

Biodiversity and resilience of ecosystem functions

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1 **Biodiversity and resilience of ecosystem functions**

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23

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25

26 **Abstract**

27 Accelerating rates of environmental change and the continued loss of global biodiversity

28 threaten functions and services delivered by ecosystems. Much ecosystem monitoring and

29 management is focused on the provision of ecosystem functions and services under current

30 environmental conditions, yet this could lead to inappropriate management guidance and

31 undervaluation of the importance of biodiversity. The maintenance of ecosystem functions

32 and services under substantial predicted future environmental change, (i.e. their

33 'resilience') is crucial. Here, we identify a range of mechanisms underpinning the resilience

34 of ecosystem functions across three ecological scales. Although potentially less important in

35 the short-term, biodiversity, encompassing variation from within-species to across

36 landscapes, may be crucial for the longer-term resilience of ecosystem functions and the

37 services that they underpin.

38

39

40

Glossary

Beta diversity: Variation in the composition of species communities across locations

Ecosystem functions: The biological underpinning of ecosystem services. While ecosystem services are governed by both ecological and social factors (e.g. business demand-supply chains), in this article, we focus on the proximate biological processes – such as productivity, pest control, pollination – that determine the supply of ecosystem services.

Effect traits: Attributes of the individuals of a species that underlie its impacts on ecosystem functions and the services.

Ecosystem services: Outputs of ecosystem processes that provide benefits to humans (e.g. crop and timber production).

Functional redundancy: The tendency for species to perform similar functions, such that they can compensate for changes in each other's contribution to ecosystem processes. Functional redundancy arises when multiple species share similar effect traits but differ in response traits.

Resilient ecosystem function: See main text for history of the term resilience. The definition used here is the degree to which an ecosystem function can resist or recover rapidly from environmental perturbations, thereby maintaining function above a socially acceptable level.

Resistance/recovery: In the context used here these refer to the tendency of ecosystem function provision to remain stable in the face of environmental perturbation or the tendency to rapidly return to pre-perturbation levels.

Response traits: Attributes that influence the persistence of individuals of a species in the face of environmental changes.

Phenotypic plasticity: Gene-by-environment interactions that lead to the same genotypes expressing changed behaviour or physiology under different environmental conditions.

(Demographic) Allee effects: Where small populations exhibit very slow or negative growth, contrary to the rapid growth usually expected. Explanations range from an inability to find mates, avoid predators or herbivores, or a limited ability to engage in co-operative behaviours.

Alternate stable states: When an ecosystem has more than one stable state (e.g. community structure) for a particular set of environmental conditions. These states can differ in the levels of specific ecosystem functions.

44 **The importance of resilience**

45 Across the globe, conservation efforts have not managed to alleviate biodiversity loss [1],
46 and this will ultimately impact many functions delivered by ecosystems [2, 3]. To aid
47 environmental management in the face of conflicting land use pressures, there is an urgent
48 need to quantify and predict the spatial and temporal distribution of ecosystem functions
49 and services [see Glossary; 4, 5, 6]. Progress is being made in this area, but a serious issue is
50 that monitoring and modelling the delivery of ecosystem functions has been largely based
51 on the *current* set of environmental conditions (e.g. current climate, land use, habitat
52 quality). This ignores the need to ensure that essential ecosystem functions will be provided
53 under a range of environmental perturbations that could occur in the near future (i.e. the
54 provision of *resilient* ecosystem functions). The objective of this review is to identify the
55 range of mechanisms which underpin the provision of resilient ecosystem functions to
56 inform better environmental monitoring and management.

57 A focus on current environmental conditions is problematic because future conditions
58 might be markedly different from current ones (e.g., increased frequency of extreme
59 weather events [7] and pollution [8]), and might therefore lead to rapid, non-linear shifts in
60 ecosystem function provision that are not predicted by current models. Reactive
61 management might be too slow to avert consequent deficits in function, with impacts for
62 societal well-being [9]. An analogy of this situation is the difference between monitoring
63 whether a bridge is either standing (i.e. providing its function) or collapsed, prompting need
64 for a re-build, as opposed to monitoring and repairing damage to prevent the collapse from
65 ever happening. In environmental science, attempts have been made to identify this 'safe
66 operating space' at a global level to ensure that boundaries are not crossed that could lead

67 to rapid losses in ecosystem functions [10, 11]. However, there is a danger that current
68 regional and local assessments of ecosystem functions and management advice do not
69 incorporate such risk assessments. This could result in poor management advice and
70 undervaluation of the importance of biodiversity, because whilst relatively low levels of
71 biodiversity can be adequate to provide current function [12], higher levels might be needed
72 to support similar levels of function under environmental change [2, 13-18]. Therefore,
73 there is a need to identify the characteristics of resilient ecosystem functions and capture
74 these in both predictive models and management guidance.

75

76 **Defining and applying the resilience concept**

77 Resilience is a concept with numerous definitions in ecological [19], social [20] and other
78 sciences [21]. In ecology, an initial focus on the stability of ecosystem processes and the
79 speed with which they return to an equilibrium state following disturbance [recovery or
80 'engineering resilience'; 22] has gradually been replaced by a broader concept of 'ecological
81 resilience' recognising multiple stable states and the ability for systems to resist regime
82 shifts and maintain functions, potentially through internal reorganisation [i.e. their 'adaptive
83 capacity'; 23]. Recent definitions of resilience encompass aspects of both recovery and
84 resistance, although different mechanisms can underpin these, and in some cases there
85 might be trade-offs between them [24]. However, some mechanisms can promote both
86 resistance and recovery depending on the timeframe in which a system is observed (e.g.
87 very rapid recovery can look like resistance). Therefore, we treat resistance and recovery
88 here as two related complementary aspects of resilience [25].

89 There has been much semantic and theoretical treatment of the resilience concept, but
90 here we are concerned with identifying metrics for real world applications. An ecological
91 system can be defined by the species composition at any point in time [26] and there is a
92 rich ecological literature, both theoretical and experimental, that focusses on the stability of
93 communities [16, 27-29] with potential relevance to resilience. Of course, the species in a
94 community are essential to the provision of many ecosystem functions which are the
95 biological foundation of ecosystem services [3]. However, the stability of species
96 composition itself is *not* a necessary pre-requisite for the resilience of ecosystem functions.
97 Turnover in species communities might actually be the very thing that allows for resilient
98 functions. For example, in communities subjected to climatic warming, cold-adapted species
99 are expected to decline whilst warm-adapted species increase [30]. The decline of cold-
100 adapted species can be limited through management [31], but in many cases their local loss
101 might be inevitable [32]. If these species have important functional roles, then ecosystem
102 functions can suffer unless other species with similar functional roles replace them. In fact,
103 similar sets of functions might be achieved by very different community structures [33].
104 Therefore, while the species composition of an ecosystem is typically the target of
105 conservation, it is ecosystem functions, rather than species composition *per se*, that need to
106 be resilient, if ecosystem services are to be maintained (Figure 1). In this case the most
107 relevant definition of resilience is: *the degree to which an ecosystem function can resist or*
108 *recover rapidly from environmental perturbations, thereby maintaining function above a*
109 *socially acceptable level*. This can be thought of as the ecosystem-functions related meaning
110 of resilience [19], or alternatively as the inverse of ecological ‘vulnerability’ [34]. Resilience
111 in this context is related to the stability of an ecosystem function as defined by its constancy

112 over time [35], but the approach of using a minimum threshold more explicitly measures
113 deficits of ecological function that impact upon human well-being [e.g. 14]. Note that here
114 we focus on the resilience of individual ecosystem functions, which might be appropriate for
115 policy formulation (e.g. pollination resilience), although ecosystem managers will ultimately
116 want to consider the suite of ecosystem functions supporting essential services in a given
117 location.

118

119 **Threats to ecosystem functions.**

120 Environmental change is not unusual (ecosystems have always faced periodic and persistent
121 changes), but anthropogenic activity (e.g. land conversion, carbon emissions, nitrogen cycle
122 disruption, species introductions) is now increasing both the rate and intensity of
123 environmental change to previously unprecedented levels [36-38]. Rapid changes to the
124 abiotic environment might alter local and regional species pools through environmental
125 filtering and disrupting biotic interactions, leading to changes in the suites of traits and
126 interactions that affect ecosystem functioning [39]. The timescales involved tend to be
127 measured with respect to relevant human interventions, i.e. usually over years to decades.
128 The environmental changes may be: rapid onset (e.g. disease), chronic (e.g. habitat loss) or
129 transitory perturbations (e.g. drought; Figure 2a). Some environmental pressures can show
130 complex temporal patterns. For example, climate change includes transitory perturbations
131 due to climatic extremes overlaid on a background of long-term warming, with the potential
132 for rapid onset changes if tipping points are reached [40].

133 The impacts of environmental perturbations on ecosystem functions will depend on the
134 presence of ecosystem characteristics that confer resilience, involving interacting

135 mechanisms at multiple ecological scales (see next section). These processes govern the
136 form of functional response to environmental change (Figure 2b), and their rates relative to
137 the environmental change driver will govern the resilience and ultimate temporal trends in
138 ecosystem function (figure 2c).

139

140 **Mechanisms underpinning resilient ecosystem functions**

141 Previous studies have attempted to identify characteristics of resilient systems from a broad
142 socioeconomic perspective [20, 21], but here we focus on the biological underpinnings of
143 the resilience of ecosystem functions, to inform targeted environmental management
144 practices. The resilience of ecosystem functions to environmental change is likely to be
145 determined by multiple factors acting at various levels of biological organisation; namely,
146 species, communities and landscapes (Table 1). These ecological levels are interconnected
147 so that changes at a particular level can cascade to other levels in the same system. For
148 instance, individual species' responses to environmental change mediate changes in the
149 population abundance and resulting interactions with other species, thus affecting
150 community structure and composition as well as the distribution of effect and response
151 traits [39]. These changes can extend to the level of whole ecosystems, but are mediated
152 the ecosystem context, such as landscape level heterogeneity or habitat connectivity, to
153 determine the resilience of ecosystem function.

154 Here, we provide a new assessment of evidence for the mechanisms underpinning the
155 resilience of ecosystem functions across these ecological levels (Table 1). Our assessment is
156 focussed on promoting general resilience to a range of different primary threats to
157 ecosystem function.

158

159 **Table 1, Mechanisms underpinning the resistance and recovery of ecosystem functions to**

160 **environmental perturbation.** The abbreviations ‘RES’, ‘REC and ‘RES/REC’ indicate the

161 importance of each mechanism for resistance, recovery or both respectively.

Species (intraspecific)	Community (interspecific)	Landscape (ecosystem context)
Sensitivity to environmental change (RES)	Correlation between response and effect traits (RES)	Local environmental heterogeneity (RES)
Intrinsic rate of population increase (RES/REC)	Functional redundancy (RES/REC)	Landscape-level functional connectivity (RES/REC)
Adaptive phenotypic plasticity (RES/REC)	Network interaction structure (RES)	Potential for alternate stable states (RES/REC)
Genetic variability (RES/REC)	-	Area of natural habitat cover at the landscape scale (RES/REC)
Allee effects (RES/REC)	-	-

162

163 *Species-level mechanisms*

164 Species rarely experience identical impacts of environmental change due to interactions

165 between traits, landscape composition and the scale at which they experience

166 environmental drivers [41, 42]. This variation in response within and between individual

167 species determines both the short-term provision and long-term resilience of ecosystem

168 functions. Below we list five key mechanisms operating at the species level and provide

169 hypotheses for their effects on the resilience of ecosystem functions.

170

171 **Sensitivity to environmental change:** Species vary in their capacity to persist in the face of

172 the environmental perturbations, mediated by a range of behavioural and physiological

173 adaptations (response traits) [43]. Such traits show both interspecific and intraspecific

174 variation. Individuals with traits conferring reduced sensitivity to environmental change will

175 confer higher resistance to ecosystem functions [44]. For example, trees vary in their
176 sensitivity to drought depending on non-structural carbohydrate levels [44], which in turn
177 might affect the resistance of ecosystem functions that they provide. Broader suites of
178 traits, such as the plant resource economics spectrum [45], are also likely to explain
179 variation in sensitivity. Note, however that there might be negative correlations between
180 sensitivity and intrinsic growth rates, with slow-growing species providing more resistant
181 ecosystem functions but with lower capacity to recover if perturbation does occur.

182

183 **Intrinsic rate of population increase:** The capacity of species populations to grow rapidly
184 from low numbers is determined by a suite of related characteristics including generation
185 time, mortality and fecundity rates. Species with a high intrinsic rate of increase will recover
186 more quickly from environmental perturbations [46], or show resistance if this population
187 reinforcement occurs during the perturbation.

188

189 **Adaptive phenotypic plasticity:** Individuals have the capacity to respond to environmental
190 changes through flexible behavioural or physiological strategies which promote their
191 survival [43] and resistance of ecosystem functions. For example, thermoregulatory
192 behaviour appears to be an essential survival tool in many ectotherms that operate in
193 temperature conditions close or beyond their physiological limits [47]. Additionally,
194 adaptations might allow flexibility to maximise resource acquisition and growth rates in
195 changed environmental conditions enabling more rapid population recovery and recovery of
196 ecosystem function.

197

198 **Genetic variability:** Higher adaptive genetic variation increases the likelihood that
199 genotypes which are tolerant to a given environmental perturbation will be present in a
200 population [18]. This reduces the population impacts of environmental perturbations [48]
201 and promotes resistance of ecosystem functions [49]. In addition, the persistence of
202 tolerant genotypes locally means that population recovery rates are likely to be higher,
203 leading to enhanced function recovery rates [48, 50]. Adaptive genotypes can be present in
204 standing genetic variation, which is more likely at higher effective population sizes.
205 Alternatively they can arise locally through mutation or through immigration from other
206 populations [18]. It is also becoming increasingly apparent that epigenetic effects can
207 provide heritable variation in ecologically relevant traits [51].

208

209 **Allee effects:** Allee effects make populations more susceptible to environmental
210 perturbations causing crashes from which it is difficult to recover [52, 53]. Certain species
211 are more susceptible to Allee effects through mechanisms such as an inability to find mates,
212 avoid predators or a limited ability to engage in co-operative behaviours.

213

214 *Community-level mechanisms*

215 Beyond the tolerance and adaptability of individuals, the composition and structure of the
216 biological community is of particular importance for the resilience of ecosystem functions.
217 Below we list three key underpinning mechanisms.

218

219 **Correlation between response and effect traits:** If the extent of species' population decline
220 following an environmental perturbation (mediated by response traits) is positively

221 correlated with the magnitude of species' effects on an ecosystem function (via effect traits)
222 then this will lead to less resistant ecosystem functions [39, 54]. This might occur if the same
223 traits mediate both response and effects, or through indirect associations between different
224 traits. Correlations and trade-offs are probably a common aspect of traits as a result of
225 biophysical limitations in structure and function [55]. For example, traits such as body size
226 have been linked with both sensitivity to environmental change (response traits) and the
227 maintenance of ecosystem functions (effects traits) such as pollination by bees [56, 57],
228 nutrient recycling by dung beetles [56] and pest control from predatory invertebrates [58,
229 59]. In contrast, completely uncorrelated response and effects traits cause higher resistance
230 in ecosystem function, since responses of species to environmental change are decoupled
231 from their effects on function [54, 56]. For example, Diaz *et al.* [39] summarise several
232 studies which show no correlation between decomposability in plants (an effect trait for
233 nutrient cycling and soil fertility) and persistence in the seedbank (a response trait to
234 disturbance under agricultural intensification).

235

236 **Functional redundancy:** When multiple species perform similar functions, i.e., species
237 exhibit some redundancy in their contributions to ecosystem processes, then resistance of
238 an ecosystem function will be higher if those species also have differing responses to
239 environmental perturbations [60, 61]. This gives rise to the 'insurance effect' of biodiversity
240 [62], which is well supported both empirically [14, 15] and theoretically [16, 28].
241 Underpinning mechanisms include a statistical effect, where averaging across independently
242 fluctuating species populations results in higher resistance ('portfolio effects'), which is
243 enhanced further where there is negative spatial and/or temporal covariance (asynchrony)

244 between species' population sizes, driven by differing responses to environmental change or
245 competition [14-16, 28, 62].

246 The functional roles of species can be mediated by either continuous or categorical
247 traits [e.g. complementary effect traits such as sward- and ground-active predators for pest
248 control; 63]. Resistance is increased by both more species in total (assuming that there is
249 variation in their response traits) and, for a given total number of species, when they are
250 dispersed equally across effect trait space (Figure 3). In reality, intraspecific variation in
251 traits also occurs and, where this is substantial relative to interspecific variation, it might be
252 relevant to consider redundancy and dispersion of *individuals* across effect trait space [64].

253

254 **Network interaction structure:** The majority of the theory and empirical work discussed
255 above concerns organisms occupying a single trophic level, but interactions between species
256 (e.g. predation, parasitism, mutualism) can have large influences on community responses
257 to environmental change [2, 65]. Loss of highly connected species in interaction networks
258 can cause extinction cascades and reduce network stability [66-68]. If these species are
259 particularly sensitive to environmental change then the resistance of the ecosystem
260 functions they provide will be low [69]. Impacts on ecosystem function will be greater when
261 response and effect traits are correlated and patterned in networks along extinction
262 cascades. For example, body size is linked with both extinction risk and the provision of
263 ecosystem functions in taxa including pollinators [56] and pest control agents [70]. In
264 general, highly-connected nested networks dominated by generalised interactions are less
265 susceptible to cascading extinction effects and provide more resistant ecosystem functions,
266 in contrast to networks dominated by strong specialised interactions [71, 72].

267 An important consideration is that the impacts of species loss are likely to lead to
268 changes in the abundances of surviving species, so that the presence or absence of density
269 compensation following species loss can be the key predictor of ecosystem function
270 provision [56, 67, 73]. For example, atmospheric deposition of nitrogen can result in species
271 loss from some plant communities, but density compensation of remaining species might
272 support net primary productivity [74].

273

274 *Landscape-level mechanisms*

275 The intraspecific- and community-level mechanisms described above are influenced by the
276 environmental context of both the local site and wider landscape. The landscape context
277 determines the local and regional species pool and also the abiotic environment which can
278 modify the impacts of environmental perturbations on individuals and communities.

279

280 **Local environmental heterogeneity:** Spatial heterogeneity can enhance the resistance of
281 ecosystem functions by a) facilitating the persistence of individual species under
282 environmental perturbations by providing a range of resources and microclimatic refugia
283 [75-78], and b) increasing overall species richness [79] and, therefore, functional
284 redundancy. These heterogeneity effects can operate at: the fine-scale, for example,
285 through vegetation structural diversity [75]; the medium scale, for example, through
286 topographic diversity [76]; or the larger scale, for example, through diversity of land cover
287 types [77, 78]. Additionally, environmental heterogeneity across locations (promoting beta
288 diversity) has been shown to increase stability of ecosystem functions [27].

289

290 **Landscape-level functional connectivity:** Metapopulation theory suggests that populations
291 in well-connected landscapes will persist better or re-colonise more rapidly following
292 environmental perturbation (the ‘rescue effect’). Empirical studies confirming this
293 hypothesis range from mesocosm experiments [80, 81] to landscape-level field studies [82,
294 83]. This prediction extends to metacommunities and experiments have shown that
295 connectivity enhances community recovery after local perturbations [81, 84]. In a few cases,
296 this recovery of community structure through dispersal has been shown to lead to recovery
297 of ecosystem functions, such as productivity and carbon sequestration, to pre-perturbation
298 levels; a process termed “spatial insurance” [85, 86]

299
300 **Area of natural habitat cover at the landscape scale:** In addition to improving functional
301 connectivity for particular species, larger areas of natural or semi-natural habitat tend to
302 provide a greater range and amount of resources, which promotes higher species richness
303 and larger population sizes of each species [87, 88]. This, in turn, is likely to mean greater
304 genetic diversity, and functional redundancy, both of which promote resistance of
305 ecosystem functions [18, 60, 61].

306
307 **Potential for alternate stable states:** Alternate stable states are associated with abrupt
308 shifts in ecosystems, tipping points and hysteresis, all of which challenge traditional
309 approaches to ecosystem management [17, 89]. Ecosystem states maintain their stability
310 through internal feedback mechanisms, which confers resistance to ecosystem functions.
311 However, environmental perturbations can increase the likelihood of regime shift leading to
312 a fundamental change in the assemblages of species providing functions [17]. Systems can

313 be more susceptible to environmental stochasticity and transient perturbations close to
314 these critical tipping points leading to sudden changes to a new equilibrium [53]. Some
315 alternative stable states might be unfavourable in terms of ecosystem functions with return
316 to previous states possible only through large and costly management interventions
317 (hysteresis), thereby limiting the recovery capacity of ecosystem function. Alternative states
318 are documented in a wide variety of ecosystems from local to global scales, although how
319 stable and persistent these are remains uncertain [89-91].

320

321 **Managing for resilience**

322 *Applied ecosystem management*

323 Ecosystem services are beginning to be integrated within major land management
324 programmes (e.g. the EU Common Agricultural Policy, REDD+). However, the measurement,
325 monitoring and direct management of ecosystem function resilience in these programmes is
326 lacking [92]. The ecological theory and empirical evidence discussed above suggest that
327 multiple factors will determine ecosystem resilience. However, we do not yet know which
328 will be the most important in determining resilience in particular functions or ecosystems. It
329 is clear that some factors will be more amenable to management (e.g. population-level
330 genetic variability and landscape structure [18, 31]) than others (e.g. environmental
331 sensitivity of individual species, presence of alternative stable states). Additionally, there
332 can be trade-offs and synergies between resilience and the short-term performance of
333 ecosystem functions [49, 93] .

334

335 *Synergies and trade-offs with short-term performance*

336 In some cases there are synergies between the short-term performance of ecosystem
337 functions and their longer-term resilience , e.g. if species richness is associated with higher
338 levels of function under current conditions due to complementarity [13], and with higher
339 resilience of function due to higher functional redundancy [39, 54]. In these cases,
340 management targeted towards short-term performance will also enhance resilience. In
341 other cases, however, trade-offs can occur. For example, maintaining genetic diversity for
342 resilience of ecosystem functions, may conflict with the aim to produce ‘best locally adapted
343 phenotype’[49]. Much intensive agricultural management currently focusses on such low
344 diversity systems that produce high levels of provisioning services but which might have low
345 resilience [93]. Furthermore, while habitat heterogeneity can promote the persistence of
346 species through climatic extremes [77, 78], it can, in the shorter term, reduce the availability
347 of specific habitats required by key species. In these cases, short-term management for
348 higher levels of ecosystem function might hinder resilience.

349

350 *Measuring and monitoring resilience*

351 Reporting on ecosystem services has focussed on the short-term [6], despite the
352 acknowledgement of long term resilience in earth systems management [10, 92]. Therefore,
353 a challenge is the development of robust, yet cost-effective, indicators of the resilience of
354 ecosystem functions and services (Box 1). To develop indicators, research is needed into
355 current data availability, feasibility of data collection, and validation of indicator metrics.
356 The subsequent implementation of resilience indicators to inform environmental
357 management will also require significant interdisciplinary research with the socio-economic
358 sciences; for example, in order to ascertain target suites of ecosystem functions in different

359 areas and to set socially-acceptable minimum thresholds for functions. An additional
360 challenge will be to identify and balance trade-offs between the resilience of multiple
361 functions. Such research, however, is essential to safeguard the provision of ecosystem
362 functions under the significant environmental perturbations expected within the next
363 century (see Box 2- Outstanding Questions).

364

365 **Conclusions**

366 In this review we have highlighted mechanisms by which biodiversity, at different
367 hierarchical scales, can influence the resilience of ecosystem functions. We hope that a
368 focus on resilience rather than short-term delivery of ecosystem functions and services, and
369 the consideration of specific underpinning mechanisms, will help to join the research areas
370 of biodiversity-ecosystem function and ecological resilience, and ultimately aid the
371 development of evidence-based, yet flexible, ecosystem management. Further work will
372 also need to draw significantly upon other disciplines in order to develop appropriate
373 indicators for the simultaneous resilience of multiple ecosystem functions.

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Box 1- Indicators of short-term ecosystem function flows versus resilience

The development of indicators for ecosystem functions is hampered by a lack of primary data and there is strong reliance on proxy measures such as habitat extent [94, 95]. These proxy measures are currently used to inform on spatial and temporal trends in ecosystem function for the reporting and management of biodiversity change [4-6]. Such models use abiotic variables such as land cover, topography and climate data as explanatory variables in spatially-explicit statistical correlative models [96, 97] or process models [98, 99] in order to predict the provision of ecosystem functions and services. However, because models are parameterised and validated (where undertaken) on the *current* set of environmental conditions they are often only suitable for producing indicators of short-term ecosystem function flows rather than *resilience* under environmental perturbations (Figure 4).

Attempts at developing resilience indicators for ecological functions have been limited mostly to ‘early warning systems’ [53, 92]. These focus on emergent properties of systems that might precede impending critical state transitions, e.g. ‘critical slowing down’ [53]. However, these properties only occur before critical transitions in a subset of cases and thus are likely to be poor general predictive indicators of resilience [91]. A focus on emergent properties of systems also ignores the mechanisms that underpin resilience and therefore has limited ability to inform management advice.

Therefore, assessments of the resilience of ecosystem functions and services are currently severely lacking. The development of robust, yet cost-effective, indicators is likely to be dependent on proxy measures that can be both derived from existing monitoring [4] and shown to covary with resilience. For example, an attempt to assess importance and feasibility of resilience indicators based on expert opinion for coral reef systems is provided by McClanahan et al. [100]. Validation of practicable proxy measures is then important to ensure they are reliable.

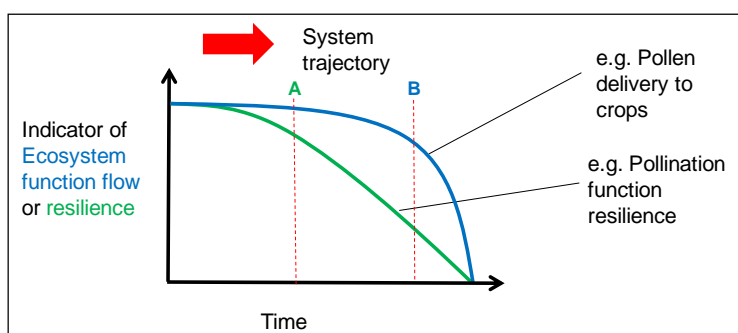


Figure 4 Hypothetical example of indicator values for an ecosystem function flow (pollen delivery to crops) or resilience of that function (pollination under environmental perturbations) as an ecosystem is degraded over time. The thresholds to initiate management action (red dotted lines) differ depending on which indicator is used (A for resilience indicator, B for the ecosystem function flow indicator). Given remedial management takes time to put in place and become effective, unacceptable losses of ecosystem function might occur if ecosystem function flow indicators are solely relied upon. These losses can be costly for society and difficult to reverse.

Box 2- Outstanding questions

The following research questions have particular priority for advancing research into the management of resilient ecosystem functions:

1. Are there thresholds that should be avoided to prevent sudden collapse of ecosystem functions? If so, how quickly are systems moving towards these thresholds and do the thresholds themselves move?
2. How exactly can each of the mechanisms identified in this article and any others be used to inform applied management to enhance resilience of ecosystem functions?
3. How can the relevance and feasibility of these mechanisms be assessed in order to develop robust indicators for the measurement and monitoring of resilience?
4. Given that values people give to ecosystem services are likely to be context-dependent over space and time, how do we decide which services and the underpinning functions are priorities in a given area and what the minimum thresholds are?
5. Given that ecosystem services are the products of both natural capital (i.e. ecosystem functions) and other socioeconomic capitals, what is the relative contribution of resilient ecosystem functions to the maintenance of different ecosystem services over time?
6. How can the measures to promote resilience be justified to when, under stable environmental conditions and in many decision-making relevant time-scales, they lead to apparent redundancy?

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Figure Legends

Figure 1, Schematic showing varying resilience levels of an ecosystem function (Ψ) to environmental perturbations (red arrows). Panel 'a' shows a system with high resistance but slow recovery; panel 'b' shows a system with low resistance but rapid recovery; panel 'c' shows a system with both low resistance and slow recovery. Lack of resilience (vulnerability) could be quantified as the length of time that ecosystem functions are provided below some minimum threshold set by resource managers (this threshold shown with the symbol Ψ_1), or the total deficit of ecosystem function (i.e. the total shaded red area). Note that, in the short-term, mean function is similar in all systems but in the longer term mean function is lower and the extent of functional deficit is higher in the least resilient system (panel 'c').

Figure 2, Different possible relationships between environmental change (ϵ), time (t) and level of ecosystem function provided (Ψ). Panel 'a' shows three types of environmental change: rapid onset (A), chronic (B) and transitory perturbation (C). Panel 'b' shows ecosystem function might be relatively resistant to increasing levels of environmental change (D), less resistant (E) or demonstrate hysteresis (F). Panel 'c' shows the four qualitatively different outcomes for how ecosystem function varies over time, whether the system is fully resistant to an environmental change (H), shows limited resistance but full recovery (I); or shows limited- (J) or low- resistance (K) with no recovery of function. The horizontal line at Ψ_1 indicates some minimum threshold for ecosystem function that is set by resource managers. In both panels 'a' and 'c', short-term stochasticity about trends is omitted for clarity.

Figure 3, Functional redundancy and effects on resilience of ecosystem functions.

Complementary effect trait space occupied by all species in a community can be characterised by an n -dimensional hypervolume for continuous traits (main panels a-c), or as discrete functional groups for categorical traits (inset panels a-c). A high density of species spread evenly across complementary trait space (panel a, shown for two of n possible traits) leads to higher resistance of ecosystem functions. This is shown in panel d (scenario A) which shows the hypothetical average impact on ecosystem function as species are lost from a community under increasing environmental perturbation. The same number of species less evenly dispersed across complementary effect trait space (i.e. a more 'clumped' distribution, panel b) leads to less resistant ecosystem functions (panel d, scenario B). Similarly, fewer species that are evenly, but thinly, spread across complementary effect trait space (panel c), also leads to less resistant ecosystem functions. In both cases, the communities are said to have lower 'functional redundancy'. The exact rate of loss of ecosystem function will be context dependent (e.g. depending on initial number species, ordering of species extinctions and degree of species clustering in trait space).

Figure 4 Hypothetical example of indicator values for an ecosystem function flow (e.g. estimates of pollen delivery to crops) or resilience of that function (e.g. pollination under environmental perturbations as measured by some combination of the mechanisms highlighted in this paper) as an ecosystem is degraded over time. The thresholds to initiate management action (red dotted lines) differ depending on which indicator is used (A for resilience indicator, B for the ecosystem function flow indicator). Given remedial

management takes time to put in place and become effective, unacceptable losses of ecosystem function might occur if ecosystem function flow indicators are solely relied upon. These losses can be costly for society and difficult to reverse.

References

- 1 Butchart, S.H.M., *et al.* (2010) Global biodiversity: indicators of recent declines. *Science* 328, 1164-1168
- 2 Cardinale, B.J., *et al.* (2012) Biodiversity loss and its impact on humanity. *Nature* 486, 59-67
- 3 Mace, G.M., *et al.* (2012) Biodiversity and ecosystem services: a multilayered relationship. *Trends Ecol. Evol.* 27, 19-26
- 4 Geijzendorffer, I.R., *et al.* (2015) Bridging the gap between biodiversity data and policy reporting needs: An Essential Biodiversity Variables perspective. *J. Appl. Ecol.*, online early
- 5 Helfenstein, J. and Kienast, F. (2014) Ecosystem service state and trends at the regional to national level: A rapid assessment. *Ecol. Ind.* 36, 11-18
- 6 Maes J. et, a. (2013) Mapping and Assessment of Ecosystems and their Services. An analytical framework for ecosystem assessments under action 5 of the EU biodiversity strategy to 2020. Publications office of the European Union, Luxembourg.
http://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/MAESWorkingPaper2013.pdf.
- 7 Mora, C., *et al.* (2013) The projected timing of climate departure from recent variability. *Nature* 502, 183-187
- 8 Fowler, D., *et al.* (2013) *The global nitrogen cycle in the twenty-first century.*
- 9 Oliver, T.H. and Roy, D.B. (2015) The pitfalls of ecological forecasting. *Biol. J. Linn. Soc.* 115, 767-778
- 10 Steffen, W., *et al.* (2015) Planetary boundaries: Guiding human development on a changing planet. *Science* 347

- 11 Scheffer, M., *et al.* (2015) Creating a safe operating space for iconic ecosystems. *Science* 347, 1317-1319
- 12 Winfree, R., *et al.* (2015) Abundance of common species, not species richness, drives delivery of a real-world ecosystem service. *Ecol. Lett.* 18, 626-635
- 13 Balvanera, P., *et al.* (2013) Linking Biodiversity and Ecosystem Services: Current Uncertainties and the Necessary Next Steps. *BioScience*
- 14 Allan, E., *et al.* (2011) More diverse plant communities have higher functioning over time due to turnover in complementary dominant species. *PNAS* 108, 17034-17039
- 15 Downing, A.L., *et al.* (2014) Multiple diversity–stability mechanisms enhance population and community stability in aquatic food webs. *Ecology* 95, 173-184
- 16 Loreau, M. and de Mazancourt, C. (2013) Biodiversity and ecosystem stability: a synthesis of underlying mechanisms. *Ecol. Lett.* 16, 106-115
- 17 Folke, C., *et al.* (2004) Regime shifts, resilience, and biodiversity in ecosystem management. *Ann. Rev. Ecol. Evol. Syst.* 35, 557-581
- 18 Sgrò, C.M., *et al.* (2011) Building evolutionary resilience for conserving biodiversity under climate change. *Evol. Appl.* 4, 326-337
- 19 Brand, F. (2009) Critical natural capital revisited: Ecological resilience and sustainable development. *Ecol. Econ.* 68, 605-612
- 20 Biggs, R., *et al.* (2012) Toward principles for enhancing the resilience of ecosystem services. *Ann. Rev. Env. Res.* 37, 421-448
- 21 Zolli, A. and Healy, A.M. (2013) *Resilience: Why Things Bounce Back*. Headline Publishing Group
- 22 Pimm, S.L. (1984) The complexity and stability of ecosystems. *Nature* 307, 321-326

- 23 Gunderson, L., *et al.* (2010) *Foundations of Ecological Resilience* Island Press
- 24 MacGillivray, C.W., *et al.* (1995) Testing Predictions of the Resistance and Resilience of Vegetation Subjected to Extreme Events. *Func. Ecol.* 9, 640-649
- 25 Hodgson, D., *et al.* (2015) What do you mean, 'resilient'? *Trends Ecol. Evol.*, online early
- 26 Standish, R.J., *et al.* (2014) Resilience in ecology: Abstraction, distraction, or where the action is? *Biol. Cons.* 177, 43-51
- 27 Wang, S. and Loreau, M. (2014) Ecosystem stability in space: α , β and γ variability. *Ecol. Lett.* 17, 891-901
- 28 Morin, X., *et al.* (2014) Temporal stability in forest productivity increases with tree diversity due to asynchrony in species dynamics. *Ecol. Lett.* 17, 1526-1535
- 29 Karp, D.S., *et al.* (2011) Resilience and stability in bird guilds across tropical countryside. *PNAS* 108, 21134-21139
- 30 Devictor, V., *et al.* (2012) Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Clim. Change* 2, 121-124
- 31 Oliver, T.H., *et al.* (2012) A decision framework for considering climate change adaptation in biodiversity conservation. *J. Appl. Ecol.* 49, 1247-1255
- 32 Thomas, C.D., *et al.* (2006) Range retractions and extinction in the face of climate warming. *Trends Ecol. Evol.* 21, 415-416
- 33 Gallagher, R.V., *et al.* (2013) Species loss and gain in communities under future climate change: consequences for functional diversity. *Ecography* 36, 531-540
- 34 Mumby, P.J., *et al.* (2014) Ecological resilience, robustness and vulnerability: how do these concepts benefit ecosystem management? *Curr. Opin. Env. Sust.* 7, 22-27

- 35 Hautier, Y., *et al.* (2015) Anthropogenic environmental changes affect ecosystem stability via biodiversity. *Science* 348, 336-340
- 36 Steffen, W., *et al.* (2015) The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* 2, 81-98
- 37 Krausmann, F., *et al.* (2013) Global human appropriation of net primary production doubled in the 20th century. *PNAS* 110, 10324-10329
- 38 Simberloff, D., *et al.* (2013) Impacts of biological invasions: what's what and the way forward. *Trends Ecol. Evol.* 28, 58-66
- 39 Díaz, S., *et al.* (2013) Functional traits, the phylogeny of function, and ecosystem service vulnerability. *Ecol. and Evol.* 3, 2958-2975
- 40 McNeall, D., *et al.* (2011) Analyzing abrupt and nonlinear climate changes and their impacts. *WIREs: Clim. Change* 2, 663-686
- 41 Swift, T.L. and Hannon, S.J. (2010) Critical thresholds associated with habitat loss: a review of the concepts, evidence, and applications. *Biol. Rev.* 85, 35-53
- 42 Chase, J.M. and Bengtsson, J. (2010) Increasing spatio-temporal scales: metacommunity ecology. In *Community Ecology: Processes, Models, and Applications* (Verhoef, H.A. and Morin, P.J., eds), Oxford University Press
- 43 Hofmann, G.E. and Todgham, A.E. (2010) Living in the Now: Physiological Mechanisms to Tolerate a Rapidly Changing Environment. *Ann. Rev. Phys.* 72, 127-145
- 44 O'Brien, M.J., *et al.* (2014) Drought survival of tropical tree seedlings enhanced by non-structural carbohydrate levels. *Nature Clim. Change* 4, 710-714
- 45 Reich, P.B. (2014) The world-wide 'fast-slow' plant economics spectrum: a traits manifesto. *J. Ecol.* 102, 275-301

- 46 Grman, E., *et al.* (2010) Mechanisms contributing to stability in ecosystem function depend on the environmental context. *Ecol. Lett.* 13, 1400-1410
- 47 Sunday, J.M., *et al.* (2014) Thermal-safety margins and the necessity of thermoregulatory behavior across latitude and elevation. *PNAS* 111, 5610-5615
- 48 Forsman, A. and Wennersten, L. (2015) Inter-individual variation promotes ecological success of populations and species: evidence from experimental and comparative studies. *Ecography*, online early
- 49 Kettenring, K.M., *et al.* (2014) Application of genetic diversity–ecosystem function research to ecological restoration. *J. Appl. Ecol.* 51, 339-348
- 50 Reusch, T.B.H., *et al.* (2005) Ecosystem recovery after climatic extremes enhanced by genotypic diversity. *PNAS* 102, 2826-2831
- 51 Bossdorf, O., *et al.* (2008) Epigenetics for ecologists. *Ecol. Lett.* 11, 106-115
- 52 Berec, L., *et al.* (2007) Multiple Allee effects and population management. *Trends Ecol. Evol.* 22, 185-191
- 53 Dai, L., *et al.* (2012) Generic Indicators for Loss of Resilience Before a Tipping Point Leading to Population Collapse. *Science* 336, 1175-1177
- 54 Suding, K.N., *et al.* (2008) Scaling environmental change through the community-level: a trait-based response-and-effect framework for plants. *Glob. Ch. Biol.* 14, 1125-1140
- 55 Weiher, E., *et al.* (1999) Challenging Theophrastus: a common core list of plant traits for functional ecology. *J. Veg. Sci.* 10, 609-620
- 56 Larsen, T.H., *et al.* (2005) Extinction order and altered community structure rapidly disrupt ecosystem functioning. *Ecol. Lett.* 8, 538-547

- 57 Williams, N.M., *et al.* (2010) Ecological and life-history traits predict bee species responses to environmental disturbances. *Biol. Cons.* 143, 2280–2291
- 58 Kotze, D.J. and O'Hara, R.B. (2003) Species decline - but why? Explanations of carabid beetle (Coleoptera, Carabidae) declines in Europe. *Oecologia* 135, 138-148
- 59 Dixon, A.F.G. and Hemptinne, J.L. (2001) Body size distribution in predatory ladybird beetles reflects that of their prey. *Ecology* 82, 1847-1856
- 60 Mouillot, D., *et al.* (2013) A functional approach reveals community responses to disturbances. *Trends Ecol. Evol.* 28, 167-177
- 61 Mouillot, D., *et al.* (2014) Functional over-redundancy and high functional vulnerability in global fish faunas on tropical reefs. *PNAS* 111, 13757-13762
- 62 Yachi, S. and Loreau, M. (1999) Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. *PNAS* 96, 1463-1468
- 63 Losey, J.E. and Denno, R.F. (1998) Interspecific variation in the escape responses of aphids: effect on risk of predation from foliar-foraging and ground- foraging predators. *Oecologia* 115, 245-252
- 64 Schindler, D.E., *et al.* (2010) Population diversity and the portfolio effect in an exploited species. *Nature* 465, 609-612
- 65 Duffy, J.E. (2002) Biodiversity and ecosystem function: the consumer connection. *Oikos* 99, 201-219
- 66 Dunne, J.A., *et al.* (2002) Network structure and biodiversity loss in food webs: robustness increases with connectance. *Ecol. Lett.* 5, 558-567
- 67 Fung, T., *et al.* (2015) Impact of biodiversity loss on production in complex marine food webs mitigated by prey-release. *Nature Communications* 6

- 68 Memmott, J., *et al.* (2004) Tolerance of pollination networks to species extinctions. *Proc. Roy. Soc. B* 271, 2605-2611
- 69 Schleuning, M., *et al.* (2014) Predicting ecosystem functions from biodiversity and mutualistic networks: an extension of trait-based concepts to plant–animal interactions. *Ecography*, online early
- 70 Isikber, A.A. and Copland, M.J.W. (2001) Food consumption and utilisation by larvae of two coccinellid predators, *Scymnus levallanti* and *Cycloneda sanguinea*, on cotton aphid, *Aphis gossypii*. *Biocontrol* 46, 455-467
- 71 Rooney, N. and McCann, K.S. (2012) Integrating food web diversity, structure and stability. *Trends Ecol. Evol.* 27, 40-46
- 72 Lever, J.J., *et al.* (2014) The sudden collapse of pollinator communities. *Ecol. Lett.* 17, 350-359
- 73 Berg, S., *et al.* (2014) Ecological communities are vulnerable to realistic extinction sequences. *Oikos* 124, 486-496
- 74 Stevens, C.J., *et al.* (2011) Addressing the Impact of Atmospheric Nitrogen Deposition on Western European Grasslands. *Environmental Management* 48, 885-894
- 75 Kindvall, O. (1996) Habitat heterogeneity and survival in a bush cricket metapopulation. *Ecology* 77, 207-214
- 76 Godfree, R., *et al.* (2011) Multiscale topographic heterogeneity increases resilience and resistance of a dominant grassland species to extreme drought and climate change. *Glob. Ch. Biol.* 17, 943-958
- 77 Piha, H., *et al.* (2007) Anuran abundance and persistence in agricultural landscapes during a climatic extreme. *Glob. Ch. Biol.* 13, 300-311

- 78 Oliver, T., *et al.* (2010) Heterogeneous landscapes promote population stability. *Ecol. Lett.* 13, 473-484
- 79 Stein, A., *et al.* (2014) Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales. *Ecol. Lett.* 17, 866-880
- 80 Mora, C., *et al.* (2007) Experimental simulations about the effects of overexploitation and habitat fragmentation on populations facing environmental warming. *Proc. Roy. Soc. B* 274, 1023-1028
- 81 Altermatt, F., *et al.* (2011) Effects of Connectivity and Recurrent Local Disturbances on Community Structure and Population Density in Experimental Metacommunities. *PLoS ONE* 6, e19525
- 82 Oliver, T.H., *et al.* (2013) Population resilience to an extreme drought is influenced by habitat area and fragmentation in the local landscape. *Ecography* 36, 579-586
- 83 Piessens, K., *et al.* (2009) Synergistic effects of an extreme weather event and habitat fragmentation on a specialised insect herbivore. *Oecologia* 159, 117-126
- 84 Perdomo, G., *et al.* (2012) The role of temperature and dispersal in moss-microarthropod community assembly after a catastrophic event. *Philosophical Transactions of the Royal Society B-Biological Sciences* 367, 3042-3049
- 85 Ziter, C., *et al.* (2013) Functional diversity and management mediate aboveground carbon stocks in small forest fragments. *Ecosphere* 4, art85
- 86 Symons, C.C. and Arnott, S.E. (2013) Regional zooplankton dispersal provides spatial insurance for ecosystem function. *Glob. Ch. Biol.* 19, 1610-1619
- 87 Hodgson, J.A., *et al.* (2011) Habitat area, quality and connectivity: striking the balance for efficient conservation. *J. Appl. Ecol.* 48, 148-152

- 88 Fahrig, L., *et al.* (2010) Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecol. Lett.* online early
- 89 Petraitis, P. (2013) *Multiple Stable States in Natural Ecosystems*. Oxford University Press
- 90 Schröder, A., *et al.* (2005) Direct experimental evidence for alternative stable states: a review. *Oikos* 110, 3-19
- 91 Dakos, V., *et al.* (2015) *Resilience indicators: prospects and limitations for early warnings of regime shifts*.
- 92 Spears, B.M., *et al.* (2015) Effective management of ecological resilience – are we there yet? *J. Appl. Ecol.*, online early
- 93 Foley, J.A. (2005) Global consequences of land use. *Science* 309, 570-574
- 94 Eigenbrod, F., *et al.* (2010) The impact of proxy-based methods on mapping the distribution of ecosystem services. *J. Appl. Ecol.* 47, 377-385
- 95 Stephens, P.A., *et al.* (2015) Management by proxy? The use of indices in applied ecology. *J. Appl. Ecol.* 52, 1-6
- 96 Lavorel, S., *et al.* (2011) Using plant functional traits to understand the landscape distribution of multiple ecosystem services. *J. Ecol.* 99, 135-147
- 97 Henrys, P.A., *et al.* (2014) Mapping natural capital: optimising the use of national scale datasets. *Ecography* 38, 632-638
- 98 Nelson, E., *et al.* (2009) Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Env.* 7, 4-11
- 99 Villa, F., *et al.* (2014) A Methodology for Adaptable and Robust Ecosystem Services Assessment. *PLoS ONE* 9, e91001

100 McClanahan, T.R., *et al.* (2012) Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate. *PLoS ONE* 7, e42884

Figure 1

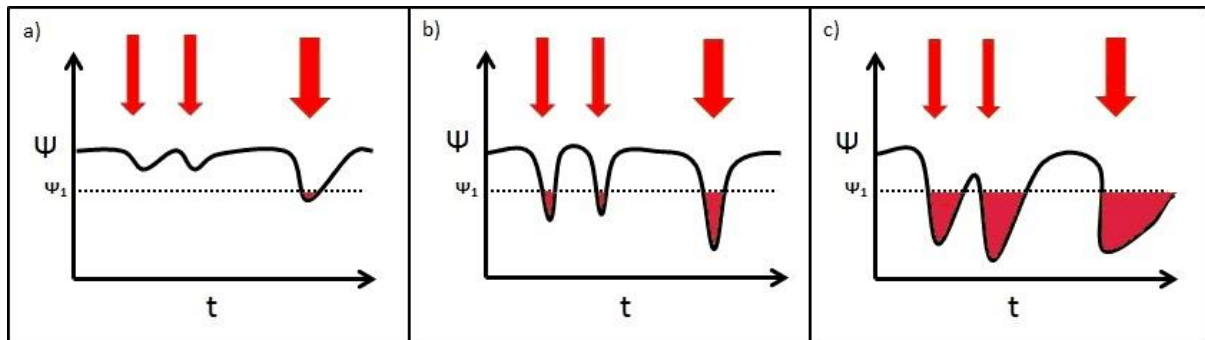


Figure 2

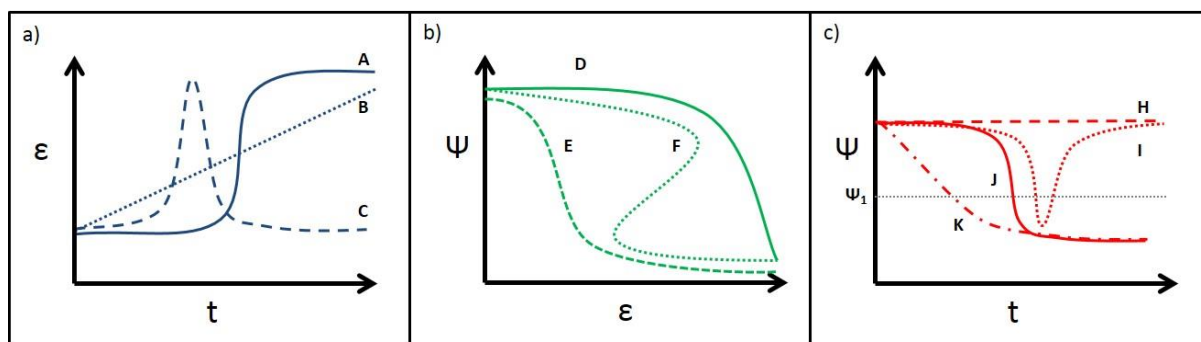


Figure 3

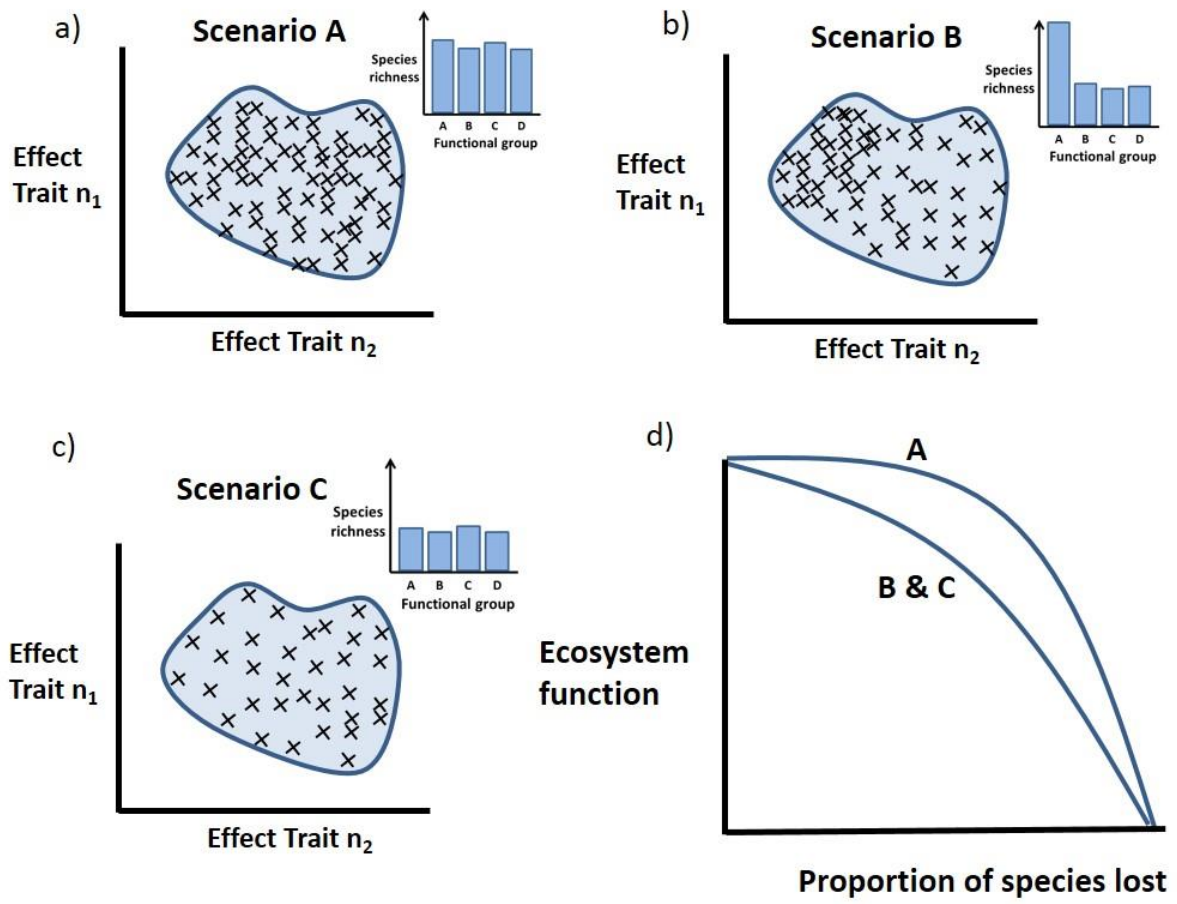


Figure 4

