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1 **Opinion for *Trends in Ecology and Evolution***

2 **Title:** Re-introducing environmental change drivers in biodiversity-ecosystem functioning  
3 research

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38

39 **Abstract**

40 For the past 20 years, research on biodiversity and ecosystem functioning (B-EF) has only  
41 implicitly considered the underlying role of environmental change. We illustrate that  
42 explicitly re-introducing environmental change drivers in B-EF research is needed to predict  
43 the functioning of ecosystems facing changes in biodiversity. Next, we show how this re-  
44 introduction improves experimental control over community composition and structure,  
45 which helps to obtain mechanistic insight about how multiple aspects of biodiversity relate to  
46 function, and how biodiversity and function relate in food-webs. We also highlight  
47 challenges for the proposed re-introduction, and suggest analyses and experiments to better  
48 understand how random biodiversity changes, as studied by classic approaches in B-EF  
49 research, contribute to the shifts in function that follow environmental change.

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69 **Predicting effects on ecosystem functions from changes in biodiversity: a brief history**

70 Various types of environmental change, such as climate change, habitat fragmentation, or  
71 chemical pollution, can profoundly alter multiple facets of biodiversity [1-4]. The past 25  
72 years have seen a rise in different empirical approaches to examine how such changes affect  
73 ecosystem functions and services [5, 6]. Many focus on altering biodiversity while observing  
74 corresponding changes in function [7]. These approaches can be first classified based on the  
75 nature of the manipulation, whether species densities are altered randomly or non-randomly  
76 (see ‘Glossary’). Random manipulations assume a random extinction or colonization order,  
77 while non-random manipulations are done based on the (presumed) response of species to  
78 environmental change [8], or based on the effects of species on function (e.g. species with a  
79 greater effect on function are removed first) [9]. A second distinction can be based on  
80 whether manipulations of biodiversity are direct or indirect (see ‘Glossary’). Direct  
81 biodiversity manipulations are performed by manually altering species densities [10],  
82 whereas with indirect manipulations, a relevant environmental change is introduced to alter  
83 biodiversity [11, 12].

84

85 Indirect and non-random manipulations of biodiversity make intuitive sense because they are  
86 rooted in a recognition that environmental change drivers (see ‘Glossary’) are often the cause  
87 of biodiversity alterations [3] and that these alterations are non-random [9, 13]. As a  
88 consequence, early research on biodiversity and ecosystem functioning (‘B-EF research’ [7])  
89 often adopted indirect and non-random biodiversity manipulations [11, 12, 14]. However,  
90 such approaches were increasingly subject to controversy and disagreement. In his seminal  
91 paper, Huston [15] criticized indirect and non-random biodiversity manipulations for  
92 difficulties in separating ‘true’ biodiversity effects from the effects of ‘hidden treatments’.  
93 Huston argued that by indirectly altering biodiversity using an environmental variable,  
94 researchers precluded partitioning the biodiversity-mediated effects on ecosystem function  
95 from the many other effects environmental change can have on function (see ‘Glossary’).  
96 Non-random manipulations were also shown to suffer from inherent bias, because results  
97 were highly dependent on the chosen order of species removal or addition. Collectively, the  
98 critiques by Huston and others [15-18] pushed the field towards direct and random  
99 biodiversity manipulations [7, 10]. The advantage of this methodological shift was that the  
100 causal relationship between biodiversity and ecosystem functioning, a main research gap at  
101 that time, could be more rigorously established. Today, however, a main research gap in  
102 ecology is to understand how the data produced using random and/or direct manipulations of

103 biodiversity can be used to meet two of ecology's current challenges: (1) to support  
104 quantitative prediction of the ecological effects of anthropogenic activities [7]; and (2) to  
105 unravel the mechanisms linking community structure (relative abundances) and composition  
106 to ecosystem function [19, 20]. In the present contribution, we submit that re-introducing  
107 non-random and indirect manipulations of biodiversity using environmental change drivers  
108 [21-25] (1) is a prerequisite to predicting the functioning of ecosystems facing changes in  
109 biodiversity that are caused by environmental change (section 2); and (2) facilitates  
110 unravelling mechanistic insight into the connections between community structure and  
111 composition and ecosystem function (section 3).

112

### 113 **The re-introduction of environmental change drivers is needed to predict ecosystem** 114 **functioning following changes in biodiversity**

115 In many ecosystems, environmental change causes biodiversity declines or increases [26-29].  
116 Experiments that directly and randomly manipulate biodiversity are unlikely to predict  
117 function in these ecosystems (Fig. 1, shaded area). This is because biodiversity changes that  
118 are non-random with respect to species' contributions to function will affect ecosystem  
119 functioning more or less than do random biodiversity changes [9, 30]. In addition,  
120 environmental change can alter the effect species have on ecosystem functions by altering (1)  
121 per-capita contributions to function [31, 32], and (2) population density [33, 34]. Depending  
122 on the type of environmental change, these alterations can be mostly positive (e.g. nutrient  
123 enrichment [35]), mostly negative (e.g. drought [36] or pollution [37]), or negative for some  
124 species and positive for others (e.g. warming [38-40]).

125

126 Trait-based frameworks are available to predict how non-random effects of environmental  
127 change on per-capita contributions to function, population densities, and biodiversity  
128 translate to changes in ecosystem function [9, 30]. A simple extension of this framework with  
129 species interactions (Box 1) and using richness as a biodiversity indicator illustrates two  
130 important points. First, environmental change can cause a variety of B-EF relationships (Fig.  
131 1). The shape of this relationship critically depends on (1) whether the responses elicited by  
132 the environmental change driver are positive or negative, and (2) the type of non-randomness  
133 exerted by the environmental change driver [29, 41] (Box 1). Second, changes in function are  
134 expected before any change in species richness is observed (Fig. 1A and D; levels 0-0.1), and  
135 – more generally – the variability of ecosystem function within one level of species richness  
136 is substantial (Box 1, Box 3, 'Outstanding questions'). The ensemble of B-EF relationships

137 constructed through direct and random biodiversity manipulation (Fig. 1, shaded area) does  
138 not capture the variation in B-EF shapes arising from indirect and non-random biodiversity  
139 manipulation, and can both over- (e.g. Fig. 1B) and underestimate variation of function  
140 within one biodiversity level (e.g. Fig. 1C).

141

#### 142 **The re-introduction of environmental change drivers can augment mechanistic insight**

143 Many descriptors of biodiversity (e.g. richness and evenness, and based on traits, taxonomy,  
144 or genes), but also community structure and composition, total density (community size) and  
145 per-capita contributions to function, can affect ecosystem functioning [33, 42-45]. A main  
146 research theme in ecology is to understand their relative importance to functioning [7, 46,  
147 47]. Using environmental change drivers to indirectly manipulate biodiversity, community  
148 structure and composition, total density, and per-capita contributions to function facilitates  
149 such studies. This is because different environmental change levels trigger effects on  
150 different subsets of these variables (Fig. 1). For example, in Fig. 1A, environmental change  
151 levels between 0.25 and 0.7 will all lead to the same species richness, but will alter total  
152 density and per-capita contributions to function. In Fig. 1B, effects on richness are always  
153 more important than effects on total density or per-capita contributions to function. In Fig.  
154 1A and D, low levels of change only affect per-capita contributions to function and total  
155 density. In general, the fact that different levels of environmental change cause different  
156 effects offers greater control over the different mechanisms underlying change of function  
157 than do direct manipulations of biodiversity. Controlling per-capita contributions to function  
158 is by definition impossible through direct manipulations of biodiversity, since per-capita  
159 contribution to function is no descriptor of biodiversity. However, even community  
160 composition, structure, and richness will often be uncontrollable through direct  
161 manipulations. For example, in the model presented in Fig. 1, persistence of species 0 or  
162 dominance by any other species than species 9 is only possible in the continuous presence of  
163 an appropriate environmental change driver, i.e. through indirect manipulations. Without this  
164 presence, community structure will always converge to the one shown in Box 1, and richness  
165 will be 9, even when all 10 species are added to the initial community. Many examples  
166 illustrate community compositions and structures that only emerge in the presence of specific  
167 environmental change drivers and do not occur in their absence. For example, drought in  
168 streams reduces the relative density of large-bodied consumers, predators, and encrusting  
169 green algae [36]. Nitrogen enrichment in grasslands increases the relative density of nitrogen  
170 demanding grasses [35], while increased precipitation in grasslands increases the relative

171 density of nitrogen-fixing forbs [48]. Even though most of the available studies are based on  
172 taxonomic diversity, case studies showing how environmental change drivers can cause loss  
173 or gain of genetic diversity are rapidly accumulating [29, 49].

174 The relationship between biodiversity and functioning in multi-trophic communities (food-  
175 webs) has been an important research theme in ecology since the 1990s [7, 50-52]. For  
176 example, the biodiversity of one food-web compartment can drive functions performed by  
177 other parts of the food-web [53], or both can be unrelated [54]. Using environmental change  
178 drivers to indirectly and non-randomly manipulate food-webs facilitates studying such links.  
179 This is because environmental change drivers often target specific food-web compartments so  
180 that it becomes possible to experimentally alter biodiversity and related functions of specific  
181 food-web compartments and measure corresponding changes in other compartments. For  
182 example, resource enrichment can be used to increase functions performed by basal species  
183 groups (e.g. bacterial decomposition, water purification, primary production), while  
184 desiccation can be used to target functions performed by non-basal species [36]. In addition  
185 to the well-known cases of resource addition or manipulation of climate variables, chemical  
186 stressors comprise an exceptionally useful group of experimental agents that can be used for  
187 both non-random manipulations as well as for manipulations that are random with respect to  
188 the effects species have on function. This is illustrated by the many studies that have exposed  
189 relatively complex food-webs composed of field organisms (typically primary producers and  
190 invertebrate grazers and predators) to concentration series of chemical stressors during  
191 several weeks to months (Fig. 2). For example, many pyrethroid insecticides will target  
192 arthropod consumers and predators [55, 56], while photosystem-inhibiting herbicides will  
193 target specific algal taxa [57, 58]. Certain biocides such as triphenyltin [59] and narcotic  
194 chemicals [60] are examples of chemical stressors that exert effects that are random with  
195 respect to the effects species have on function. Directly manipulating food-webs to  
196 persistently exclude certain trophic levels or functional groups (e.g. small-bodied benthic  
197 grazers, specific bacterial communities or, algal taxa) will be nearly impossible. Indirect non-  
198 random manipulations might therefore be the only solution.

199

## 200 **Back to the future: methods to connect indirect and non-random manipulations with** 201 **classic B-EF research**

202 Most classic B-EF designs focus on the effect of random biodiversity changes on ecosystem  
203 function through direct manipulations. To quantify the contribution of such effects to the

204 functioning of ecosystems following environmental change (Box 3, ‘Outstanding questions’)  
205 [23] analysing available data is a useful starting point. The literature is replete with studies  
206 exposing communities to environmental gradients. When a sufficient number of change  
207 levels has been tested across a sufficiently broad gradient of change, the contributions of  
208 biodiversity-mediated effects can be separated from the other effects of environmental  
209 change on ecosystem function using available analytical techniques. One possible way to do  
210 so is by applying multivariate statistical techniques, such as structural equation modelling  
211 [61, 62] (Box 2). However, sophisticated structural equation models [21, 24] can also be used  
212 to partition the effects on function that are not mediated by biodiversity into their  
213 constituents. In addition, methods based on versions of the Price equation that do not require  
214 monoculture data but only need species contributions to function before and after  
215 environmental change can be used to separate the effects of species loss and gain that is  
216 random and non-random with respect to the effects species have on function from all other  
217 effects environmental change can have on function [42].

218

219 Post-hoc analyses are a useful first step to quantify biodiversity-mediated effects on function.  
220 However, we recommend combining direct and indirect biodiversity manipulations as  
221 separate treatments in a single experiment. In a first design, we recommend using a well-  
222 known environmental change driver to non-randomly manipulate a community, while setting  
223 up a second treatment where the same community is manipulated directly. Importantly, the  
224 direct manipulation should be done in the absence of the environmental change driver but  
225 aim to match the community resulting from the application of the environmental change  
226 driver, as observed in the first treatment, and should therefore be non-random. For example,  
227 in Fig. 1B, applying a level of change of 0.1 would constitute an indirect biodiversity  
228 manipulation that excludes species 1. Higher levels would exclude species 2, 3, and so on.  
229 Thus, the direct biodiversity manipulation treatments should represent the same gradient of  
230 community compositions, by consecutively excluding species 1, 2, 3, and so on. Next, the B-  
231 EF relationship resulting from the indirect manipulation (e.g. Fig. 1B, ‘resulting B-EF’ panel)  
232 could be compared to the one resulting from direct species removal. If both were not  
233 significantly different, this would suggest that the chosen type of environmental change  
234 mainly acts upon ecosystem functioning through compositional effects. If B-EF relationships  
235 do differ, follow-up studies could examine in more detail the potential mechanisms  
236 explaining this difference, for example by inspecting the magnitude of effects on per-capita  
237 contributions to function [25], or by considering effects on community structure. However,

238 we recognize that this design can be challenging because, as mentioned in section 3, certain  
239 community compositions are impossible to reconstruct without the use of environmental  
240 variables. This problem could be addressed by statistically testing if per-capita contributions  
241 to function (functional contribution of a species, e.g. its total biovolume divided by its  
242 population density) differ between the direct and indirect biodiversity treatment. If the  
243 inferred values of per-capita contributions to function do not differ between both treatments,  
244 this suggests that the selected type of environmental change impacts on ecosystem  
245 functioning through other mechanisms than effects on per-capita contributions to function.

246

247 A second design consists of a factorial experiment where the presence or absence of a direct  
248 biodiversity manipulation that aims to match the community structure resulting from the  
249 indirect biodiversity manipulation is crossed with the presence and absence of an  
250 environmental change driver [63]. If all the effects of the driver on ecosystem functioning are  
251 mediated by biodiversity changes, then the combination of direct biodiversity manipulation  
252 and the environmental change treatment should display the same level of ecosystem  
253 functioning as both the direct manipulation alone and the environmental change treatment  
254 alone. If this were not the case, then it would suggest non-biodiversity-mediated effects on  
255 ecosystem functioning. Interestingly, the same design has been recently proposed by Vellend  
256 [64], yet motivated by a different objective. Vellend proposed to use this design to test if a  
257 community structure shaped by environmental change maximizes function under that same  
258 type of environmental change, a prediction based on the analogy between community  
259 ecology and population genetics.

260

### 261 **Challenges of re-introducing environmental change drivers in B-EF research**

262 Although we advocate re-introducing environmental change drivers in B-EF research, there  
263 are at least two challenges that need to be addressed for successful application. First, in the  
264 approach we advocate, we implicitly assume that environmental change does not affect per-  
265 capita species interactions (the  $\alpha$  in Box 1). In our model, the effects of species interactions  
266 on a focal species are only altered through changes in the density of species with which it  
267 interacts. This assumption has been shown to prevail in some systems [65], but not in others  
268 [66, 67]. Arguably the best-known example of environmental effects on per-capita  
269 interactions is the ‘stress gradient hypothesis’, where there is a shift from competitive (i.e.  
270 negative) to facilitative (i.e. positive) interactions as the level of stress increases [66, 67].  
271 Such effects can lead to a variety of effects of stress on community structure and composition

272 and ecosystem function, depending on the type of stress factor and species traits [68]. Suttle  
273 et al. [48] found that sustained increased precipitation eventually caused negative interactions  
274 among plant species that were not apparent before the treatment. In alfalfa communities,  
275 Barton and Ives [69] found that reduced precipitation changed interactions between spotted  
276 aphids and their ladybeetle predators through dietary shifts of the latter. These examples  
277 make clear that species interactions prevailing in the pre-change system cannot always be  
278 used to predict the chain of secondary and higher-order effects occurring after the change. In  
279 such cases, knowledge about shifts of per-capita species interactions is needed to gain control  
280 over community structure and composition in experiments (Box 3, ‘Outstanding questions’),  
281 and to correctly interpret the observed effects of environmental change on biodiversity and  
282 ecosystem functioning.

283

284 Second, we have discussed environmental change drivers eliciting either positive or negative  
285 responses that change monotonically as the level of environmental change increases, and stay  
286 constant through time. However, many environmental change drivers can elicit positive  
287 responses in some species but negative responses in others (e.g. temperature [38]), and many  
288 responses are non-monotonic, with the sign of the response depending on the level of  
289 environmental change (e.g. [47]). In addition, depending on the life history of the considered  
290 species, populations can genetically adapt [49], which can alter their response to  
291 environmental change through time. While these features do not threaten the general  
292 principle of our thesis, they do indicate that community structure and composition can be  
293 harder to interpret and predict, and therefore also more difficult to control in experiments, for  
294 certain combinations of environmental change drivers and ecosystem types.

295

### 296 **Opportunities for ecosystem assessment and management**

297 Novel tools for biological monitoring will substantially increase the amount of biodiversity  
298 data [70, 71]. However, linking monitored biodiversity trends to ecosystem functions remains  
299 a major difficulty for ecosystem assessment, as has been discussed in the framework of  
300 several environmental regulations worldwide [72, 73]. Re-introducing environmental change  
301 drivers in B-EF research could help ecosystem assessors by realistically translating observed  
302 biodiversity trends to trends of ecosystem function for a suite of well-studied environmental  
303 change drivers. Studies compiling and comparing different types of environmental change  
304 [22, 74] will be instrumental to ask if knowledge about one type of environmental change can  
305 be transposed to other types of environmental change (Box 3, ‘Outstanding questions’).

306 Following ecosystem assessments, predicted changes of ecosystem functions could be used to  
307 inform management as well, for example by triggering mitigating measures if needed. In  
308 addition, ecosystem managers could propose critical levels of biodiversity change that, when  
309 exceeded, lead to unacceptable loss of ecosystem functioning. The connection of B-EF  
310 research to applied science has often been debated [75]. Re-introducing the use of  
311 environmental change drivers to B-EF research can reinforce this connection.

312

### 313 **Concluding remarks**

314 We have identified two reasons why environmental change drivers should be re-introduced in  
315 B-EF research. First, the amount of ecosystem function loss or gain following biodiversity  
316 change depends on the type of underlying environmental change driver(s). Second,  
317 environmental change drivers can serve as experimental agents to control various aspects of  
318 biodiversity and community composition and structure. These features facilitate studying to  
319 what extent changes in ecosystem function are caused by biodiversity change and which  
320 aspects of biodiversity are most important to ecosystem function.

321

322 Re-introducing environmental change drivers into B-EF research can be realised by analysing  
323 existing data of well-known environmental change drivers and through novel experimental  
324 designs. Designs combining direct and indirect biodiversity manipulations constitute a  
325 particularly useful research avenue as they allow to directly test how biodiversity,  
326 environmental change, and ecosystem function relate. However, unexpected effects of  
327 environmental change on per-capita species interactions and the variety of species' responses  
328 to such change are two main challenges to the use of environmental change drivers in B-EF  
329 research. Opportunities include an improved capacity to assist ecosystem assessment and  
330 management, by translating monitored biodiversity trends to trends of ecosystem function,  
331 which are rarely monitored. We conclude that re-introducing environmental change drivers in  
332 B-EF research is a prerequisite for predicting shifts of ecosystem function in a changing  
333 world, facilitates understanding the mechanisms causing these shifts, and strengthens the  
334 connections between B-EF research and applied ecology.

335

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375 **Box 1: Non-random and indirect vs. random and direct biodiversity manipulations.** We  
376 simulate richness and ecosystem functioning in a community of 10 species responding to a  
377 level  $l$  of an environmental change driver and contributing to an ecosystem function  $F$  [9]:

378 
$$\frac{dN_i}{dt} \cdot \frac{1}{N_i} = [\mu_i(l) + \sum_{j=1}^{10} \alpha_{i,j} \cdot N_j]$$
 (based on [50])

379 
$$F = \sum_{i=1}^{10} f_i(l) \cdot N_i^*$$

380 The  $\alpha_{i,j}$  are per-capita effects of species  $j$  on species  $i$  ( $\alpha_{i,j} = \alpha_{j,i} = -0.2$ ; intraspecific effects  $\alpha_{i,i}$   
381 are set to  $-1$ ).  $N_i$  is the density of species  $i$  (asterisks denote equilibrium densities);  $\mu_i(l)$  and  
382  $f_i(l)$  are growth rates and per-capita contributions to  $F$  as a function of  $l$ :

383 
$$\mu_i(l) = \mu_{i,max} \cdot (1 + r_i \cdot l)$$

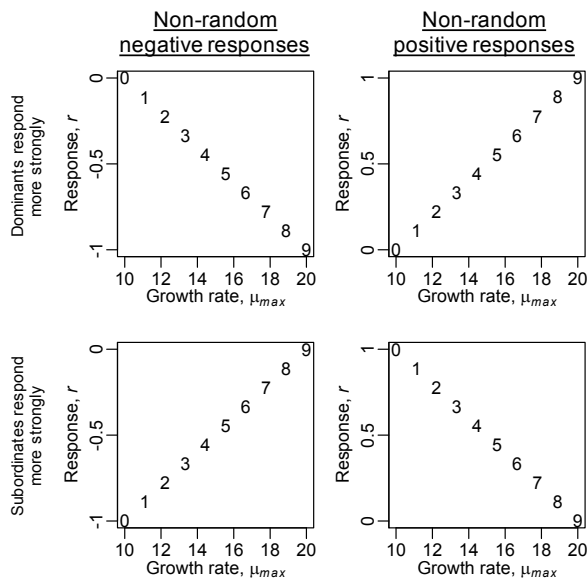
384 
$$f_i(l) = f_{i,max} \cdot (1 + r_i/2 \cdot l)$$

385 where  $r_i$  represents the response of species  $i$  to environmental change and the division by two  
386 ensures per-capita contributions to function responds more strongly than density [76]. All  
387 species have  $f_{i,max} = 10$ , respond differently to environmental change (Fig. I), have different  
388 growth rates (Fig. I) and therefore different competitive strengths (Fig. II).

389 We manipulated richness indirectly and non-randomly by exposing the community to levels  $l$   
390 between 0 (no change) and 1 (100% increase or decrease of  $\mu$  of the most responsive  
391 species), and measured the corresponding  $F$  (Fig. 1, colored symbols). When dominants  
392 respond most negatively (Fig. 1A), function decreases but richness is higher with than  
393 without environmental change because of competitive release of species 0. Thus,  
394 environmental change promotes co-existence and richness only decreases at high levels of  
395 change. The resulting B-EF relationship is therefore non-monotonic. When environmental  
396 change mostly elicits negative responses of subordinates (Fig. 1B), richness decreases already  
397 at low levels of change because subordinates (species 1) combine a low density, which makes  
398 them inherently prone to competitive exclusion, with a large negative response. In this case, a  
399 monotonic positive B-EF relationship emerges. When environmental change elicits positive  
400 responses, negative (Fig. 1C) or positive B-EF relationships (Fig. 1D) emerge from exactly  
401 the same mechanisms as in Fig. 1A and 1B.

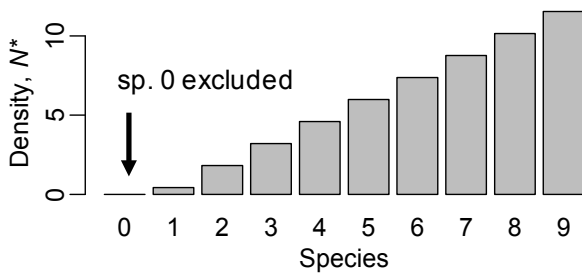
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403 We also manipulated richness directly and randomly by removing all possible combinations  
404 of 1 to 5 species from the community and measuring the corresponding  $F$  while setting  $l=0$   
405 (Fig. 1, shaded area, identical for all four scenarios).



407

408 Figure I: Environmental change elicits negative (left panels) or positive responses (right  
 409 panels) that are strongest for species with high (top row) or low (bottom row) growth rates,  
 410 i.e. species that are dominant and subordinate in pre-change conditions, respectively (Fig. II).  
 411 Numbers give species identity.



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413 Figure II: Equilibrium densities in absence of environmental change.

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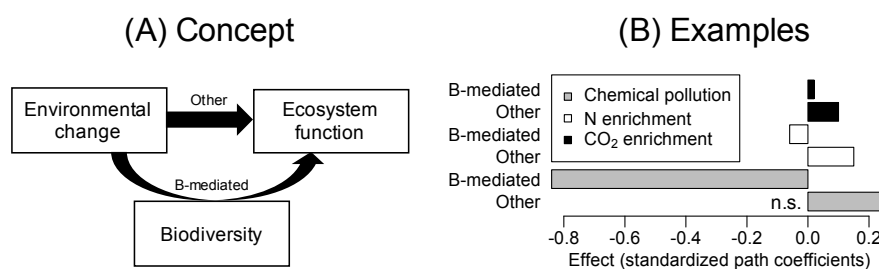
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425 **Box 2: Separating biodiversity-mediated effects on ecosystem functioning.** Structural  
 426 equation models (SEMs) can be used to compare biodiversity-mediated effects on ecosystem  
 427 functioning with the other effects environmental change can have on function. A SEM is  
 428 described as “the use of two or more structural [cause-effect] equations to model multivariate  
 429 relationships”, which allows for an intuitive graphical representation of complex causal  
 430 networks [61, 62]. Most notably, a SEM cannot only be used to isolate biodiversity-mediated  
 431 effects on ecosystem functioning, but also to investigate the partial contributions of correlated  
 432 explanatory variables to test alternative hypotheses [61].

433 For illustrative purposes, we analysed data from a previously published microcosm study  
 434 evaluating the effects of chemical stress (a mixture of insecticides) on aquatic invertebrate  
 435 richness and decomposition in a ditch community [77, 78] with a simple structural equation  
 436 model. We also present previously published effects of nitrogen and carbon dioxide  
 437 enrichment on plant richness and biomass production in grasslands [23]. These analyses show  
 438 that richness-mediated effects on function are negative for environmental change drivers that  
 439 have negative effects on richness, and that these richness-mediated effects can be partly  
 440 compensated by other effects of environmental change. Many examples in the literature  
 441 support the conclusion that environmental change studies can be successfully analysed with  
 442 SEMs, including SEMs with more extended effect pathways [21, 24]. In more replicated  
 443 experimental setups [61], different biodiversity and community metrics could be tested in  
 444 parallel to extract the most relevant biodiversity metric causing alterations in ecosystem  
 445 functioning.



446  
 447 Figure I. A: Environmental change drivers can affect functions by altering biodiversity or  
 448 through other mechanisms [23]. B: Structural equation models for three environmental  
 449 change drivers. All effects are significant ( $P < 0.05$ ) except when indicated (n.s.). The  
 450 variance of diversity and function explained by the model ( $R^2$ ) for the case of chemical stress  
 451 was 68% and 65%, respectively. Effects are standardized path coefficients [62]. Details on  
 452 the analysis for the other two drivers can be found in the original publication [23].

453

454 **Glossary**

455 **Environmental change driver:** An environmental variable that exhibits long-term changes,  
456 often as a result of anthropogenic activities. Examples include nutrient deposition, climate  
457 warming, habitat fragmentation, and chemical pollution.

458 **Direct biodiversity manipulation:** If biodiversity is manipulated directly, communities with  
459 different biodiversity levels are composed, e.g. by taking different subsets of a species pool in  
460 case of richness.

461 **Indirect biodiversity manipulation:** If biodiversity is manipulated indirectly, one applies  
462 different levels of an environmental change driver to create a biodiversity gradient. Indirect  
463 biodiversity manipulations are by definition non-random with respect to species responses to  
464 environmental change.

465 **Random biodiversity manipulation:** If biodiversity is manipulated randomly, community  
466 composition or structure is varied within a diversity level. By doing so, one can statistically  
467 control for effects of community composition or structure on ecosystem function.

468 **Non-random biodiversity manipulation:** Non-random biodiversity manipulations are done  
469 based on known or presumed extinction or colonization orders (non-random with respect to  
470 species responses to environmental change), or based on the contribution of species to  
471 function (non-random with respect to species effects on ecosystem functions).

472 **Biodiversity-mediated effect of environmental change on ecosystem function:** Effects  
473 occurring through changes in any aspect of biodiversity (mostly richness or evenness).

474 **Other effects of environmental change on ecosystem function:** Effects occurring through  
475 mechanisms other than biodiversity changes. Examples include changes of community  
476 composition or structure, of total density (community size), of per-capita contributions to  
477 function ( $f_i(l)$  in Box 1, e.g. physiological responses to warming), or of the bioavailability of  
478 macronutrients such as carbon, nitrogen, or phosphorous [79].

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488 **Figure titles and legends**

489 Figure 1: Indirect and non-random manipulations of biodiversity can result in a multitude of  
490 biodiversity-ecosystem function relationships ('Resulting B-EF', simulated from the model in  
491 Box 1;  $l$  is the level of environmental change and colours represent a scale from  $l=0$  (yellow)  
492 to  $l=1$  (red), the value for  $l=0$  is indicated with a 'x' for clarity). These relationships emerge  
493 as a consequence of effects on richness, per-capita contributions to function (average effect  
494 across all species), and total density (sum of all species). The strength of these effects  
495 depends on  $l$  ('level-dependent effects') and the shape of the resulting B-EF critically  
496 depends on whether dominants (A and C) or subordinates (B and D) respond more strongly to  
497 environmental change, and on whether the elicited responses are negative (A and B) or  
498 positive (C and D). The shaded area indicates the expected B-EF under direct and random  
499 biodiversity manipulations.

500

501 Figure 2: Chemical stressors can be used to non-randomly and indirectly manipulate food-  
502 webs. This is illustrated by empirically observed effects of continuous exposure of freshwater  
503 ditch food-webs to chemical stressors in published micro- and mesocosm experiments. A:  
504 Predators, herbivores and detritivores are separated into arthropod (Arth) and non-arthropod  
505 (Non-arth) species; primary producers are separated into macrophytes (Macro) and algae;  
506 Det. represents detrital material and its associated microflora. B: Results for exposure to  
507  $50\mu\text{g}\cdot\text{L}$  linuron, a photosystem ('PS') inhibitor [57, 58]. C: Results for exposure to  $35\mu\text{g}\cdot\text{L}$   
508 chlorpyrifos, a pyrethroid insecticide [55, 56]. Significant primary responses by the  
509 corresponding chemical stressor are shown in red, secondary effects mediated by species  
510 interactions are shown in green. White circles indicate that there was no effect. The relative  
511 sizes of the coloured and dotted circles indicate whether the effect was positive (increase in  
512 abundance - coloured circle larger than dotted circle) or negative (decrease of abundance -  
513 coloured circle smaller than dotted circle).

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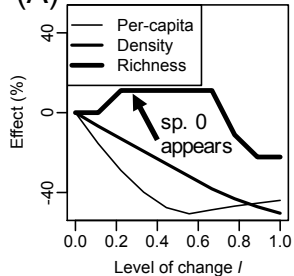
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## Non-random negative responses

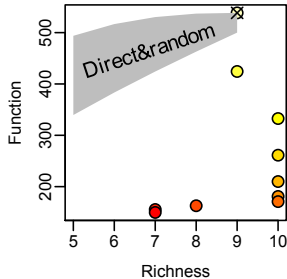
## Non-random positive responses

Dominants respond more strongly

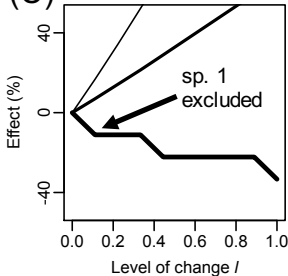
(A) Level-dependent effects



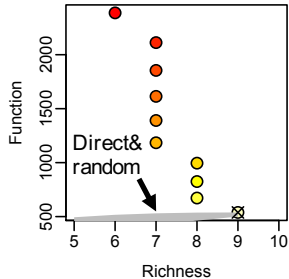
Resulting B-EF



(C) Level-dependent effects

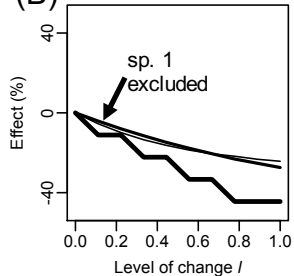


Resulting B-EF

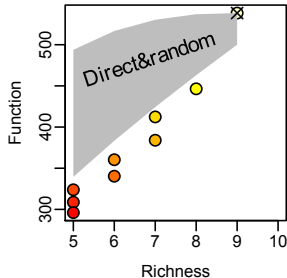


Subordinates respond more strongly

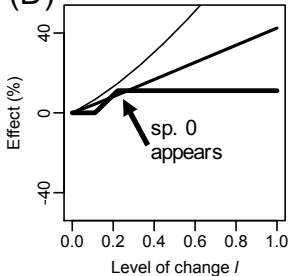
(B) Level-dependent effects



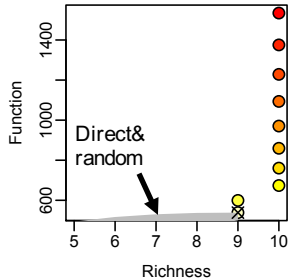
Resulting B-EF



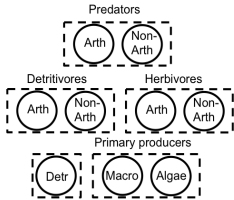
(D) Level-dependent effects



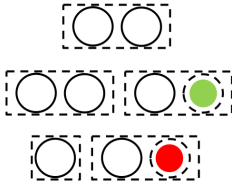
Resulting B-EF



(A) Key



(B) PS inhibitor



(C) Pyrethroid

