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Navigating the complexity of ecological stability

IAN DONOHUE^{1,2}, HELMUT HILLEBRAND³, JOSÉ M. MONTOYA⁴, OWEN L. PETCHEY⁵, STUART L. PIMM⁶, MIKE S. FOWLER⁷, KEVIN HEALY^{1,2}, ANDREW L. JACKSON^{1,2}, MIGUEL LURGI⁸, DEIRDRE MCCLEAN^{1,2}, NESSA E. O'CONNOR⁹, EOIN J. O'GORMAN¹⁰ & QIANG YANG^{1,2}

¹*School of Natural Sciences, Trinity College Dublin, Ireland*

²*Trinity Centre for Biodiversity Research, Trinity College Dublin, Ireland*

³*Institute for Chemistry and Biology of the Marine Environment, Carl von Ossietzky University Oldenburg, Germany*

⁴*Theoretical and Experimental Ecological Station, CNRS, UPS, Moulis, France*

⁵*Institute of Evolutionary Biology and Environmental Studies, University of Zurich, Zurich, Switzerland*

⁶*Nicholas School of the Environment, Duke University, Durham, USA*

⁷*Department of Biosciences, Swansea University, UK*

⁸*Environment Institute and School of Biological Sciences, University of Adelaide, Adelaide, Australia*

⁹*School of Biological Sciences, Queen's University Belfast, Northern Ireland*

¹⁰*Faculty of Natural Sciences, Department of Life Sciences, Imperial College London, UK*

Author emails: ID: ian.donohue@tcd.ie; HH: helmut.hillebrand@uni-oldenburg.de; JMM: Josemaria.MONTOYATERAN@sete.cnrs.fr; OLP: owen.petchey@ieu.uzh.ch; SLP: stuartpimm@me.com; MSF: m.s.fowler@swansea.ac.uk; KH: HEALYKE@tcd.ie; ALJ: JACKSOAN@tcd.ie; ML: m.lurgi@creaf.uab.es; DM: MCCLEADM@tcd.ie; NOC: n.oconnor@qub.ac.uk; EOG: e.ogorman@imperial.ac.uk; QY: QYANG@tcd.ie.

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Corresponding Author: Ian Donohue, School of Natural Sciences, Zoology Building, Trinity College, Dublin 2, Ireland. *Email:* ian.donohue@tcd.ie. *Telephone:* +35318961356. *Fax:* +35316778094.

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1 **Abstract**

2 Human actions challenge nature in many ways. Ecological responses are ineluctably complex,
3 demanding measures that describe them succinctly. Collectively, these measures encapsulate the
4 overall “stability” of the system. Many international bodies, including the Intergovernmental
5 Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), broadly aspire to
6 maintain or enhance ecological stability. Such bodies frequently use terms pertaining to stability
7 that lack clear definition. Consequently, we cannot measure them and so they disconnect from a
8 large body of theoretical and empirical understanding. We assess the scientific and policy literature
9 and show that this disconnect is one consequence of an inconsistent and one-dimensional approach
10 that ecologists have taken to both disturbances and stability. This has led to confused
11 communication of the nature of stability and the level of our insight into it. Disturbances and
12 stability are multidimensional. Our understanding of them is not. We have a remarkably poor
13 understanding of the impacts on stability of the characteristics that define many, perhaps all, of the
14 most important elements of global change. We provide recommendations for theoreticians,
15 empiricists and policymakers on how to better integrate the multidimensional nature of ecological
16 stability into their research, policies and actions.

17 **Introduction**

18 Species live in a web of prey and other resources, mutualists, competitors, predators, diseases,
19 and other enemies (Montoya *et al.* 2006; Bascompte 2009; McCann & Rooney 2009; Kéfi *et al.*
20 2012; Tilman *et al.* 2012). All encounter a profusion of diverse perturbations in their environment,
21 both natural and human-induced, that vary in their spatial extents, periods, durations, frequencies
22 and intensities (Tylianakis *et al.* 2008; Miller *et al.* 2011; Pincebourde *et al.* 2012; MacDougall *et*
23 *al.* 2013). These multifaceted disturbances precipitate a range of responses that can alter the many
24 components of ecological stability and the relationships among them (Donohue *et al.* 2013). This
25 complexity necessitates a multidimensional approach to the measurement of stability. We examine
26 the extent of our understanding of the multidimensional nature of both disturbances and stability.
27 We find that it is highly restricted. Consequently, our ability to maintain the overall stability of
28 ecosystems for different management and policy goals is limited. If ecology is to support and
29 inform robust and successful policy, we must rectify this.

30 At least three scientific communities use terms that map onto various dimensions of
31 ecological stability. Theoreticians, for example, have developed an extensive literature on whether
32 the population dynamics of multi-species systems will be asymptotically stable in the strict
33 mathematical sense (May 1972; Thébault & Fontaine 2010; Allesina & Tang 2012; Rohr *et al.*
34 2014), or resilient, in the sense of a fast return to equilibrium following a small disturbance (Pimm
35 & Lawton 1977; Okuyama & Holland 2008; Suweis *et al.* 2013), and other well-defined measures
36 (see, for example, Pimm 1984; McCann 2000; Ives & Carpenter 2007). Empiricists observe and
37 manipulate natural systems or variously perturb experimental ones to measure ecological responses
38 in constant or naturally changing environments (Tilman *et al.* 2006; O’Gorman & Emmerson 2009;
39 Grman *et al.* 2010; Carpenter *et al.* 2011; de Mazancourt *et al.* 2013; O’Connor & Donohue 2013;
40 Hautier *et al.* 2014). Finally, many international bodies concerned with environmental conservation
41 aspire to maintain, protect, and sustain nature and avoid altering and degrading it, all for informing

42 decision makers and aspiring to enrich people's lives and well-being (Mace 2014; Díaz *et al.* 2015;
43 Lu *et al.* 2015).

44 We explore whether the associated three scientific literatures engage each other in using the
45 same terms and employ the same meanings for them when they do. Generally, they do not. We
46 must remedy this. International bodies need terms that are simple and flexible, but surely not to the
47 point of being meaningless. Theory cannot advance usefully in isolation from tests of it (Scheiner
48 2013), and theory, experiment, and observation must sensibly inform decision makers at all levels.
49 Most importantly, the multidimensional complexity of natural responses to environmental change
50 needs to be recognised by all communities, both separately and collectively.

51 We suggest solutions to help achieve these goals. For theoreticians, we provide suggestions
52 on where to focus future research to incorporate the sort of complexities commonly encountered in
53 natural systems. Empiricists will find useful our summary of the methodologies developed so far to
54 study the different facets of ecological stability and our recommendations for better assessing
55 stability in collaboration with theoreticians and policymakers. Finally, we provide suggestions for
56 environmental policymakers on how to develop and frame objectives and targets that are not only
57 relevant for policy but at the same time facilitate much closer links with the supporting, and
58 evolving, science.

59

60 **The multifaceted nature of disturbances and ecological responses**

61 Disturbances are changes in the biotic or abiotic environment that alter the structure and
62 dynamics of ecosystems. Although they occur at a variety of scales and vary in their direct and
63 indirect effects on species, all disturbances comprise four key properties; their magnitude, their
64 duration, their frequency and how they change over space and time (Sousa 1984; Benedetti-Cecchi
65 2003; García Molinos & Donohue 2011; Pincebourde *et al.* 2012; Tamburello *et al.* 2013). The
66 magnitude of a disturbance is defined by how much the aspect of environmental change departs
67 from its undisturbed state (*i.e.* “*a measure of the strength of the disturbing force*”; Sousa 1984). A

68 minor storm versus a once in 100-year hurricane is an example of disturbances that vary in
69 magnitude. Their duration refers to a continuum with instantaneous pulses — short, sharp
70 shocks — and sustained presses — constant, long-term change — at the ends of the spectrum (Fig.
71 1a). A discrete pollution event, such as a chemical spill, is a pulse, and the extinction of a species
72 from an ecosystem is a press. Theoreticians focus primarily on one of these two extremes of the
73 duration gradient (Ives & Carpenter 2007). Empiricists sometimes refer to these extremes as acute
74 and chronic disturbances, respectively.

75 Natural disturbance regimes are clearly more complicated than this. Changes in the
76 magnitude, duration and frequency of disturbances over time or in space can combine to give
77 disturbances directionality (Fig. 1b). Directionality measures the trajectory of change, which can be
78 highly dynamic and variable in terms of its mean and variance. Both can elicit distinct ecological
79 responses (Bertocci *et al.* 2005; Benedetti-Cecchi *et al.* 2006; García Molinos & Donohue 2010,
80 2011; Pincebourde *et al.* 2012; Mrowicki *et al.* 2016). Many of the most globally important
81 disturbances in nature are of this kind (Fig. 1c). Therefore, while a focus on pure pulse or press
82 disturbances provides some important insight into mechanisms that can underpin biological
83 responses to disturbances, the relevance of this to predicting responses to real disturbances in the
84 natural world may be limited.

85 While the multifaceted nature of disturbances creates a problem for assessing, understanding,
86 and predicting how ecological systems respond (García Molinos & Donohue, 2010; Mrowicki *et al.*
87 2016), the ecological responses themselves are also complex. Ecological stability is a
88 multidimensional concept that tries to capture the different aspects of the dynamics of the system
89 and its response to perturbations. Pimm (1984) reviewed five components of ecological stability
90 that are in common use. *Asymptotic stability* is a binary measure describing whether a system
91 returns asymptotically to its equilibrium following small disturbances away from it. One measures
92 *variability*, the inverse of stability, as the coefficient of variation of a variable over time or across
93 space. *Persistence* is the length of time a system maintains the same state before it changes in some

94 defined way. It is often used as a measure of the susceptibility of systems to invasion by new
95 species or the loss of native species. *Resistance* is a dimensionless ratio of some system variable
96 measured after, compared to before, some perturbation. *Resilience* is the rate at which a system
97 returns to its equilibrium, often measured as its reciprocal, the return time for the disturbance to
98 decay to some specific fraction of its initial value. Systems with shorter (faster) return times are
99 more resilient than those that recover more slowly. Holling (1973) introduced another definition of
100 resilience that is currently in common use, particularly in policy fora (Walker *et al.* 2004; Hodgson
101 *et al.* 2015). It “*is a measure of the persistence of systems and of their ability to absorb change and*
102 *disturbance and still maintain the same relationships between populations or state variables.*” This
103 definition is multidimensional. It integrates persistence, resistance and the existence of local
104 asymptotic stability at multiple equilibria. It has come to mean whether or not a system returns to
105 its former equilibrium following disturbance or moves to another one. This idea may be expanded
106 further to compare systems in terms of what range of disturbances a system can withstand before
107 being shifted to a new equilibrium (Ives & Carpenter 2007). If there is a limit beyond which a
108 system cannot return directly to its former state, this is termed a *tipping point*.

109 The different components of stability are all based in some way on the composition, function
110 and dynamics of communities. They are unlikely to be independent. Furthermore, the strength and
111 even the nature of relationships among stability components can change when communities are
112 disturbed in different ways (Donohue *et al.* 2013). This complexity has critical implications for our
113 understanding of the impacts of disturbances on ecosystems. It means that restricting our focus to
114 single measures of stability in isolation, or to amalgamated ones such as Holling’s resilience, when
115 they are used to reduce the multidimensional complexity of stability to a single dimension and its
116 measurement to a single number, risks significantly underestimating the impacts of perturbations. It
117 also risks incomplete understanding of the mechanisms that underpin the overall stability of
118 ecosystems. The multidimensionality of ecological responses demands explicit multidimensional
119 measurement of both disturbances and stability.

120 The definitions of the various components of stability all come with underlying assumptions
121 about the nature of ecosystems and the disturbances that affect them. Measures of variability, for
122 example, commonly assume the presence of stationary fluctuations [*i.e.* without an underlying
123 directional trend (Tilman *et al.* 2006; Loreau & de Mazancourt 2013)]. The ecological definitions of
124 resilience (Quinlan *et al.* 2016) argue for different worldviews, one where a single equilibrium
125 dominates, the other where two or more equilibrium domains are possible, with tipping points
126 between them. The Aichi Targets (UN 2010) that consider “safe ecological limits” may invoke the
127 latter view, as do related concepts, such as planetary boundaries, that are the subject of considerable
128 debate (Box 1). Other definitions may read into a simpler notion of, for example, preventing
129 overexploitation. Irrespective of definitions, theoretical studies of stability are generally based on
130 the dynamics of communities at, or very close to, some form of equilibrial state. Given the highly
131 dynamic nature of the natural world and the strong directionality of many elements of global
132 change, this limits the applicability of existing theory to the real world and creates significant
133 challenges for empiricists trying to test its predictions.

134

135 **What do ecologists measure?**

136 To understand the differences in what theoreticians and empiricists study, we surveyed three
137 high impact multidisciplinary journals and four leading general ecology journals: *Nature*, *Science*,
138 *PNAS*, *Ecology Letters*, *Ecology*, *Oikos* and *American Naturalist*. Using relevant search terms
139 (“ecolog* stability”; “ecolog* resilience”; “ecolog* resistance”; “stability and diversity”), this
140 yielded 894 papers, 354 of which measured ecological stability in one or more ways. About half of
141 these studies were purely theoretical, the other half empirical. Of the latter, there were nearly equal
142 proportions of experimental and observational studies. Only 4% of papers combined both theory
143 and empirical measurement.

144 In our survey, 93% of theoretical studies and 85% of experimental and observational studies
145 focus on a single facet of stability (Fig. 2a). Some 83% of theoretical studies and 80% of

146 experimental and observational studies also focus on only a single disturbance component (Fig. 2b).
147 This demonstrates a restricted, largely one-dimensional, perspective. It means that we have little
148 understanding of either the multidimensional nature of ecological stability or the correspondence of
149 different components of stability to different types of perturbations.

150 There is also a significant disjoint between theoretical and empirical approaches to, and
151 understanding of, ecological stability. The majority (57%) of theoretical studies focus on
152 asymptotic stability, whereas experimental (61%) and observational (72%) studies concentrate
153 primarily on variability (Fig. 3a). In contrast, asymptotic stability comprises the focus of only 4%
154 of empirical studies, while only 18% of theoretical studies quantified variability. Only a small
155 minority of studies, either theoretical or empirical, examine persistence (10% of studies), resilience
156 (7%) or resistance (7%). Within these latter three measures, there are notable differences.
157 Theoretical studies most often examine persistence, resilience and a particular measure of resistance
158 called robustness – the susceptibility to species extinctions, usually caused by the initial loss of a
159 species (Solé & Montoya 2001; Staniczenko *et al.* 2010). Observational studies emphasise
160 resistance, while experimental studies consider resistance and resilience in equal measure. Our
161 survey identified very few empirical studies of robustness. Additional aspects of stability are
162 potentially addressed in more specialized journals than those scanned in our survey. However, the
163 literature we surveyed came from the general ecological journals most probably read by both
164 theoreticians and empiricists, potentially making the divergence we found in terms and concepts
165 even more significant.

166 We found similar disparities between the focus of theory and empirical research on the
167 different types of disturbance durations and frequencies. The majority (70%) of theoretical studies
168 focus on the effects of single pulse perturbations on stability (Fig. 3b). In contrast, 83% of
169 observational studies examine the effects of combined, multiple pulse disturbances (Fig. 1a),
170 usually in the form of natural environmental fluctuations. Experimental studies prioritise the effects
171 of press and multiple pulse disturbances in broadly equal measure (respectively, 38% and 47%).

172 Only 15% of studies we surveyed incorporate the effects of disturbance magnitude. The problem is
173 more acute when we account for different components of stability. For example, our survey
174 identified no theoretical studies of the effects of disturbance magnitude, pulse or multiple pulse
175 disturbance frequencies on ecological resistance. Nor did we find any experimental or observational
176 studies of the effects of pulse disturbances on asymptotic stability (Fig. S1). In spite of its
177 importance to characterising disturbances in the real world, our survey identified only one study
178 (van Nes & Scheffer 2004) that explored the effects of the directionality of a disturbance on
179 ecological stability.

180 Almost exclusively, just two characteristics of communities provide the basis upon which
181 studies measure ecological stability. Population or community biomass comprises the focus of
182 approximately two-thirds (63%) of studies included in our survey, while almost all of the remaining
183 studies (35%) examine the stability of taxonomic composition in some way (Fig. 3c). This pattern is
184 broadly consistent across both theoretical and empirical studies and across all components of
185 stability, except for persistence, where the majority of studies focus on composition, and
186 robustness, whose definition is constrained to community composition (Fig. S2). We found few
187 (six) studies that measured the resilience of community composition.

188 In spite of the strong policy focus on ensuring the sustained provision of ecosystem services
189 (*e.g.* TEEB 2010; Díaz *et al.* 2015), we found remarkably few empirical or theoretical assessments
190 of the stability of related ecosystem functions or processes. Only 2% of studies in our survey
191 examined the stability of an ecosystem function or process, in spite of their importance to the
192 perceived economic value of ecosystems (Armsworth & Roughgarden 2003). Of those, almost all
193 measured the variability of ecosystem function in time or space. We found only one study (Zavaleta
194 *et al.* 2010) that also examined thresholds for the persistence of multiple functions. Our survey
195 identified no studies of the resilience, asymptotic stability or resistance of ecosystem functions.

196 There is significant bias towards terrestrial ecosystems (52%) among empirical studies of
197 stability, of which most (53%) are from grasslands. Of the remaining studies, 29% are from

198 freshwater ecosystems, while only 16% are from marine systems. Experimental and observational
199 studies are represented approximately equally across all ecosystem types.

200 What are the conclusions we draw from this? Clearly, experimentalists and empiricists can
201 estimate the clearly-defined measures used by theoreticians. The problem is that some things are
202 easy to measure and other things not, a distinction that likely leads to the differences we have noted.
203 The differences are even greater on closer inspection: theory does not always address what
204 empiricists can measure. This is, at least in part, because the mathematics of dynamical systems
205 lacks tools for evaluating quantities of interest to empirical ecologists. Take resilience, for example.
206 Models measuring resilience use the engagingly simple idea of asymptotic stability. They calculate
207 return times over long intervals — when transient changes have decayed — and close to the
208 equilibrium — where one can use linear approximations to the underlying non-linear nature of the
209 system (Pimm 1982). Empiricists, on the other hand, tend to look at short intervals and disturbances
210 far from the equilibrium, where transient effects in the models may be significant (De Vries *et al.*
211 2012; Hoover *et al.* 2014; O'Connor *et al.* 2015). Here, the simplifying mathematics are
212 unavailable, and so are ignored. The models may still provide broadly the right insights, but there is
213 no guarantee that they do. Theoreticians could take the extra step and explore the dynamics of their
214 models over short intervals away from equilibrium, even if only using simulations, to check their
215 generality (*e.g.* Hastings 2004; Ives & Carpenter 2007; Ruokolainen & Fowler 2008). More
216 generally, theoreticians might recognise that certain aspects of their theories are far more likely to
217 be tested — and to be more widely useful — if they addressed metrics that empiricists can more
218 easily measure (Shou *et al.* 2015).

219 A more fundamental problem arises from the lack of exploration of the multidimensional
220 nature of either disturbances or stability. This gap in knowledge limits our ability to understand and
221 predict the effects of disturbances on the overall stability of ecosystems. If the science of ecology is
222 to support and inform robust and successful policy, we should close this gap.

223

224 **The goals of policy and their measurement**

225 Many consequences of human actions on nature are simple and have clearly defined units.
 226 For instance, the United Nations Convention on Biological Diversity (CBD) and related
 227 conventions sets targets that include the numbers of species and areas of habitat to be protected, and
 228 rates of extinction, habitat loss and fragmentation, and overexploitation of fisheries and rangelands
 229 to be minimised (UN 1992). Assisting developing countries reduce carbon emissions from
 230 deforestation and forest degradation is the simply stated goal of the United Nations REDD
 231 (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries)
 232 Programme (UN 2008). These may neither be easy to measure in practice nor to manage
 233 effectively, but they do not pose conceptual challenges.

234 Much more problematic are associated terms. *Sustainability* is ubiquitous (Bosch *et al.* 2015),
 235 and has a large associated literature. For some, it is used in a normative way, that is, as some
 236 desired goal or set of goals. Thus, it is part of the mission of the Global Environment Facility
 237 (GEF), and about half of the CBD's Aichi Biodiversity Targets for 2010-2020 include the word
 238 (UN 2010). IPBES includes conservation and sustainability of ecosystem services to provide long-
 239 term human well-being in its conceptual framework (Díaz *et al.* 2015). Responsibilities of the UK
 240 Department for Environment, Food and Rural Affairs include sustainable development, which
 241 China adopted explicitly as a national strategy in 1996 (Chinese Ministry of Finance *et al.* 2014).
 242 Most commercial enterprises now include statements about corporate and environmental
 243 sustainability in their mission statements. Normative definitions of sustainability therefore play an
 244 important role in policy, and environmental decision makers clearly do not only concern themselves
 245 with ecological components of stability. But neither should they ignore them.

246 We defer to the Oxford English Dictionary that defines “sustainable” as “*the quality of being*
 247 *sustainable at a certain rate or level*” and environmentally sustainable as “*the degree to which a*
 248 *process or enterprise is able to be maintained or continued while avoiding the long-term depletion*
 249 *of natural resources.*” Following this, we take sustainability (in its non-normative sense) to mean

250 that a particular resource persists, or persists above (or below) some pre-determined level, or is
251 resistant to disturbances. Its translation to ecological concepts is conceptually straightforward.

252 Other terms are less so. For example, the 20 Aichi Targets include: *safe ecological limits*
253 (Targets 4 & 6), *degradation* (Target 5), *function* (Targets 8, 10 & 19), and *integrity* (Target 10)
254 (UN 2010). These terms lack definitions, or have more than one definition, and have no clear units
255 for quantification. This imprecision is unfortunate in itself (Bosch *et al.* 2015; Lu *et al.* 2015). It
256 also denies the integration of the large body of empirical and theoretical literature that deals with
257 broadly similar, but quantifiable, measures of multi-species systems that might provide key
258 insights.

259 Differences among terms used, and in the meanings of common terms (Grimm *et al.* 1992;
260 Grimm & Wissel 1997; Ives & Carpenter 2007; Hodgson *et al.* 2015), are likely a consequence of
261 the different goals of theoretical and empirical ecologists and policymakers and practitioners. They
262 also reflect the fact that ecologists have perhaps less influence on these terms and their use than we
263 might hope. These differences create significant challenges for translating research findings into
264 policy-relevant information, for communication among individuals from different groups, and for
265 dealing with the complexity and multifaceted nature of ecological stability. We now examine the
266 terms used by policymakers and practitioners, then explore the potential for common ground.

267

268 **How do ecologists and policymakers differ in the terms they use?**

269 We surveyed policy targets and mission and vision statements of 42 key international
270 agreements, organisations and agencies (Table 1) that are concerned primarily with the conservation
271 and protection of nature. We searched for terms that are associated positively with stability. The
272 most common terms we found were, by some distance, '*sustain*' and '*sustainability*'. These were
273 present in more than half of the targets and statements examined (Table 2). They occurred almost
274 twice as frequently as the next most common terms, '*conserve*' and '*conservation*'. We identified
275 14 other terms that occurred less frequently across the documents we examined (Table 2). Of all of

276 the terms we identified, only two, ‘*stabilise*’/‘*stable*’ and ‘*resilience*’/‘*resilient*’, have clear
277 ecological definitions. Unfortunately, their use in the documents implied different meanings to
278 those widely used in ecological theory, relating most strongly to, respectively, variability and
279 resistance.

280 In spite of the widely different terminologies used by ecologists and policymakers and
281 practitioners, all of the terms we identified in policy targets and statements could be associated in
282 some way with at least one, and frequently more than one, component of ecological stability (Table
283 2). In fact, the stability components that associate most strongly with these terms are among the
284 least studied by ecologists (Fig. 3a). For some terms, the link with components of stability was
285 clear, for others less so. For example, to ‘*constrain impacts*’ necessitates increasing the resistance of
286 systems to disturbances. It also implies increasing their resilience (*i.e.* reducing their return times).
287 The fact that the majority of the terms used in policy integrate across different components of
288 ecological stability means that they are also, at least implicitly, multifaceted. ‘*Sustainable*’ is a good
289 example of this. In order to be sustainable, ecosystems must be resistant to disturbances. They must
290 recover quickly from them (*i.e.* have high resilience). This implies that at least some properties (*e.g.*
291 primary production) remain relatively unchanged through time (*i.e.* have high robustness, low
292 variability) even though there may be considerable turnover in other properties (*e.g.* species
293 composition; indeed, it may be the turnover in species composition that results in sustainable
294 primary production).

295 Thus, key terms may lack unambiguous and clear definitions, and are not therefore directly
296 quantifiable. Yet, the widespread use of such holistic terms implies that the multidimensionality of
297 ecological stability is already integrated, even if unconsciously, in the language and targets of
298 policymakers. This observation provides the motivation for closer integration with the science of
299 ecology.

300

301 **Solutions and recommendations**

302 Nature responds to human pressures in complex ways. Conversely, political and governance
303 decisions often demand simplicity (OECD 2001; Harwood & Stokes 2003; Lu *et al.* 2015).
304 Acknowledging this dilemma is a first step towards enhancing the quality of the communication of
305 “stability” at the science-policy interface and within both science and policy. It is incumbent upon
306 ecologists to ensure that this process does not dilute the integrity of the underlying science.

307 The necessary second step involves the definition of terms and their measurement. There is a
308 fundamental need for interdisciplinary discussions about both of these (Box 2). Policymakers have
309 to attach measurable quantities to the terms used in their documents, while scientists must address
310 these concepts directly in their studies. The proliferation of undefined and, indeed, unmeasurable
311 ideals, such as many of the tasks that underpin the recently published United Nations Sustainable
312 Development Goals (SDGs) for the conservation of ecosystems (Goals 14 and 15), hinders progress
313 and is self-defeating. For example, SDG Task 14.2 sets the target that, “*By 2020, (countries will)*
314 *sustainably manage and protect marine and coastal ecosystems and avoid significant adverse*
315 *impacts, including by strengthening their resilience*”. This statement is ambiguous to the point of
316 being meaningless. Not a single aspect of this target is measurable. What constitutes “significant”?
317 What does resilience mean in this context? The goals of policy and the terminology used to describe
318 them *always* need to be defined and measurable.

319 Consider two examples from the Aichi Targets that contrast how measurable are their
320 aspirations. First, Aichi Target 11: “*By 2020, at least 17 per cent of terrestrial and inland water,*
321 *and 10 per cent of coastal and marine areas...are conserved through effectively and equitably*
322 *managed, ecologically representative and well connected systems of protected areas*”. These goals
323 are explicit and measurable, but those for Aichi Target 6 are not: “*By 2020 all fish and*
324 *invertebrate stocks and aquatic plants are managed and harvested sustainably...so that ... fisheries*
325 *have no significant adverse impacts on threatened species and vulnerable ecosystems and the*
326 *impacts of fisheries on stocks, species and ecosystems are within safe ecological limits*”. This
327 statement contains three particularly obscure terms that lack clear methods for measurement –

328 *sustainably*, *significant adverse impacts* and *safe ecological limits* – each of which appears to mean
329 two distinct things. As used in this context (see also Table 2), *sustainably* has a compositional
330 aspect – that species present in the system persist – and another related to biomass stability – that
331 variability of biomass at both population and community level is minimised at least to a level that
332 ensures the persistence of species. *Significant adverse impacts* requires that the persistence of both
333 ‘threatened species’ and the functioning of ‘vulnerable ecosystems’ is ensured, while *safe*
334 *ecological limits* requires ensuring the persistence of each of the biomass, composition and
335 functioning of ecosystems, presumably by enhancing their resistance to fishing activities.
336 Removing the obscure terms and replacing them with the clearly defined ones we suggest would
337 make the goal measurable. This would enable closer links with the supporting science and
338 highlight key research needs, which, in turn, make the goal attainable.

339 For their part, scientists need to take a coherent approach to quantifying stability, such as the
340 one we describe here. The field will not advance by publishing more, partly overlapping, definitions
341 of single terms used in isolation within a discipline. We need to employ broadly accepted terms and
342 apply them consistently across different communities. Both theoreticians and empiricists also need
343 to be more explicit about the basis upon which they are measuring stability. Conclusions drawn
344 about the factors that drive biomass resilience, for example, are likely to be very different from
345 those that underpin compositional resilience.

346 The third step is crucial. Both scientists and policymakers need to recognise that the
347 multidimensional nature of environmental change *always* requires a multidimensional assessment
348 of responses. To date, scientists and policymakers alike have tended to assess the response to one
349 driver of change using one aspect of stability or amalgamated concepts such as Holling’s resilience.
350 The hope is that this strategy provides a piece of the jigsaw that, in total, provides insight into the
351 overall complexity of responses. Rather, such simplification blurs the overall picture. For example,
352 increasing temporal variability of algal biomass may indicate transient dynamics in changing lake
353 food-webs (Carpenter *et al.* 2011). It tells us little about any underlying changes in community

354 structure that may be undermining, or indeed enhancing, resistance to different kinds of
355 disturbances. The one-dimensional approach to disturbances and stability means that we
356 underestimate the impacts of perturbations and cannot identify the mechanisms that underpin the
357 overall stability of ecosystem structure or functions. The existence of trade-offs (*i.e.* inverse
358 correlations) between different components of stability exacerbates this situation. Such trade-offs
359 exist in nature (Donohue *et al.* 2013) and there is some theoretical insight into why they occur
360 (Harrison 1979; Loreau 1994; Dai *et al.* 2015). Their existence has profound implications for
361 policymakers and practitioners, necessitating decisions on which aspects of stability to prioritise for
362 different management goals. They also provoke an environmental cost to those decisions, where
363 some aspects of ecological stability are necessarily diminished to enhance others. The lack of
364 exploration of the multidimensional nature of ecological stability means that our ability to *optimise*
365 the overall stability of ecosystems for different management and policy goals is at present
366 extremely limited.

367

368 *What science is needed to support these steps and enhance the efficacy of policy?*

369 We make three recommendations. First, the necessity for improved and mechanistic insight
370 into the multidimensional nature of disturbances and stability requires more realistic theory and
371 experimental designs and an improved ability to integrate across studies from different spatial and
372 temporal scales and different kinds of ecosystem (*e.g.* Peters *et al.* 2011). Even single pulse
373 disturbances (*e.g.*, a chemical spill) often have a legacy (*e.g.*, contamination, loss of rare species)
374 that corresponds to a press disturbance. Pulse and press disturbances likely affect different
375 components of stability in different ways. Likewise, many press disturbances exhibit clear
376 directionality and dynamic variation around the mean, with single extreme events occurring more
377 frequently. For instance, the nature of climate disruption calls for new theory (Ives *et al.* 2010;
378 Stenseth *et al.* 2015) and long-term experiments. These need to consider the incrementally
379 increasing magnitude of, for example, temperature change, and the possibility of including large

380 variability up to extreme climatic events. They must employ stability metrics that do not require
381 strong equilibrium assumptions (*e.g.* fixed point attractors). Moreover, they must be able to
382 evaluate ecosystems in continuous transient dynamics (Fukami & Nakajima 2011). The research of
383 theoretical and empirical ecologists has to include the complex nature of disturbances and stability,
384 and the result of such multidimensional approaches has to inform policymakers.

385 Some existing theoretical approaches may be extended to deal with this range of natural
386 complexity. For example, Floquet theory can be used to explore the stability properties of periodic
387 (cyclical, non-single point equilibrium) systems (*e.g.* Lloyd & Jansen 2004, Klausmeier 2008). This
388 can be developed in a similar way to assess how locally stable, single point equilibria respond to
389 perturbations. Lyapunov exponents can be used to investigate more complex, chaotic intrinsic
390 dynamics in naturally variable systems (Ellner & Turchin 1995). Gao *et al.* (2016) have proposed
391 general methods that can reduce the high dimensionality of multi-species systems to predict the loss
392 of resilience (defined there as the ability to avoid switching from a relatively high to much lower
393 mean value of a focal state variable). In parallel, new theoretical developments are starting to
394 explore links between what empiricists measure (*e.g.* variability) and what theoreticians analyse
395 (*e.g.* asymptotic resilience), showing that some fundamental relationships can be established
396 (Arnoldi *et al.* 2016). Together, these approaches offer promising new directions for further
397 theoretical research that incorporate the sort of complexities empiricists commonly encounter in
398 their study systems.

399 Second, we need simple, yet scientifically sound, ways to integrate across the multiple
400 dimensions to quantify the overall stability of ecosystems. These methods will need to distil the
401 most important elements of stability and make accurate quantitative measures on each dimension.
402 Only then can we combine them (Fig. 4). These methods also need to be adaptable to the priorities
403 of specific policies. Such adaptation is fundamental to optimising the overall stability of ecosystem
404 structure and/or functioning for different management and policy objectives. Agricultural
405 management, for example, aims to minimise variability of yield production and maximise

406 resistance of biomass to pathogens and insect pests. In contrast, many conservation programs might
407 try to maximise the compositional persistence and resilience of communities (rare species are often
408 the most endangered and they tend to determine the slowest return times of the system). Such semi-
409 quantitative methods of holistic assessment may seem too broad-brush and inaccurate to satisfy
410 many scientists. They may also be too complex for some policymakers. The solution has to be
411 something that sits between the two.

412 Third, we need to evaluate and monitor stability through space and time. Ecologists have
413 experience in doing this for single populations and key functional groups (*e.g.* Ives *et al.* 2008;
414 Carpenter *et al.* 2011) and, more recently, for monitoring changes in the provision of ecosystem
415 goods and services (Tallis *et al.* 2012). Monitoring the dynamic stability of whole networks has
416 largely been the province of economists, among others, with numerous financial stability
417 monitoring programs continuously tracking sources of systemic risk (Adrian *et al.* 2014).
418 Analogous programs for monitoring the dynamic multidimensional stability of whole ecological
419 systems over time and space are essential to help assess the effectiveness of policy and management
420 actions. These programmes are needed to help identify ecosystems whose stability is being
421 compromised in the face of global change.

422

423 **Conclusions**

424 There are policies concerned with the protection of nature that set defined and measurable
425 targets. Aichi Target 5 (UN 2010) constitutes a good exemplar: “*By 2020, the rate of loss of all*
426 *natural habitats, including forests, is (to be) at least halved and where feasible brought close to*
427 *zero*”. This statement is clear and unambiguous – progress can be quantified, success or failure
428 evaluated. It exemplifies the only way that policies can effect meaningful change.

429 Such policies are in the minority. Many policy documents describe targets that may appear,
430 on face value, explicit and measurable, yet contain terms that are ambiguous, or have multiple
431 definitions that mean different things to different people. Such targets cannot be connected to

432 measureable ecological processes or properties. Policies aiming to increase “resilience” provide
433 pervasive examples. In fact, the majority of policy documents we surveyed contain goals using
434 terms that lack definition within ecology. Such ambiguity paralyses policy.

435 This incoherence is, at least in part, a consequence of the inconsistent and one-dimensional
436 approach that ecologists have taken to ecological stability. This approach has led to confused
437 communication of the nature of stability and the level of our insight into it. Disturbances and
438 stability are multidimensional. Our understanding of them is not. We have a remarkably poor
439 understanding of the impacts on stability of the characteristics that define many, perhaps all, of the
440 most important elements of global change.

441 The solution requires a range of actions. We need more realistic theory based on measures
442 that are of practical significance and empirically quantifiable. Empiricists need to test this theory at
443 a range of spatial and temporal scales. Policymakers need to use these defined and measurable
444 quantities in their targets. Most importantly, theoreticians, empiricists, policymakers and
445 practitioners each need to incorporate the multidimensional complexity of natural responses to
446 environmental change into their research, policies and actions.

447

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460

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747 **Table 1.** International agreements, organisations and agencies whose policy targets and mission and vision statements we searched for terms associated
 748 with ecological stability.

| Entity | Stability related term(s) found | Document link |
|---|--|---|
| Aichi biodiversity targets (CBD) | 'integrity'; 'safe ecological limits'; 'resilience'; 'sustain'; 'conserve' | http://www.cbd.int/sp/targets/ |
| Biodiversity International | 'sustain'; 'safeguard' | http://www.biodiversityinternational.org/about-us/who-we-are/ |
| Birdlife International | 'sustain'; 'maintain' | http://www.birdlife.org/worldwide/partnership/our-vision-mission-and-commitment |
| Convention on Biological Diversity | 'sustain'; 'conserve' | http://www.cbd.int/convention/articles/default.shtml?a=cbd-01 |
| Conservation International | 'healthy'; 'sustainable'; 'stable' | http://www.conservation.org/about/Pages/default.aspx#mission |
| UK Department for Environment, Food & Rural Affairs | 'safeguard' | https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs/about |
| Diversitas (now rolled into Future Earth) | 'secure'; 'conserve'; 'sustain' | http://www.diversitas-international.org/about/mission-and-history |
| Earthwatch | 'sustain' | http://eu.earthwatch.org/about/earthwatch-mission-and-values |
| European Environment Agency | 'sustainable' | http://www.eea.europa.eu/about-us |
| European Platform for Biodiversity Research Strategy | 'maintain'; 'sustain'; 'conserve' | http://www.epbrs.org |
| Earth System Science Partnership | 'sustainable' | http://www.essp.org |
| European Union Biodiversity Observation Network | None found | http://www.eubon.eu/show/project_2731/ |
| Food and Agriculture Organisation | 'security'; 'sustainable' | http://www.fao.org/about/en/ |
| Future Earth | 'sustainable' | http://www.futureearth.org |
| Global Environment Facility | 'sustainable' | https://www.thegef.org/gef/whatisgef |
| GreenPeace | 'protect' | http://www.greenpeace.org/international/en/about/our-core-values/ |
| International Association for Landscape Ecology | 'altered' | http://www.landscape-ecology.org/index.php?id=14 |
| Intergovernmental platform on biodiversity and ecosystem services | 'conserve'; sustain' | http://dx.doi.org/10.1016/j.cosust.2014.11.002 |
| Intergovernmental Panel on Climate Change | None found | http://www.ipcc.ch/organization/organization.shtml |
| International tropical timber organisation | 'sustainable'; 'conservation' | http://www.itto.int/about_itto/ |
| International Union for Conservation of Nature | 'conserve'; 'sustain' | http://www.iucn.org |
| LifeWatch infrastructure for biodiversity and ecosystem research | None found | http://www.lifewatch.eu |

| | | |
|---|---|---|
| Living with Environmental Change | None found | http://www.lwec.org.uk/about |
| Natural Capital Project | 'sustainable' | http://www.naturalcapitalproject.org |
| Organisation for Economic Co-operation and Development | 'sustainable'; 'resilience' | http://www.oecd.org/env/ |
| Rainforest Alliance | 'conserve'; 'sustain'; 'safeguard' | http://www.rainforest-alliance.org/about |
| The Economics of Ecosystems and Biodiversity | None found | http://www.teebweb.org/about/ |
| The Nature Conservancy | 'conserve' | http://www.nature.org/about-us/vision-mission/index.htm?intc=nature.tnav.about.list |
| United Nations Reducing Emissions from Deforestation and Forest Degradation | 'constrain impacts' | http://www.un-redd.org |
| United Nations Convention to Combat Desertification | 'sustain'; 'secure' | http://www.unccd.int/en/Pages/default.aspx |
| United Nations Environment Programme | 'sustain' | http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=43 |
| Kyoto protocol (UNFCCC) | 'stabilise' | http://unfccc.int/kyoto_protocol/items/2830.php |
| United Nations Sustainable Development Goals | 'security'; 'sustainable'; 'resilient'; 'conserve'; 'protect' | https://sustainabledevelopment.un.org/post2015/transformingourworld |
| Wetlands International | 'resilience' | http://www.wetlands.org/Aboutus/VisionMission/tabid/58/Default.aspx |
| World Meteorological Organisation | 'safety' | https://www.wmo.int/pages/about/mission_en.html |
| World Nature Organisation | 'sustainable' | http://www.wno.org/mission |
| Stern Review on the Economics of Climate Change | None found | http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/destaques/sternreview_report_complete.pdf |
| Worldwatch Institute | 'sustainable' | http://www.worldwatch.org/mission |
| World Wildlife Fund for Nature | 'harmony'; 'safeguard' | http://wwf.panda.org/wwf_quick_facts.cfm |
| York Environment Sustainability Institute | 'resilient'; 'maintain'; 'conservation' | http://www.york.ac.uk/media/yesi/downloaddocuments/YESI%20Brochure-WEB.pdf |
| Convention on International Trade in Endangered Species of Wild Fauna and Flora | 'survival' | http://www.cites.org/eng/disc/what.php |
| International Whaling Commission | 'conservation' | https://iwc.int/history-and-purpose |

750 **Table 2.** Stability-like terms used in policy targets and mission and vision statements of the international agreements, organisations and agencies
 751 highlighted in Table 1, ranked in order of frequency of occurrence, and the components of stability that they associate with in the context of their use.
 752 The use of resistance here incorporates robustness. We assume that the necessity for systems to be asymptotically stable around an equilibrium point or
 753 limit cycle is implicit in the use of every term.

754

| Terms used in policy | Occurrence | Stability component(s) associated most strongly | Other associated stability components |
|-----------------------------|-------------------|--|---|
| 'sustain'/'sustainable' | 25/42 | Persistence | Resistance, Resilience, Variability |
| 'conserve'/'conservation' | 13/42 | Persistence | Resistance, Resilience |
| 'resilience'/'resilient' | 5/42 | Resistance | Resilience, Persistence |
| 'safeguard' | 4/42 | Persistence | Resistance |
| 'maintain' | 3/42 | Persistence | Resistance, Variability |
| 'secure'/'security' | 4/42 | Persistence | Resistance, Resilience |
| 'stabilise'/'stable' | 2/42 | Variability | Resistance, Resilience, Persistence |
| 'protect' | 2/42 | Persistence | Resistance |
| 'altered' | 1/42 | Persistence | Resistance |
| 'constrain impacts' | 1/42 | Resistance | Resilience |
| 'harmony' | 1/42 | Variability | |
| 'healthy' | 1/42 | Resistance | Resilience |
| 'integrity' | 1/42 | Resistance | Persistence, Resilience |
| 'safety' | 1/42 | Resistance | Persistence |
| 'survival' | 1/42 | Persistence | Resistance, Resilience |
| 'safe ecological limits' | 1/42 | Resistance | Persistence, Resilience, Variability, Multiple locally stable equilibria |

755

756 **Figure legends**

757

758 **Fig. 1.** Conceptual summary of multifaceted disturbances. Characterisation of pure pulse
759 and press disturbances (a) that are the focus of most theoretical and experimental studies,
760 and an intermediate multiple pulse form of disturbance (dotted blue line) that is also
761 studied frequently, mostly in the form of natural environmental fluctuations in
762 observational studies. Most disturbances are, however, neither pulse nor press and
763 instead change in magnitude over time (b), frequently with shifting mean and variance
764 components. We lack theory and have very limited empirical evidence on the impacts of
765 these directional aspects of disturbances on ecological stability, yet they represent many
766 of the most important and widespread aspects of human impacts (c).

767

768 **Fig. 2.** The restricted focus of studies on single components of stability (a) and disturbances
769 (b). The total number of studies is slightly lower in (b) because some of the studies we
770 surveyed did not incorporate an explicit disturbance.

771

772 **Fig. 3.** Overview of studies of ecological stability. Number of studies identified by our
773 survey of the literature that quantified different facets of stability (a), examined the effects
774 of different components of disturbance on those (b), and that used biomass, taxonomic
775 composition or ecosystem functioning as a basis for measuring stability (c).

776

777 **Fig. 4.** Integrating across multiple dimensions to quantify overall ecological stability. We
778 suggest a method that incorporates multiple stability facets and allows for their differential
779 weighting. This method is based loosely on one developed for the assessment of biodiversity
780 effects on multiple ecosystem functions (Byrnes *et al.* 2014). A multiple-criteria decision-
781 making approach would also be suitable here. First, the method identifies which stability

782 facets can be quantified and provides a scoring system for each facet (a). This could be as
783 simple as low, moderate and high, although more sophisticated scoring systems could be
784 developed. It then applies a weighting factor to each score, depending on their perceived
785 relative importance for a given policy or management practice (b). The sum of the weighted
786 scores then corresponds to the stakeholder's value of the stability of the system (c). Even
787 though different facets of stability may be correlated, there is no need to assume this. Trade-
788 offs and synergies among stability metrics can be incorporated, but the method does not
789 assume dependencies.

790 **Box 1: Why the attempt to define planetary boundaries is flawed**

791 Human actions are changing the biosphere in unprecedented ways. One view is that, given the
792 magnitude and novelty of these impacts, there will be thresholds, beyond which abrupt non-linear
793 change will bring the biosphere to a new and undesirable equilibrium. This view of nature, founded
794 upon Holling's (1973) definition of resilience, explicitly engages policymakers with its invocation
795 of catastrophic tipping points and the conclusion that Earth has already exceeded them. The view is
796 becoming increasingly pervasive in the scientific literature.

797 Certainly, there may be systems that show the tipping points that underpin this worldview.
798 Importantly, there is nothing to suggest they are ubiquitous and so demand their having logical
799 primacy. Nature might work this way sometimes, but there is no compelling argument that it must.

800 In attempting to define global tipping points and, from those, "planetary boundaries",
801 Rockström *et al.* (2009) have extended this view to circumstances where it is unlikely to operate.
802 We take as an example the variable they deemed already to be outside the planetary boundary
803 arising from our work (Pimm *et al.* 1995; Pimm *et al.* 2014): the rate of species extinctions. The
804 metric is simple — a fraction of species going extinct per unit time. The comparison to a natural
805 background rate is also conceptually easy, though there are practical difficulties (De Vos *et al.*
806 2015). The notion that the current global species extinction rate — about a thousand times higher
807 than background — has exceeded some tipping point where catastrophic ecological changes must
808 follow is problematical in several ways (Mace *et al.* 2014).

809 First, it is not clear over what spatial and temporal scales extinction rates have exceeded the
810 boundary. For example, how are the locally high rates of plant and animal extinctions on remote
811 Pacific Islands following first contact with Polynesians and later with Europeans supposed to "tip"
812 processes globally or (say) in the Amazon? And over what time period might these catastrophic
813 changes unfold?

814 Subsequent clarifications by Rockström and colleagues (Stockholm Resilience Centre 2012;
815 Steffen *et al.* 2015) indicate that the proposed 'planetary' boundary for extinctions operates at

816 regional scales, but they are not explicit in defining either the spatial or temporal extents of these
817 regions. This leaves open the vitally important question for policymakers of what scales are most
818 important.

819 Second, there are models of the consequences of losing species and how many more species
820 will be lost consequently at local and regional scales (Pimm 1991). None shows the kind of
821 runaway processes that Rockström and colleagues imagine. Certainly, there is both an extensive
822 theoretical and empirical literature on how species richness (as opposed to its rate of change) affects
823 a variety of ecosystem functions including primary productivity and nutrient cycling (Loreau *et al.*
824 2001; Cardinale *et al.* 2012). This literature shows degradation as species numbers decline
825 (Cardinale *et al.* 2011), but no clear thresholds.

826 Box 2: Learning from experience: biodiversity-ecosystem functioning and service provision

827 Even when theoreticians and empiricists converge in what they quantify, there is no guarantee
828 of immediate and successful translation into the policy and management arena. Research on
829 Biodiversity-Ecosystem Functioning (BEF) and Biodiversity-Ecosystem Services (BES)
830 relationships exemplifies this and, as such, we can learn from it.

831 A large body of experiments (> 600 since 1990) developed in close relation with
832 mathematical theory and showed how genetic, species and functional diversity of organisms
833 regulate basic ecological processes – functions – in ecosystems (Cardinale *et al.* 2012). As a result,
834 there is now unequivocal evidence supported by theory that biodiversity loss reduces biomass
835 production, decomposition and recycling of essential nutrients, and the efficiency at which
836 ecosystems capture biological resources. In parallel, a strong policy impulse developed trying to
837 guarantee the provision of ecosystem services to society, now under the umbrella of the recently
838 established Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
839 (IPBES; Díaz *et al.* 2015). Despite the mechanistic understanding of the effects of biodiversity on
840 functioning provided by theoreticians and empiricists, the mechanistic links between biodiversity
841 and ecosystem services are far from being established. This disconnect effectively impairs the
842 distillation of conclusions to inform policy on how biodiversity loss will affect service provisioning
843 and regulation and, ultimately, human wellbeing.

844 An example is Payment for Ecosystem Services (PES), where beneficiaries of nature's
845 services pay owners or stewards of ecosystems that generate those services. Naeem *et al.* (2015)
846 suggested recently that few PES studies get the science right, with most projects based on weak
847 scientific foundations. The main reason for this was poor interdisciplinary communication and
848 coordination. The absence of unifying definitions and associated metrics, baseline data, monitoring,
849 recognition of the dynamic nature of ecosystems, and poor interdisciplinary communication and
850 coordination helps to explain this gap. The BEF community measures functions without linking
851 those to known services. The BES community commonly describe services without linking them to

852 their underlying ecological function. A more active communication and convergence on what to
853 measure and at what scale, and how to monitor over space and time is needed (Cardinale *et al.*
854 2012; Naeem *et al.* 2015).