Accounting for complexity in resilience comparisons

A reply to Yeung and Richardson and further considerations

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Transferring any conceptual approach to real-world systems requires accounting for the complexity of real-world situations in an appropriate way. For conceptual clarity, in our recent paper [1] we adopted the simplest possible set of cases and (i) depicted the baseline state of an undisturbed reference system as constant, (ii) did not account for overshooting recovery responses, i.e. when during recovery from disturbance an ecosystem state exceeds that of an undisturbed reference system, and (iii) restricted our discussion to cases when disturbance leads to a reduction in ecosystem state. In the following, we will discuss for each of these points how more complex system behaviour can be considered in a bivariate resilience framework for addressing both science- and management-related questions. Finally, we demonstrate how a bivariate approach can be applied for identifying critical impacts, which lead to alternative stable states.

Shifting baselines

As pointed out by Yeung & Richardson (hereafter Y&R) [2], baselines are rarely constant in nature, given that the state of an ecosystem is continuously modified by the intrinsic dynamics of species and populations, and their responses to environmental fluctuations and ongoing global changes. For this reason, experimental studies assessing resilience (should) always include an undisturbed reference system as control treatment, which permits a monitoring of the baseline dynamics [3]. For observational studies the challenge for identifying shifting baselines is more profound [2] and a good understanding of an undisturbed system's behaviour is essential, ideally based on comprehensive long-term datasets, jointly with statistical analysis and modelling [4–6]. As such datasets are often not

available, many studies have been using pre-disturbance state for defining the baseline [7]. We agree with Y&R that one should caution against the unreflected use of pre-disturbance state as baseline. We also agree that the establishment of „desired working baselines“ [2] may be useful for identifying the proximity of an ecosystem state to a management target, but note that the resulting resilience metrics always need to be referenced against those derived from the true baseline, which is ultimately required for any coherent resilience comparison.

Non-linear and overshooting recovery responses

From a mathematical perspective resilience can be characterized by the maximum deflection of an ecosystem state by a disturbance (i.e. the amplitude or „maximum impact“, $I_{\max}$) and the area resulting from the difference between the disturbance response trajectory and the baseline (i.e. the „cumulative impact“, CI) (Fig. 1A). The smaller the maximum impact and the smaller the total cumulative impact (CI_T), the larger the overall resilience of a system.

The area covered during ecosystem recovery from $I_{\max}$ to the baseline (CI_R , i.e. area 2 in Fig. 1A) corresponds to what we termed „perturbation“ in [1] and is directly related to the mean recovery rate and the recovery time (Fig. 1D, see also [1]), in case there is no overshooting recovery response. CI_R does not assume any specific shape of the recovery response and therefore implicitly accounts for non-linearity resulting from changing recovery rates. We therefore suggest that an improved bivariate scheme uses cumulative impact as metric on the y-axis (Fig. 1D), and includes baseline-normalized CI_T , CI_R and CI_{RT} for each system to be compared. CI_{RT} depicts the total area covered during the recovery response and permits an immediate assessment of whether and to what degree an overshooting recovery response has occurred. If the recovery response does not overshoot the baseline, CI_R and CI_{RT} coincide (Fig. 1B, 1D).

Directionality of impact

Resilience reflects the ability of a system to minimize the overall impact of a disturbance (CI_T ; see Fig 1A), irrespective of the direction of the impact. Therefore the bivariate scheme for resilience comparisons (Fig. 1D) requires only the absolute values of maximum impact and cumulative impact. However, as pointed out by Y&R, it is useful both in a scientific and a management context to account for the fact that disturbances can lead to increases or reductions in ecosystem states. Furthermore, it is important to consider that an overshooting recovery response can reduce the net impact of a disturbance. For example, growth enhancement after grazing or extreme drought can lead to higher productivity and transiently higher post-disturbance biomass than in undisturbed grassland (Fig. 1B, trajectory α) [8]. As such overshoot responses can also influence the recovery debt (CI_{RT}) beyond the

measure suggested by Moreno-Mateos et al. (CI_R) [9], resilience studies should always monitor recovery responses well beyond the initial recovery of a system to the baseline state.

Fig. 1E demonstrates for four hypothetical response trajectories (shown in Fig. 1B) how the directionality of disturbance impacts and of overshooting recovery responses can be accounted for in a bivariate framework. By relating the negative or positive maximum impact to the net cumulative impact, this scheme can provide useful information for scientific and management-related questions. However, this scheme does not attribute important components of resilience, such as recovery rate, recovery time or overshoot responses. We therefore recommend a joint application of the bivariate schemes shown in Fig. 1D and 1E for consistent and informative resilience comparisons.

Partial recovery and alternative stable states

In case a system does not fully recover to the baseline state or displays a permanent overshoot it has reached an alternative (stable) state [10] (Fig. 1C), and is therefore not resilient by definition. The proximity of the state of such a permanently displaced system to the undisturbed reference system can nevertheless be depicted in a bivariate scheme, and is best related to the maximum impact of a disturbance (Fig. 1 F). Such a bivariate analysis may e.g. be useful for inferring critical impacts leading to tipping points and could bridge between the complementary perspectives of „engineering“ and „ecological“ resilience [1].

Figure 1: An extended bivariate framework for comparing resilience and its major components.

(A) Components of the response of a system state to disturbance, including (1) initial impact of disturbance until the maximum impact ($I_{\max}$) has been reached, (2) recovery from disturbance until the baseline state of the system has been first reached, (3) recovery responses overshooting the baseline state. Based on these components the total cumulative impact ($Cl_T = 1+2+3$), the total cumulative impact during recovery ($Cl_{RT} = 2+3$) and the cumulative impact during recovery until the baseline state of the system has been first reached ($Cl_R = 2$), as well as the net cumulative impact ($Cl_N = 1+2-3$) can be quantified. The system state (S_{base}) has been expressed relative to the baseline state of an undisturbed reference system and is thus 100% for the reference system also in the case of shifting baselines. t refers to time since the start of the disturbance.

(B) Hypothetical response trajectories of disturbance responses with complete recovery of the ecosystem state to baseline conditions, and without (a, d) or with (b, c) overshooting recovery responses, and with disturbance leading to an initial negative (a, b, c) or positive impact (d) on an ecosystem state.

(C) Hypothetical response trajectories of disturbance responses with complete (e) or incomplete ($f-h$) recovery of ecosystem state. t_s refers to the time after disturbance when a stable state has been reached.

(D) Bivariate scheme for a comparable quantification of resilience based on the maximum impact ($I_{\max}$) and the cumulative impact (Cl_R, Cl_{RT}, Cl_T , for symbols and definitions see Fig. 1A). In the case of complete recovery without overshoot ($Cl_R = Cl_{RT}$, trajectories a and d), the mean recovery rate and the recovery time can be derived from the scheme. Note that both for $I_{\max}$ and Cl the absolute values are used (see text).

(E) Bivariate analysis of the net cumulative impact (Cl_N) in relation to the maximum impact ($I_{\max}$), accounting for the direction of the impact and the recovery responses (trajectories $a-d$ in Fig. 1B).

(F) Bivariate analysis of the proximity of a post-disturbance stable state to the state of the undisturbed reference system, in relation to the maximum impact ($I_{\max}$). For explanation of t_s and for response trajectories $e - h$ see Fig. 1C.

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