



Early Warning Signals Toolbox: A novel approach for Detecting Critical Transitions

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1 In a nutshell

Critical transitions have been identified in seemingly disparate systems ranging from ecology and climate to medicine and finance [1, 2]. Global finance occasionally suffers from market crashes [3], while asthma attacks [4] and epileptic seizures [5, 6] are examples of sudden medical systemic failures. Abrupt shifts in ocean circulation have occurred in the past climate [7] and may be triggered again under present trends of global environmental conditions [8]. Acknowledging the existence of such critical transitions is only the first step towards anticipating them. What we are currently lacking are efficient tools to quantify the probability of an approaching critical transition. As for most systems we neither have sufficient records of past transitions nor reliable models to study their behavior, novel approaches are urgently needed. Recent work has proposed an alternative, more generic way of approaching the forecasting challenge: instead of constructing case-specific models or indicators it is possible to assess the proximity to a critical transition by measuring the overall resilience of a system as suggested by complex systems theory on *Generic Early Warning Signals for Critical Transitions* [9].

Here, we present our newly developed **Early Warning Signal Toolbox** designed for **estimating** and **visualizing** fingerprints of upcoming critical transitions based on time series data. Our toolbox is characterized by three unique features: ***First***, it is of a truly generic nature and can be applied to any system that may undergo critical transitions. ***Second***, it is based on high-profile published, state-of-the-art methodology with already tested real-world cases [10, 11, 12, 13, 14, 15]. ***Third***, it is easy to use and developed under a popular open access statistical program (R Project for Statistical Computing¹).

In the next sections, we provide an intuitive explanation of the theory our toolbox is based on, we demonstrate the usage of the toolbox, and we highlight the opportunities it offers for the management of critical transitions in complex systems.

2 The Early Warning Signals - Theoretical background

2.1 Why should we expect Early Warnings before Critical Transitions?

A simple way to understand why we should expect early warnings before critical transitions is to think of the behavior of a system as the motion of a ball in a landscape of valleys and hilltops (Fig. 1a). Balls represent the state of the system, and valleys correspond to the basins of attraction of alternative stable states. The width and the steepness of the basin of attraction determine the capacity of the system to absorb a perturbation without shifting to an alternative state, and reflects the resilience of the state of the system. As conditions bring the system close to a critical transition (Fig. 1b), the basin of attraction of the current state of the system shrinks and so does its resilience: even a tiny perturbation is enough to shift the sphere to the alternative valley. At the same time, the steepness of the basin of attraction becomes lower: this means that the same perturbation that may not tip the system, it will definitely take longer to dissipate due to the phenomenon of ***critical slowing down*** (Fig. 1b). *Mathematically*, critical slowing down is connected to vanishing dominant eigenvalue of the system at equilibrium and close to the critical transition; this has been proven to be a universal phenomenon preceding critical transitions

[16, 17]. *Practically*, critical slowing down enables us to probe the dynamics of the system in order to assess its resilience and the risk of an upcoming transition. An increasing time required by a system to recover from a perturbation can serve as early-warning signal of an approaching tipping point ([18]; Fig. 1a1, b1).

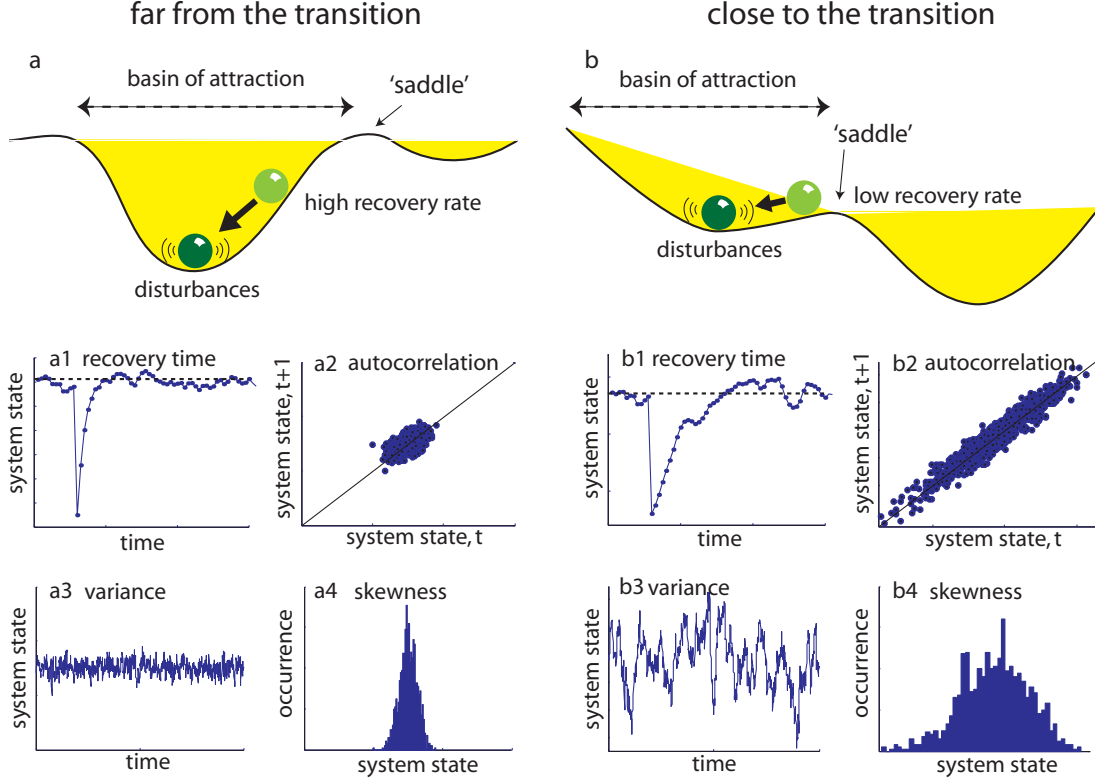


Figure 1: Early-warnings in the dynamics of a system as it approaches a critical transition. Far from the transition resilience is high (a): the system lies in a broad and steep basin of attraction. Small disturbances are damped by high recovery rates back to equilibrium. As a result the time to recover from perturbations is short (a1), the dynamics are characterized by low correlation between subsequent states (a2), low variance (a3), and low skewness (a4). Close to transition resilience is low (b): the system lies in a narrow and flat basin of attraction. Small disturbances are not effectively damped due to critical slowing down. As a result the time to recover from perturbations is short (b1), the dynamics are characterized by high correlation (b2), high variance (b3), and high skewness (b4).

2.2 What are Early Warning Signals?

While an increase in recovery time after a disturbance is the most direct indicator of the vicinity to a tipping point, for most natural systems it will be very difficult to measure. Take for instance the impossibility of conducting a perturbation experiment for measuring recovery time of the thermohaline circulation in the Atlantic Ocean. There is, however,

a way out. As all systems are permanently subjected to natural perturbations we may perhaps use these continuous disturbances to indirectly probe critical slowing down prior to a tipping point. Indeed, critical slowing down may lead, first, to an *increase in autocorrelation* [19, 20]: the state of the system today looks more like its state yesterday when it is close to a tipping point (Fig. 1a2, b2). Second, it may cause an *increase in variance* [21]: the state of the system will fluctuate more widely around its equilibrium. As perturbations accumulate and are not damped down sufficiently fast due to critical slowing down, variance will increase (Fig. 1 a3, b3). Also, the basin of attraction may become asymmetric close to a transition [9] (Fig. 1 a, b). Such asymmetry may cause the state of the system to spend more time in the flatter part of the basin that may lead to an *increase in skewness* [22] in the distribution of the monitored system state before a transition (Fig. 1a4, b4).

3 The Early Warning Signals Toolbox - Application

3.1 General characteristics

The Early Warning Signals Toolbox is designed to **estimate** and **visualize** a series of **14 characteristic indicators** that reflect the effects of critical slowing down in a system approaching a critical transition (Table 1) [23]. In particular, the toolbox:

- operates on time series collected by monitoring the state of a system that might undergo a critical transition. No other information than a time series is required.
- is generic and applicable to a wide variety of data sources, including temperature data, nutrient concentrations, microbial biomass, brain activity, stock market indices or similar.
- is applicable to both real world observations as well as simulations derived from models that are, for instance, developed to understand future scenarios, like climatic transitions, ecological shifts or social collapses.

Table 1: Indicators provided by the Early Warning Signals Toolbox

Autocorrelation at-lag-1	Autoregressive coefficient of AR(1) model
Return rate	Spectral density
Spectral ratio	Spectral exponent
Standard deviation	Coefficient of variation
Skewness	Kurtosis
Conditional heteroskedasticity	BDS test
Nonparametric drift-diffusion-jump models	Potential analysis

3.2 Using the toolbox - An example of tipping to overexploitation

Consider a managing institution of a harvested resource (be it grazing grounds, or fish stocks) that has been monitoring a resource and is concerned with the risk of a regime shift due to increased harvesting pressure. The manager has been collecting a time series of the resource and is aware of a slight decline in resource biomass (Fig. 2a), but it is difficult to assess the risk of reaching the point of no return at which the resource may tip to overexploitation. Thus, the manager is hesitant to restrict harvesting and start implementing a restoration program.

However, the manager has now at her disposal the *Early Warning Signal Toolbox*. The toolbox allows her to regularly run a *Quick Detection Analysis (QDA)* online on a personal computer to quantify the resilience of the system and the risk of approaching a tipping point. In this case, the manager finds out that after removing the slow declining trend in mean resource biomass (red line in Fig. 2Ai), the residuals (Fig. 2Aii) show a rise in autocorrelation and variance when estimated within rolling windows along the monitored time series (Fig. 2Aiii,iv). Interestingly, the estimated positive trends in the two indicators (0.914 for autocorrelation and 0.699 for variance) are alarming signals for a decline in the system's resilience and a potential tipping.

But how significant are these trends? From the drop-down menu of the **QDA**, the manager performs a trend significance analysis to test if the same trends estimated from the monitored data could be also found by chance. The significance analysis shows that the trend in autocorrelation is significant at a level below 0.05, and the trend in variance is close to being significant at the same level. The manager now has starting to have serious concerns that the resource is losing resilience and tipping may not be that far.

Could it be that the resource has also passed the point of no return and started moving to the overharvested alternative state? **QDA** offers the possibility to explore whether an alternative attractor has already appeared by performing a potential analysis. In this case, potential analysis does not support such conclusion (Fig. 2C). Still the resource is riding the current underexploited state. Perhaps the manager has still the chance to take action and avoid further undermining the resilience of the resource!

The above **Quick Detection Analysis** estimates the flagship indicators for the detection of critical transitions and is only part of the toolbox capacities (for the full functionality listing see 3.3). It does so, under an interactive environment (RShiny) that allows the user to directly perform the analysis without the need of knowledge of specific statistical packages. In detail, **QDA** performs three operations:

1. **Indicator trend analysis** of autocorrelation and variance along a time series based on sliding windows. The user can optionally log-transform or interpolate data (eg. if there are missing values or the data are unevenly spaced) (Fig. 2, Box 1), as well as filter the data using smooth, linear, or first-difference detrending from a drop-down menu (Fig. 2, Box 2). It is also possible to select the size of the sliding window (defined as a fraction of the time series length) (Fig. 2 upper panel, Box 3).
2. **Trend significant analysis** of autocorrelation and variance. Two drop-down menus allow the user to choose the number of surrogate datasets and the level of significance to control the (Fig. 2 middle panel, Box 4, 5).
3. **Potential analysis** for reconstructing the potential landscape of the system states, which helps to identify alternative attractors from the data. The user can choose the threshold for the detection of alternative attractors, the number of points to evaluate the potential, as well as a cutoff level for the visualization of the alternative attractors (Fig. 2 lower panel, Box 6).

Interested to know how **QDA** works for a real-world example? Select *real climate data* from the drop-down menu in xxx, and try to detect yourself the Earth's last climate shift from a cold period to the stable climate conditions as we know them today!

3.3 Resources

Apart from the toolbox, we have also made available a complete set of resources to understand the methodology, apply the tools, and encourage its further development. In particular:

- The toolbox is supported by a dedicated **Early Warning Signals website**² that hosts all theoretical and practical background information, original publications, case studies, and updates of the science around the theme of early warnings and critical transitions.
- The toolbox is developed and hosted in the widely-used open source statistical language **R**, which means that it is ready-to-use, constantly maintained, and fully documented^{3,4}.
- The development version of the toolbox is available under an open source license to download on any operating system. By hosting our project **github**⁵: an open-access, free-sharing platform that allows further contributions from the user community.

4 Potential impact and future perspectives

The **Early Warning Signals Toolbox** presents a state-of-the-art approach for detecting generic indicators of critical transitions in time series for a wide range of systems. Derived from a solid theoretical background and given the increasing availability of time series monitoring data (e.g. from tweeter, remote sensing, to high throughput data), the toolbox can provide a new perspective for anticipating and managing transitions in cases as diverse as fisheries, ocean circulation patterns, migraine attacks, psychological disorders, or social transformations. It is flexible, easy-to-use, open source, and designed on a community-based computing philosophy. Additionally, its interactive user-friendly character increases its potential for becoming a fast diagnostic test for expert as well as non-experts. For this

²<http://www.early-warning-signals.org>

³<http://cran.r-project.org/web/packages/earlywarnings/index.html>

⁴<https://github.com/earlywarningtoolbox/earlywarnings-R/blob/master/earlywarnings-manual.pdf>

⁵<https://github.com/earlywarningtoolbox>

proposal, we have demonstrated only part of the capacities of our toolbox. Our aim is to develop the complete content of the Early Warning Signals Toolbox into an interactive, ready-to-use interface. We hope that the WICC Data Challenge will offer us this opportunity.

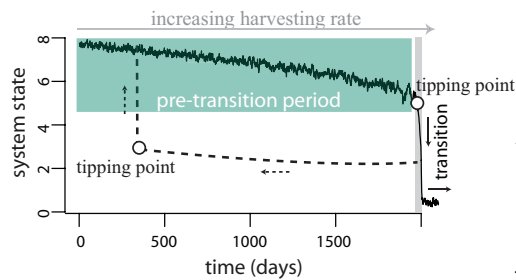
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Example 1: simulated data - overharvested resource



A. Indicator trend analysis

- 1 - interpolate data? ☐
- log-transform data? ☐
- choose filtering method:
 - no filtering
 - linear (@Leo dropdown menu)
 - gaussian
- rolling window size (in %) 3
- 0 100 (@Leo scrollbar)

B. Trend significance analysis:

- 4 - choose number of surrogate sets
50 100 200 500 1000
- choose level of significance
0.1 0.05 0.01

(@Leo dropdown menu)

C. Potential analysis

- 6 - cutoff level (from 0.01 to 0.5) ☐
- (@Leo fill in value)

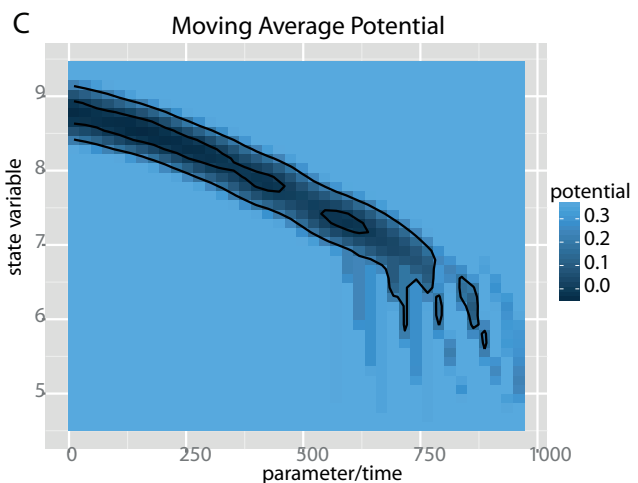
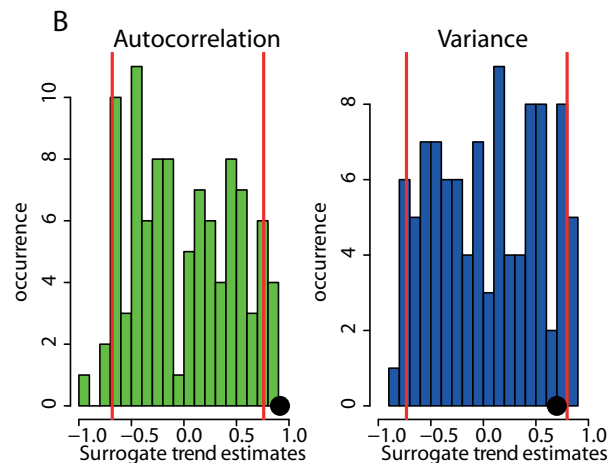
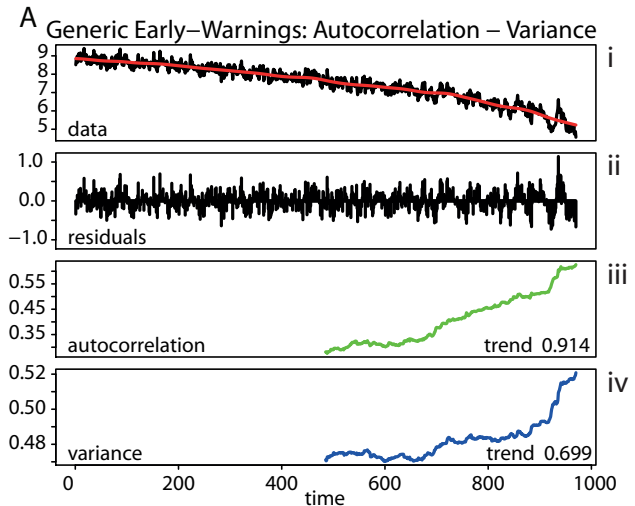


Figure 2: Demo Quick Detection Analysis in simulated data prior to shifting to overexploitation