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*Correspondence: joern.fischer@uni.leuphana.de
(J. Fischer).

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Reference

1. Cumming, G.S. (2016) Heterarchies: reconciling networks and hierarchies. *Trends Ecol. Evol.* 31, 622–632

Forum

What Do You Mean, 'Tipping Point'?

Egbert H. van Nes,[1,*]
Babak M.S. Arani,[1]
Arie Staal,[1]
Bregje van der Bolt,[1]
Bernardo M. Flores,[1]
Sebastian Bathiany,[1] and
Marten Scheffer[1]

Over the past 10 years the use of the term 'tipping point' in the scientific literature has exploded. It was originally used loosely as a metaphor for the phenomenon that, beyond a certain threshold, runaway change propels a system to a new state. Although several specific mathematical definitions have since been proposed, we argue that these are too narrow and that it is better to retain the original definition.

The oldest reference to the metaphor 'tipping point' that we encountered was in studies about racial segregation, to denote the set of conditions that led to the rapid flight of the existing white majority class from neighborhoods in US cities in the 1950s [1]. For decades the term was used solely in this context. After 2000 the popularity of the term rose exponentially, especially in climate science, environmental sciences, and ecology (Figure 1). This sudden increase was most likely induced by the popular book *The Tipping Point* [2], published in 2000.

In this book Malcolm Gladwell describes various social examples, such as fashion trends and changes in criminality rates, where small initial changes led to a runaway process, causing big transitions. A more recent example is the bankruptcy of Lehman Brothers investment bank on 15 September 2008, initiating a global financial crisis [3]. Such relatively small events can accelerate in surprising ways as the transition unfolds. For instance, after Lehman Brothers fell, confidence in the stability of the financial systems was rapidly declining. The rising panic on the markets led banks to increase their liquidity, which contributed further to transmitting the crisis to other economic sectors [3]. In ecology there are also well-known

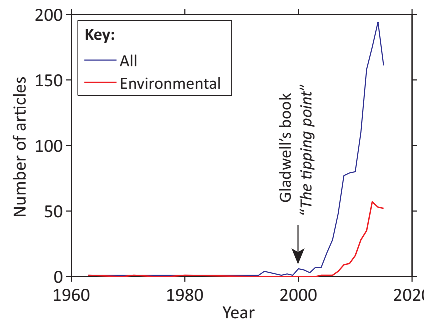

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Figure 1. The Recent Rise of the Term 'Tipping Point' in the Scientific Literature (Source: ISI Web of Science). The red line shows the number of articles that are labeled with the research field 'environmental science and ecology'.

examples of such self-propelled accelerating change. For instance, when tree mortality opens up the canopy of tropical forests, grasses might invade, increasing the chances of wildfires that subsequently

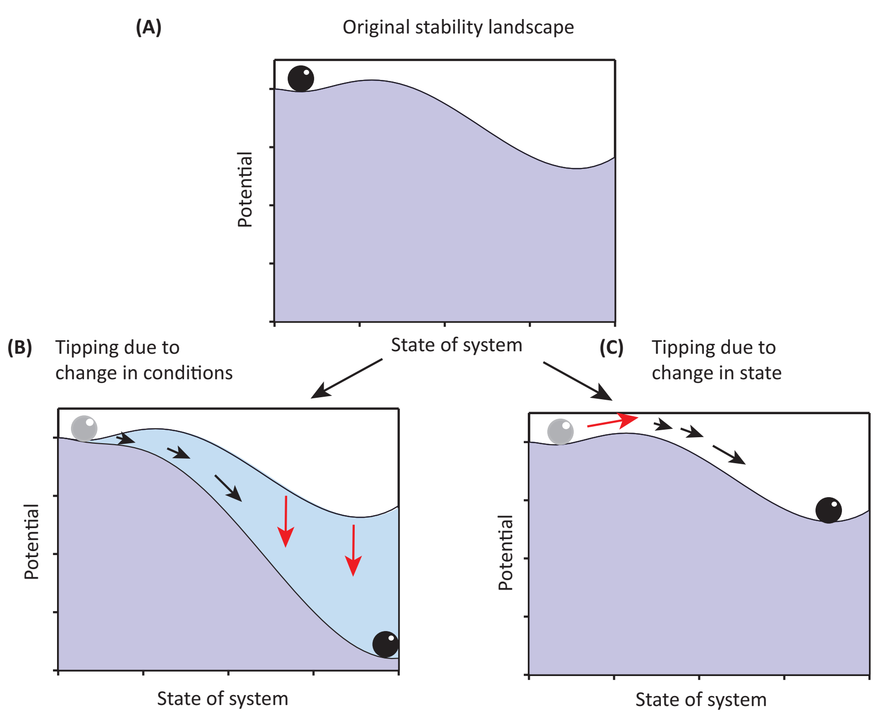

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Figure 2. Two Types of Tipping Points (after [10]). (A) The original potential landscape. (B) Change in external conditions until the current state becomes unstable in a bifurcation, and (C) change in state until the current state becomes unstable in an unstable equilibrium (or saddle point). Red arrows show how the system changes; black arrows show the accelerated change of the system. We used the well-known model of overgrazing $\frac{dx}{dt} = x\left(1-\frac{x}{K}\right)-c\frac{x^2}{x^2+H^2}$; where c = 2.1 or 1.7; H = 1; K = 10, and the potentials are calculated using the formula of Strogatz [12] (see also Videos V1 and V2).

kill more trees, allowing more grasses to come in, further raising the risk of fire and propelling the forest system to an alternative open savanna system [4]. Lake ecosystems are another famous example. As a specific case, consider the shallow Dutch Lake Veluwemeer. After many years of clear water, gradually increasing nutrient loads raised turbidity to a level that started to hamper the growth of submerged vegetation owing to a lack of light. Because loss of vegetation – through a range of mechanisms – leads to higher turbidity, this triggered a runaway change in the late 1960s to a murky state from which recovery was very difficult [5]. Although the mechanisms behind this lake story and the financial crisis are entirely different, they have in common that, once a threshold is passed, the dynamics of the system accelerate dramatically to cause a 'runaway change'. This corresponds well to phenomena characterized in Gladwell's popular book as 'that magic moment when an idea, trend, or social behavior crosses a threshold, tips, and spreads like wildfire' [2].

Two Different Ways of Tipping

Currently this loose definition is still commonly used in the scientific literature [6]. However, we also encountered two ways in which the definition has been narrowed down. The most common specification of the term is its use as a synonym for the mathematical concept of a catastrophic bifurcation (e.g., [7]) (Figure 2B). In these cases, the tipping point corresponds to a critical level of an external condition (e.g., nutrient inflow of a lake) where a system shifts to an alternative state. However, other authors have narrowed the definition down in different ways. For instance, in recent papers published in *Trends in Ecology and Evolution*, tipping points represent 'unstable equilibrium states, which are the peaks of the potential landscape' [8,9] (Figure 2C).

These specifications relate to two fundamentally different ways in which a system can move to another stable state [10] (Figure 2). A system can shift due to (i) a change in external conditions (which in models are represented by parameters), or (ii) a change in the state of the system itself (which in models is represented by state variables). In case of changed conditions, the resilience of the current state erodes until the system reaches a bifurcation point where one of both states becomes unstable and the system must shift to another state (Figure 2B; Video V1 in the supplemental information online). Because of the gradual erosion of the resilience of the current state, this type of tipping point can potentially be detected by the recently developed early warning signals (or resilience indicators) [7]. The other perspective of a tipping point is when the state of the system is perturbed such that the unstable equilibrium is reached (Figure 2C and Video V2). Such a state change can occur as a result of large stochastic mortality events in a population, caused for instance by a severe winter or a fire. Because this does not involve a change in the stability of the system, it represents a type of tipping point that cannot be anticipated using resilience indicators based on critical slowing down [7,9].

Positive Feedback Driving Accelerated Change as a Common Factor

In both families of cases (Figure 2B,C), once the threshold is passed, intrinsic processes in the system drive accelerating change. More specifically, the drivers of such acceleration are self-enforcing (or 'positive') feedbacks. Feedbacks are defined by DeAngelis [11] as processes where changes in the state feed back to the inputs, and are termed stabilizing (or negative) if they dampen change, and self-enforcing (or positive) if they magnify change. Note that the terms 'positive' or 'negative' are value-free in this definition.

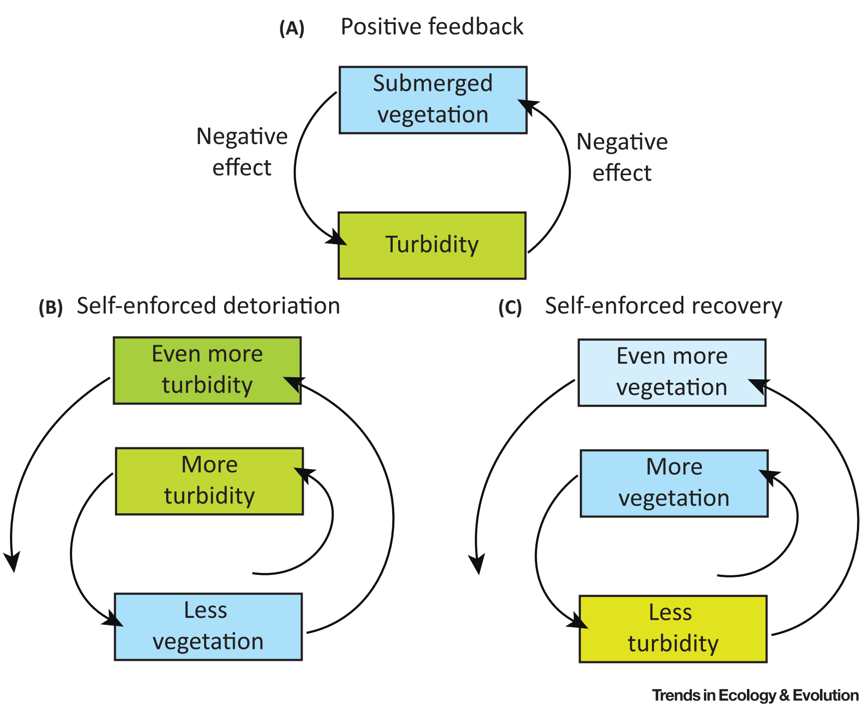

Figure 3. In Ecological Networks There Are Many Ways in Which a Net Positive (Self-enhancing) Feedback Can Arise, Even If All Individual Interactions in the Network Are Negative. An example is the feedback between submerged vegetation and turbidity in shallow lakes (A) [5], where vegetation has a negative effect on turbidity through many mechanisms and turbidity a negative effect on vegetation. The concept of feedback is value-free: positive feedback can sometimes even cause different transitions that can be either preferred by managers (C) or not (B).

They refer only to the net sign of the overall effect in the feedback loop, and do not express whether the resulting change is desired or not (Figure 3). Because positive feedbacks amplify small initial changes to large ones, they are responsible for the typical intrinsic runaway change that characterizes the behavior of a system when a tipping point is passed. This process can often be well understood and observed, as in the examples of racial segregation of neighborhoods, the financial crisis, and the shifts of lakes and tropical forests. By contrast, it is not obvious whether such situations correspond precisely to a saddle-node bifurcation, a basin-boundary crossing, or other well-defined mathematical scenarios. Using definitions that refer to different mathematical scenarios might obviously lead to confusion.

Therefore, we propose that the term 'tipping point' should simply be used for any situation where accelerating change caused by a positive feedback drives the system to a new state. If only a subclass of these phenomena is meant, we think it is better to mention that explicitly rather than to narrow down the term tipping point. Our proposed definition essentially boils down to the necessary conditions for Gladwell's examples where a small initial change makes a big difference. Last but not least, it is a beautiful thought that the exponential rise in the use of the term 'tipping point' upon the publication of Gladwell's book (Figure 1) corresponds to the very same phenomenon that fascinated him.

Acknowledgments

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Supplemental Information

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[1]Aquatic Ecology and Water Quality Management Group, Environmental Science Department, Wageningen University, Wageningen, The Netherlands

*Correspondence: egbert.vannes@wur.nl (E.H. van Nes).
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References

1. Grodzins, M. (1958) *The Metropolitan Area as a Racial Problem,* University of Pittsburgh Digital Research Library
2. Gladwell, M. (2000) *The Tipping Point,* Little, Brown and Company
3. Ivashina, V. and Scharfstein, D. (2010) Bank lending during the financial crisis of 2008. *J. Financ. Econ.* 97, 319–338
4. Hoffmann, W.A. *et al.* (2012) Ecological thresholds at the savanna–forest boundary: how plant traits, resources and fire govern the distribution of tropical biomes. *Ecol. Lett.* 15, 759–768
5. Ibelings, B.W. *et al.* (2007) Resilience of alternative stable states during the recovery of shallow lakes from eutrophication: Lake Veluwe as a case study. *Ecosystems* 10, 4–16
6. Lenton, T.M. *et al.* (2008) Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci. U.S.A.* 105, 1786–1793
7. Scheffer, M. *et al.* (2009) Early-warning signals for critical transitions. *Nature* 461, 53–59
8. Hodgson, D. *et al.* (2015) What do you mean, 'resilient'? *Trends Ecol. Evol.* 30, 503–506
9. Hodgson, D. *et al.* (2016) Resilience is complicated, but comparable: a reply to Yeung and Richardson. *Trends Ecol. Evol.* 31, 3–4
10. Beisner, B.E. *et al.* (2003) Alternative stable states in ecology. *Front. Ecol. Environ.* 1, 376–382
11. DeAngelis, D.L. *et al.* (1986) *Positive Feedback in Natural Systems,* Springer
12. Strogatz, S.H. (1994) *Nonlinear Dynamics and Chaos – With Applications to Physics, Biology, Chemistry and Engineering,* Addison-Wesley Publishing Company