles irrelevant to my purpose. Therefore, I omitted this term from the boolean.

3.2.2 Systematic literature review using Google Scholar

There was a high disparity among the number of methods of which I was previously aware and those identified in a review of Web of Science. Therefore, I conducted a similar search of the Google Scholar database, which is notoriously broader in scope. The length of boolean for the Google Scholar database is limited by the number of characters.

> ("regime shift" OR "regime change" OR "tipping point") AND ("new method" OR "new approach" OR "novel method" OR "novel approach")

Removing/retaining papers from search

```
[1] "libloc_185_b6156d26.rds" "mySJRdata.csv"
```

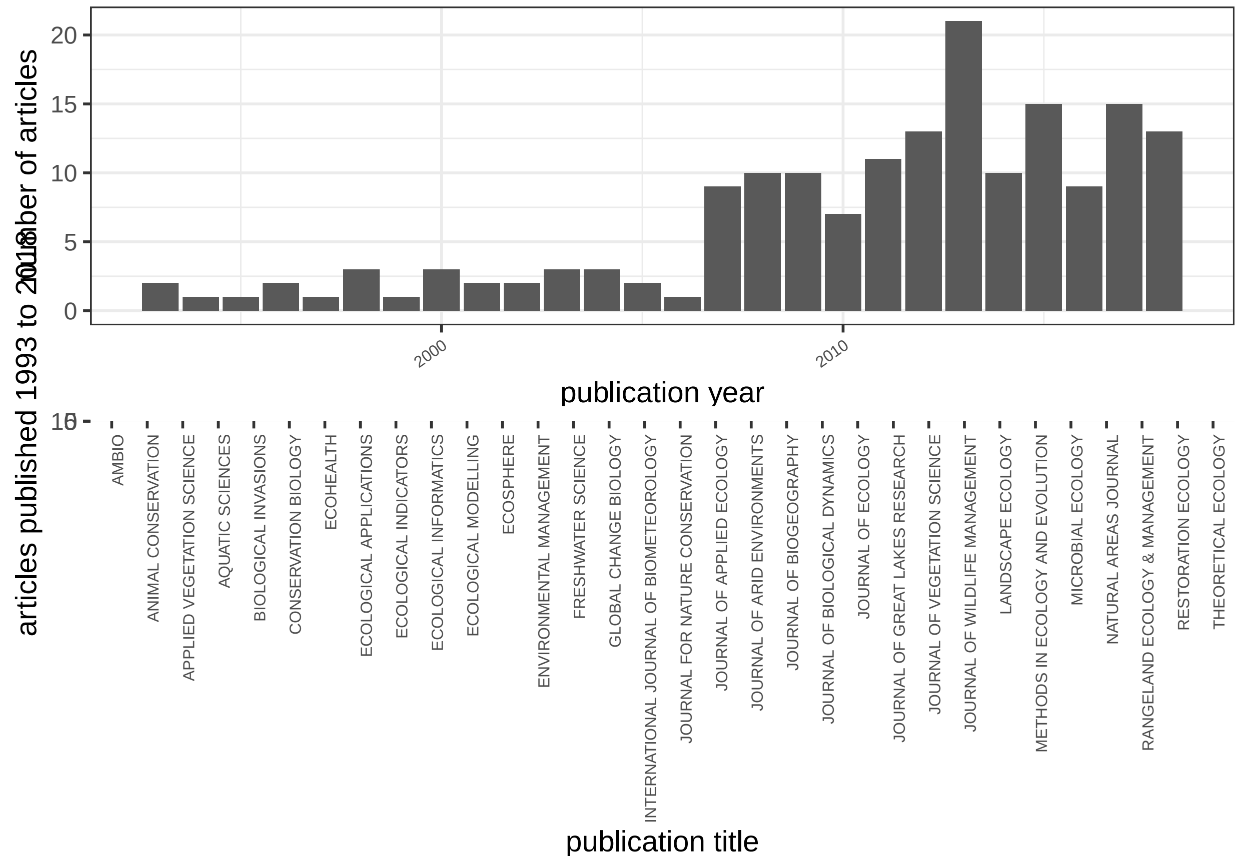

Figure 3.1: Distribution of articles related to ecological regime shift methodologies and frameworks published in the first and second quartiles of SJR *ecology* journals and in *Methods in Ecology and Ecolution* and *Ecological Modelling*.

3.2.3 WOS Search results

The initial search prior to filtering by abstract yielded (see wosResults_20190205.xls) **1209** articles.

We removed articles containing

3.3 Existing RDM and related review articles

3.4 RDMs not yet explored for ecological data

Identifying historic ecolgoical regime changes has been achieved using post-hoc analyitcal approaches Methods for reliably forecasting and predicting these changes are less common. Although numerous quantitative methods exist for detecting ecological regime shifts, new methods are proposed for achieving this aim ata XXX rate (*insert figure of number of papers per year with new methods*). These methods have proven useful in detecting shifts in atmospheric and fisheries catch data, and in systems that are well-described by a few state variables, or can be modelled reliably with matheamtical equations. Because ecological comunities are more complex than, say, a simple Lotka-Volterra predator prey system, the set of reliable regime shift detection methods narrows.

Ecological and social-ecolgical systems have many unpredictable and variably interacting components. Quantitative models and methods are available for analyzing complex systems, but often require more data than is typically available in ecological reserach and management. Hence, tracking the changes in ecological systems is rarely done so using multiple variables.

A survey of the methods available for detecting ecological regime shifts in high dimensional data is timely. Although multiple reviews of regime shift indicators exist, Recent reviews of regime shift indicators (Andersen et al, the others) are outdated, are not comprehensive (include only a subset of the available RSDMs), and do not provide recommendations for which events, systems, or data characterstics are appropriate for these methods.

Some RSDMs are proposed for and are subsequently applied to data having specific characteristics, while others are proposed to be useful in multiple systems and on data of varying characterstics (e.g., Karunithi et al; Mayer 2007; Eason). This review provides a summary of the available methods and evaluates the appropriateness of these methods to data of varying character, quality, and quantity.

This paper compiles a plethorra of quantitative methods proposed as regime detection methods for ecological data. We discuss the relevant characteristics of the data/information that are required for each method, and how these characterstics may help or hinder the ecologists' interpretation of the analytical results. We pay special attention to the RSDMs that are most appropriate for analysis of high dimensional and noisy ecological data.

3.5 Discussion

1. Major findings of the review.
2. What major assumptions are we currently making about the data and the system that we need to know more about moving forward? i.e., where are the gaps in knowledge?
3. How has or how can we take advantage of unstructured or semi-structured data to ID regime shifts?
4. How can or should we adapt our monitoring schemes to better suit these (or at least the seemingly helpful) analyses?
5. What about identifying the drivers behind the shifts?
6. Which methods posit they can identify the, or potential, drivers of the state changes? Which have shown it?

Potential text: 1. Climate change is expected to induce an increase in both the intensity and frequency of rapid ecological change or disturbance, impacting social systems, potentially to the detriment of human communities most vulnerable. Identifying and forecasting these changes is critical for community and ecological planning, management, and disaster mitigation.

1. Because ecological and social systems are tightly coupled, we have used indicators in the environment and in wildlife communities to identify change and potential changes that may impact our social communities.

2. Many regime shift analytical papers suggest that, using multiple quantitative methods to provide for evidence for a regiem shift in a specific data set is necessary (Lindegren et al. (2012), easonYYYY). Although this proposition is valid, comparing results within a single system using multiple methods has often yielded varying results. Managing systems using quantitative methods that yield different results may yield improper management techniques and objectives.

3.6 TEXT NOT USED:

3.6.1 Identifying papers/RSDMs in the literature

I used the following databases to identify scholarly works that introduce and/or explain methods for identfying regime shifts: 1. Web of Science i. ___Database searches* a. Boolean (+ = asterisk in the database search) i. WOS: ii. SCOPUS: (TITLE-ABS-KEY ((approach OR analysis OR metric OR method^) AND (detect^ OR predict^)) AND TITLE-ABS-KEY ({regime shift} OR {regime change} OR {abrupt change})) **1,473** (where ^== ___ in Scopus) ii. **Opportunistic papers** a. We used expert opinion (authors JLB, etc.) to identify any missing RSDMs that were not detected in our formal database searches. (i am making this next part up–need to double check once i have results)–>These papers are are typically found in the grey literature, or are published in journals not obvious to the general ecologist (e.g., name an obscure journal here). b. Justification for our database searches containing some of these methods which are known/obvious to the author(s).

2. Procedures for filtering the papers.
    i. We removed duplicate titles (from the merging of Scopus and WOS), which resulted in ___________ unique scholarly works.
    ii. We read the abstracts of each paper to determine the following:
        a. Was this a new method being proposed or used? (if yes, proceed to ii.))
        b. Was this just a case study or another application of a previously published method? (if yes, note the method(s) used and identify original method(s) source)

c. If this paper was an application of a method, we noted the method, and identified the orignal source for the method (if possible)

iii. Identify characteristics of the method

c. It is model-based?
d. Does it require a mathematical model?
e. Does it require *a priori* knowledge of the regime shift
f. Does it forecast or provide predicitons?
g. Assumptions required (e.g., discontinuity, step functions, normality of response vars)

iv. Identify requirements for the data input a. Require equal spacing b/w observations? b. Minimum # data points required to use? c. Minimum # of state variables required?

v. Identify the characteristics of the data USED to demonstrate the method

a. Spatial resolution and extent
b. Temporal resolution and extent
c. Number of state variables
d. System type
e. Whole-system vs. selected variables?

ii. Experimental system or observational/passive

3. Note the number of times the paper has been cited

3.6.2 Results

We identified ___________ number of quantiattive anlaytical approaches to identifying regime shifts and abrupt changes in data.

3.6.3 Potential figures

1. X = year Y = number of publications for *new* RSDMs in the ecol/env literature
2. X = year Y = # pubs for new RSDM appropriate for multidimensional systems

Chapter 4

A guide to Fisher Information for Ecologists

Placeholder

4.1 Abstract

4.2 Introduction

4.2.1 On Fisher Information

4.2.2 Notation

4.2.3 Steps for calculating Fisher Information (FI)

4.2.4 Concepts behind the calculations

Step 1. Probability of observing the system in a particular state, $p(x)$

Step 2. Distance traveled by the system, s

Step 3. $p(s)$ as a function of the rate of change of s

Step 4. Calculate the derivatives-based Fisher Information

4.3 Case Study

4.4 Conclusions

4.5 Acknowledgements

Chapter 5

An application of Fisher Information to spatially-explicit avian community data

Placeholder

5.1 Introduction

5.2 Methods

5.2.1 Data: North American Breeding Bird Survey

5.2.2 Study areas

Military bases as study sites

Focal military bases

Spatial sampling grid

Selecting routes for temporal analysis

5.2.3 Calculating the Fisher Information binning measure

5.3 Results

5.3.1 Temporal data

5.3.2 Spatial data

5.3.3 Interpreting the Fisher Information binning measure

5.4 Discussion

Appendix A

Placeholder

References

Placeholder

Catch-all, unused, to be removed from pdf

Placeholder

5.4.1 Table of definitions found throughout the dissertation

5.4.2 On critical slowing down

5.4.3 Types fo regime shifts

5.4.4 Brandolini's principle

5.5 Importance of this thesis

5.6 On the sheer number of RSDMs

Andersen, T., Carstensen, J., Hern??ndez-Garc??a, E., & Duarte, C. M. (2009). Ecological thresholds and regime shifts: Approaches to identification. *Trends in Ecology & Evolution*, *24*(1), 49–57. `http://doi.org/10.1016/j.tree.2008.07.014`

Davis, E. P., & Karim, D. (2008). Comparing early warning systems for banking crises. *Journal of Financial Stability*, *4*(2), 89–120.

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Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., … others. (2007). Complexity of coupled human and natural systems. *Science*, *317*(5844), 1513–1516.

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Scheffer, M. (2009). *Critical transitions in nature and society*. Princeton University Press.