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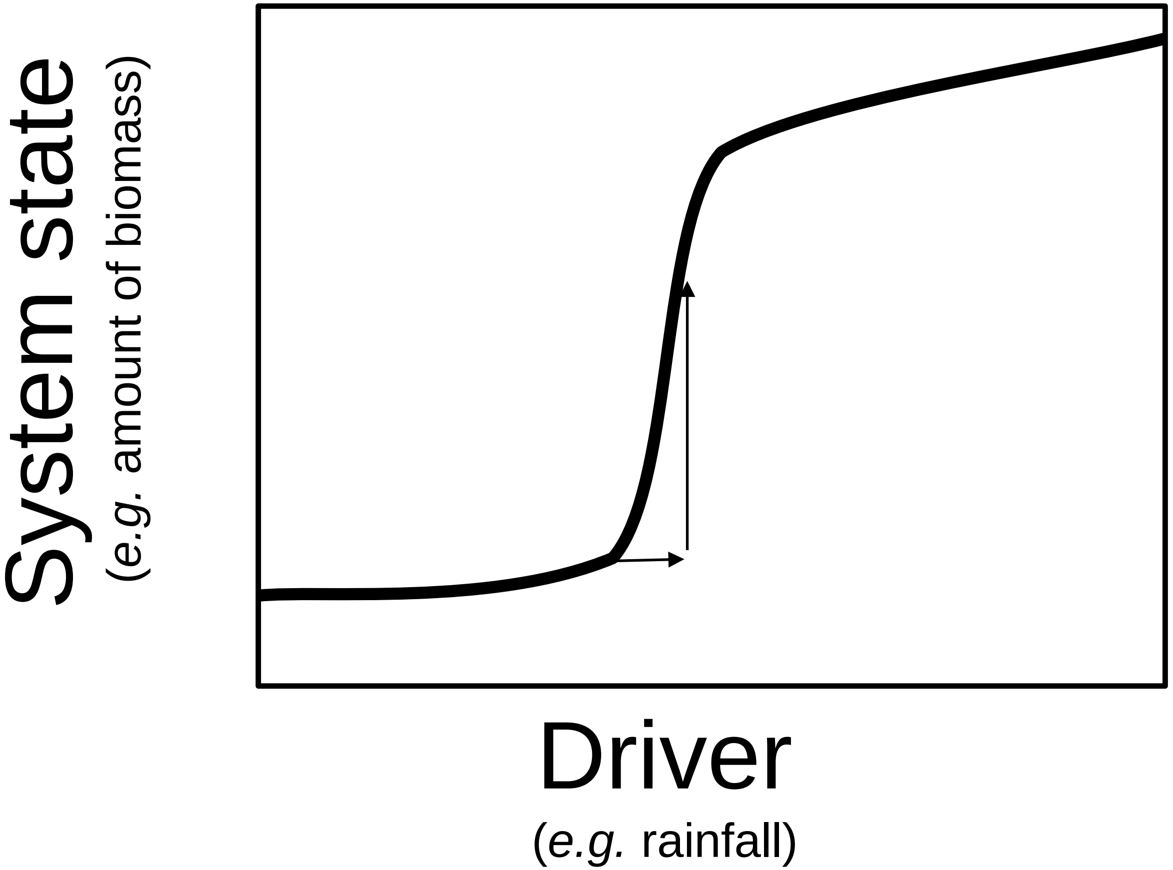
TIPPING POINTS IN ECOSYSTEMS:

HOW CAN WE USE REMOTE SENSING?

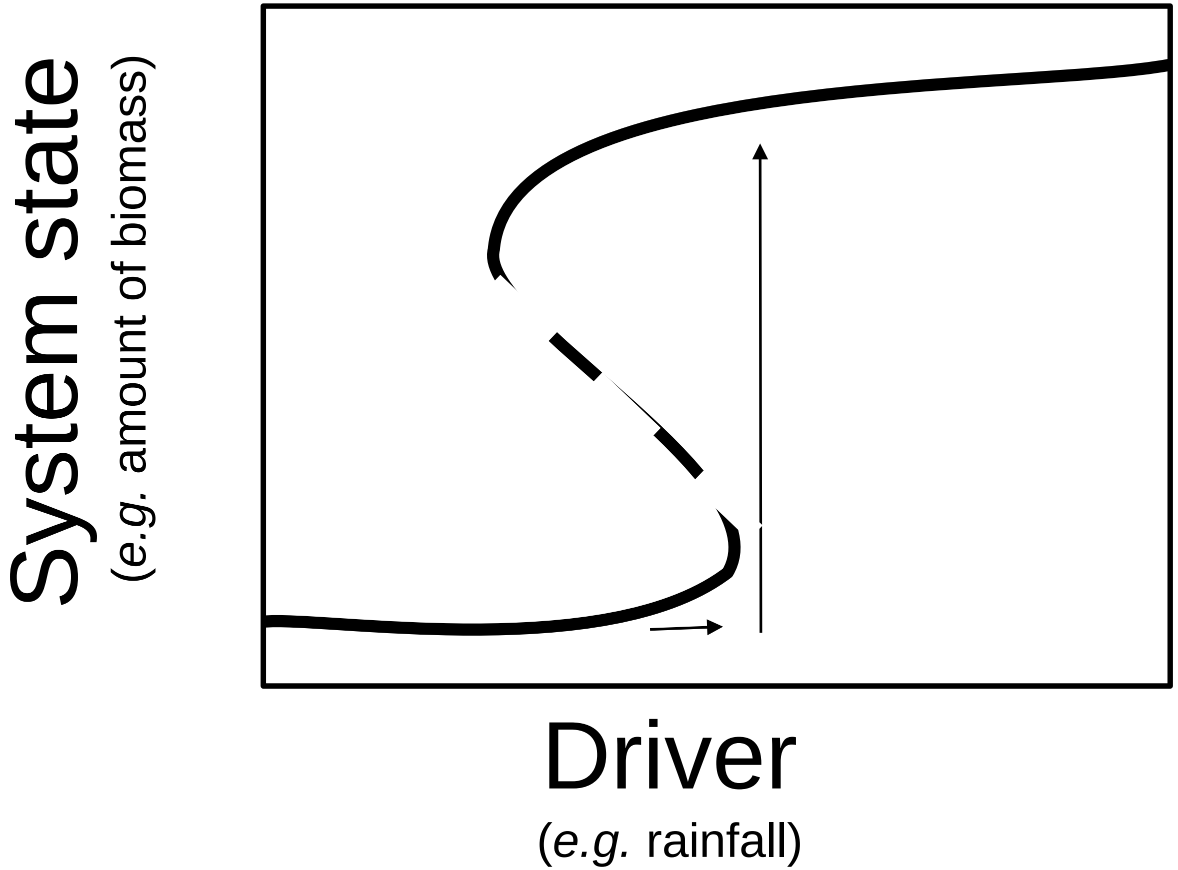
THOMAS A. GROEN WITH CONTRIBUTIONS FROM INKA DIATMIKO, GOHAR SHAHINYAN, DAN KANMEGNE, KRISHNA LAMSAL,

NIINA RAUTIAINEN, BABAK NAIMI, KOEN DE KONING, SARA ALIBAKSI AND ANTON VRIELING

WHAT ARE TIPPING POINTS?



WHAT ARE TIPPING POINTS?



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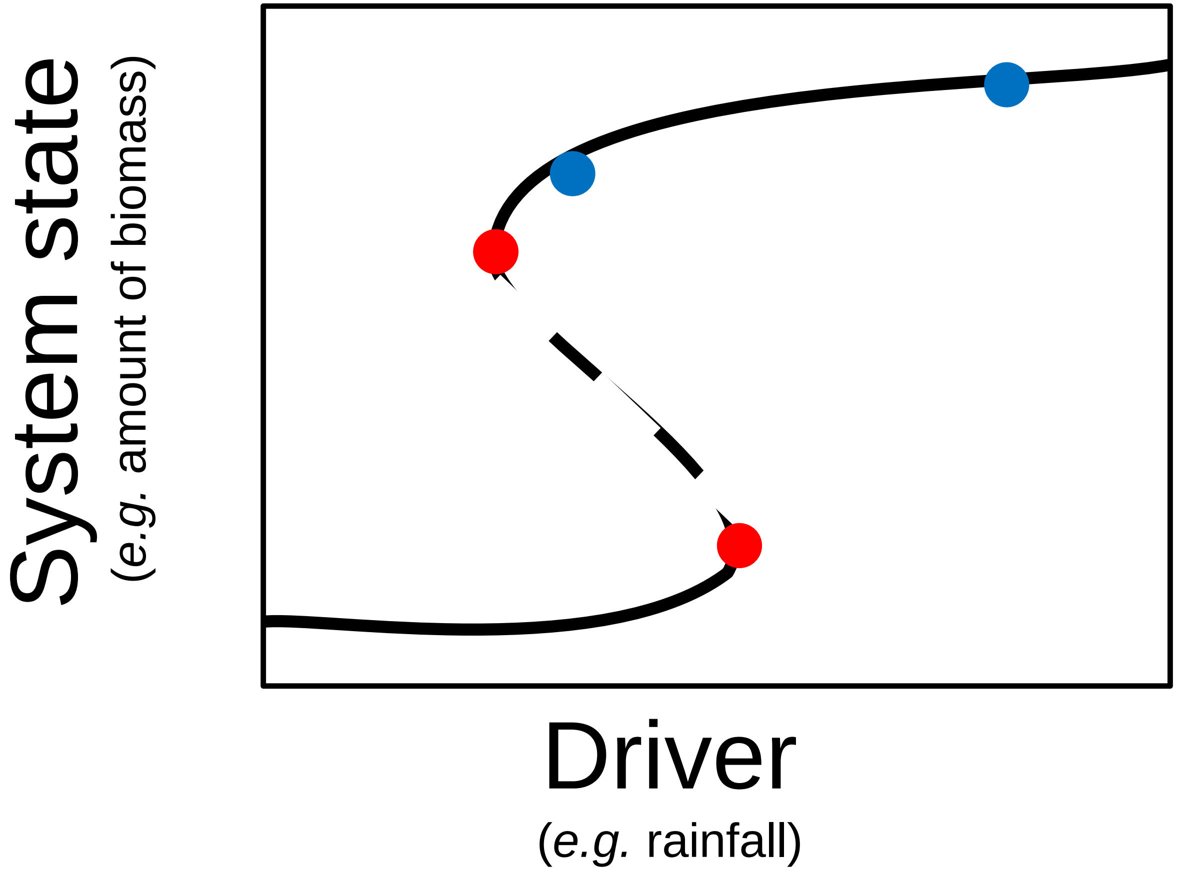
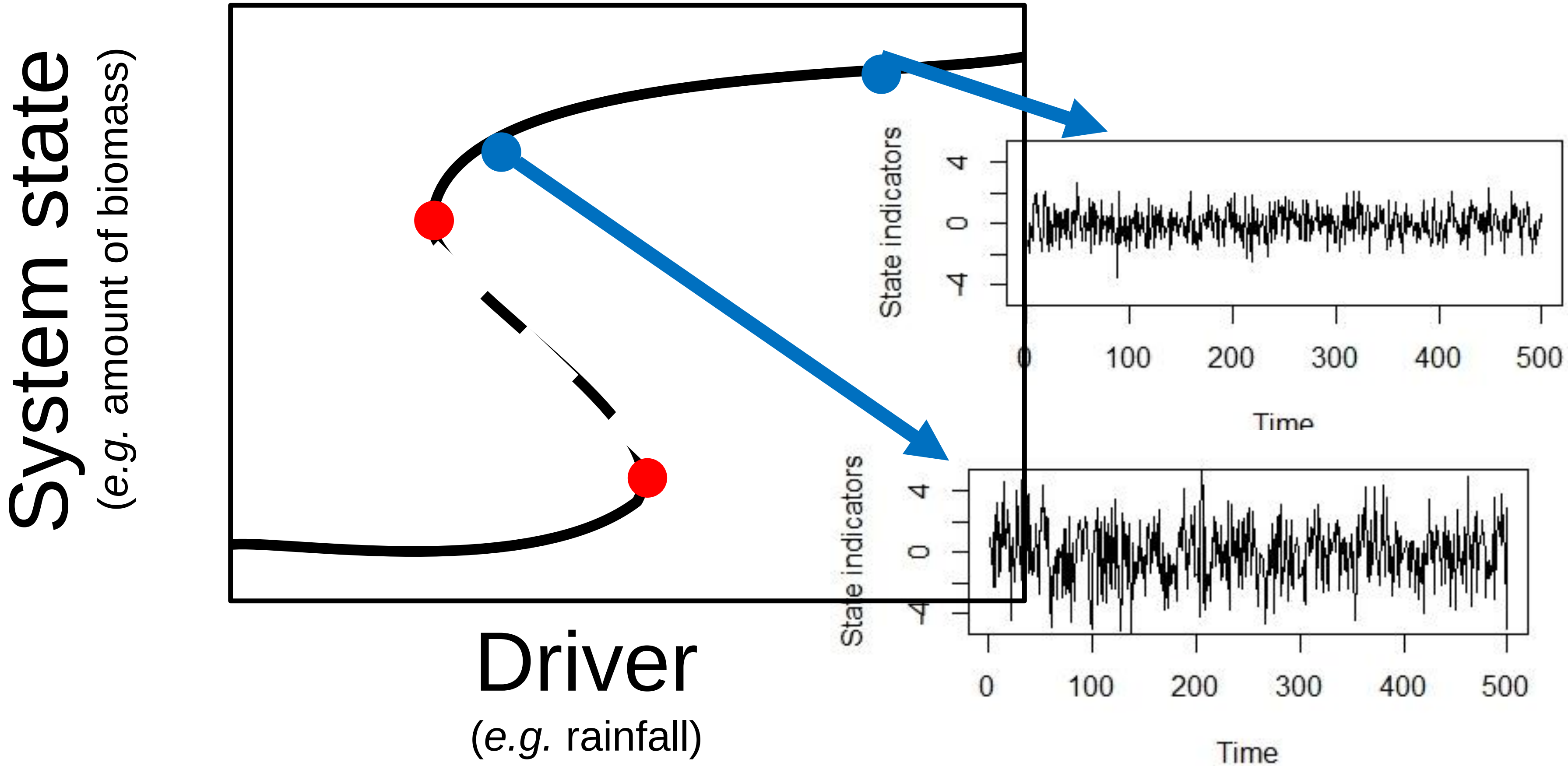
Images: http://www.taekwondo-reza.at/chagi.html

HOW TO DETECT PROXIMITY TO TIPPING POINTS



HOW TO DETECT PROXIMITY TO TIPPING POINTS



EARLY WARNING INDICATORS FOR TIPPING POINTS

OPEN ACCESS Freely available online

PLoS one

Methods for Detecting Early Warnings of Critical Transitions in Time Series Illustrated Using Simulated Ecological Data

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Abstract

Many dynamical systems, including lakes, organisms, ocean circulation patterns, or financial markets, are now thought to have tipping points where critical transitions to a contrasting state can happen. Because critical transitions can occur unexpectedly and are difficult to manage, there is a need for methods that can be used to identify when a critical transition is approaching. Recent theory shows that we can identify the proximity of a system to a critical transition using a variety of so-called 'early warning signals', and successful empirical examples suggest a potential for practical applicability. However, while the range of proposed methods for predicting critical transitions is rapidly expanding, opinions on their practical use differ widely, and there is no comparative study that tests the limitations of the different methods to identify approaching critical transitions using time-series data. Here, we summarize a range of currently available early warning methods and apply them to two simulated time series that are typical of systems undergoing a critical transition. In addition to a methodological guide, our work offers a practical toolbox that may be used in a wide range of fields to help detect early warning signals of critical transitions in time series data.

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Introduction

The Earth's past has been characterized by rapid and often unexpected punctuated shifts in temperature and climatic conditions [1], lakes and coral reefs have shifted among alternative

To overcome these challenges, numerous studies have suggested the use of generic early warning signals (or *leading indicators*) that can detect the proximity of a system to a tipping point [6]. Such indicators are based on common mathematical properties of

Table 1. Early warning signals for critical transitions.

		Phenomenon		
	Method/Indicator	**Rising memory**	**Rising variability**	**Flickering**
metrics	Autocorrelation at-lag-1	x		
	Autoregressive coefficient of AR(1) model	x		
	Return rate (inverse of AR(1) coefficient)	x		
	Detrended fluctuation analysis indicator	x		
	Spectral density	x		
	Spectral ratio (of low to high frequencies)	x		
	Spectral exponent	x		
	Standard deviation		x	x
	Coefficient of variation		x	x
	Skewness		x	x
	Kurtosis		x	x
	Conditional heteroskedasticity		x	x
	BDS test		x	x
models	Time-varying AR(p) models	x	x	
	Nonparametric drift-diffusion-jump models	x	x	x
	Threshold AR(p) models			x
	Potential analysis (potential wells estimator)			x

EARLY WARNING INDICATORS FOR TIPPING POINTS

- Theoretical - Models/simulated data
- Real ecosystems

Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment

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Catastrophic ecological regime shifts may be announced in advance by statistical early warning signals such as slowing return rates from perturbation and rising variance. The theoretical background for these indicators is rich, but real-world tests are rare, especially for whole ecosystems. We tested the hypothesis that these statistics would be early warning signals for an experimentally induced regime shift in an aquatic food web. We gradually added top predators to a lake over 3 years to destabilize its food web. An adjacent lake was monitored simultaneously as a reference ecosystem. Warning signals of a regime shift were evident in the manipulated lake during reorganization of the food web more than a year before the food web transition was complete, corroborating theory for leading indicators of ecological regime shifts.

Massive ecosystem changes affect water supplies, fisheries, productivity of rangelands and forests, and other ecosystem services (*1*, *2*). Nonlinear regime shifts often come as surprises. However, recent research has revealed statistical signals that precede some nonlinear transitions, such as rising autocorrelation, steep increases in variance, and extreme changes in skewness and shift in variance spectra toward low frequencies (*3*–*7*). If the transition is approached slowly and the right variables are sampled frequently, warnings may be evident well before the regime shift is complete. Empirical evidence for early warnings of environmental regime shifts comes from a time series of major changes in paleoclimate (*8*), spatial pattern of dryland vegetation during desertification (*9*), variability of exploited fisheries (*10*, *11*), and laboratory studies (*12*). Here, we present a test of early warning indicators from a large-scale multiyear field experiment using a manipulated and a reference ecosystem.

Gradual addition or removal of top predators destabilizes food webs, and extreme manipulations of predators cause trophic cascades, a type of regime shift that alters food web structure and ecosystem processes such as primary production, ecosystem respiration, and nutrient cycling (*13*, *14*).

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Predator-driven transitions in lakes involve nonlinear dynamics of fish, zooplankton, and phytoplankton populations (*15*). Over 3 years, we gradually added a top predator, largemouth bass (*Micropterus salmoides*), to a lake dominated by planktivorous fishes to destabilize the food web and induce a trophic cascade leading to dominance of the food web by piscivores (*16*). A nearby lake, dominated by adult largemouth bass, was not manipulated and served as a reference ecosystem. The reference ecosystem allows us to evaluate the possibility that responses were caused by external drivers rather than the manipulation (*15*). Planktivorous fishes, zooplankton, and phytoplankton were monitored daily in both lakes for 3 years of summer stratification (2008 to 2010) (*16*).

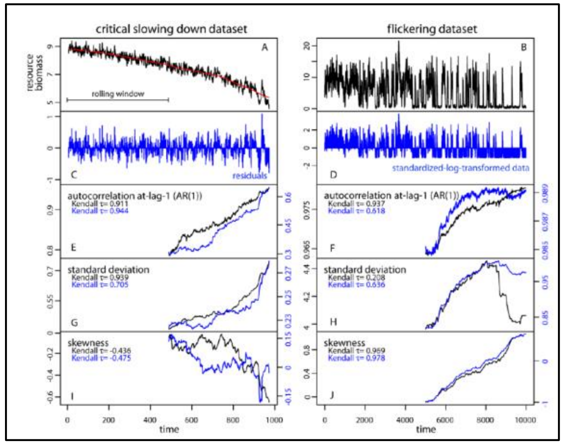
Predicted responses of the food web follow from previous experiments in these lakes (*15*) and an ecosystem model calibrated for the manipulated lake (*17*). Before manipulation, the manipulated ecosystem was dominated by a variety of small fishes [hereafter planktivores (*16*)], and largemouth bass were few. We expected that the addition of largemouth bass would trigger recruitment of juvenile bass that were planktivorous initially but became omnivorous, adding benthos and fish to their diets, as they grew. Piscivory by largemouth bass would cause planktivorous fishes to seek refuge from predation by occupying littoral refugia and shoaling (aggregating). Eventually piscivory would drive planktivorous fishes to low densities. As planktivory declined in the open water, larger-bodied zooplankton (including migratory *Daphnia pulex*) would increase in relative abundance. Increased grazing would lead to cyclic oscillations of zooplankton and phytoplankton biomass. Thus, the food web transition would exhibit a sequence of nonlinear changes resulting from shoaling and diel movements of consumers, species replacement, and predator-prey cycles as the manipulated ecosystem became more similar to the reference ecosystem. We hypothesized that dynamics during this transitional period would generate early warning signals of a regime shift toward a piscivore-dominated food web.

Transitional dynamics of the food web were consistent with our expectations (Fig. 1). In the manipulated lake, 39 adult largemouth bass were present at the beginning of the experiment. We added 12 largemouth bass on day 193 of 2008, and 15 largemouth bass on each of days 169 and 203 of 2009. Enhancement of adult largemouth bass triggered a recruitment event in 2009, leading to 1281 young-of-year largemouth bass (95% confidence interval of 1088 to 1560) by day 240 of 2009. Numbers of this cohort (1+ in Fig. 1C) declined through 2010, whereas surviving individuals grew in body mass and became piscivorous. Planktivore numbers in the manipulated lake declined through the study as piscivory increased and were similar to those of the reference lake by about day 230 of 2010 (Fig. 1F).

The spatial pattern of planktivores was occasionally patchy in 2008 and 2009, indicated by high values in the discrete Fourier transform (DFT) of spatial data (*16*, *18*) (Fig. 2). Patchy distributions were more frequent and of longer duration in 2010. Patchy distributions indicate shoaling behavior, a likely response to predation risk.

Zooplankton biomass of the manipulated lake declined during the summers of 2008 and 2009 and became strongly oscillatory in 2010 (Fig. 1). Through 2009 and 2010, dominance of the zooplankton shifted toward larger-bodied cladocerans, including *D. pulex*, in the manipulated lake (fig. S1), consistent with previous whole-lake experiments in which body size but not biomass of zooplankton responded to fish manipulations (*15*, *19*). Phytoplankton biomass as measured by chlorophyll a of the manipulated lake displayed strong oscillations in 2009 and the first half of 2010. By day 230 of 2010, manipulated and reference lakes were similar in planktivore numbers, zooplankton biomass, and chlorophyll.

Modeling predicts that early warning indicators would appear after the largemouth bass addition in 2008 and continue until stabilization of a new food web dominated by largemouth bass



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WHAT DO WE NEED FOR THIS DETECTION METHOD

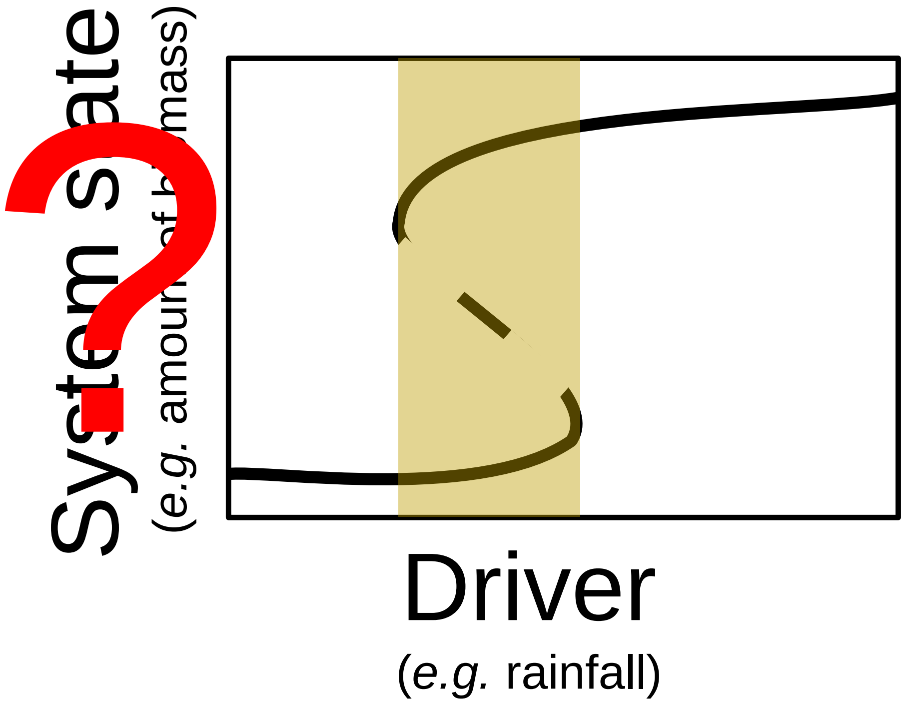
THINKING OF REMOTE SENSING

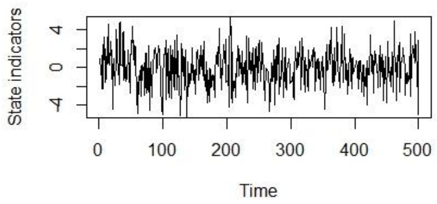
- Continuous time series of observations
- Of sufficient duration
- High frequency
- Measuring a relevant quantity
- At the right spatial scale

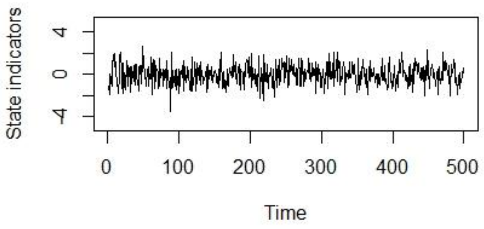
POSSIBLE RESEARCH QUESTIONS

WHEN IT COMES TO TIPPING POINTS, ECOLOGY AND RS

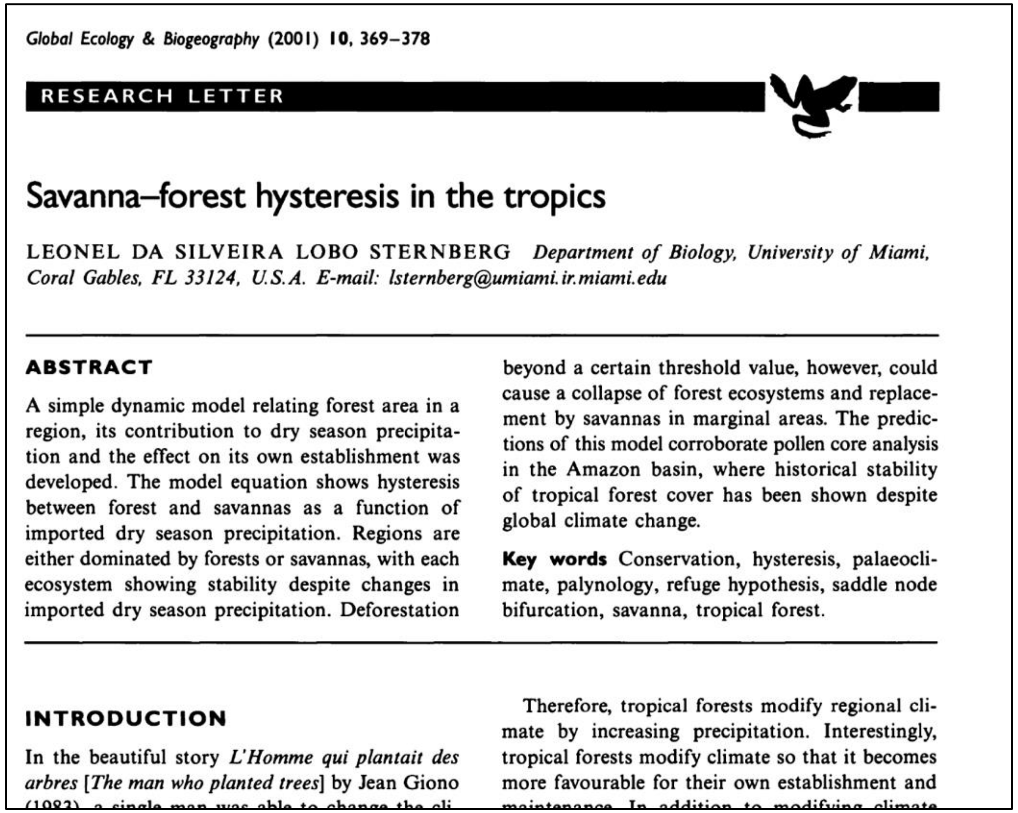
- Does a system have bi-stable states?
- How to quantify the state?
  - Which RS products (NDVI? Others?)
- Can we detect temporal patterns in this state that match with the theory?







DOES A SYSTEM HAVE BI-STABLE STATES?



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RESEARCH LETTER

Savanna–forest hysteresis in the tropics

LEONEL DA SILVEIRA LOBO STERNBERG *Department of Biology, University of Miami, Coral Gables, FL 33124, U.S.A. E-mail: lsternberg@umiami.ir.miami.edu*

ABSTRACT

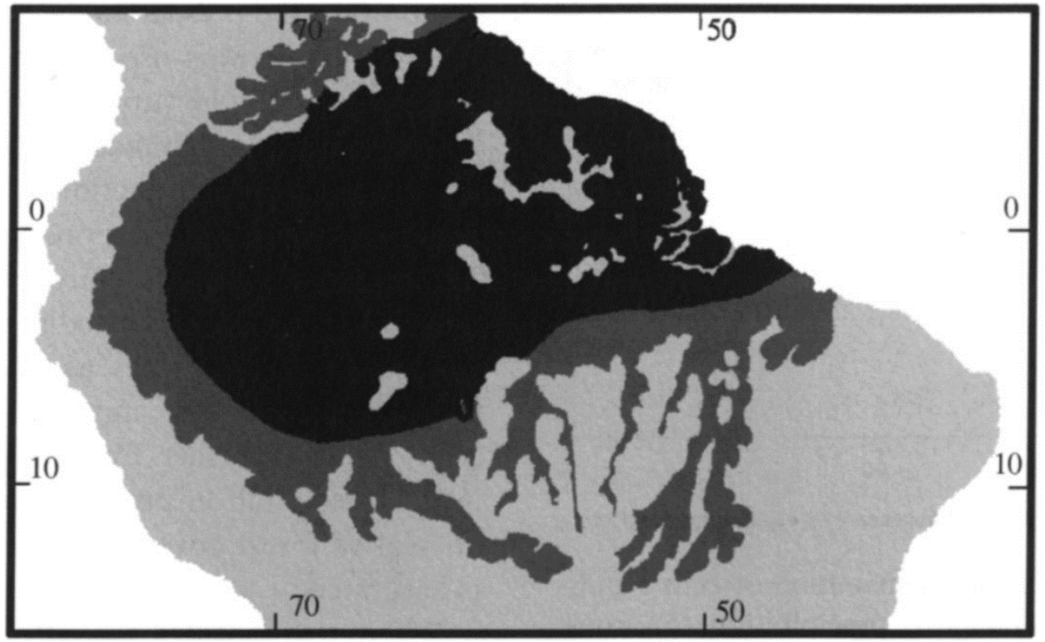
A simple dynamic model relating forest area in a region, its contribution to dry season precipitation and the effect on its own establishment was developed. The model equation shows hysteresis between forest and savannas as a function of imported dry season precipitation. Regions are either dominated by forests or savannas, with each ecosystem showing stability despite changes in imported dry season precipitation. Deforestation beyond a certain threshold value, however, could cause a collapse of forest ecosystems and replacement by savannas in marginal areas. The predictions of this model corroborate pollen core analysis in the Amazon basin, where historical stability of tropical forest cover has been shown despite global climate change.

Key words Conservation, hysteresis, palaeoclimate, palynology, refuge hypothesis, saddle node bifurcation, savanna, tropical forest.

INTRODUCTION

In the beautiful story *L'Homme qui plantait des arbres* [*The man who planted trees*] by Jean Giono

Therefore, tropical forests modify regional climate by increasing precipitation. Interestingly, tropical forests modify climate so that it becomes more favourable for their own establishment and



DOES A SYSTEM HAVE BI-STABLE STATES?

REPORTS

The Global Extent and Determinants of Savanna and Forest as Alternative Biome States

A. Carla Staver,[1*] Sally Archibald,[2] Simon A. Levin[1]

Theoretically, fire–tree cover feedbacks can maintain savanna and forest as alternative stable states. However, the global extent of fire-driven discontinuities in tree cover is unknown, especially accounting for seasonality and soils. We use tree cover, climate, fire, and soils data sets to show that tree cover is globally discontinuous. Climate influences tree cover globally but, at intermediate rainfall (1000 to 2500 millimeters) with mild seasonality (less than 7 months), tree cover is bimodal, and only fire differentiates between savanna and forest. These may be alternative states over large areas, including parts of Amazonia and the Congo. Changes in biome distributions, whether at the cost of savanna (due to fragmentation) or forest (due to climate), will be neither smooth nor easily reversible.

Fire is a strong predictor of the global distribution of the savanna biome (*1*, *2*) and of tree cover within savannas (*3*–*5*). Experimental work shows that fire can impact tree cover and can maintain savanna where climate can ...

... tree cover or on the potential distribution of fire effects. Locally, big differences in soil texture can have substantial effects on tree cover (*11*, *12*), whereas at the continental scale, soil texture and fertility have limited effects on tree cover (*2*, *3*, *5*). ...

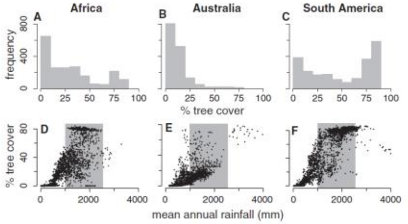


Fig. 1. Frequency distribution of tree cover (**A** to **C**) and relation of tree cover to mean annual rainfall (**D** to **F**). Gray zones denote intermediate rainfall [1000- to 2500-mm mean annual rainfall (MAR)].

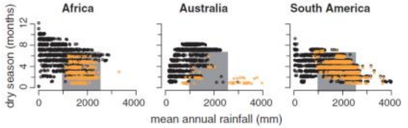


Fig. 2. Dry season length versus mean annual rainfall for areas with forest (>55% tree cover, yellow crosses) and savanna (≤55% tree cover, black circles). Gray zones denote intermediate rainfall (1000- to 2500-mm MAR) with mild seasonality (<7 months).

Global Resilience of Tropical Forest and Savanna to Critical Transitions

Marina Hirota,[1] Milena Holmgren,[2*] Egbert H. Van Nes,[1] Marten Scheffer[1]

It has been suggested that tropical forest and savanna could represent alternative stable states, implying critical transitions at tipping points in response to altered climate or other drivers. So far, evidence for this idea has remained elusive, and integrated climate models assume smooth vegetation responses. We analyzed data on the distribution of tree cover in Africa, Australia, and South America to reveal strong evidence for the existence of three distinct attractors: forest, savanna, and a treeless state. Empirical reconstruction of the basins of attraction indicates that the resilience of the states varies in a universal way with precipitation. These results allow the identification of regions where forest or savanna may most easily tip into an alternative state, and they pave the way to a new generation of coupled climate models.

Tree cover is one of the defining variables of landscapes, their ecological functioning, and their impact on climate. Despite insights into the effects of resource availability and disturbances on tree growth and survival (*1*–*4*), our understanding of the mechanisms determining global patterns of tree cover remains fragmented. A major question is whether tree cover will respond smoothly to climatic change and other stressors (*5*) or exhibit sharp transitions between contrasting stable states at tipping points (*6*). In some regions, forest, savanna, and treeless (barren or grassy) states have been suggested to represent alternative attractors (*7*–*9*). However, the case for multiple stable states of tree cover is largely based on models and on local observations of sharp transitions (*6*–*9*). Systematic studies of tree-cover distributions could help distinguish between hypotheses (*1*) but have been largely restricted to particular continents or biome types (*4*–*6*, *10*, *11*). To explore whether global patterns of tree abundance suggest gradual responses or, rather, alternative stable states, we

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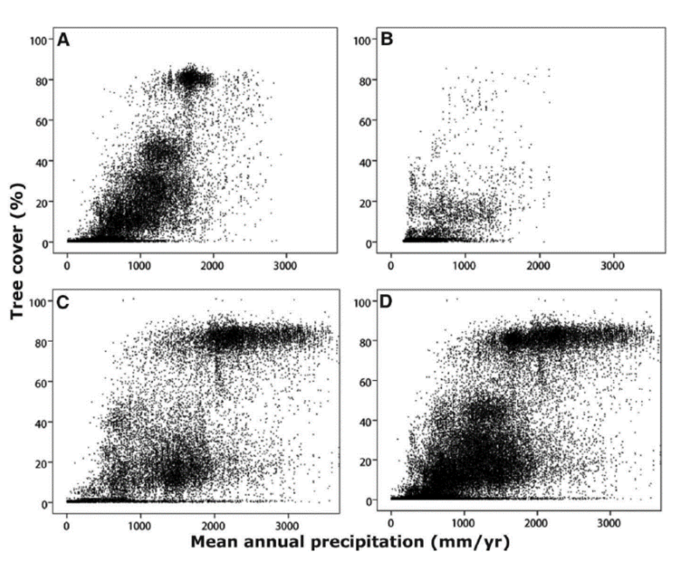

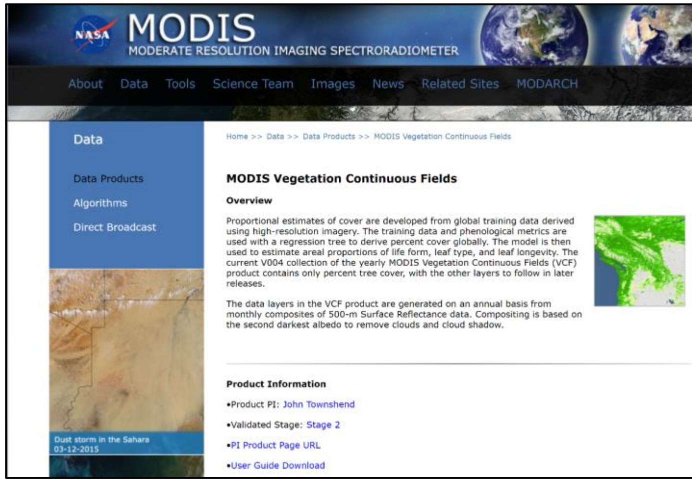

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CRITIQUE TO USED DATA

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CORRESPONDENCE

WILEY Global Ecology and Biogeography A Journal of Macroecology

MODIS VCF should not be used to detect discontinuities in tree cover due to binning bias. A comment on Hanan et al. (2014) and Staver and Hansen (2015)

France Gerard[1] | Danny Hooftman[1,2] | Frank van Langevelde[3] | Elmar Veenendaal[4] | Steven M. White[1,5] | Jon Lloyd[6,7]

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Abstract

In their recent paper, Staver and Hansen (*Global Ecology and Biogeography*, 2015, 24, 985–987) refute the case made by Hanan et al. (*Global Ecology and Biogeography*, 2014, 23, 259–263) that the use of classification and regression trees (CARTs) to predict tree cover from remotely sensed imagery (MODIS VCF) inherently introduces biases, thus making the resulting tree cover unsuitable for showing alternative stable states through tree cover frequency distribution analyses. Here we provide a new and equally fundamental argument for why the published frequency distributions should not be used for such purposes. We show that the practice of pre-average binning of tree cover values used to derive cover values to train the CART model will also introduce errors in the frequency distributions of the final product. We demonstrate that the frequency minima found

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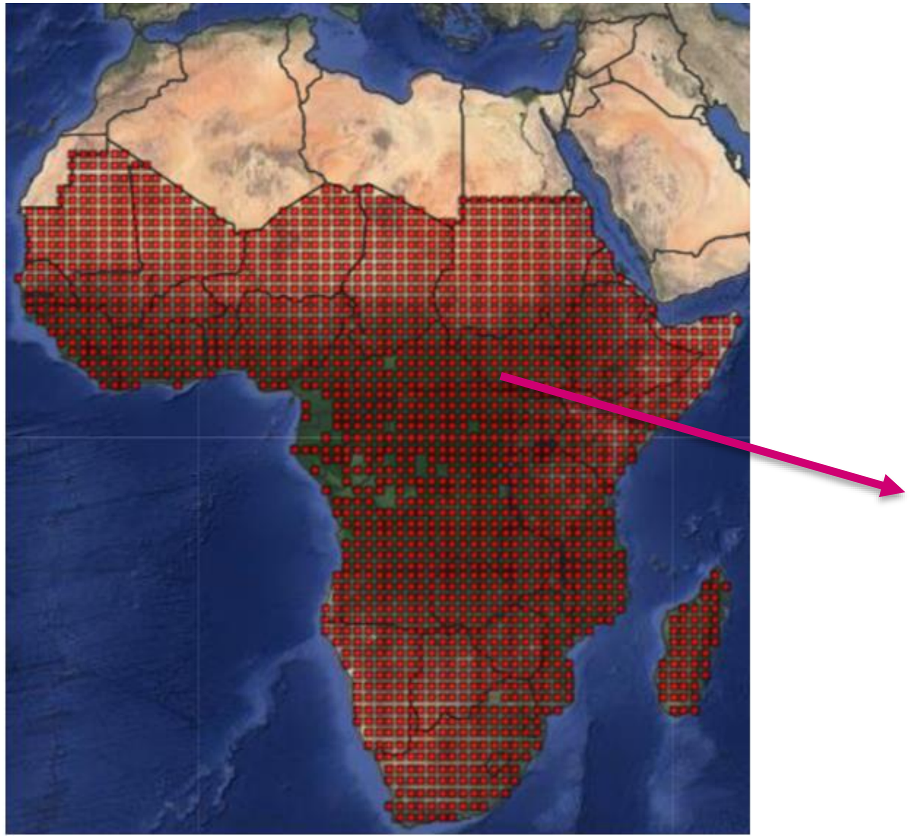
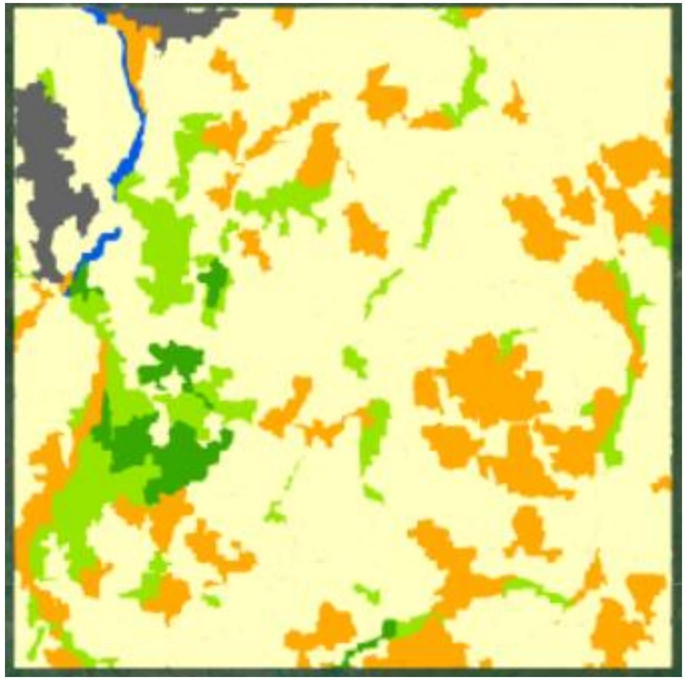
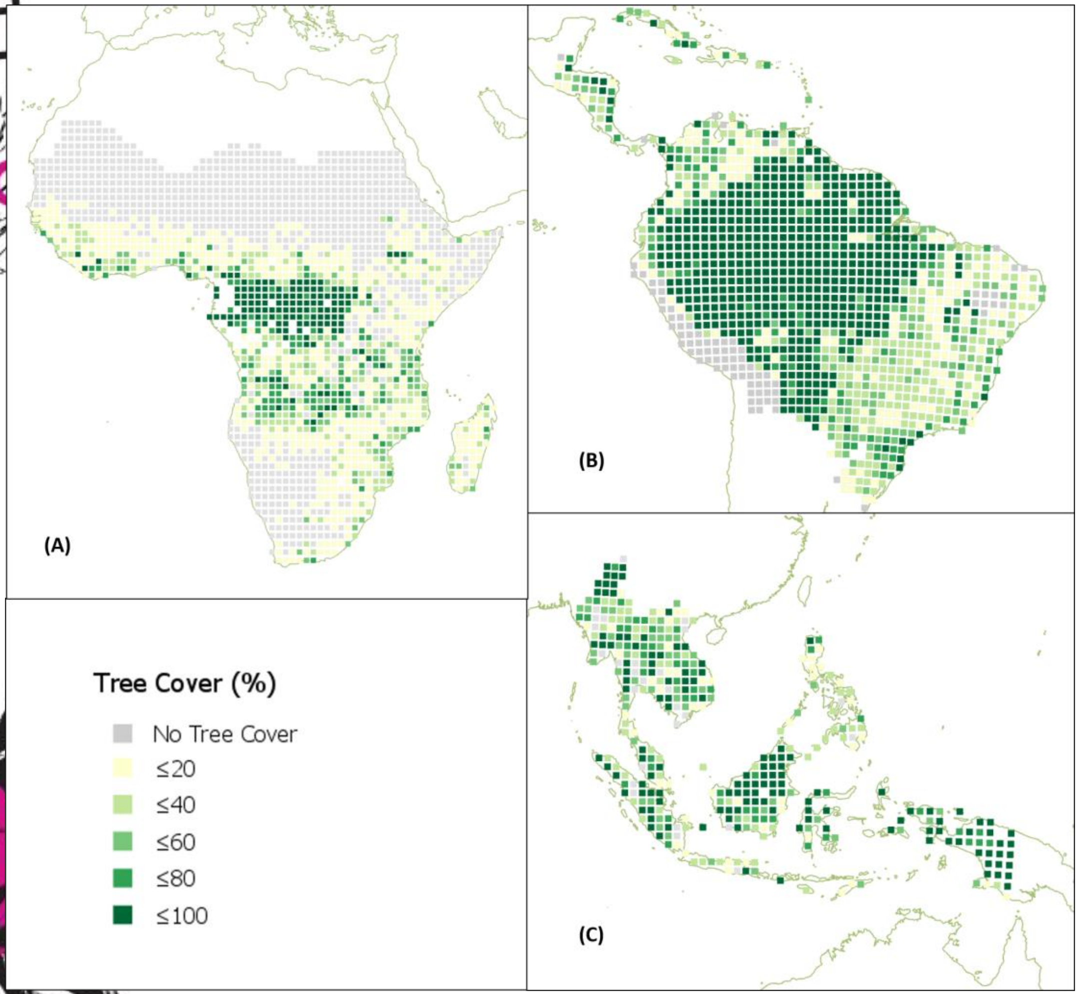
OTHER DATA AVAILABLE?

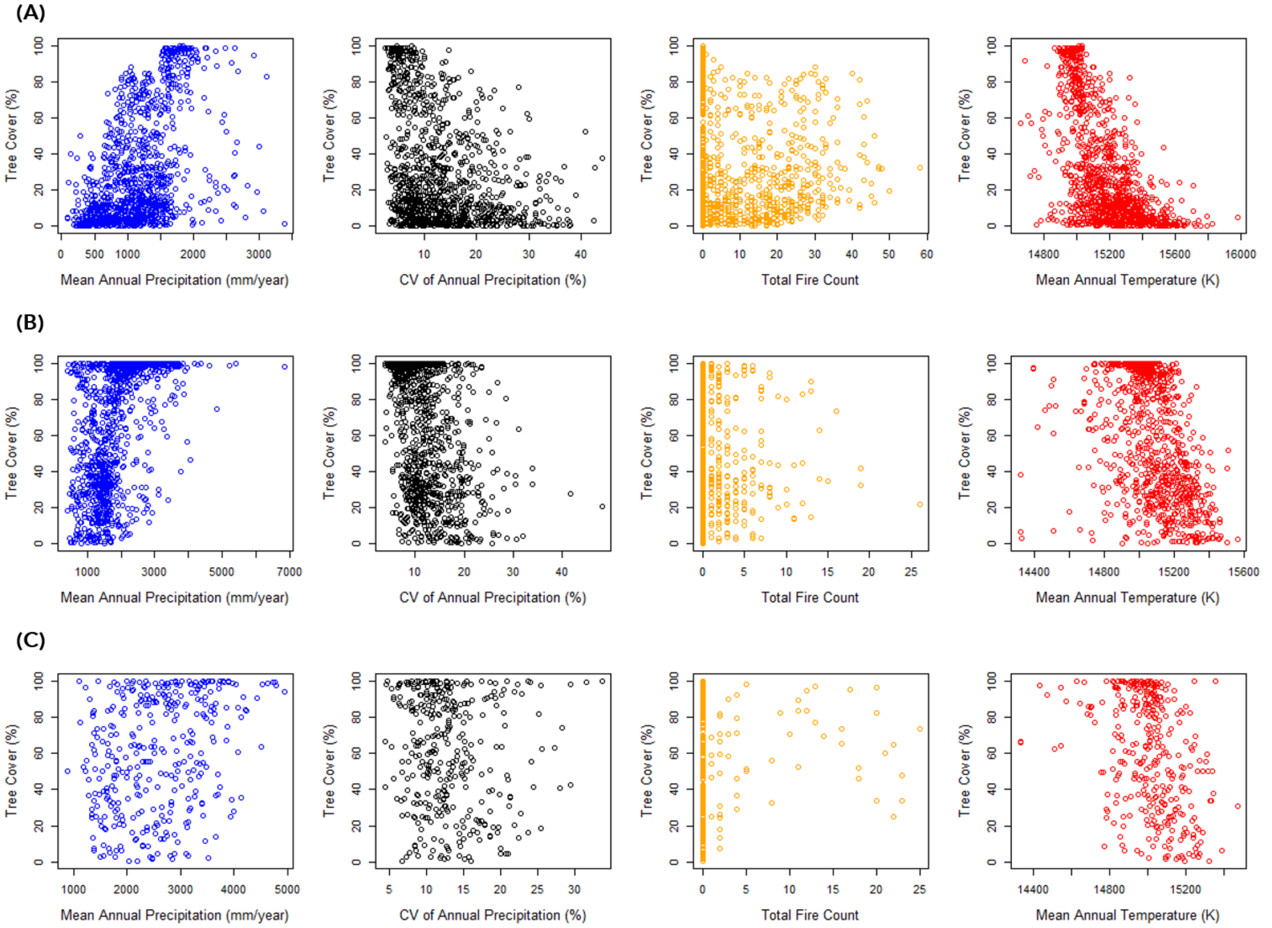
- **TREES data** of JRC (2000-2010)
- 2066 sample units (10 x 10 km each)
- Systematic distribution of 20 x 20 km



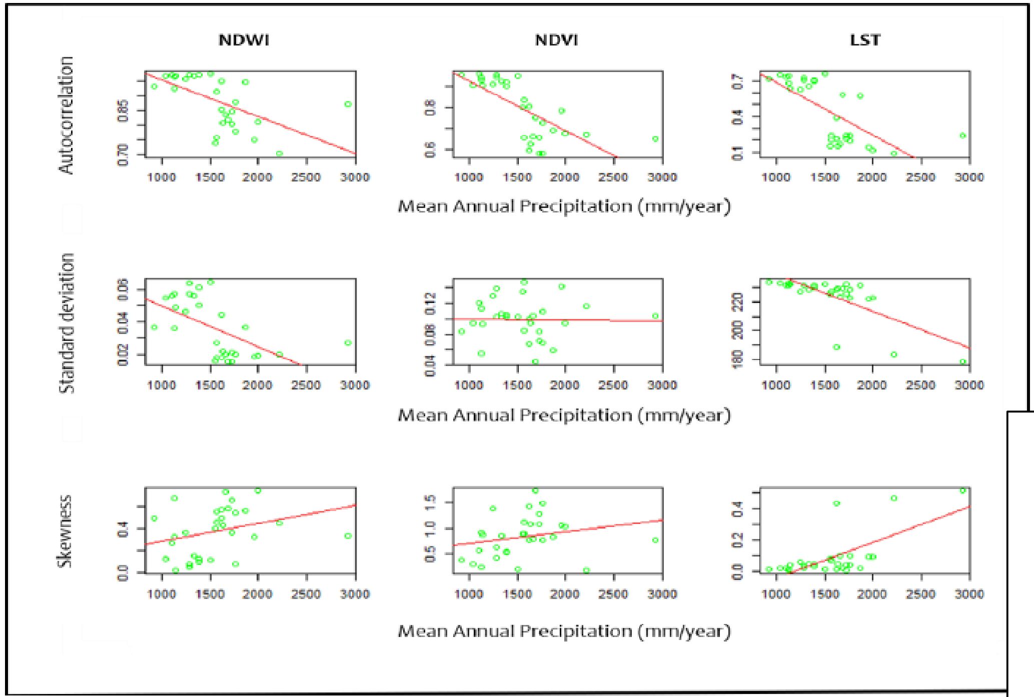


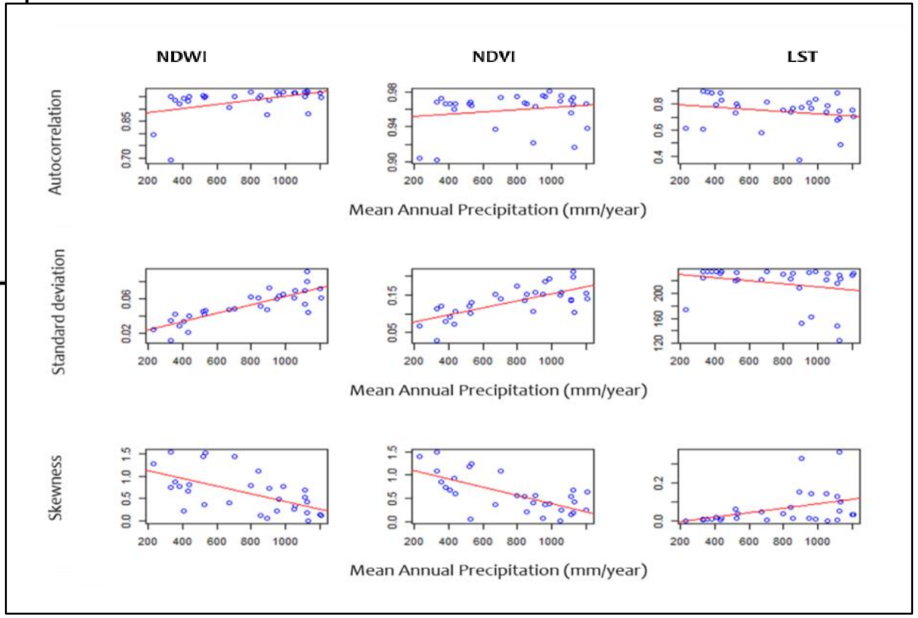
ARE THERE SIGNS OF BISTABILITY?





DO TIME SERIES BEHAVE AS WOULD BE EXPECTED?





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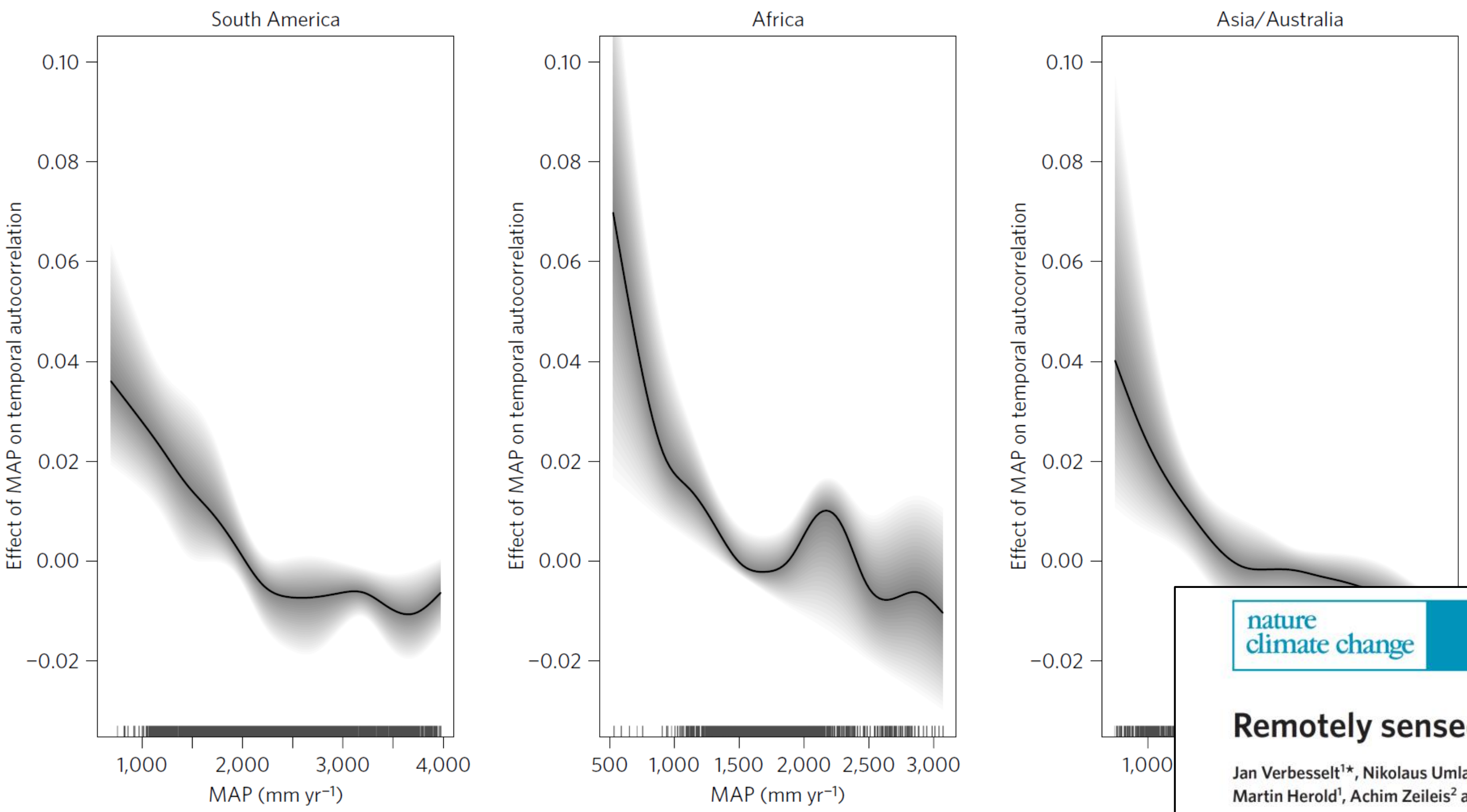

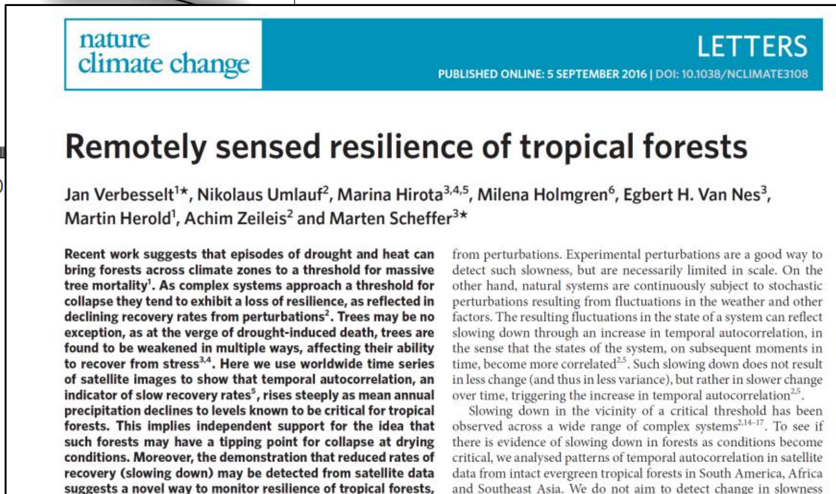
nature climate change
LETTERS
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Remotely sensed resilience of tropical forests

Jan Verbesselt[1]*, Nikolaus Umlauf[2], Marina Hirota[3,4,5], Milena Holmgren[6], Egbert H. Van Nes[3], Martin Herold[1], Achim Zeileis[2] and Marten Scheffer[3]*

Recent work suggests that episodes of drought and heat can bring forests across climate zones to a threshold for massive tree mortality[1]. As complex systems approach a threshold for collapse they tend to exhibit a loss of resilience, as reflected in declining recovery rates from perturbations[2]. Trees may be no exception, as at the verge of drought-induced death, trees are found to be weakened in multiple ways, affecting their ability to recover from stress[3,4]. Here we use worldwide time series of satellite images to show that temporal autocorrelation, an indicator of slow recovery rates[5], rises steeply as mean annual precipitation declines to levels known to be critical for tropical forests. This implies independent support for the idea that such forests may have a tipping point for collapse at drying conditions. Moreover, the demonstration that reduced rates of recovery (slowing down) may be detected from satellite data suggests a novel way to monitor resilience of tropical forests,

from perturbations. Experimental perturbations are a good way to detect such slowness, but are necessarily limited in scale. On the other hand, natural systems are continuously subject to stochastic perturbations resulting from fluctuations in the weather and other factors. The resulting fluctuations in the state of a system can reflect slowing down through an increase in temporal autocorrelation, in the sense that the states of the system, on subsequent moments in time, become more correlated[2,5]. Such slowing down does not result in less change (and thus in less variance), but rather in slower change over time, triggering the increase in temporal autocorrelation[2,5].

Slowing down in the vicinity of a critical threshold has been observed across a wide range of complex systems[2,14–17]. To see if there is evidence of slowing down in forests as conditions become critical, we analysed patterns of temporal autocorrelation in satellite data from intact evergreen tropical forests in South America, Africa and Southeast Asia. We do not aim to detect change in slowness

STABILITY DETECTION WITH RS

remote sensing

MDPI

Article

Remotely-Sensed Early Warning Signals of a Critical Transition in a Wetland Ecosystem

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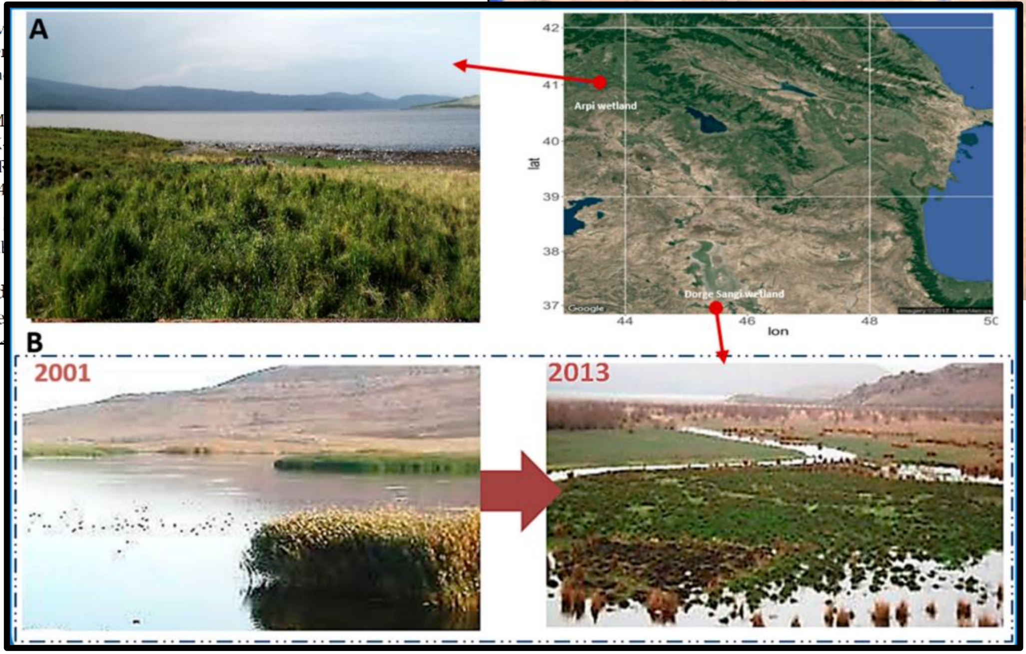
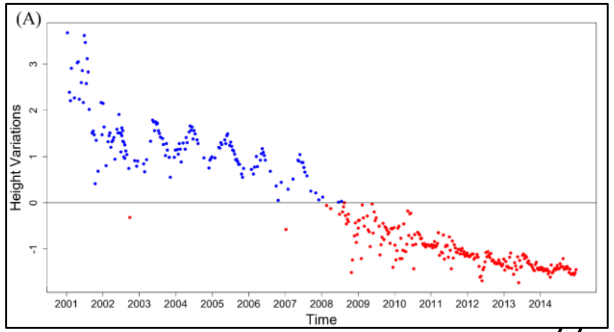
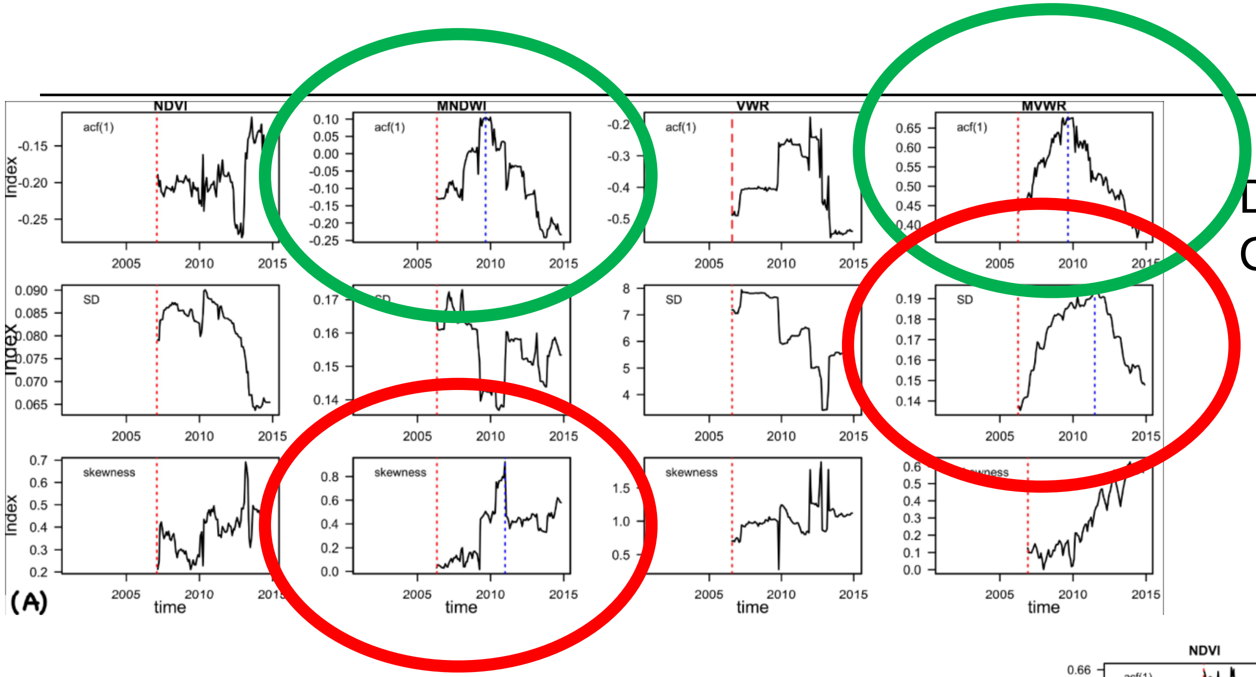
Abstract: The response of an ecosystem to external d
Discontinuous and sometimes irreversible change



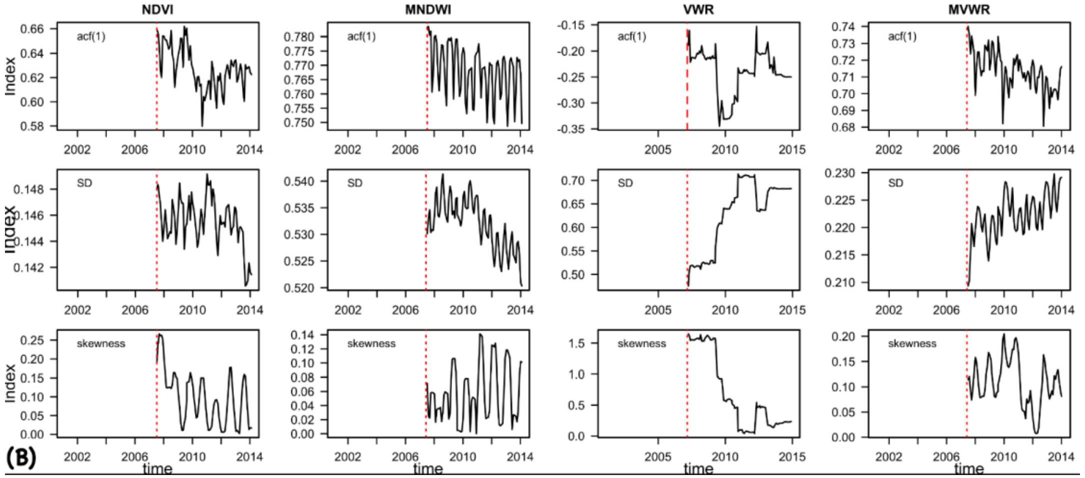


STABILITY DETECTION WITH RS

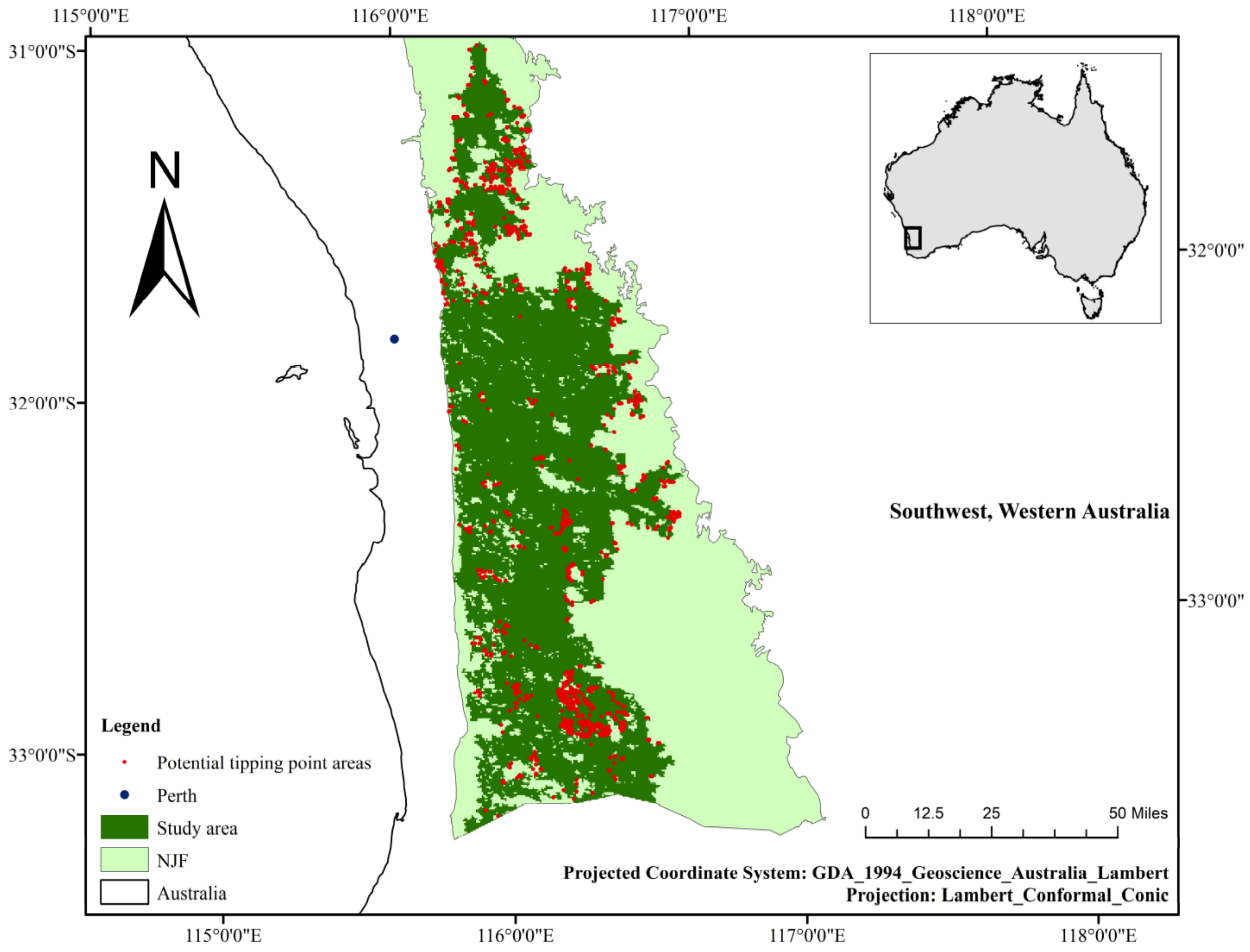


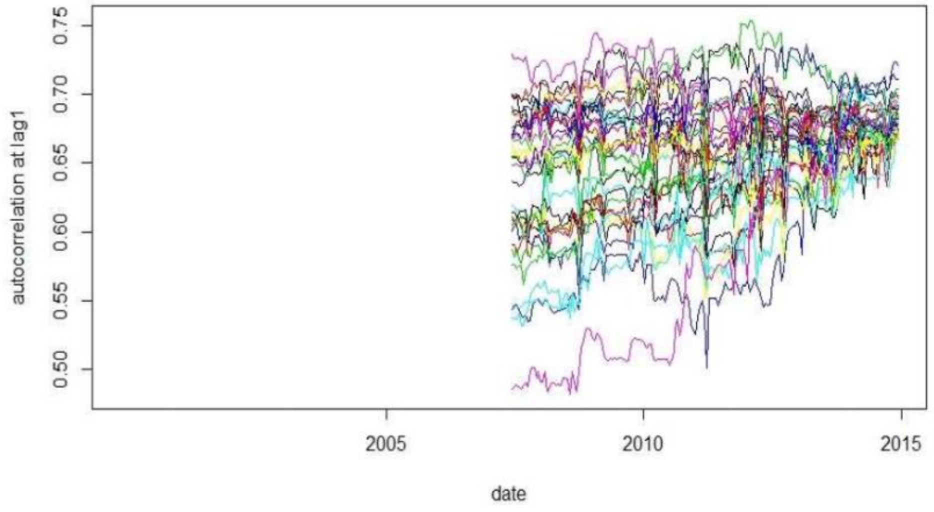
Dorge Sangi Wetland (Iran)
Converted into a vegetated state

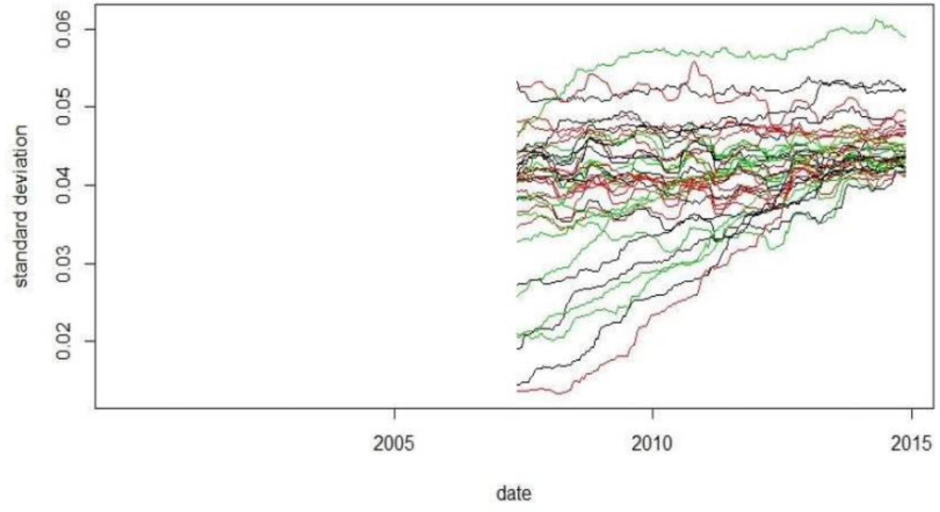
Arpi Wetland (Armenia)
Remained a wetland



WHAT CAN WE DETECT MORE







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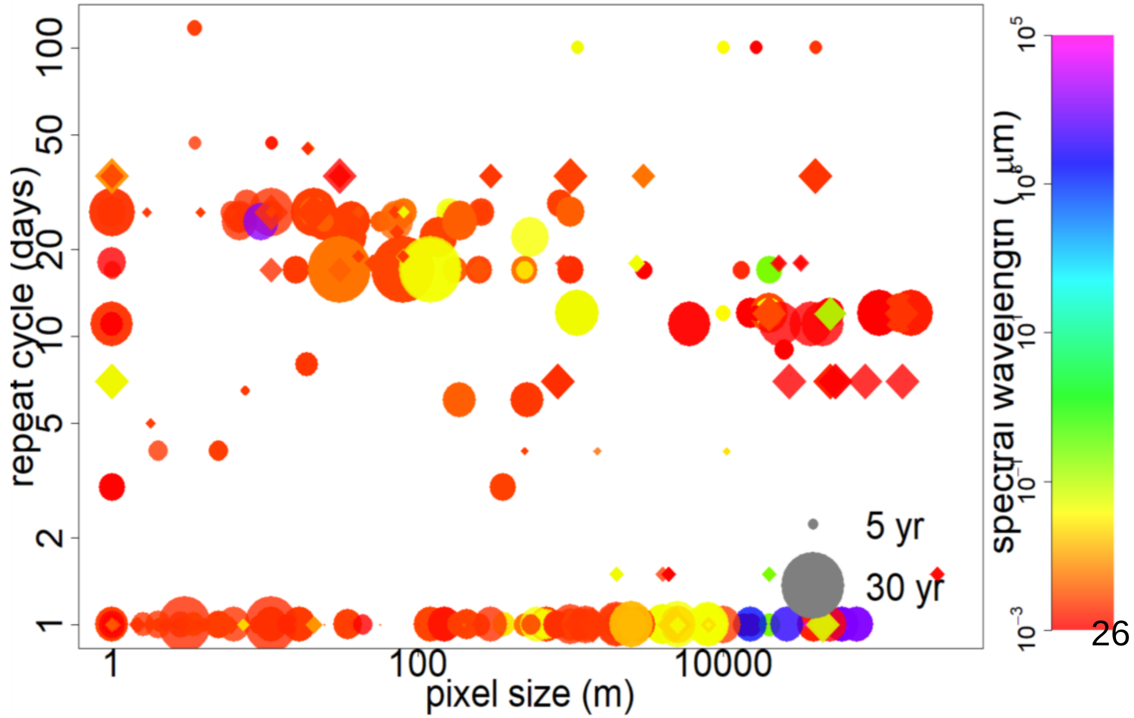
WHAT'S NEXT?

- When you know about collapsed ecosystems -> let me know!
- Optimize detrending
  - Trade off between cleaning data (applying SG filtering) and keeping the original signal
- Identify the best RS products to detect stability indicators



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THANK YOU FOR LISTENING