Some conceptual and operational considerations when measuring ‘resilience’: a response to Hodgson *et al.*

Alex C.Y. Yeung¹ and John S. Richardson¹

¹Department of Forest and Conservation Sciences, the University of British Columbia, Vancouver, BC, Canada V6T 1Z4

Corresponding author: Yeung, A.C.Y. (alex.yeung@alumni.ubc.ca)

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Hodgson *et al.* [1] propose to represent the ‘resilience’ of natural systems bivariately, using ‘resistance’ and ‘recovery’ as quantifiable components. There has been a recent interest in simultaneously measuring two or more components of change in ecological units following disturbance [2,3]. However, it is of foremost importance to discern which components are being measured in these studies, given the previously unstandardized uses of ‘resistance’ and ‘resilience’ [4]. Their multiple meanings can cause terminological confusion in usage. For instance, the measure of return time by Hodgson *et al.* [1], and the capacity of the ecological units to bounce back after disturbance in the ‘resistance-resilience’ framework by Nimmo *et al.* [2], represent different aspects of ‘engineering resilience’ [4]. They differ from the capacity of the units to absorb disturbance to persist, which reflects ‘ecological resilience’ [5]. Key ecological processes and dynamics underlying resilience could vary remarkably among studies and ecosystems [6], and could greatly limit the utility of this approach for broad-scale comparisons and management purposes. Here we offer ecosystem- and disturbance-specific considerations when examining two or more independent components of change, so as to widen the scope of applying the concept of resilience (or ecological stability) in ecosystem management and restoration.

Ecosystem managers are nowadays concerned with the amount of disturbance that could cause an irreversible shift of an ecosystem to an undesired alternative stability domain, and the threshold(s) associated with it. These inherent properties could practically guide the setting of conservation and restoration targets, although they are mostly inferred from controlled experiments, or *in-situ* empirical measurements along a gradient of disturbance severity/history. The bivariate measure by Hodgson *et al.* does

not clearly indicate how close the ecological unit is to the nearest threshold (i.e. precariousness), which depends on both the magnitude of disturbance and the distance from original equilibrium. Therefore, for ecosystems with well-supported existence of alternative stable states or stability domains, such as coral reefs [7], shallow lakes [8] and savannah-forest systems [9], we suggest a mutual consideration of precariousness and the bivariate measure. A system with high precariousness should deserve particular attention, as it may be tipped into alternative stable states with a small amount of disturbance. Also, such a system is commonly predicted to require longer time to recover from small perturbations of the state – a phenomenon called ‘critical slowing down’ (CSD; also shown in Fig. 2C in [1]). Indeed, CSD-based indicators have been demonstrated to detect regime shifts in advance in some systems, which illustrate the practicality of this concept [6,10].

When adopting the bivariate measurement, we suggest a better characterization of any given exogenous disturbance on the system. The measurement is probably applicable for pulse disturbance, but not press and ramp disturbance if they remain persistent (e.g. spread of exotic species, dam construction, river channelization), since disturbance has to cease or become substantially alleviated for the measurement of return time [4]. It has to be made clear whether disturbance refers to changes in a particular abiotic/biotic variable, or natural (e.g. storms, wildfires, hurricanes) and human-related events (e.g. forest harvesting, pesticide application, bottom trawling) which can encompass multiple variables. For the latter, attention should be paid to the variables affected, and their possible non-additive interactions [11], because the change in state will not necessarily increase monotonically with the magnitude of disturbance.

The suitability of using the bivariate measure for comparative analyses across systems and fields of research is influenced by their past and present disturbance patterns. In addition to single disturbance events triggering the initial change of state, differences in disturbance regimes could affect the variability of recovery patterns. Recent evidence shows that the frequencies and intensities of past disturbances can mediate recovery rates from current disturbances [12]. Moreover, global environmental change and increased human activities often cause other co-occurring and/or subsequent disturbances. These additional disturbances can prolong recovery, and even cause baselines to be shifted, thereby inhibiting the system from returning to a 'truly' stable equilibrium state. For systems considered to exhibit only partial recoveries after disturbances, the measure of return time could be substituted by another component of change, such as the capacity to recover from disturbance (i.e. completeness of recovery) [2], to alternatively represent resilience. This representation does not need to assume full recovery, and would be more suitable for tracking the long-term resilience of systems affected by frequent, multiple disturbances (see Fig. 2 in [2]).

We welcome Hodgson *et al.*'s bivariate measure [1] which provides a new, easily understandable representation for monitoring changes in resilience. However, similar to other developed indicators of resilience [2,6], it cannot be relied on as a silver bullet approach. Rather, these indicators should be specifically tailored to the study systems and disturbances affecting them. Future efforts should address how a combination of these metrics, when available, can be applied to set quantifiable management and restoration targets to operationalize the concept of 'resilience management' [6].

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