Forum

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Feature Issue: Some Thoughts on Resilience

What do you mean, ‘resilient’?

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In a world beset by environmental disasters and anthropogenic disturbances, resilience might be the key to the persistence of natural systems. Yet, the ‘measurement’ of resilience is hampered by the multiple (and often conflicting) processes that yield the response of systems to insult. We recommend the simultaneous consideration of ‘resistance’ and ‘recovery’ as measurable components that together represent resilience.

The definition and measurement of resilience

Resilience is the capacity of a system to persist or maintain function in the face of exogenous disturbance [1,2]. Resilience resonates with the modern view that natural systems are pushed, pulled, and sometimes battered by disturbances that vary in structure, amplitude, and frequency [3]. Owing to the rise of this non-equilibrium paradigm in biology, resilience has become the focus of a growing proportion of ecological and evolutionary research, and is popular at the interface among conservation, engineering, and the social sciences [2,4]. A search of the ISI Web of Knowledge database reveals that the prevalence of ‘resilience’ as a keyword in peer-reviewed research papers has risen from 0% in the early 1970s to over 1% of all papers in the ‘Ecology’ scientific category. ‘Evolution’ lags behind at 0.2%, but in both categories the study of resilience is rising fast. Unfortunately, with popularity comes confusion, which hampers interdisciplinarity. Empiricists hope to measure what they study, and this has yielded a profusion of metrics and indices that are all called ‘resilience’ [5,6]. We argue that resilience cannot be captured in a single metric. However, the plural features that make some systems more resilient than others can be measured and have well-established names.

The confusion of resilience

Holling’s [1] classic exposition defined resilience to be the ability of a system to resist change in the face of disturbance, and stability to be the ability of a system to return to a stable state following disturbance. A contradictory view [5,7] is that resilience is the process of recovery following disturbance, not the ability to resist disturbance in the first place. Our own survey of recently published empirical studies suggests that resilience is commonly used to represent resistance, or recovery, or both. Resilience has come to mean so many different things that it must assume its broadest definition.

The components of resilience

When exposed to disturbance, systems vary in their ‘resistance’ and in their ‘recovery’. ‘Resistance’ describes the instantaneous impact of exogenous disturbance on system state, while ‘recovery’ captures the endogenous processes that pull the disturbed system back towards an equilibrium. The rate at which the disturbed system recovers is called ‘elasticity’ [5]. The duration of the journey from disturbed to stable state is ‘return time’. If alternative stable states exist, then ‘latitude’ describes the distance to a tipping point, past which the system will move, at a different rate, to a new stable state [2]. ‘Precariousness’ measures the distance from the disturbed state to the nearest tipping point [2].

Resilience of what, and to what?

We can measure ‘resistance’, ‘elasticity’, ‘return time’, ‘precariousness’, and ‘latitude’, as long as we understand the dynamics of the system. One might measure the level of disease exposure required to cause infection (‘resistance’); the rate of evolution of an exaggerated display trait when sexual selection is relaxed (‘elasticity’) [8]; how long it takes for primary forest to recover from hurricane damage (‘return time’); the magnitude of cull that flips a population beyond the Allee threshold [9] towards certain extinction (‘latitude’); or how close a disturbed coral reef is to tipping into an algae-dominated system (‘precariousness’) [10]. In any study of resilience it is crucial to (i) define and model the system; (ii) define and measure the system state that is at risk; (iii) define the stable states to which the system might recover; and (iv) define the magnitude, frequency, and structure of disturbance [11].

If the metrics of resilience can be measured, then we can compare resilience among systems. For a given exogenous disturbance, we might find that one system is more resilient because it recovers with high ‘elasticity’ and therefore low ‘return time’, while another is more resilient because it is more ‘resistant’.

The representation of resilience

It is common to represent the broad concept of resilience using a rolling ball analogy (Figure 1A) [2,12]. The state of the system is a flat base, while the vertical axis describes the potential of the system (ball) to move from one state to another [12]. If the slope is steep, then the ball appears

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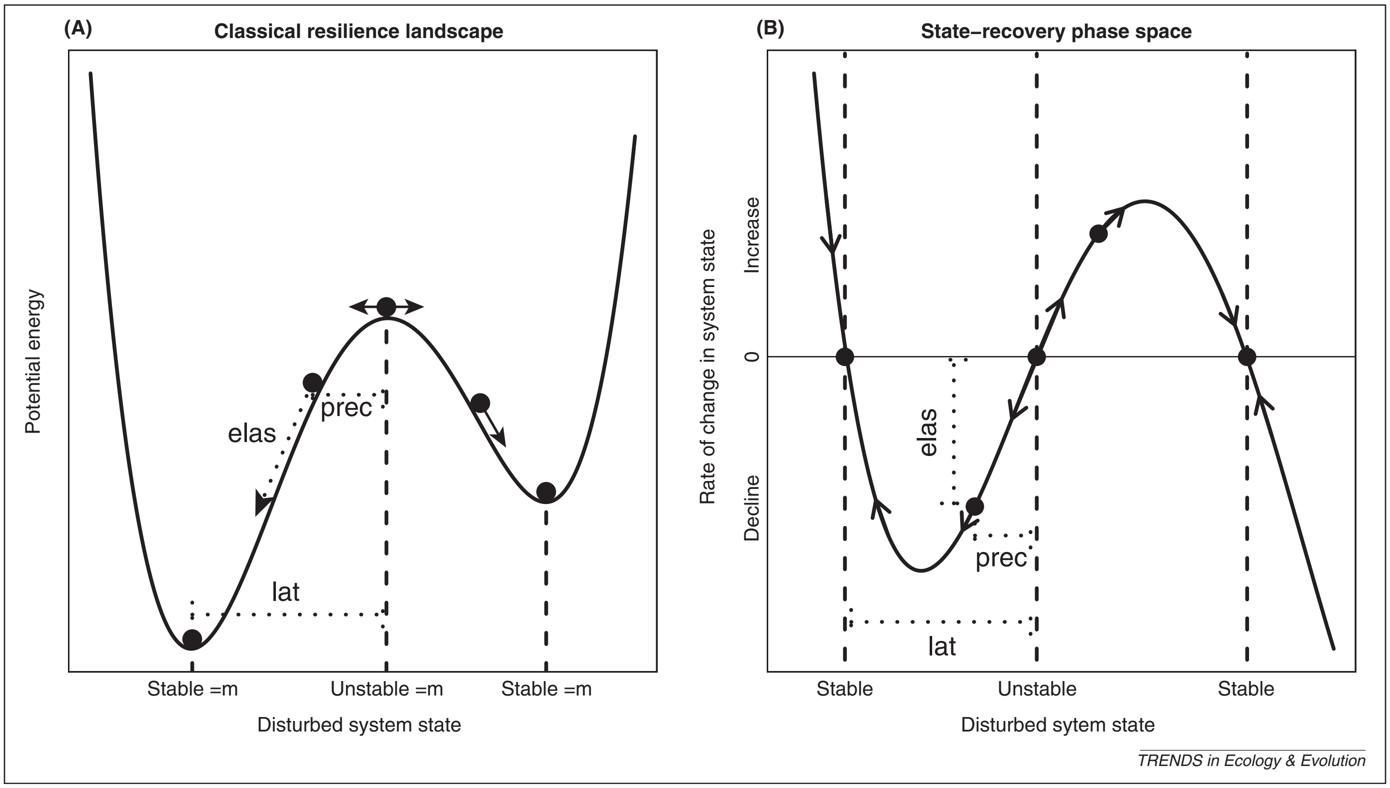

Figure 1. Classical representations of resilience landscapes. **(A)** Resilience is often plotted conceptually using a rolling ball analogy: each ball represents a disturbed system, and it rolls downhill owing to 'gravity'. If not further disturbed, the ball settles into troughs, representing stable states of the *x*-axis. Tipping points, representing unstable equilibrium states, are the peaks of the landscape. Each stable equilibrium (=m) has 'latitude' (lat: distance in state to the nearest tipping point), and each disturbed state has 'precariousness' (prec: distance in state to the nearest tipping point), and 'elasticity' (elas: rate of return to the local attractor equilibrium). **(B)** A more mathematical representation measures the rate of change in state of any disturbed system, yielding a recovery phase space. All equilibria sit on the line $y = 0$, but only some are stable attractors. Disturbed systems recover to their local stable attractor, and the axes allow simple measurement of 'latitude', 'precariousness', and 'elasticity'. However, neither representation describes the 'resistance' of the system to disturbance.

simultaneously resistant to disturbance and able, following disturbance, to recover quickly to its trough. We argue that the analogy helps to conceptualise resilience, but is not useful in application, for two reasons. First, while the resilience 'landscape' that the ball rolls across has a clearly defined base, the unit of measurement of the y-axis is much less clear. The only label we have found, 'potential energy' [12], makes some sense, but we defy any biologist to measure the 'potential energy' of a complex natural system. Another representation, familiar to engineers and ecological modellers, is a phase plot showing the rate of change of a system when disturbed away from an equilibrium (Figure 1B). Here, there is no ambiguity on the y-axis, although it requires deep understanding of the system, and its equilibria, to be modelled and parameterised.

Second, the use of a single resilience landscape suggests that the post-disturbance, endogenous dynamic of a system will mirror the instantaneous response to exogenous events. But, just because a system recovers quickly from disturbance does not mean it is resistant to disturbance in the first place. For example, elephants persist at low densities and have low reproductive potential. Their life history makes them resistant to disturbances but, if disturbed, their populations recover very slowly, suggesting a direct trade-off between 'resistance' and 'elasticity'. The 'latitude' and 'elasticity' components of resilience could also trade off against each other: if a system has large 'latitude', then there is little risk of tipping into alternative stable states, hence 'elasticity' can be sacrificed during evolution of the system. For example, it requires a substantial reduction in grazing to tip coral reefs into algal-dominated systems [10], but coral reefs have slow rates of recovery. There might also exist trade-offs between 'resistance' and 'latitude': the risk of tipping into an unfavourable state, imposed by small 'latitude', might be so great that the only systems that persist are those that are sufficiently resistant to disturbance.

We therefore suggest that the resilience of a system requires a new representation: first, of 'resistance'; second, of 'recovery'. The change in state caused by a disturbance will tend to rise monotonically with the magnitude of disturbance (Figure 2B), irrespective of the existence of alternative stable states. The instantaneous impact of disturbance then maps onto the 'recovery' landscape (Figure 2C): recovery is only possible if the system resists disturbance within the limits set by 'latitude'. If the system does recover to its pre-disturbance state, then its 'return time' will also increase with increasing impacts of disturbance on system state (Figure 2C). This yields a bivariate resilience space (Figure 2D) in which systems and disturbances can be represented and compared. When systems are disturbed beyond tipping points, 'return time' will cross a natural breakpoint, but this can still be measured and represented graphically (Figure 2C,D).

The future of resilience

Our aim here is to encourage better theoretical and empirical work on the topic of resilience. This requires recognition