EXECUTIVE SUMMARY

Global Change, Vulnerability and Resilience: Management Options for an Uncertain Future

SERDP Project RC-2510

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ACRONYMS AND ABBREVIATIONS

DoD Department of Defense

EPA Environmental Protection Agency

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The project team (the team) thanks the natural resource divisions at Eglin Air Force base and Fort Riley military base for their enthusiastic participation in this program and their efforts in making data available for the team's use, the volunteers of the United States Geological Survey's North American Breeding Bird Survey who collected the data used in many components of the team's project, Drs. Nathaniel B. Price and Andrew J. Tyre for their valuable input regarding the design of Fisher Information sensitivity analyses for detecting ecological regime shifts, Dr. Trisha Spanbauer for assistance with discontinuity analysis interpretation, and Dr. Tarsha Eason for input regarding Fisher Information and regime shift detection.

1.0 INTRODUCTION

The Earth has entered a new epoch, the Anthropocene, wherein the footprints of human activity (e.g., overfishing, eutrophication, acidification, climate change) may manifest in erosion of ecological resilience. Ecological resilience is defined as the ability of an ecological system to absorb disturbance without experiencing a catastrophic shift into an alternative regime (Figure 1). Examples of alternate regimes include: a flatland woods existing in a pine savanna or oak-dominated forest, a shallow lake that may exist in a clear, low nutrient, low algae, oxygen-rich state (oligotrophic) versus a turbid, high nutrient, high algae, oxygen-poor state (eutrophic); or a semi-arid terrestrial ecosystem existing in a grassland versus a woody-plant dominated state. Increasing pressures from growing human populations will likely continue to push ecosystems beyond their capacity to cope with stress. Consequently, increasing incidences and magnitudes of regime shifts will likely characterize the Anthropocene and trigger complex social-ecological responses that can transcend scales from local to regional to global. There is also concern that regime shifts will ultimately result in the loss of some of the crucial ecosystem goods and services upon which humanity relies.

Resilience in complex systems is in part a result of the distribution of function within and across the scales of a system (Figure 2). Central to ecological resilience theory is that ecological structures, functions and processes are regulated by a few key variables that operate at characteristic temporal and spatial scales. The potential benefits to understanding resilience for managing systems in the Anthropocene (e.g., predicting regime shifts, assessing effects of humans on ecological resilience) have made quantification of resilience a central pursuit in ecology for decades.

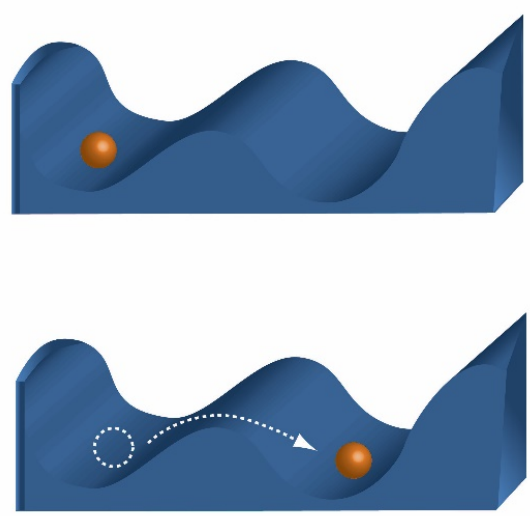

Figure 1. A Conceptual Diagram of the Basins of Attraction for Two Possible Ecosystem States, Characterized by Two Different Regimes.

The position of the ball in the left basin of the upper diagram represents the current state of the system.

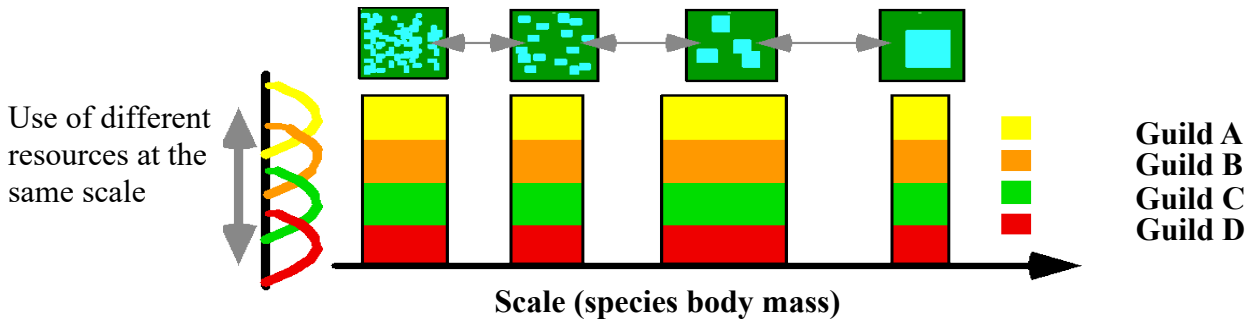

Figure 2. Hypothesized Relationship between the Scale of a Species' Interaction with their Environment (as Assayed by Their Body Size) and Their Membership in a Functional Group.

Differently-sized species use resources at different spatial and temporal scales. Species in the same functional group use similar resources, but those that operate at larger scales require those resources to be more aggregated in space than do species that operate at smaller scales. Within scales, a diversity of functional groups provides robust ecological functioning, whereas replication of function across scales reinforces ecological function. The combination of a diversity of ecological function at specific scales and the replication of function across a diversity of scales produces resilient ecological function.

Here, the team reports the final conclusions and implications of the team's research on developing models to detect ecological regime shifts in space and time, identifying components of adaptive capacity, and identifying species and techniques that may serve as leading indicators of thresholds of changing ecological regimes. This work will enable land managers to create and assess resilience-based frameworks that allows managers to target, and eventually reduce, the uncertainties related to predictability and generalization of vulnerabilities of ecosystems and landscapes to global change.

2.0 OBJECTIVES

The team's chief objectives were to 1) construct a conceptual framework for ecosystem-based management that accommodates multiple alternative futures, 2) track ecosystem response to non-stationary conditions by identifying and monitoring appropriate benchmarks of ecosystem status, 3) assess vulnerability using the cross-scale resilience model of ecological community assembly, 4) link this work to regime shift theory to explore potential methods and tools for early detection of non-linear ecosystem responses to non-stationary conditions via management intervention or adaptation, and 5) identify those species traits that are most susceptible to change.

These models will provide means for detecting ecological regime shifts in space and time, identify components of adaptive capacity as relevant to ecological resilience, and identify species, quantitative techniques, and management programs that may serve as leading indicators of thresholds of regime shifts.

3.0 TECHNICAL APPROACH

The team obtained publicly- available data from the US Geological Survey's North American Breeding Bird Survey. The team also obtained proprietary data from natural resource managers at Fort Riley military base from Fort Riley, KS and remotely sensed vegetation data from the Rangeland Analysis Platform.

With these data, the team developed novel statistical tools and tested existing tools to assess long-term trends in resilience of landscapes, detect and predict ecological regime shifts in both space and time, and identify species vulnerable to decline and extinction, with a focus on the management of Department of Defense (DoD) properties. The team carried out this approach in the following six tasks.

First, the team quantified within-scale and cross-scale aspects of resilience for understanding the capacity of ecosystems to withstand change and avoid shifting to alternate regimes. For instance, cross-scale resilience metrics should be quantifiably different from species richness, cross-scale metrics should constrain species turnover but not variance in turnover, and cross-scale metric patterns should synchronize with abrupt shifts in communities. The team tested these predictions by calculating cross-scale resilience model metrics (within-scale redundancy, cross-scale diversity, cross-scale redundancy, number of body mass aggregations) on 46 years of breeding bird data across the United States and testing cross-scale resilience model predictions. The team conducted these tests at three different spatial scales per Environmental Protection Agency (EPA) ecoregion Levels II, III, and IV.

Second, the team tested methods for detecting broad-scale shifts in regimes across space and time. The team used Fisher Information to detect the location of regimes shifts at broad spatial extents, and the occurrence of regime shifts that have occurred over time at specific locations using long-term data available with a spatial and temporal component (e.g., Breeding Bird Survey). Fisher Information has been proposed recently as a technique for capturing the dynamic order of ecosystems and detecting dynamic changes in ecological regimes.

Third, the team identified discontinuities in species body mass distributions. Discontinuity analysis can provide an objective and independent assessment of scales of structure in a system and can identify early warnings of regime shifts. Using breeding bird presence-absence and body mass data, the team performed discontinuity analysis along a 250 km wide and > 3000 km long transect in North America over 46 years to identify shifts in spatial boundaries of regimes and determine if this could be used to detect early warnings of regime shifts on military bases.

Fourth, the team identified species with stochastic abundance patterns in space and time. Species with stochastic patterns are hypothesized to be a critical element of resilience in the face of global change, in particular by providing adaptive capacity. The team defined adaptive capacity as the probability of species to shift from being rare (showing stochastic dynamics) to become dominant and explained deterministic patterns over time in the landscape. The team performed this task using distance-based Moran's Eigenvector Mapping, which objectively identifies dominant and stochastic species in space/time. The team then compared the richness and diversity of stochastic species to regime boundaries (identified in Task 3) and determined how stochastic species contribute to adaptive capacity in neighboring regimes over time.

Fifth, the team detected ecosystem-level shifts and warning indicators within a military installation. In this task, the team tested the ability of spatial covariance to track spatial regime boundary shifts at Fort Riley. The team also tested a novel method called "wombling" to track spatial regime boundaries with avian community data collected by Fort Riley personnel.

Sixth, military installations are vulnerable to the occurrence of regime shifts at multiple spatial and temporal scales. In this Task, the team synthesized the team's multi-faceted approaches to identify and adapt to 1) regime shifts and vulnerabilities in the matrix surrounding installations and 2) ecosystem-level shifts and vulnerabilities within installations.

4.0 RESULTS AND DISCUSSION

4.1 TASK 1

Cross-scale resilience metrics followed patterns predicted by ecological resilience theory: cross-scale resilience metrics did not correlate with species richness; cross-scale resilience metrics constrained the magnitude of species turnover, but they had little effect on the variance of species turnover; and cross-scale resilience metrics both synchronized (cross-scale diversity) and were asynchronous (cross-scale redundancy) with abrupt shifts in community composition. These patterns were mostly consistent across scales of analysis. However, the team only observed asynchrony of cross-scale redundancy with abrupt shifts at the middle (EPA Ecoregion Level III) scale.

The team's results indicated cross-scale resilience metrics can assess the relative resilience of systems. Thus, using data from a single military installation or multiple within the same ecoregion, cross-scale resilience metrics can be calculated and used to assess the ecological resilience of military bases over time. The team showed how monitoring changes in these metrics over time can predict when an undesirable regime shift is occurring or about to occur.

4.2 TASK 2

Interpreting the Fisher Information is currently a qualitative effort. Effective regime detection measures should provide sufficient evidence of the drivers and/or pressures associated with the identified regime shifts. The team's findings suggest that Fisher Information is useful for temporal regime shift detection for socioecological data (Spanbauer et al. 2016; Ahmad et al., 2016), but care must be taken when interpreting Fisher Information in spatial contexts and for predictive or management planning purposes. However, Fisher Information is clearly more useful and interpretable—even if only evaluated qualitatively—compared to univariate early warning/regime shift detection methods.

4.3 TASK 3

Discontinuity analysis revealed three consistent spatial regimes along the south-north transect from 1970–2015 (Figure 3a). Tracking these three spatial regime boundaries over 46 years, the team found the southernmost spatial regime boundary moved > 260 km northward and the northernmost boundary moved > 590 km northward (Figure 3b). Using discontinuity analysis to track movement of spatial regime boundaries provided > 40 years of early warning of regime shifts. This greatly improved upon traditional early warning methods, which often provide < 1 year of early warning.

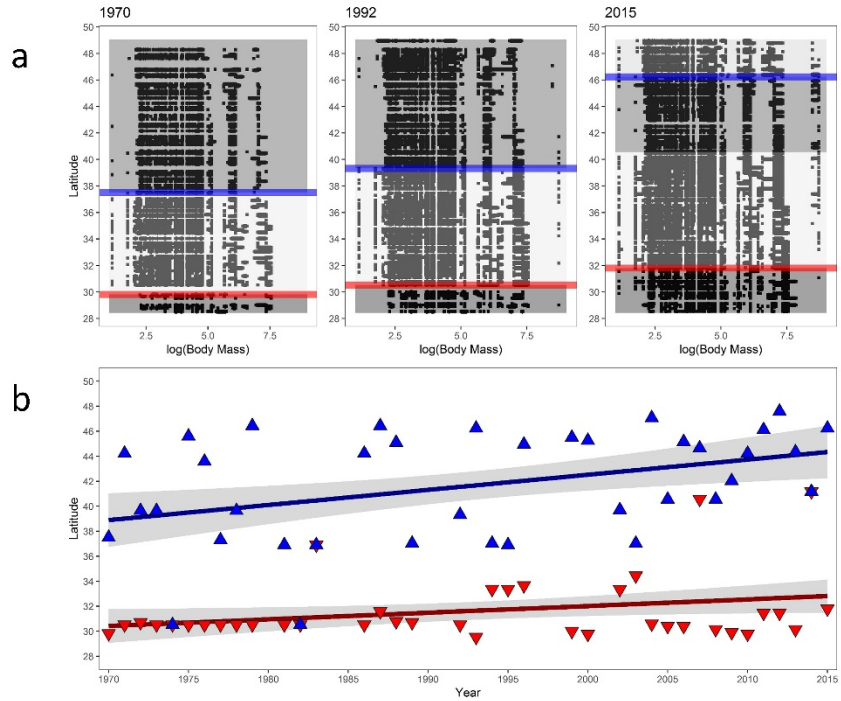

Figure 3. Shifts in Spatial Regime Boundaries Demonstrated by Breeding Bird Body Mass Discontinuities from 1970-2015 in North American Great Plains.

a – b, (a) Latitudinal spatial regime boundaries (y-axis) determined by log-ranked avian body mass discontinuities (x-axis). Black dots represent body mass aggregations identified via discontinuity analysis in each breeding bird survey route within the transect. Gray-scale boxes represent spatial regimes, and the northernmost and southernmost spatial regime boundaries are highlighted by blue and red lines, respectively. (b) Spatial regime boundaries (blue triangles = northernmost, red triangles = southernmost) detected each year, and lines represent modeled northernmost and southernmost spatial regime boundary movement over time with 90% confidence (grey ribbon). When northernmost and southernmost boundaries were the same (i.e., when only one spatial regime boundary was detected in a year), blue and red triangles overlap.

4.4 TASK 4

Using time series modeling of breeding bird survey data and a space-for-time substitution approach, the team found that stochastic species of one regime contribute marginally to within- and cross-scale resilience of a new regime. This refuted the team's hypothesis that stochastic species may become a critical element of adaptive capacity and resilience after a system has shifted into a new regime. However, the team also found the richness and diversity of species with spatially stochastic abundance patterns was highest near the spatial centers of spatial regimes (see spatial regimes identified in Task 3).

4.5 TASK 5

The team showed that bird and vegetation spatial regimes corresponded with each other in space and time (Figure 4). The wombling method applied to bird community data responded to tree-grass spatial regime boundaries at Fort Riley Army Base, KS over 27 years (Figure 4).

In fact, bird spatial regime boundaries preceded vegetation spatial regime boundaries by > 1 km, suggesting shifts in bird communities may serve as an "earlier" early warning of regime shifts than vegetation data. The team's results indicated that wombling applied to biotic community data can provide spatially-explicit warnings of regime shifts and help military bases prioritize management.

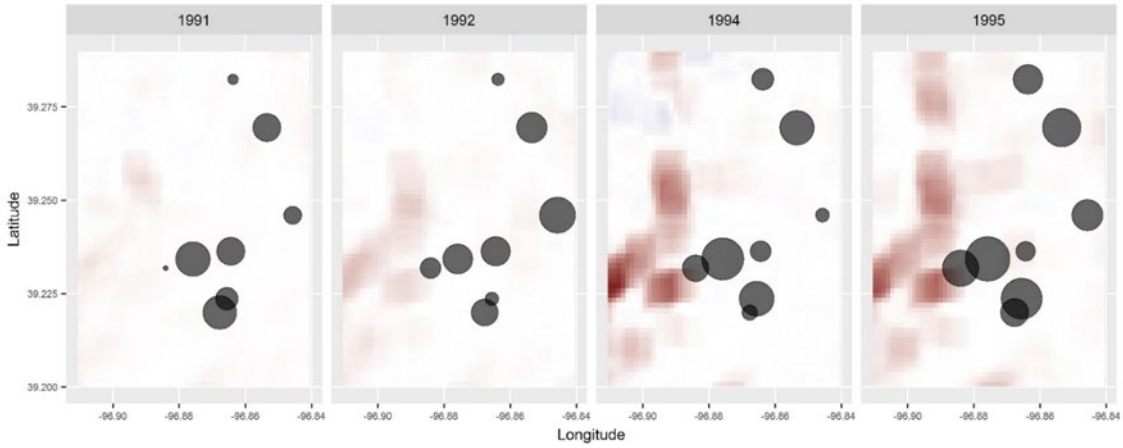

Figure 4. A Selected Portion of the Study Area that Was Likely to Exhibit Early Warnings of Changing Spatial Regime Boundaries (Regime Shifts) Due to Encroaching Tree Regimes into Grassland Regimes.

This portion was less disturbed and is near a ravine in which a few trees could have escaped fire and from which tree regimes could expand without fire disturbance. Panels correspond with 4 years in which tree regime boundaries (red shading) rapidly expanded and displaced grassland regimes. Dots indicate bird community sampling locations. Dot size corresponds with wombling (R2) values, with larger dots indicating greater likelihood of a spatial regime boundary and smaller dots indicating greater similarity lower likelihood of a boundary.

4.6 TASK 6

In this task, the team reviewed and discussed multivariate metrics used to detect early warnings and regime shifts along with their utility in rangeland evaluation and monitoring. The team focused on multivariate metrics with potential utility for detecting regime shifts and early warnings, as opposed to univariate indicators, because multivariate methods are more likely to capture the complexity of the systems in question and because comprehensive reviews of univariate metrics already exist that can guide rangeland specialists.

To assist in the appropriate selection and application of multivariate early warning metrics in DoD environmental management, the team categorized metrics hierarchically according to their assumptions and data type requirements (Figure 5) and organized the review accordingly. The primary division lies in whether driving state variables are known or unknown for the system in question and whether a relatively small (i.e., limited), or a relatively large (i.e., unlimited) number of state variables have been measured (Figure 5). The second division separates metrics by whether they require the spatial or temporal "location" of a regime shift to be hypothesized *a priori* (Figure 5). The tertiary division splits metrics by specific data type requirements (Figure 5).

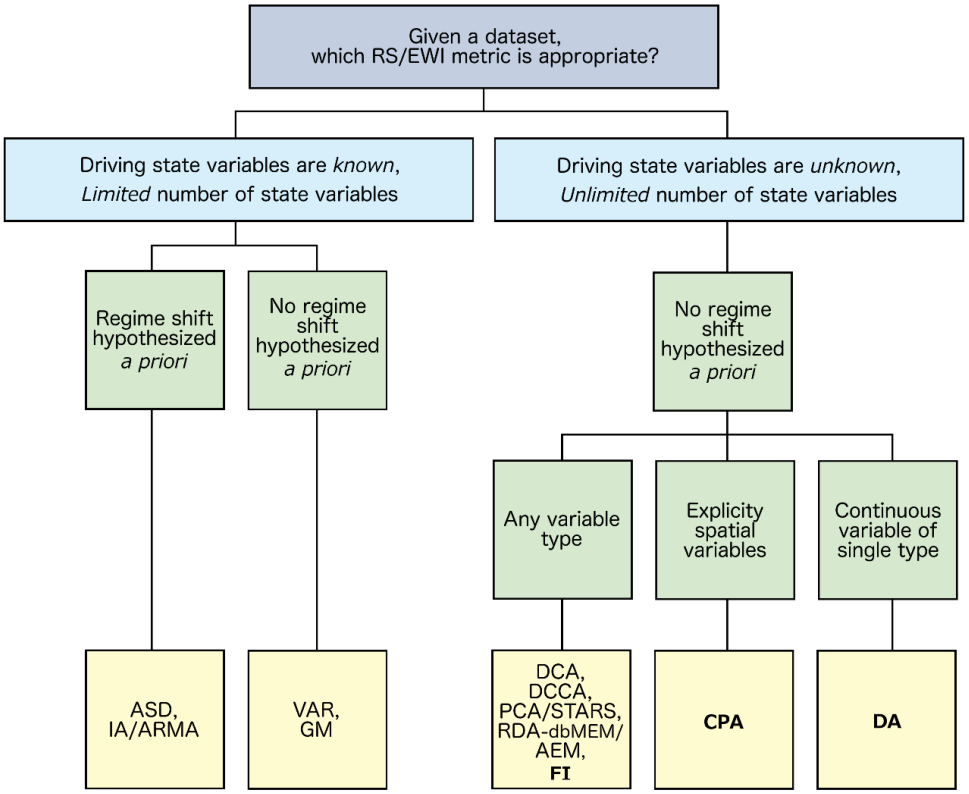

Figure 5. A Flowchart for Determining Which Multivariate Metrics for Regime Shift/Early Warning Detection Are Appropriate for a Given Set of State Variables.

"Limited" state variables indicates those metrics are suitable for relatively small number of input variables, and "known drivers" means that the input state variables represent known fundamental influences on system state. The lowest tier lists appropriate metrics for a given data type. Metrics in bold have been tested as early warning indicators of regime shifts. Metrics not in bold have been proposed as early warning metrics but only tested as regime shift indicators. Note: RS = proposed early warning indicator, EWI = tested early warning indicator, ASD = Average Standard Deviates, IA/ARMA = Intervention Analysis/Autoregressive Moving Averages, VAR = Vector Autoregression, GM = Generalized Modeling, DCA = Detrended Correspondence Analysis, DCCA = Detrended Canonical Correspondence Analysis, PCA/STARS = Principal Components Analysis/Sequential T-Test Analysis of Regime Shifts, RDA-dbMEM/AEM = Redundancy Analysis- , FI = Fisher Information, CPA = Conditional Probability Analysis, DA = Discontinuity Analysis.

5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

5.1 FUTURE RESEARCH

Future research should center on the identification and detection of scales of regime shifts. Theory suggests regimes should manifest at discontinuous scales. By identifying these ecologically-meaningful scales, the predictive power of the team's methods may be improved. Here, the team has used several scale detection methods (see methods for Task 4) which hold potential, but as yet, they have not been specifically tested for this pursuit.

5.2 BENEFITS

Tracking spatial regime boundaries over time provided decades worth of early warnings of regime shifts along the team's study transect (Figure 6). This can be interpreted as a "vulnerability assessment" of military bases (Figure 6). That is, if a spatial regime boundary is moving toward a given base, is spatially close to a given base, or both, that base would be considered vulnerable to a regime shift. Thus, by monitoring spatial regime boundary proximity and trajectories over time, military bases can be forewarned of ecological change.

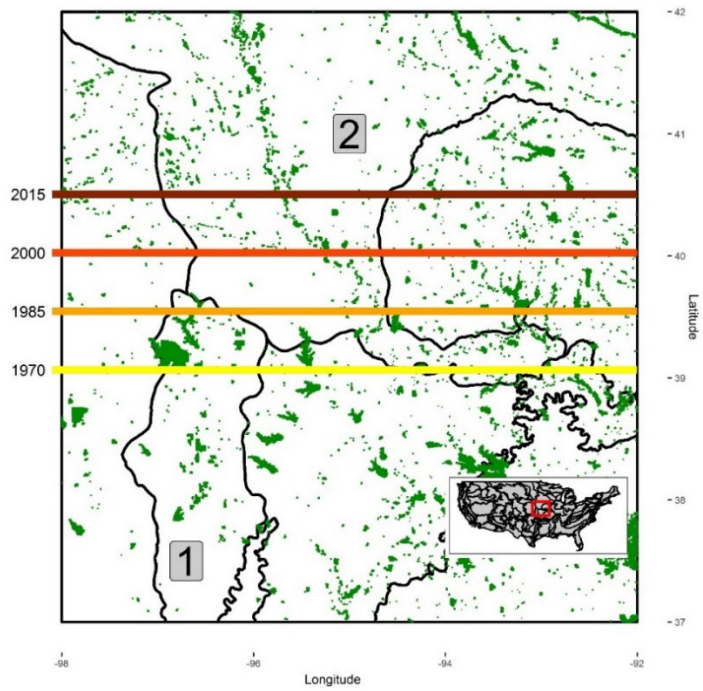

Figure 6. Spatial Regime Boundary Movement Between 37 – 42 Degrees Latitude Across a Network of Protected Areas Covering in Central North America.

Black lines indicate level III US Environmental Protection Agency ecoregion boundaries, and green polygons indicate protected areas. The ecoregion labeled No. 1 is the Flint Hills ecoregion, and the ecoregion labeled No. 2 is the Western Corn Belt Plains ecoregion. Predicted spatial regime boundaries (colored horizontal lines) correspond with linear prediction for the years 1970, 1985, 2000, and 2015 ($\beta = 0.032 \pm 0.026$ degrees latitude per year; 90% confidence; $F = 4.093$; $P = 0.052$).

Both individual and a network of military installations stand to benefit from the team's methods. Tracking spatial regime boundaries over time provides an early warning of regime shifts for both individual bases and for a network of bases in the path of the regime shift. While a single base may not be able to halt or overcome a continental-scale regime shift, a network of bases, working in tandem, working with other land management agencies, and forewarned by spatial regime monitoring may have a chance to avert such a broad-scale shift. However, individual bases, employing spatial and temporal regime shift detection methods within their borders, also can benefit from the early warning signals: these signals, particularly spatial methods such as wombling, can help base managers pinpoint where change is occurring within their bases and more efficiently prioritize restoration, management, etc. in those areas.

6.0 LIST OF PUBLICATIONS

Ahmad, N., S. Derrible, T. Eason & H. Cabezas. 2016. Using Fisher information to track stability in multivariate systems. Royal Society open science 3 (11), 160582

Spanbauer, T. L., Allen, C. R., Angeler, D. G., Eason, T., Fritz, S. C., Garmestani, A. S., ... & Sundstrom, S. M. (2016). Body size distributions signal a regime shift in a lake ecosystem. Proceedings of the Royal Society B: Biological Sciences, 283(1833), 20160249.