Measuring resilience is essential to understand it

The terms sustainability, resilience and others group under the heading of 'stability'. Their ubiquity speaks to a vital need to characterize changes in complex social and environmental systems. In a bewildering array of terms, practical measurements are essential to permit comparisons and so untangle underlying relationships.

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Human population growth and aspirations for higher living standards lead to our overexploiting the land and oceans, disrupting the global climate and driving species to extinction. Ineluctably intertwined relationships between ecological, social, economic and political factors characterize these problems — a complexity that challenges our understanding of them. In the hope of gaining insights, various metrics synthesize complex changes among multiple variables seeking to permit comparisons across different kinds of measurements at widely different spatial and temporal scales. Like 'sustainability', 'resilience' is a widely used term, one of a myriad under the broad umbrella of 'stability'.

In recent decades, 'resilience thinking' has drawn attention in policy circles to the vulnerability of ecosystems — also broadly defined — and the need to include ecological approaches to management policies. Our first concern is that to address the stability of ecosystems requires a quantitative approach based on rigorous theory and empirical evidence. Secondly, we worry that for some, 'resilience' has turned into an ideology.

Of course, we agree with the need to define terms. What do studies mean by 'sustainability', 'resilience', 'integrity', 'healthy', 'stable', 'harmony', 'maintenance', 'persistent', 'vulnerability' and so on? Donohue et al.[1] review such terms and how different literatures use them. Their proliferation and, most importantly, a lack of clarity on their measurement lead to crippling disconnects. With measurements in hand, one can start to integrate what experimenters and theoreticians have learned about the various aspects of stability and their interrelationships. And with measurements, there is some chance of mutual dialogues with policymakers.

Pimm[2] tried to bring order to the confusing array of terms for 'stability' then in use in ecology by empiricists and theoreticians. That many others, including Grafton et al.[3], have felt the need to restate the problems and his terms, suggests he did not fully succeed. We welcome their attempt to clarify stability's various components and make them measurable and applicable in real-life situations. Their wish to "realize resilience" and their call for "better inclusion [of resilience] into decision-making" are laudable.

Unfortunately, they combine familiar, well-defined measures of stability — resilience and resistance — with new terms that lack precision and others that may be unmeasurable. Grafton et al. do not provide concrete examples of the measures' use and fail to specify the units with which to measure them. Having standard terms helps, but measurements are essential. Thus, they elude the various difficulties that appear once one makes measurements, as we now explain.

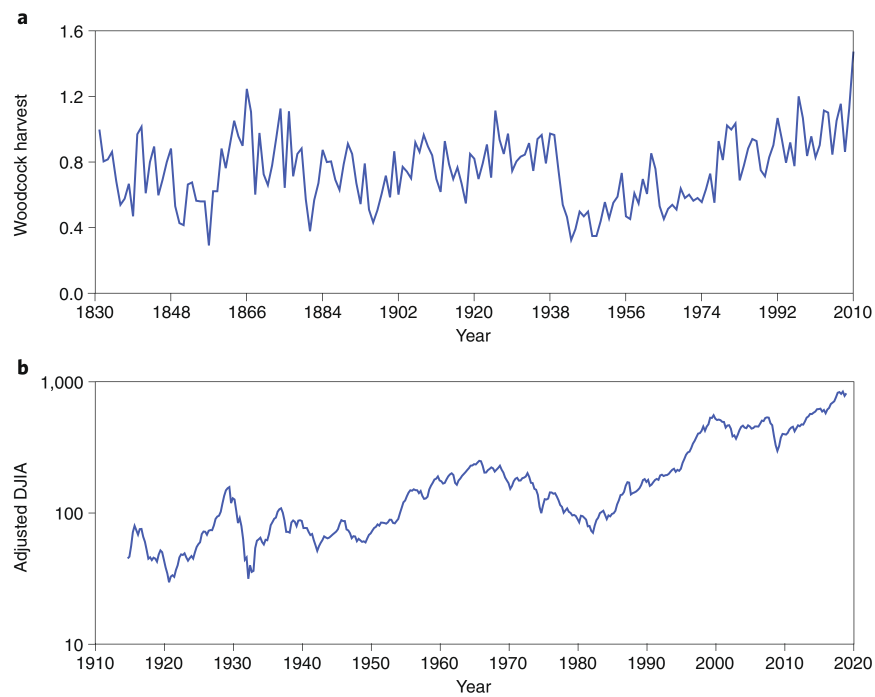

Fig. 1 | Changes in an index of the harvest of wintering woodcocks and the US stock index. a, The harvest of wintering woodcock *Scolopax rusticola* shot in the United Kingdom. **b**, Quarterly averages of the US stock index, the Dow Jones Industrial Average (DJIA), corrected for inflation. Episodic shocks appear in both series — a 35-year high in woodcock numbers in the exceptionally cold winter of 1962–1963, and the 1929 stock-market crash. Neither series demonstrate a clear equilibrium, nor even a consistent long-term trend punctuated by short, sharp shocks. Rather, there are from small to large changes operating over widely different time scales. Woodcock data courtesy of the Game & Wildlife Conservation Trust (https://www.gwct.org.uk/research/long-term-monitoring/).

Short, sharp shocks

Grafton et al. embrace a familiar but simplistic view of time series. In their idealized cartoon, 'system performance' fluctuates modestly about some clearly defined equilibrium for some time before a massive external shock hits it. For actual time series, this has numerous inadequacies. In what follows, we present ways to address these inadequacies, but they demand considerable care in their application. Unless one decides how and what one measures and for how long, one cannot surmount "the difficulty of operationalizing resilience".

Consider some examples: the stock market crashed following terrorist incidents in New York in 2001 and Madrid in 2004, the Deepwater Horizon oil spill in 2010, and various natural disasters[4]. Hurricane Katrina depleted human populations in New Orleans in 2005[5], a fungal disease (blight) devastated Ireland's potato crop in the 1840s which reduced the country's human population, and an exceptionally cold winter reduced British breeding bird populations in 1963[6].

In all cases, the external shock is manifest, and the metric is obvious: recovery times. These range from a few days to 'not yet' in the case of Ireland's population. Whatever one calls the measurements, the studies quoted were quite capable of generating insights without technical terms. We prefer 'resilience' since the Oxford English Dictionary (OED) records it has meant 'rebounding' since the seventeenth century. Even this obvious metric, however, shows bewildering complexity depending on the timescale considered[7].

Plotting actual stocks and populations over time uncovers the need for another, obvious metric. Some external shocks have more impact than others. The Dow Jones Industrial Average dropped 14% after the 2001 terrorist attack, 23% after the 1987 Black Monday crash, and 25% in two days in 1929. The Irish potato blight caused an 80% reduction in production and southern corn blight in the USA in the 1970s caused a 15% loss[8].

We consider these numbers to be measures of 'resistance' — again because resistance has meant "the act of opposing something" since the fourteenth century (OED). Once again, different literatures make comparisons without any standard language, but with numbers and explicit units.

The first complication is that resilience and resistance may be inadvertently conflated. One expects the recovery time to pre-shock levels to be longer when the system shows less resistance — the system has more ground to recover. A simple and intuitive approach is to calculate recovery time as a fixed fraction of the initial loss, analogous to the 'half-life' used to measure radioactive decay. It took seven trading days to gain back half of the initial stock-market losses from the 2001 event — from 14% to 7% — and 85 days after Black Monday. Simply, how one measures, matters.

Second, measures need not correlate: high resilience may not mean high resistance. Indeed, systems that are not resistant — they experience sharp shocks — may persist only because they are highly resilient — the recovery is short. (As it were, nature weeds out those systems that are neither resilient nor resistant.) Additionally, their values may differ dramatically within the same system depending on what variable one measures. In ecological communities, both theory and practice show that the resistance of total species abundance or biomass to external shocks may be greater in diverse communities than simple ones[9]. They achieve this, however, by showing much greater changes (that is, less resistance) in their species composition[6]. Simply, what one measures, matters.

Finally, eschewing empirical data, the figure of Grafton et al. overlooks a critical difficulty. We have provided clear examples of short, sharp shocks, but we cherry-picked them. Decades of time series of the stock market, centuries of animal populations, and millennia of the water levels in the River Nile do not show long periods of well-bounded numbers punctuated by sporadic, clearly defined disturbances.

Extensive studies[10] of environmental data confirm Pimm and Redfearn's[11] contention that "more time means more variation". Environmental time series have the characteristics of fractal noise. Put simply, this means there are small, frequent disturbances, upon larger, less frequent ones, upon even larger, even less frequent ones. Only rarely can we identify some external exceptional episodic events, with a return to clearly identifiable, prior conditions. The longer we consider a time series, the more it may move away from those 'prior conditions' and neat limits to the fluctuations about them.

The woodcock data in Fig. 1 show that the longer one studies the species, the less certain one is of any long-term equilibrium. The harvest depends on a multiplicity of factors unfolding across different time scales. The same is true of stock prices.

Certainly, to understand their stability, one can await large, external shocks to natural systems. Or one can impose them as experimenters. The more general solution is to specify robust measures. Variability — 'volatility' in stock-trading jargon — is an obvious one. It conflates what we call resilience and resistance and is indifferent as to whether one can readily identify distinct shocks amid the fractal noise. The nature of fractal noise, however, requires one to specify over what interval one would measure variability — for it increases continuously over progressively longer time series.

This fact also impacts discussions of 'sustainability'. OED's definition of sustainability as "continuing in a certain state for an extended period" suggests recording how long a measure remains within pre-set limits. Given that, with fractal noise, the longer one looks, the less likely a measure will remain within set limits. Simply, in comparing systems with robust measures, how long one measures a metric matters.

Avoiding the unmeasurable

Our second concern for why resilience thinking has not been operationalized so far is that it often embraces ideas that one cannot measure. Grafton et al. stress inherent system boundaries — tipping points — which, if transgressed, will lead to rapid environmental changes. This view echoes the definition of resilience used by Holling[12] and others.

That natural systems have what are called 'regime shifts' or 'tipping points' is undeniably appealing for theoreticians. But the evidence for them is relatively limited, they are hard or impossible to predict and, at the extreme, they lead to fanciful science and pernicious policies[13]. As a result, their use often borders on ideology.

Tipping points are theoretically possible, but their empirical demonstration requires careful measurement and analysis. The Intergovernmental Panel on Climate Change stakes the high ground, defining its terms carefully and presenting well-documented examples. Warming in the Arctic exposes more bare ground, which reflects less heat than ice, so warms more. Drying in the Amazon[14] dries the moist forest, making it more flammable, leading to more deforestation. These involve physical processes, where well-understood positive feedbacks drive rapid changes.

Physical feedbacks apart, recent reviews on the risk of regime shifts[15] give striking, but almost identical, empirical examples of threshold-driven responses in natural systems[16]. They include rapid transitions of coral reefs from being coral-dominated to algae-dominated. The former have high coral cover, are rich in species and appealing to ecotourists who snorkel or dive in them. The latter covered in green algae are otherwise. Other examples include shallow lakes changing from macrophyte dominance to phytoplankton dominance, of semi-arid landscapes from forested to unforested, and of coasts from kelp forests to barren rocks by changing trophic cascades.

In the same type of ecosystems, for example, semi-arid vegetation[17] and shallow lakes[18], others contest that these are regime shifts. Royama's detailed analysis of the spruce budworm[19] emphatically rejects this often-cited example of an ecosystem flipping between periods of low and very high numbers.

Rapid, large changes in numbers — even persistent ones — alone do not provide sufficient evidence of tipping points. For instance, massive collapses of fish stocks followed by a failure to recover may be a consequence of continued harvesting pressure on the species of concern, whether directly or as bycatch, or the evolution of life-history traits[20].

Grafton et al. stress that they are considering local scales. Even so, when thresholds exist at smaller scales, they cannot be objectively pre-determined for any complex system in the absence of models and experiments. We might detect them afterwards. Moreover, there may be early-warning signals that can indicate gradual movement towards a tipping point, but the exact location of the tipping point is unknown a priori. Thus, invoking them explicitly in measurements of stability is often unhelpful and uninformative.

More serious is the continued promotion of global biological tipping points in the literature[21]. Statements as recently as 2017 assert that planetary boundaries emerge from "massive amounts of data"[22]. This is not justified. Attempts to fix the original ideas continue a downward slide into measures with even less justification and absolutely no hope of quantification[13]. Global tipping points may be seductive to policymakers who wish to maintain 'business as usual' within imagined bounds and so avoid taking immediate action.

Inescapable lessons

The attempt of Grafton et al. to "integrate the three Rs [resistance, recovery and robustness] into a heuristic for resilience management [and] apply [it] in multiple management contexts to offer practical, systematic guidance about how to realize resilience" is at best incomplete. They do not confront their recommendations with data. Doing so would reveal the potential of confounding measures, the unexpected features ubiquitous in environmental time series, the need to move beyond the traditional implicit assumptions that the various dimensions of stability always correlate and that management has a single, well-defined objective.

Talk is cheap, but measurements are difficult. They are nonetheless essential if we are to manage our natural resources prudently. ❐

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