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1 Biodiversity effects on ecosystem functioning respond unimodal to
2 environmental stress

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14 **Author contributions**

15 JMB and FDL conceived the idea. JMB implemented the model and analysed the data. JMB, NE, CRJ
16 and FDL contributed to discussions and wrote the manuscript.

17

18 **Data accessibility statement**

19 References for all studies used in the meta-analyses with detailed descriptions of the source of the
20 data are given in Table S1.

21

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28 **Abstract**

29 Understanding how biodiversity (B) affects ecosystem functioning (EF) is essential for assessing the
30 consequences of ongoing biodiversity changes. An increasing number of studies, however, shows that
31 environmental conditions affect the shape of BEF relationships. Here, we first use a game-theoretic
32 community model to reveal that a unimodal response of the BEF slope can be expected along
33 environmental stress gradients, but also that the ecological mechanisms underlying this response may
34 vary depending on how stress affects species interactions. Next, we analyzed a global dataset of 44
35 experiments that crossed biodiversity with environmental conditions, confirming our main model
36 predictions: the effect of biodiversity on ecosystem functioning is greater at intermediate levels of
37 environmental stress, but this effect varies considerably among studies depending on the type of
38 species interactions. Together, these results suggest that increases in stress from ongoing global
39 environmental changes may amplify the consequences of future biodiversity changes.

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54 Introduction

55 Over the past 25 years, a compelling number of experiments has demonstrated that biodiversity
56 affects ecosystem functioning (Chapin *et al.* 1997; Loreau *et al.* 2001; Hooper *et al.* 2005; Cardinale *et*
57 *al.* 2011, 2012). Since most studies support a positive biodiversity-ecosystem functioning (BEF)
58 relationship, this has raised concerns that ecosystem **function** provisioning is at risk from ongoing
59 global biodiversity changes (Hooper *et al.* 2005, 2012; Cardinale *et al.* 2012). However, evidence is also
60 mounting that the consequences of biodiversity changes may not be predictable from a single,
61 universal BEF relationship (Mittelbach *et al.* 2001; Pärtel *et al.* 2010; Tilman *et al.* 2014). Not only can
62 the shape of BEF relationships differ among ecosystems (Cardinale *et al.* 2011, 2012), an increasing
63 number of studies now demonstrates that changes in environmental conditions can also alter the
64 shape of BEF relationships within a system (Pfisterer & Schmidtke 2002; Wardle & Zackrisson 2005; Li
65 *et al.* 2010; Steudel *et al.* 2011, 2012; Isbell *et al.* 2015; Baert *et al.* 2016; Guerrero-Ramírez *et al.* 2017).
66 **How** environmental changes **alter the shape of the BEF relationship** thereby appears to strongly
67 depend on both the system and environmental change driver under study (Cowles *et al.* 2016; Ratcliffe
68 *et al.* 2017). **However**, few studies have so far explored the processes underlying observed
69 **environmental change-induced** alterations in BEF relationships (Rixen & Mulder 2005; Baert *et al.*
70 2016; Hodapp *et al.* 2016). Hence, it remains unstudied if differences **among studies** in **how**
71 **environmental changes alter** BEF relationships can be reconciled within a single mechanistic
72 framework. This is a major knowledge gap as observations and prognoses suggest rapid future changes
73 in environmental conditions to go hand in hand with biodiversity change, which can cause the
74 consequences of predicted biodiversity changes to deviate from the current expectations that are
75 based on the current-day environmental conditions (Pereira *et al.* 2010; Sala *et al.* 2011; Hooper *et al.*
76 2012; Pimm *et al.* 2014).

77
78 Biodiversity research has thus far mostly focused on aggregated ecosystem functions (e.g. total
79 biomass production) in single trophic level systems (Hooper *et al.* 2005; Tilman *et al.* 2014; Ratcliffe *et*

80 *al.* 2017). Such ecosystem functions typically consist of the sum of the individual species' functional
81 contributions. Biodiversity effects on aggregated ecosystem functions therefore result from
82 differences in the relative strength of inter- and intraspecific interactions, which cause species to
83 function differently in the presence of other species (Loreau & Hector 2001; Fox 2005). Two classes of
84 biodiversity effects are thereby discerned: dominance and complementarity effects (Loreau & Hector
85 2001; Fox 2005). Dominance effects refer to changes in ecosystem functions through changes in
86 species' functional contributions as a result of competitive replacement, and hence increase
87 ecosystem functioning when functional and competitive abilities are correlated so that high-
88 functioning species replace low-functioning species. Complementarity effects, in contrast, refer to
89 changes in species functional contributions by alterations in the amount of competition through the
90 presence of heterospecifics, but without resulting in competitive replacement. Niche complementarity
91 and facilitation are hence two important drivers of positive complementarity effects, increasing
92 species' functioning by reducing the amount of competition individuals experience in mixed
93 communities compared to monocultures (Loreau & Hector 2001; Mulder *et al.* 2001; Fox 2005). A
94 distinction can thereby be made between trait-independent and trait-dependent complementarity
95 effects. Trait-independent complementarity effects refer to the average complementarity effect
96 across species as a result of all interactions in the system. Trait-dependent complementarity effects
97 designate how species deviate from this average complementarity effect in relation to their functional
98 traits, generally quantified as their monoculture yield, as a result of asymmetric or one-way
99 interactions. Both classes of biodiversity effects can also be negative. Dominance of species with low
100 functional abilities and antagonistic interactions that increase competition can accordingly result in
101 negative dominance and complementarity effects, respectively, and thus in negative BEF relationships
102 (Loreau & Hector 2001; Fox 2005).

103

104 Theoretically, the environmental dependency of BEF relationships should thus arise from changes in
105 species functional contributions that alter dominance and complementarity effects (Baert *et al.* 2016).

106 Environmental change can affect species functional contributions directly and indirectly. Interspecific
107 differences in species' sensitivities to the environmental changes determine direct effects. Species
108 interactions may cause additional indirect effects by changing the density of a species' competitors
109 (May 1974; Mccann *et al.* 1998; Ives *et al.* 1999). Opposing ecological theories exist, however, on the
110 effect of environmental stress on these species interactions themselves, assuming the per-capita to
111 either remain unaffected, change in strength, or even shift from competitive to facilitation at high
112 stress (Chesson & Huntly 1997; Hart & Marshall 2013). The importance of environmental stress effects
113 on species interactions for biodiversity effects on function remains unresolved at present (Baert *et al.*
114 2016).

115
116 Environmental stress invariably selects for tolerant species. We therefore hypothesize that the slope
117 of BEF relationships should initially increase with environmental stress. Biodiversity increases the
118 probability that a system will contain tolerant species that can replace sensitive species (in line with
119 the insurance effect of biodiversity, Yachi & Loreau 1999). Hence, more diverse systems are less likely
120 to experience severe reductions in function compared to less diverse systems, resulting in an increased
121 slope of BEF relationships (Steudel *et al.* 2012; Hodapp *et al.* 2016). However, the BEF relationship
122 should collapse to a horizontal line when stress is sufficiently high to inhibit the growth of all species.
123 Thus, overall, the slope of a BEF relationship should respond to stress in a unimodal way. Moreover,
124 stress inevitably induces a correlation between functional and competitive abilities, causing tolerant
125 species that grow relatively well in monoculture to displace sensitive species as stress intensifies (Baert
126 *et al.* 2016). Hence, we expect that the response of the dominance effect to stress will be the key driver
127 of this unimodal response.

128
129 Here, we first used a game theoretic competition model to explore how increasing environmental
130 stress alters BEF relationships for aggregated ecosystem functions and the underlying dominance and
131 complementarity effects in competitive systems. We simulated four different scenarios of

132 environmental stress effects on per-capita interactions: environmental stress had either no effect,
133 increased, or decreased the strength of per-capita interactions without changing the type of species
134 interactions, or reduced per-capita interactions with obligate shifts to complementarity at high levels
135 of environmental stress as postulated by the stress gradient hypothesis (REF). Direct effects of
136 environmental stress on fitness were modelled as reductions in species per-capita growth rates in all
137 scenarios. We tested if BEF-relationships and underlying biodiversity effects responded monotonically
138 or unimodally to increasing environmental stress, by fitting second order polynomials to the simulated
139 data. To assess the generality of our findings, we performed this analysis for a wide range of BEF
140 relationships that are theoretically possible under unstressed conditions, including negative,
141 horizontal, and positive BEF relationships. Next, we confronted model predictions with observed
142 changes in BEF relationships from a meta-analysis of 44 studies in primary producer systems that
143 manipulated species richness under at least 3 different environmental conditions.

144

145 **Methods**

146 **Model structure**

147 We used a stochastic game theoretic community model (Huang *et al.* 2015) to simulate a broad
148 spectrum of theoretically possible BEF relationships. In this model, population dynamics are thereby
149 assumed to be exclusively driven by birth, death, and inter- and intraspecific interaction processes,
150 occurring at rates b , d and a , respectively. For every species i , the rates at which its density (N_i) may
151 increase (T_i^+) or decrease (T_i^-) by one individual can be expressed as:

$$152 \quad T_i^+ = b_i N_i \quad (\text{eq. 1}),$$

$$153 \quad T_i^- = d_i N_i + N_i \sum_{j=1}^n a_{i,j} N_j \quad (\text{eq. 2}),$$

154 where n is the number of species in the community. In the absence of heterospecifics (i.e. $n=1$), the
155 equilibrium density of species i thereby equals $a_{i,i}^{-1} (b_i - d_i)$. Note that, as birth and death events

156 are independent, stochastic demographic fluctuations will occur around the equilibrium population
157 density in the system (Huang *et al.* 2015).

158 We consider a one-dimensional environmental gradient (E) along which species functioning is altered
159 through direct effects on the per-capita growth rate (Fig. 1). The species-specific functional response,
160 $r_i(E)$, was modelled by a normalised gamma distribution to restrict values between 0 and 1 (i.e.
161 maximal fitness; Fig. 1):

$$162 \quad r_i(E) = \left[\frac{E}{\theta_i (k_i - 1)} \right]^{k_i - 1} e^{-\frac{E}{\theta_i} + (k_i - 1)} \quad (\text{eq. 4}).$$

163 The shape parameter k_i and scale parameter θ_i of the gamma distribution thus determine the width
164 of the environmental niche ($\sim k_i \theta_i^2$) and the optimal environmental conditions ($k_i \theta_i$) at which the
165 maximal per-capita birth rate of species i is attained. We used a gamma distribution to allow for both
166 symmetrical and asymmetrical niches. Note that values for the environmental gradient are hence
167 restricted to positive values.

168 The per-capita growth rate of each species along the environmental gradients $b_i(E)$ can hence be
169 written as:

$$170 \quad b_i(E) = b_{0,i} r_i(E) \quad (\text{eq. 3}),$$

171 where $b_{0,i}$ is the maximal per-capita birth rate of species i at optimal environmental conditions (Fig.
172 1).

173
174 Since optimal conditions and functional responses may differ among species within a system, we
175 quantify the stressfulness of environmental conditions (E) as the stress intensity (SI), which is the
176 average species' fitness reduction at these environmental conditions (Steudel *et al.* 2012):

$$177 \quad SI(E) = 1 - \sum_{k=1}^m \frac{r_k(E)}{m} \quad (\text{eq. 5}),$$

178 where m is the number of species within the experiment (see also model simulations). Hence, stress
179 intensity ranged from 0 for on average optimal conditions to 1 for severely stressed conditions (Fig. 1).

180 We define four scenarios of environmental stress effects on per-capita interactions, representing the
181 main hypotheses commonly postulated (Hart & Marshall 2013). When the type of species interactions
182 is not altered by stress, stress effects on per-capita interactions are modelled as:

$$183 \quad a_{i,j}(E) = a_{0,i,j} [1 + \beta_i SI(E)]^\gamma \quad (\text{eq. 6}).$$

184 The species-specific parameter β_i thereby denotes the strength by increasing environmental stress
185 affects per-capita interactions for a given species. The power γ defines whether per capita interactions
186 are unaffected ($\gamma=0$; scenario 1), increase ($\gamma=1$; scenario 2) or decrease ($\gamma=-1$; scenario 4) with
187 increasing stress. For the fourth scenario in which per capita interactions shift to facilitation by
188 environmental stress, i.e. change sign as proposed by the stress gradient hypothesis (Maestre *et al.*
189 2009), stress effects on per-capita interactions are modelled as:

$$190 \quad a_{i,j}(E) = a_{0,i,j} [c_i - SI(E)][1 + \beta_i SI(E)]^\gamma \quad (\text{eq. 7}),$$

191 where the species-specific parameter c_i indicates the stress intensity at which per capita interactions
192 for species i become negative, and thus shift from competition to facilitation.

193

194 Along the one-dimensional environmental gradient, the transition rates of a system of n species under
195 given environmental conditions (E) can thus be written as:

$$196 \quad T_i^+ = b_i(E) N_i \quad (\text{eq. 8}),$$

$$197 \quad T_i^- = d_i N_i + N_i \sum_{j=1}^n a_{i,j}(E) N_j \quad (\text{eq.9}).$$

198

199 **Scenarios and parameterisation**

200 We simulated the model for four scenarios of environmental stress on per-capita interactions. In the
201 first scenario, we assumed no effects of environmental stress on per-capita interactions. Hence, the
202 parameter γ was set to zero for those model simulations (eq. 6). In the second and third scenario, we
203 assumed a continuous increase or decrease in per-capita interactions, and thus competition, but
204 without changes in the type of interactions at high stress (eq. 6). In both scenarios, β_i was sampled
205 from $U(0, 10)$ for each model simulation. The parameter γ was set to 1 (scenario 2) or -1 (scenario 3)

206 to simulate a continuous increase or decrease strength of per-capita interactions, respectively. In the
207 fourth scenario, we assumed a linear decrease in per-capita interactions with shifts to facilitation at
208 high levels of environmental stress (eq. 7). Identical to scenario 3, β_i was sampled from $U(0, 10)$ and
209 γ was set to -1. The additional parameter c , denoting the stress intensity at which per-capita
210 interactions shift from positive to negative, was sampled from $U(0.75, 1)$ for each model simulation.

211
212 We used a Monte-Carlo simulation procedure to generate 100 BEF relationships, and simulated
213 changes in each of those BEF relationships by increasing environmental stress, for each of the four
214 scenarios of environmental stress effects on per-capita interactions. The generated set of BEF
215 relationships represented an exhaustive set of ecologically relevant BEF relationships under unstressed
216 conditions, ranging from negative to strongly positive relationships (Fig. 2). Per capita birth rates under
217 optimal conditions, $b_{0,i}$ and per capita mortality rates, d_i , were randomly sampled from $U(0, 1)$ and
218 $U(0, 0.01 b_{0,i})$, respectively. The means of the gamma distributions (i.e. the optimal environmental
219 conditions for every species), were sampled from $U(95, 105)$, and the variances were sampled from
220 $U(10, 50)$. The strength of intraspecific interactions $a_{i,i}$, which is the main determinant of differences
221 among species monoculture yields, was sampled from $U(10^{-4}, 10^{-3})$. The strength of interspecific
222 interactions was subsequently sampled from $U(-0.01 a_{i,i}, 2 a_{i,i})$. A sensitivity analysis of the parameters
223 distributions revealed that the model results did not depend on the parameter distributions: using
224 different sets of ecologically relevant parameter distributions did not alter our results (Fig. S1).

225

226 **Model simulations**

227 For each simulation, we first generated a pool of 20 species by randomly drawing values for $b_{0,i}$, k_i , θ_i ,
228 d_i , $\alpha_{i,j}$ and $\alpha_{j,i}$ for all species (Fig. S2). Next, 10 communities of 2, 4, 8, and 16 species were randomly
229 assembled from this species pool, representing a standard design used in BEF studies). Community
230 dynamics were then simulated under unstressed conditions and under nine conditions of
231 environmental stress intensity (SI=0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9; Fig. S2). Community dynamics

232 were simulated using the Gillespie algorithm to shorten simulation times by optimizing the length of
 233 the time-steps used (Gillespie 1976). Initial ($t=0$) densities were set to 100 for all species. Population
 234 densities always reached their stationary distribution at $t \leq 30$. Simulations were run till $t=50$. Mean
 235 species densities were calculated from the species densities between $t=40$ and $t=50$. Each simulation
 236 was reiterated 12 times to ensure convergence of the stationary distribution (Fig. S3).

237
 238 Ecosystem functioning was calculated as the sum of the mean species' densities. BEF relationships at
 239 each level of environmental stress were subsequently calculated by linearly regressing functioning
 240 against the initial species richness of the system. Biodiversity effects for all environmental conditions
 241 were calculated according to the additive partitioning approach by Fox (Fox 2005):

$$242 \quad \Delta Y = \sum_i^n Y_{o,i} - Y_{e,i} = \sum_i^n (RY_{o,i} - RY_{e,i})M_i = n \operatorname{cov}\left(\frac{RY_{o,i}}{RYT} - RY_{e,i}, M_i\right) + \operatorname{cov}\left(RY_{o,i} - \frac{RY_{o,i}}{RYT}, M_i\right) +$$

$$243 \quad n E(\Delta RY)E(M) \text{ (eq.10),}$$

244 where ΔY is the deviation between the expected and observed yield, which is the sum of the individual
 245 species deviations between observed ($Y_{o,i}$) and expected yields ($Y_{e,i}$). RY denotes the relative yield, i.e.
 246 the fraction of the monoculture yield. The expected relative yield ($RY_{e,i}$) thereby equals the species
 247 initial proportion in the mixture (i.e. n^{-1}), whereas the observed relative yield is the mean value of each
 248 species stationary distribution divided by its monoculture yield under the same environmental
 249 conditions ($M_i = a_{i,i} [b_i(Env) - d_i]$). RYT is the relative yield total (i.e. $\sum_i^n RY_{o,i}$).

250

251 **Review of literature data**

252 We searched Thomas Reuters Web of Knowledge (www.webofknowledge.com) and Google Scholar
 253 (www.scholar.google.com) in February 2018 for experiments that manipulated species richness under
 254 at least three environmental conditions. We used the search terms "biodiversity", "ecosystem",
 255 "function", "productivity", "stress", "temperature", "nutrient", "precipitation", "chemical", "salinity",
 256 "environment" in various combinations. We additionally checked the cited literature for further
 257 original studies. Data were available as text, excel files or were digitized from the figures in the original

258 publications. Digitized data did not differ by more than 1% among different applications (e.g. Engauge,
259 WebPlot, ExtractGraph digitizer). When slopes and intercepts of BEF relationships were not reported,
260 these were calculated from the data. Only studies that manipulated biodiversity under at least three
261 environmental conditions, and reported the species monoculture functions for all environmental
262 conditions were considered, as this is a prerequisite to calculate the intensity of environmental stress
263 and discriminate between monotonic and unimodal changes in BEF relationships (see Data
264 normalisation and analysis). This yielded a total of 44 studies (Fig. S4, Table S1), all of which used
265 primary producer systems. Environmental gradients comprised drought (n=37), temperature (n=3),
266 pollutants (n=2), salt (n=1), nutrients (n=1) and shade (n=1).

267

268 **Data normalisation**

269 Literature and simulated data were normalized prior to analysis. The severity of the environmental
270 stress was calculated, analogous to model simulations (eq. 5), as the ratio between the average
271 observed monoculture under stress and unstressed conditions **for all species in the study**. Unstressed
272 conditions were defined as those environmental conditions under which species attained the highest
273 mean monoculture functions. Since the units in which aggregated ecosystem functions are measured
274 varied among studies, slopes were normalized by dividing the linear regression coefficient of the BEF
275 relationship by the average monoculture function under unstressed conditions. Thus, normalised
276 slopes all had species⁻¹ as a unit.

277

278 **Analysis of simulated and empirical data**

279 We carried out the same analyses on the simulated data (including all four scenarios of environmental
280 effects on per-capita interactions) as on the empirical data. First, we tested how the slope of BEF
281 relationships changed along environmental stress gradients using second order polynomials. Next, we
282 tested how the effect on the BEF slope varied among the range of unstressed BEF relationships
283 considered by the model or present in the empirical data. To do so, we regressed the slope under

284 unstressed conditions against the stress intensity at which the BEF slope peaked. The dataset ID (i.e.
285 simulated scenario 1, 2, 3, and 4? or empirical data) was included as an additional factorial fixed effect
286 in the linear regression model to be able to compare among simulated scenarios and between
287 simulations and empirical data. Residual diagnostics were assessed for deviations from normality and
288 homoscedasticity (Fig. S5).

289

290 **Results**

291 **Model simulations**

292 Model simulations revealed highly consistent changes in the slope of BEF relationships, irrespective of
293 how environmental stress affected per-capita interactions (Fig. 2). In all four scenarios, most
294 simulations confirmed a unimodal response of the slope of the BEF relationship to increasing
295 environmental stress: biodiversity effects peaked at intermediate levels of environmental stress (Fig.
296 2). Only when initial BEF slopes were high, the model predicted a monotonic decrease in BEF
297 relationships. When synthesising across the wide range of BEF relationships under unstressed
298 conditions considered by our modelling, we found a negative relationship between the slope under
299 unstressed conditions and the level of environmental stress where the BEF slope peaks (Fig. 2).

300

301 While BEF relationships responded consistently to environmental stress across all simulations, the
302 responses of the underlying biodiversity effects, however, depended strongly on how per-capita
303 interactions were affected by environmental stress. In all four scenarios, environmental stress-induced
304 changes in dominance effects drove the change in BEF relationships (Fig. 3). Unimodal changes in the
305 complementarity effects, in contrast, only contributed to overall changes of the BEF relationship in
306 scenarios 3 and 4, where the strength of per-capita interactions decreased with increasing
307 environmental stress. When per-capita interactions remained constant or increased with
308 environmental stress, complementarity effects instead on average decreased monotonically.

309

310 **Meta-analysis of biodiversity experiments**

311 Observed responses of the slope of BEF relationships to environmental stress, as reported in the 44
312 empirical studies, confirm predictions of a predominantly unimodal model response of BEF
313 relationships to increasing environmental stress (Fig. 4). In the majority of these studies, fitted
314 polynomials peaked at intermediate levels of environmental stress, while monotonically decreasing
315 polynomials were only supported for studies where BEF slopes in unstressed conditions were strongly
316 positive. Confirming model predictions, the environmental stress intensity where biodiversity effects
317 peaked were indeed negatively related to the slope of the BEF-relationship under unstressed
318 conditions (Fig. 4). This negative relationship was comparable between the simulated and empirical
319 data for all the tested scenarios, and did not significantly differ between the simulated and empirical
320 data for scenarios 3 and 4 (per-capita interactions decreased with increasing stress, Table 1).

321

322 **Discussion**

323 Our results demonstrate that environmental stress changes biodiversity effects on ecosystem
324 functioning, and that the strength of these changes may vary considerably, yet predictably, among
325 systems. We presented a model that, based on a minimal set of mechanisms, disentangles a general
326 response driven by stress effects on dominance, from system-specific effects resulting from stress
327 effects on complementarity (Fig. 2 and 3). While dominance effects and the BEF slope tend to respond
328 in a unimodal way to increasing environmental stress, the response of complementarity effects to
329 stress strongly depends on the per-capita species interactions and how these are affected by
330 environmental stress (Fig. 3). Our meta-analysis of current biodiversity experiments confirms a key
331 model prediction: the consequences of biodiversity changes for ecosystem functioning are likely to
332 increase at low to intermediate levels of environmental stress (Fig. 4).

333

334 Model simulations suggest that the unimodal change in the BEF relationship to increasing
335 environmental stress is primarily driven by species differences in sensitivity to environmental stress

336 through shifts of the dominance effect. As postulated, positive dominance effects are promoted by
337 increasing fitness differences under increasing environmental stress, as species experiencing smaller
338 fitness reductions will increasingly replace species experiencing severe fitness reductions. However,
339 when levels of environmental stress become so high that fitness of most species is severely reduced,
340 the strength of the dominance effect and the slope of the BEF relationship decrease again, because
341 the potential for functional replacement is lost, even in more diverse systems. From this threshold
342 stress level onward, the slope of the BEF relationship decreases until it reaches a flat line at extreme
343 levels of environmental stress, where the functioning of all species is inhibited (Fig. 2). However, when
344 dominant high-functioning species are also most sensitive to environmental stress, increasing stress
345 will replace these with low-functioning species, causing loss of function. This will cause dominance
346 effects to monotonically decrease with increasing environmental stress (Fig. 3).

347
348 Unlike the dominance effect, changes in complementarity effects are more system-specific and vary
349 with the strength of, and environmental effects on, species interactions. Changes in complementarity
350 effects strongly differ among model scenarios. Along an environmental stress gradient, the number of
351 species that can significantly contribute to ecosystem functions is progressively reduced, which
352 decreases the ratio between inter- and intraspecific interactions experienced by the remaining species.
353 When per-capita interactions remain constant, this will reduce both positive and negative
354 complementarity effects at these elevated stress levels. This results in a decrease of complementarity
355 effects along an environmental stress gradient (Fig. 3).

356
357 When environmental stress increases the strength of per-capita interactions, i.e. increases
358 interspecific competition, complementarity effects are likely to decrease even faster with increasing
359 stress. This is because, in this case, stress additionally reduces the potential for positive
360 complementarity effects. Although changes in complementarity effects do not match the overall
361 changes in BEF relationships in both scenarios, per-capita interactions can have a profound effect on

362 the environmental stress level at which biodiversity effects peak. The slope of the BEF relationship can
363 only increase as long as decreases in complementarity effects are offset by larger increases in
364 dominance effects. Maximal biodiversity effects can therefore be expected to be attained at lower
365 levels of environmental stress when systems are driven by highly positive complementarity effects
366 under unstressed conditions (Fig. 3).

367
368 If the strength of per-capita interactions decreases with increasing stress, the reduction in competition
369 can in contrast counteract negative direct effects of environmental stress by increasing
370 complementarity effects under stress. Higher diversity thereby increases the potential for positive
371 complementarity effects, increasing the slope of the BEF relationship, **which is even higher when**
372 **interactions become positive under high environmental stress.** However, identical to dominance
373 effects, extreme stress levels will cause direct effects on fitness that are so high that complementarity
374 effects and BEF relationships start to decrease to reach a flat line (Fig. 2 and 3). In all **four** scenarios,
375 the responses of trait-dependent complementarity effects are similar to those of trait-independent
376 complementarity effects. This can be expected as both are driven by the same mechanisms and only
377 express the extent by which complementarity effects are (a)symmetrical across all species in the
378 system. Only their relative contribution to changes in BEF relationships is highly community-specific
379 and depends on the asymmetry of the species interactions within the system (Fox 2005).

380
381 Our results reveal that separating a general from a system-specific response over an environmental
382 gradient will be an important step in reconciling the apparent contradictions among the results
383 reported by experiments manipulating biodiversity under different environmental conditions (ADD
384 SOME CITATIONS+citation to recent forest paper by Lander?). While biodiversity experiments
385 conducted over the past decades almost unequivocally yielded positive relationships (Hooper *et al.*
386 2005; Cardinale *et al.* 2012), changing environmental conditions have resulted in either increases
387 (refs), decreases (refs), or no effects on the slope of the BEF relationship (refs). The theory presented

388 in the present study allows these results to be interpreted within a single generalised framework,
389 reflecting different system-specific realisations of a unimodal response of BEF relationships to
390 environmental stress gradients. Monotonically decreasing relationships in both simulated and
391 empirical data may thereby in fact represent unimodal relationships that peak at extremely low levels
392 of environmental stress, but which remained undetected by a too coarse resolution of the
393 environmental gradient. Still, only few studies to date have manipulated species richness under a
394 sufficiently broad range of environmental conditions to reveal such a unimodal response (Fig. 4 and
395 S4) as many studies apply only two or three environmental stress levels.

396
397 Our model simulations revealed that shifts in per-capita interactions have important consequences for
398 the mechanisms that can drive shifts in BEF relationships across environmental gradients. Increased
399 niche complementarity and facilitation under environmental stress have been documented to increase
400 in several plant systems (Rixen & Mulder 2005; Maestre *et al.* 2010; Hart & Marshall 2013). Hence, this
401 may explain why the empirical relationship between the slope under unstressed conditions and the
402 stress intensity under which maximal biodiversity effects were attained best corresponded to the
403 model scenarios under which per-capita interactions and competition decreased with increasing stress
404 (Table 1, Fig. 4). Still, only few studies have assessed the biodiversity effects underlying BEF
405 relationships at different environmental conditions (De Boeck *et al.* 2008; Li *et al.* 2010; Steudel *et al.*
406 2011; Baert *et al.* 2016). As such, little empirical support exists for whether changes in BEF relationships
407 are merely driven by dominance effects, or by a combination of dominance and complementarity
408 effects. In addition, it should be noted that throughout this study we have focussed on equilibrium
409 conditions. Environmental stress was assumed to affect species functional contributions through the
410 per-capita growth rate, which caused the system to respond fast to any environmental change. In
411 primary producer systems, environmental stress can affect both somatic growth and reproduction
412 (Ref). As produced seeds generally only germinate in the following growth season, species turnover
413 can be much slower in real systems compared to our model simulations, and may lead to a reduced

414 importance of shifts in dominance in real systems compared to our model simulations. Finally, in this
415 study, we have restricted our model to first order species interactions. Although there is a growing
416 awareness that higher-order (including multi-trophic) interactions may significantly contribute to
417 ecosystem functions (Soliveres *et al.* 2016; Grilli *et al.* 2017; Barnes *et al.* 2018; Wang & Brose 2018),
418 we focussed on aggregated ecosystem functions within a single trophic level throughout this study.
419 While this might be an oversimplification of real ecosystems, this approach enabled the integration of
420 a maximal number of experimental studies, since most considered single trophic level systems. Our
421 findings reveal that major patterns in primary producer systems, changes in the BEF relationship and
422 underlying biodiversity effects primarily depend on, and can be predicted from, interactions within
423 this single trophic level.

424

425 Environmental and biodiversity changes pose major threats to ecosystems worldwide (Hooper *et al.*
426 2012). Understanding how both processes are intertwined is therefore a major challenge to
427 appropriately assess the consequences of ongoing and future biodiversity changes (Isbell *et al.* 2013,
428 2015; De Laender *et al.* 2016). The presented results provide a theoretical framework to meet this
429 challenge, as they allow predicting the context-dependence of BEF relationships. Our model
430 simulations revealed testable hypotheses on a consistent change in BEF relationships in response to
431 environmental stress, but also on how the underlying mechanisms and differences in the magnitude
432 of changes in BEF relationships may differ between systems based on differences in the strength and
433 environmental response of per-capita interactions. Moreover, while underlying mechanisms may be
434 strongly system-dependent, our results suggest that the joint effects of forecasted biodiversity and
435 environmental changes are likely to cause greater effects on ecosystem functions than previously
436 anticipated.

437

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447

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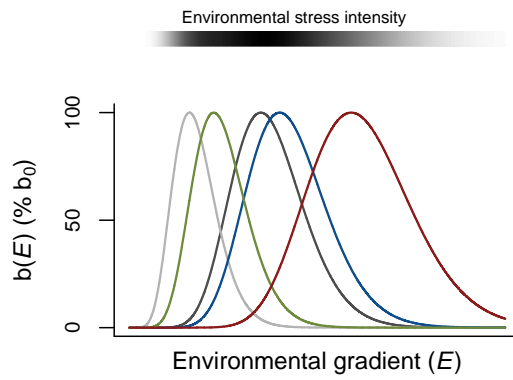
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549 **Figures**

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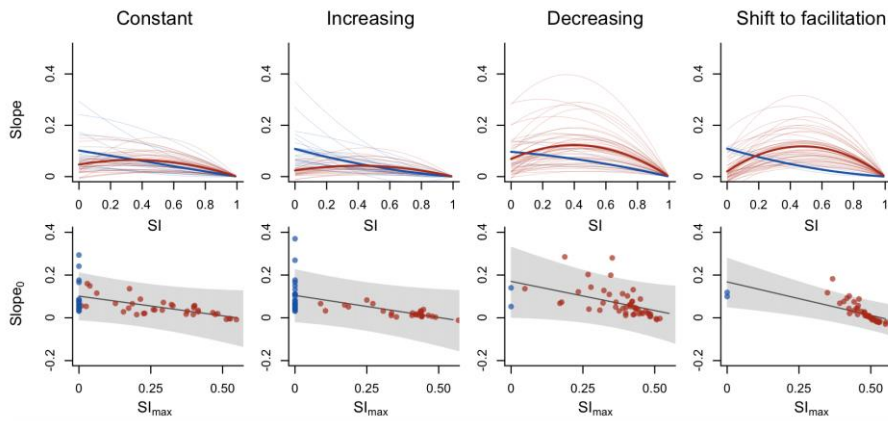
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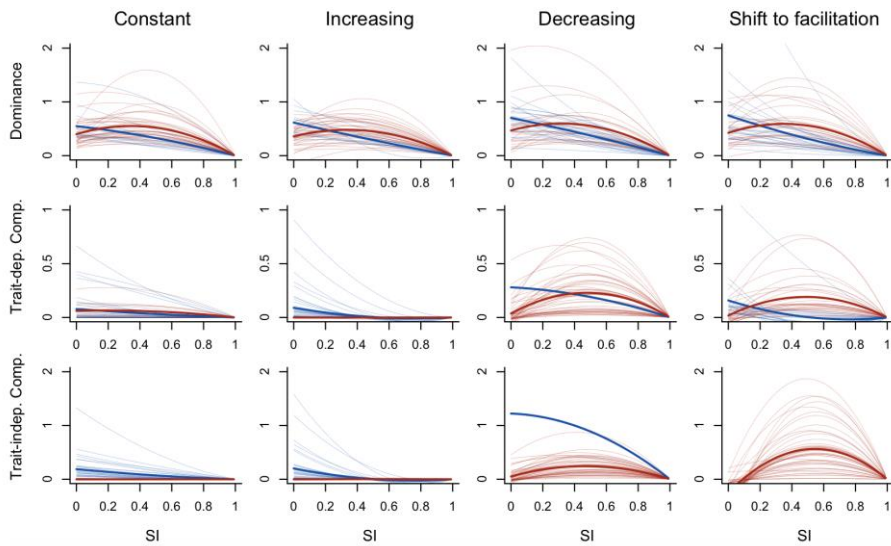
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 554 **Fig. 1.** Species functional responses and definition of environmental stress as assumed in the model.
 555 Niches of five hypothetical species are depicted as the change in the per-capita birth rate (b) over an
 556 environmental gradient (E). Note that values have been normalised to the percentage reduction in the
 557 maximal per-capita birth rate, $b_{i,0}$. The stress intensity of an environmental condition is calculated as
 558 the average % reduction in the maximal per capita birth rate of the species. Lighter colours indicate
 559 higher environmental stress intensity.

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 571 **Fig. 2:** Upper panels: simulated changes in slopes of BEF relationships with increasing environmental
 572 stress intensity (SI) for constant, increasing, decreasing, and shifts from competitive to facilitative per-
 573 capita interactions under increasing environmental stress intensity. Lower panels: simulated
 574 relationship between the slope of the BEF relationship under unstressed environmental conditions
 575 ($Slope_0$) and the stress intensity at which a maximal slope is attained (SI_{max}). Red lines and dots indicate
 576 unimodal relationships, blue lines and dots indicate monotonic relationships. Thick lines represent the
 577 model predictions for unimodal and monotonic relationships. The grey shaded area corresponds to
 578 the 95% prediction interval.

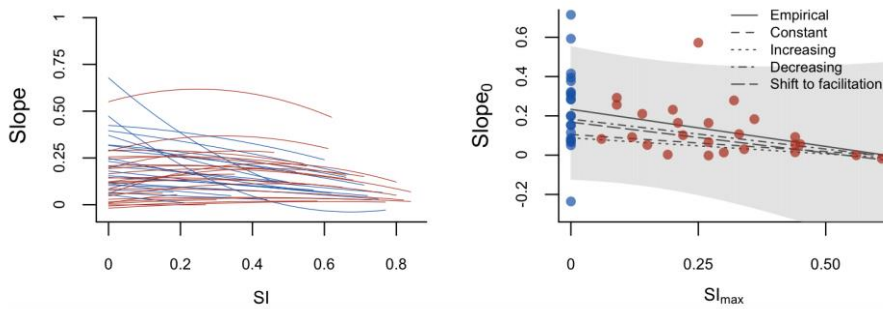
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 588 **Fig. 3:** Simulated changes in dominance, trait-dependent and trait-independent complementarity
 589 effects with increasing environmental stress intensity (SI) for constant, increasing and decreasing per-
 590 capita interactions under increasing environmental stress intensity. Red lines indicate unimodal
 591 relationships, blue lines indicate monotonic relationships. Thick lines represent the mean model
 592 predictions for unimodal and monotonic relationships.

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606 **Fig. 4:** Left panel: Empirical observed changes in slopes of BEF relationships with increasing
607 environmental stress intensity (SI). Right panel: Empirical and modelled relationship between the slope
608 of the BEF relationship under unstressed environmental conditions (Slope₀) and the stress intensity at
609 which a maximal slope is attained (SI_{max}). Red lines and dots indicate unimodal empirical relationships,
610 blue lines and dots monotonic empirical relationships for the empirical data. The grey shaded area
611 corresponds to the 95% prediction interval for the empirical data.

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618 **Tables**

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620 **Table 1:** Estimated relationship between the the slope under unstressed conditions and the stress
 621 intensity at which maximal biodiversity effects are attained. Significances for model simulations are
 622 expressed against the value of the empirical regression.

	Estimate	p-value
Intercept empirical data	0.233	<0.001
Intercept constant interactions	0.105	<0.001
Intercept increasing interactions	0.087	<0.001
Intercept decreasing interactions	0.183	0.136
Intercept shift to facilitation	0.165	0.314
SI_{max} empirical data	-0.379	<0.001
SI_{max} constant interactions	-0.174	<0.001
SI_{max} increasing interactions	-0.163	<0.001
SI_{max} decreasing interactions	-0.305	0.38
SI_{max} Shift to facilitation	-0.311	0.68

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