Thresholds, tipping points and limits

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Introduction and State-of-the-Art

In the ecological literature the terms "threshold" and "tipping points" are often used synonymously. It is suggested to make a difference between the two here, considering **threshold** as the more generic term in the sense of the colloquial definition, which the Merriam Webster Dictionary defines as *"the point or level at which something begins or changes"* (Merriam Webster Dictionary online). Among "**ecological thresholds**" (the qualifier is important here), referring to ecological systems, some of them can be described as "**tipping points**". Tipping points are defined here as *"a point at which an (ecological) system experiences a qualitative change, mostly in an abrupt and discontinuous way"* (own definition) and subsequently use tipping point and *ecological* threshold largely interchangeably. In contrast to ecological thresholds, another type of thresholds important for conservation and resource management are (following the terminology of Johnson, 2013) **regulatory limits** – by some authors also called *decision thresholds* or *management thresholds*. Regulatory limits refer to points in some variable or state up to which a risk of system change is permitted or accepted (like in regulations of nitrate or pesticides levels in drinking water). While ecological thresholds are largely descriptive, regulatory limits involve societal choices and negotiation of values and aims.

The question of how these different types of thresholds are related and how they can be detected or determined first requires some further explanation of the concepts and the contexts in which they are used.

Thresholds and tipping points are discussed mainly in connection with the existence of multiple stable states (also called alternative stable states) of ecosystems and their functioning (Anderson et al. 2009), and/or their resilience. The concepts are used mostly with respect to natural systems but sometimes also for coupled ecological and societal systems (Scheffer, 2009).

The basic idea is depicted in Figure 1: Ecosystems respond to external changes in different ways. If the external driver (e.g. nutrient input or temperature) changes gradually, the ecosystem state may either respond gradually itself (a), e.g. by a slow change in relative species abundances or by a change in productivity. In this case, there are no tipping points involved for the properties observed that characterise the ecosystem state. In other cases, the response is abruptly (b, c), even though the external variable changes only gradually. While there is little response below a certain threshold value, a small change in the environmental condition will lead to a fast change of the system state once that threshold is crossed. Cases b and c, however, are decisively different. The system state in b (as well as in a) are easily reversible, in the sense that the way back to former states is the same as that to the new states (reducing the magnitude of the driver below the threshold value). In case c, however, the change is either is irreversible or at least not reversible on the original path. The latter phenomenon is called, **hysteresis,** meaning that the environmental factor which triggered the change has to be set back to much lower levels than that of the threshold for the "forward journey". There are thus different thresholds for system transitions in the different directions (T1 and T2 in Fig.1). Within the range of environmental conditions between these two thresholds (i.e. under the same environmental conditions), the system can persist in either state. A system transition with a hysteresis effect is also called "**regime shift**".

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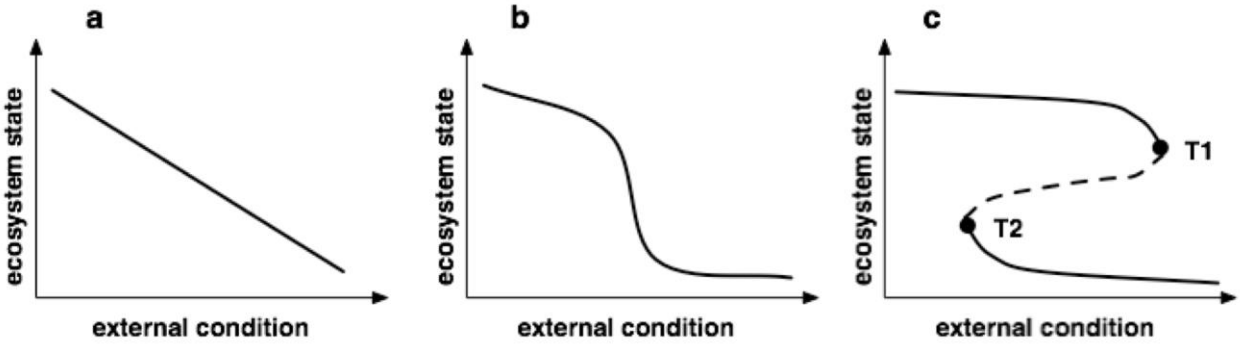

Fig. 1: Different types of ecosystem responses to changing external conditions (from Scheffer and Carpenter, 2003; copyright Elsevier 2003, reprinted with permission). See text for explanation.

The very general definition of a "tipping point" presented above was chosen to account for the differences of definition in the literature and therefore presents a more generic definition. Some of these definitions, for example, refer to ecological thresholds and tipping points only in case of irreversibility and hysteresis (i.e. only in case c), for others also b) constitutes a tipping point behaviour.

Some of these (ecological) threshold transitions (e.g. from oligotrophic to eutrophic states of lakes) appear to be rather evident. Yet, in detail, it often very difficult to determine if, when, and under what conditions ecosystems experience thresholds. The difficulties are partly due to a terminological muddle and conceptual difficulties, but it is also due to the unclear questions of defining reference states of ecosystems. Determining the functioning of an ecosystem by means of its ability to provide ecosystem services (e.g. Swift et al., 2004) is one possible option, and certainly the provision of ecosystem services often can change dramatically when an ecosystem moves beyond a tipping point (e.g. Crépin et al., 2012). But reference states might also be defined without reference to (potential) human uses, depending on the question of interest. Moreover, the question when a change in an ecosystem is just a gradual or marginal one, or when a tipping point for the whole system is reached is far from trivial (Jax, 2010). Questions that arise and which have to be answered in specific cases are, thus: How much difference between two system states is different enough ("qualitative change") to talk about a tipping point or even about alternative stables states? Which variables are relevant for describing the system's state (as not all properties of a system will shift abruptly at one time)? Which is the relevant temporal scale (also in terms of the meaning of "abrupt and discontinuous change" and "stable" states)? Is the tipping point a matter of internal dynamics of the system or of abrupt changes of external factors (see e.g. Anderson et al., 2009)?

Thus while the description and detection of ecological threshold requires methodological decisions of the observer, such thresholds are determined by properties of biophysical systems and are the objects of scientific research. *Regulatory limits*, in contrast, are also set by society (and specifically politics) on the basis of what is accepted as a risk, and/or to remain if a "safe operating space" (e.g. limits for nitrogen in drinking water as given in EU regulations), even in the absence of tipping points, or – if a tipping point exists – in cases of uncertainty about its precise position (see also the – contested – notion of planetary boundaries; Rockström et al., 2009). Ideally, the results of research on ecological thresholds should inform regulatory limits (Johnson, 2013), and especially in case of high risks and/or high uncertainty it would be wise to keep away from possible undesired tipping points ("precautionary principle"). This, however, always remains a matter of negotiation and of trading off societal risks and opportunities.

Significance to OpenNESS and specific Work Packages[2]:

In the OpenNESS DOW there are several references to tipping points and thresholds, and specifically task 3.1 and 3.2 are dealing with these concepts: *"Analysis of the data from the review will evaluate the feasibility of detecting possible thresholds where further biodiversity loss would severely compromise ecosystem functioning and service delivery."*

WP1 (Key challenges and conceptual frameworks): The relevance and possible operationalisation of ecological thresholds and regulatory limits must be scrutinised with respect to the four challenges of OpenNESS (see below).

WP2 (Regulatory frameworks and drivers of change): The influence of societal perceptions and decisions on tipping points, thresholds and (regulatory) limits, as well as the possible occurrence of biophysical thresholds and limits must be scrutinised with respect to existing regulatory frameworks and the use of ES and NC therein.

WP3 (Biophysical control of ecosystem services): see description of tasks 3.1. and 3.2 and quote from DOW above.

WP4 (Valuation of the demand for ecosystem services): Tipping points may be a limitation to economic valuation methods. How does evaluation of ecosystem services change when ecosystems suddenly change (by surpassing a tipping point)?

WP5 (Place-based exploration of ES and NC concepts): Case studies should give specific attention to the possible occurrence of tipping points and existence of regulatory limits relevant for the management of ecosystems and the provision of ES.

Open problems / Issues to be discussed

1) In general: How useful and necessary are the concepts of tipping points and other thresholds for tackling the challenges of OpenNESS, in which social and ecological contexts could they be useful and in which not?
2) What are the minimum requirements for operationalising the concepts (especially ecological thresholds; see also questions above)? Which aspects have to be defined and made measurable? On what scales?
3) What is the relation between scientific research and societal choices in determining ecological thresholds and even more regulatory limits, and what does this imply for the methodology of OpenNESS?
4) When might it be appropriate to look for thresholds at the level of the whole system, versus at the level or selected services?"
5) What is an adequate (political) procedure for setting regulatory limits in terms of ecosystem services?

Relationship to four challenges[3]

Human well-being:	**Sustainable Ecosystem Management:**
Conceptions of human well-being must take into account e.g. lower limits of human needs and vice versa define regulatory limits for minimal ES provision.	Must take into account ecological thresholds that influence ES provision and define limits of sustainable use.

[2] For a brief description of the OpenNESS Work Packages see: http://openness-project.eu/about/work-packages

[3] There are certainly more societal challenges; the reduced number presented here is due to the four major challenges mentioned in the work programme of FP7 to which OpenNESS responded.

Governance:	**Competitiveness:**
Governance mechanisms must take into account the consequences of possible occurrence of thresholds and assess the effects of policy setting regulatory limits.	Uncertainties about ecological thresholds can impede political decisions and planning processes, and thus competitiveness.

Recommendations to the OpenNESS consortium:

In general, it will be our task in OpenNESS to provide some clarity about the concepts and provide options for less ambiguous conceptualisations of tipping points, thresholds and reference states of ecosystems, NC and ES. It is recommended to use *threshold* in a generic sense as *the point or level at which something begins or changes* and in detail distinguish between *ecological thresholds (synonymus: tipping point)* and *management thresholds (synonymous: regulatory limits).* Ecological thresholds are defined here as *"a point at which an (ecological) system experiences a qualitative change, mostly in an abrupt and discontinuous way".* For more specific recommendations with respect to the definitions and to the WPs see above.

Three 'must read' papers

Andersen, T.; Carstensen, J.; Hernández-García, E. and Duarte, C. M. (2009): Ecological thresholds and regime shifts: approaches to identification. *Trends in Ecology & Evolution* 24: 49-57.

Crépin, A.-S., Biggs, R., Polasky, S., Troell, M. and De Zeeuw, A. (2012): Regime shifts and management. *Ecological Economics* 84: 15-22.

Scheffer, M. and Carpenter, S. R. (2003): Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology and Evolution* 18: 648-656.

Related papers and books

Huggett, A. J. (2005): The concept and utility of 'ecological thresholds' in biodiversity conservation. *Biological Conservation* 124: 301-310.

Jax, K. (2010): Ecosystem functioning, Cambridge: Cambridge University Press (Chapter 5).

Johnson, C. J. (2013): Identifying ecological thresholds for regulating human activity: Effective conservation or wishful thinking? *Biological Conservation* 168: 57-65.

Merriam-Webster online: *"Threshold."* Merriam-Webster.com, accessed 26 Sept. 2014. <http://www.merriam-webster.com/dictionary/threshold>.

Petraitis, P. S. and Hoffman, C. (2010): Multiple stable states and relationship between thresholds in processes and states. *Marine Ecology-Progress Series* 413: 189-200.

Rockström, J; Steffen, W.; Noone, K. et al. (2009): A safe operating space for humanity. *Nature* 461 (7263): 472-475.

Scheffer, M. (2009): *Critical transitions in nature and society*, Princeton, New Jersey: Princeton University Press.

Swift, M. J.; Izac, A. M. N. and Van Noordwijk, M. (2004): Biodiversity and ecosystem services in agricultural landscapes - are we asking the right questions? *Agriculture Ecosystems & Environment* 104: 113-134.

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Disclaimer: This document is the final version of the Synthesis Paper on the topic within the OpenNESS project. It has been consulted on formally within the consortium in 2014 and updated in 2016.