A brief overview of ecological regime detection methods methods

Introduction

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

- **No** when a regime shift is defined as a change in a system which negatively impacts humans.
- **Yes** when a regime shift is defined simply as a shift in the underlying strucutre of a system.

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 [@mac2014scrutiny; @scheffer2015generic; @rodionov_brief_2005; @roberts2018early; @dakos2015resilience; @mantua_methods_2004; @litzow_early_2016; @kefi2014early; @andersen_ecological_2009; @boettiger_early_2013; @dakos_resilience_2015; @clements2018indicators; @filatova2016regime; @deyoung_regime_2008], the most comprehensive presentation of available methods as they is outdated [@rodionov_brief_2005]* [1]

There is currently not a single, current resource to which the practical ecologist can refer for identifying potential regime detection measures. Previous reviews of this literature 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. Following the style of @rodionov_brief_2005, I present a brief, yet exhaustive, over regime detection measures in the ecological literature. I then sugest next steps for ameliorating the plethora of regime detection measures in ecology.

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 *inhomogeneities* is common in meterology and climatology and *structural change* is largely confined to econometrics. Although the definition of, e.g., a regime shift and a structural change vary across and within fields of study, some methods 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 conducted a systematic literature review to identify original papers introducing quantiative regime detection measures. Although the literature review was designed to detect as many methodological papers as possible, most methods of which I was previous aware were not identified in this search. Therefore, I filled the gaps using prior knowledge and an informal search using Google Scholar. ### Identifying candidate articles

Web of Science

I first queried the Thomson-ISI Web of Science (WoS) database (on 06 March 2019) to identify articles which mention terms related to regime shifts, or abrupt changes, using the following boolean: > TS=(('regime shift'

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[1]I also refer the reader to @kefi2014early and @yin2017methods spatial methods, and to @ducre2003comparison select tests for homogeneity in climate data.

OR 'regime shifts' OR 'regime change' OR 'regime changes' OR 'catastrophic change' OR 'catastrophic shift' OR 'catastrophic changes' OR 'catastrophic shifts' OR 'sudden change' OR 'sudden changes' OR 'abrupt shift' OR 'abrupt shifts OR 'abrupt change' OR 'abrupt changes' OR bistab* OR threshol* OR hystere* OR 'phase shift' OR 'phase shifts' OR 'phase change' OR 'phase changes' OR 'step change' OR 'step changes' OR 'stepped change' OR 'stepped changes' OR 'tipping point' OR 'tipping points' OR 'stable states' OR 'stable state' OR 'state change' OR 'state changes' OR 'stark shift' OR 'stark change' OR 'stark shifts' OR 'stark changes' 'structural change' OR 'structural changes' OR 'change-point' OR 'change point' OR 'change-points' OR 'change point' OR 'break point' OR 'break points' OR 'observational inhomogeneity' OR 'observational inhomogeneities') AND ('new method' OR 'new approach' OR 'novel method' OR 'novel approach'))

where '*' indicates a wildcard.

Limiting the search to the fields of 'Ecology' and 'Biodiversity Conservation' (by adding AND WC=(Ecology OR 'Biodiversity Conservation') to the above boolean) excludes many methods used solely in climatology and data science/computer science literatures, where change-point analyses are abundant. Although numerous additional methods could be identified by searching these fields, this dissertation focuses on using methods for analysing *multivariable* data. Consequently, many of the time-series and change-point analyses excluded in this review are not of relevance.

I filtered the results to identify articles which propose a 'new' method by retaining papers which included at least one of the following phrases in the title and/or abstract: > 'new method', 'novel method', 'new approach', 'new practical method', 'new simple method', 'new multivariate method', 'new tool', 'novel tool', 'novel multivarte', 'novel approach', 'new numerical', 'novel numerical', 'new quantitative', 'novel quantitative', 'i introduce', 'we introduce'

Prior knowledge and snowball method

Next; I removed articles from the above search (WoS) results based on both prior knowledge (in my personal database) and those highlighted in previous reviews related to regime detection measures [@scheffer2015generic; @rodionov_brief_2005; @roberts2018early; @dakos2015resilience; @mantua_methods_2004; @litzow_early_2016; @kefi2014early; @andersen_ecological_2009; @boettiger_early_2013; @dakos_resilience_2015; @clements2018indicators; @filatova2016regime; @deyoung_regime_2008].

Google Scholar

There was a high disparity among the number of methods of which I was previously aware and those identified in an initial Web of Science review. In an attempt to collect as many new methods as possible, I conducted an informal 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. Unfortunately, this, coupled with the wide breadth of Google Scholar's search boundaries, limits the capacity to which Google Scholar can be used to refine the literature to a manageable number of articles. For these reasons I arbitrarily skimmed the titles of the first 25 pages of the Google Scholar results (25 pages = 250 articles). It should be noted that the order of terms appearing in the boolean are regarded as the order of desired relevancy. I used the following boolean: > ('regime shift' OR 'regime change' OR 'tipping point') AND ('new method' OR 'new approach' OR 'novel method' OR 'novel approach')

Additional filtering

In addition to using the abovementioned search booleans, I excluded the following types of articles: those which proposed a combination of previously-used methods [e.g., PCA combined with other techniques, see @kong2017hydrological; @seddon2014quantitative; @vasilakopoulos2017resilience] as a 'novel' method; those making relatively minor methodological updates/additions to existing methods [@zhou2008one; but see @nicholls2011biological for an addition of variable optimization to the method in @nicholls_detection_2011 that was not included in the results]; and articles proposing new methodologies in mathematical journals

[@byrski2016double; @salehpour2011line] that have yet to be associated with or tested ecological data, or suggested to be useful for empirical data.

Results

Web of Science

The search boolean for WoS boolean *not* including restriction to fields (WC) 'Ecology' and 'Conservation Biology' yielded over 20,000 results. Restricting to the abovementioned fields created a manageable database from which to filter. This search yielded 2,776 articles. 654 of these papers included terms relating to 'regime shifts' (Figure @ref(fig:wosRegimePubsByYear)), many appearing in the journal *Ecological Modelling* (Figure @ref(fig:wosRegimePubsByJrnlmin10Pubs)). The rate of publication of 'regime shift' articles is not strongly correlated with the rate of papers published in 'Ecology' and 'Biodiversity Conservation' fields (Figure @ref(fig:wosRegimePubsByYearwithNumEcolPubs)).

Filtering this WoS results to include only articles mentioning terms related to 'new method' yielded 202 articles. After removing prior knowledge, only 93 articles remained to be reviewed 'by hand' (i.e., reading the entire paper). Only 2 'new' methods were identified from the WoS search (@ref(fig:rdmReviewFlow)).

Google Scholar and prior knowledge

Of the 250 articles scanned in Google Scholar, I retained 3 methods. I was previously aware of an additional 68 articles containing 'new' methods (@ref(fig:rdmReviewFlow)).

List of new methods

Using my prior knowledge of the relevant litearture, referring to previous review articles, and searching both Web of Science and Google Scholar, I identified 64 unique regime detection measures (Figure @ref(fig:rdmReviewFlow); Table @ref(tab:methodsMetricsListTab1)).

Discussion

In this chapter I highlighted the plethora of regime detection metrics proposed in the literature for analyzing ecological data (Table @ref(tab:methodsMetricsListTab1)). Although multiple reviews of regime detection measures exist, they are not comprehensive in their survey of the possible methods. Most reviews have summarized various aspects of regime detection measures. For example, @roberts2018early summarizes methods capable of handling multiple (c.f. a single) variable, and @dakos2015resilience review only methods designed to detect the phenomenon of critical slowing down. Here, I did not discriminate–rather, I present an exaustive list of the plethora of methods proposed for detecting ecological detect regime shifts, *sensu lato*, providing a much-needed update to collection provided by @rodionov_brief_2005, and other review papers [@mac2014scrutiny, @scheffer2015generic, @rodionov_brief_2005, @roberts2018early, @dakos2015resilience, @mantua_methods_2004, @litzow_early_2016, @kefi2014early, @andersen_ecological_2009, @boettiger_early_2013, @dakos_resilience_2015, @clements2018indicators, @filatova2016regime, @deyoung_regime_2008].

Barriers to identifying new regime detection measures

Clearly, as was shown in this chapter (Figure @ref(fig:rdmReviewFlow)), a systematic review of the ecological literature will likely not yield anywhere near a comprehensive list of the regime detection measures proposed and/or used. This disaparity may be due to both my search methods and to the current state of regime shift research in ecology.

First, my review restricted articles to articles suggesting they were introducing a 'new method' as n RDM. Avoiding this potential barrier would have required I review the titles, abstracts, and bodies of over 22,000 articles (Figure @ref(fig:rdmReviewFlow)). Alternatively, this may also be ameliorated by searching the relevant literature for *applications* of regime detection measures to ecological data, however, I suspect this would similarly yield a large number of articles to review.

Next, only a handful of methods have been introduced to the mainstream methodological journals in ecology (e.g., *Ecological Modelling*, *Methods in Ecology and Evolution*; Figure @ref(fig:jrnlDistFig)). Although many mainstream publications (e.g., *Science*, *Ecology Letters*) include applications of some of the methods identified in this chapter (Table @ref(tab:methodsMetricsListTab1)), I argue that celebrity and 'new and shiny' [@steel2013applied] methods may influence which methodological articles are printed in these popular journals.

A critical survey of potetial and realized applications of these methods would be useful for highlighting the needs of future research and methodological improvements. Many of the methods presented in Table @ref(tab:methodsMetricsListTab1) have either not been applied to empirical data at all, or were tested only once (often but not always in the article introducing the method). Some methods, especially those dubbed 'early warning indicators' (variance, autoregressive model coefficients) have become relativley mainstream in their application to empirical data, however, have been shown to be less robust to noisy and nonlinear systems data [@burthe2016early] and systems not exhibiting catstrophic shifts [@dutta2018robustness]. Most other methods have yet to be rigorously tested on noisy, high dimensional, empirical data. Further, the methods which are not mainstream but have been applied to one of these data types have not any statistical indicators associated with confirming the existence and location of the regime shift.

As shown this chapter, identifying regime detection measures using traditional literature review techniques may prove difficult. Many of the methods identified in my review were not identified using Web of Science or Google Scholar–rather, I was either previously aware of most of the methods, and many others were highlighted in previous RDM reviews. To facilitate this process, an online, comprehensive database may prove useful to the practical ecologist.

Reducing the barriers to regime detection measures

To make the regime detection measures more available and transparent to the practical ecologist, I recommend the following: 1. consitent use of fewer methods 1. persistent collection and maintenance of baseline data (reference data) 1. an on-line database of all methods - open-sourced - linked to the original sources (in ecology and statistics or mathematics) - linked to applications 1. a critical review of the current state of methods in ecology - including methodological advancements - especially highlighting where the method fails to perform - including historical tracking of specific methods to identify which may need to be retired, rather than resuscitated 1. more empirical applications of these methods (especially of those only tested on toy and experimental data) 1. relation of RDMs in ecology to other fields (computer science, data science, climatology and oceanography)

I suggest below a suite of questions which may provide useful in a critical review of the characteristics, rigor, and promise of methods in the context of ecological data analysis.