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Predicting catastrophic shifts

Haim Weissmann*, Nadav M. Shnerb

Department of Physics, Bar-Ilan University, Ramat-Gan IL52900, Israel

HIGHLIGHTS

- Catastrophic shifts pose a threat to ecology, early warning indicators are needed.
- The tools suggested so far are aimed at predicting the tipping point.
- However in spatial system the transition occurs when alternative state invades.
- We suggest a cluster tracking technique to identify imminent shifts on spatial domains.
- This technique also distinguish between smooth and catastrophic transitions.

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ABSTRACT

Catastrophic shifts are known to pose a serious threat to ecology, and a reliable set of early warning indicators is desperately needed. However, the tools suggested so far have two problems. First, they cannot discriminate between a smooth transition and an imminent irreversible shift. Second, they aimed at predicting the tipping point where a state loses its stability, but in noisy spatial system the actual transition occurs when an alternative state invades. Here we suggest a cluster tracking technique that solves both problems, distinguishing between smooth and catastrophic transitions and to identify an imminent shift in both cases. Our method may allow for the prediction, and thus hopefully the prevention of such transitions, avoiding their destructive outcomes.

1. Introduction

The stability of ecosystems, and in particular the response of populations and communities to external perturbations, is one of the main topics in contemporary science (Müller et al., 2010). As an impact of anthropogenic changes (carbon emission, habitat fragmentation, introduction of non-indigenous species and pathogens) reaches the global scale, worries about their potential outcomes are growing (Dawson et al., 2011). Recently, there is an increasing concern about the scenario known as catastrophic regime shift, where a relatively small change in the environmental conditions leads to a sudden jump from one steady state to another (Scheffer et al., 2001, 2012). This change is often irreversible and accompanied by hysteresis: once the system relaxes to its new state, it will not recover even when the environmental conditions are restored.

One of the main topics considered in the context of catastrophic shifts is the possibility of a sudden extinction of populations as the environment varies (Drake and Griffen, 2010; Takimoto, 2009; Peters et al., 2012). For example, changes in solar radiation owing to variations in the Earth's orbit may have triggered the sudden mid-Holocene (5000 yr ago) desertification of the Sahara (Scheffer et al., 2001). The standard model used to describe this phenomenon involves nonlinear dynamics that supports two alternate steady states with a (backward) fold bifurcation (Scheffer et al., 2001; Rietkerk and Van de Koppel, 1997). This mechanism is illustrated in Fig. 1a, in which the various states of the system are shown for different values of the parameter α that stands for environmental *stress* (e.g. grazing, or

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* Corresponding author.
E-mail address: wchaimw@gmail.com (H. Weissmann).

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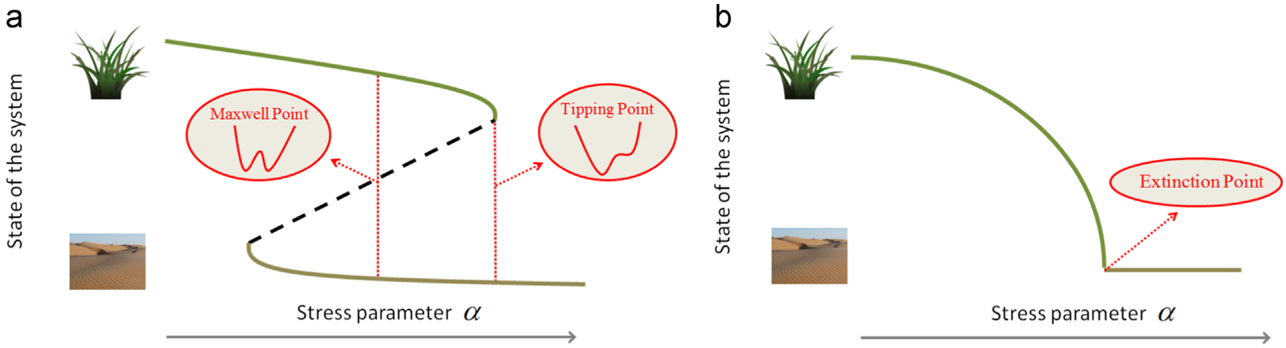

Fig. 1. Catastrophic shift vs. continuous transition. The generic features of a nonlinear system that supports catastrophic shift are illustrated in panel a (left). The two stable state (full lines, here one represents vegetation, the other bare soil) coexist for some region of the stress parameter α. The transition may take place at the tipping point (right dotted line), where the basin of attraction of the vegetation state (corresponding to the right well in the circled cartoon) vanishes, and its attractiveness (the curvature of the well) approaches zero. In spatial systems, on the other hand, large bare-soil clusters will invade vegetation to the right of the Maxwell point (left dotted line), where the stability of both alternate states becomes equal. Under disturbances, the transition takes place at the MP (Bel et al., 2012). A continuous transition scenario is illustrated in panel b (right), where vegetation went extinct as the stress keeps growing. The theory of extinction transitions of this type also suggests diverging spatio-temporal fluctuations at the transition point (Hinrichsen, 2000).

decreased precipitation). For certain values of α the system supports two stable states, one corresponds to vegetation, say, and another to bare soil. This bistability is related to the nonlinearity of the system and reflects a positive feedback mechanism (HilleRisLambers et al., 2001; Holmgren et al., 1997), such that vegetation grows above some critical density, while below this density the vegetation declines.

For such a system, with positive feedback and alternative steady states, the vegetation collapses from a finite value to zero once α crosses a critical value at the tipping point. Vegetation density by itself provides no indication to the distance of the system from the tipping point, therefore the search for early warning indicators that will allow one to predict an imminent transition has become a major research topic in the last decade.

Most of these efforts were focused on the phenomenon of critical slowing down, i.e., on the diverging sensitivity of the system to external perturbations in the vicinity of a tipping point (Eslami-Andergoli et al., 2014; Scheffer et al., 2009). This feature has, indeed, been demonstrated in recent experiments (e.g. Drake and Griffen, 2010; Dai et al., 2013; Veraart et al., 2012; Carpenter et al., 2011). Basically, the idea is to trace the rates at which the system recovers from spatial or temporal perturbations, and when these rates are becoming slower and slower, this will indicate that the system is approaching catastrophe.

However, a few recent studies cast a severe doubt about the relevance of these indicators to empirical ecological dynamics. First, critical slowing down and its consequences, like fat tailed or skewed patch statistics, do not necessarily indicate a tipping point or a discontinuous transition (Manor and Shnerb, 2008; von Hardenberg et al., 2010; Kéfi et al., 2007, 2010). These features are also a characteristic of continuous transitions, where the system changes its state smoothly and reversibly without any hysteresis (Kéfi et al., 2013; Eslami-Andergoli et al., 2014). A schematic illustration for such a scenario is given in Fig. 1b, where the increase in stress leads to a gradual extinction without bistability. Continuous transitions of this type characterize various generic ecological models, including logistic growth without an Alley effect and the susceptible–infected–susceptible (SIS) model for epidemics. In these cases, and under many other types of dynamics, the transition to extinction as the birth rate decreases is continuous with no sudden jumps, yet the response of the system to external perturbations becomes infinitely slow close to the transition point (see, e.g., Kessler and Shnerb, 2007; Kessler et al., 2008). A few recent studies, showing a non-hysteretic recovery from desertification when the external pressure (grazing, in most cases) has been removed (Fuhlendorf et al., 2001; Rasmussen et al., 2001; Valone et al., 2002; Zhang et al., 2005; Allington and Valone, 2010), also suggest that the transition is, at least in some cases, continuous and reversible.

Another line of criticism has to do with the effects of systems' spatial structure. When a system admits two stable states, local disturbances and fluctuations often generate patches of an alternate states, like regions of bare soil surrounded by vegetation and vice versa. As pointed out by Durrett and Levin (1994), in a spatial system the Maxwell point (MP, see in Fig. 1a) marks the boundary between two regimes: to the right of the MP, large patches of bare soil invade vegetation, while to the left of the MP vegetation invades bare soil. Accordingly, for the generic case of a spatial system with stochastic dynamics one should expect the transition to take place close to the Maxwell point, not at the tipping point (Bel et al., 2012). At the Maxwell point both states are stable, as seen in Fig. 1a, and there is no critical slowing down. Therefore, the early warning criteria which are based on the slow recovery of the system at the vicinity of the tipping point will fail to predict the crossing of the Maxwell point.

It may be instructive to draw an analogy to the physics of phase transition. A first order transition, like the process of water freezing as the temperature decreases, has also the features illustrated in Fig. 1a: under standard pressure water and ice are two alternative stable states of the system up to the tipping point at −48.3 °C, where the state associated with water loses its stability, and at the vicinity of this critical temperature the healing of fluctuations indeed slows down. But the actual transition in almost any practical situation happens at the melting point (which is the analogous of the Maxwell point) at $T = 0$ °C, when ice invades water. This happens because the system is spatial, and thermal fluctuations generate microscopic ice droplets that invade water below the melting temperature. In the same manner small bare soil patches will invade the vegetation to the right of the Maxwell point in Fig. 1a, meaning that under inevitable effect of stochastic perturbations (that generate these patches) the transition happens close to the Maxwell point, where indicators like critical slowing down are inefficient.

Here we would like to suggest a new method aimed at identifying the state of the system. Our method both distinguishes between continuous transitions and catastrophic shifts and provides a quantitative measure of the distance from the transition. This method is based on the monitoring of the cluster dynamics, and in particular the probability of a cluster to grow or shrink as a function of its size. It turns out that this technique reveals the