

1 **Agenda 2050: Challenges for biodiversity-ecosystem functioning research**

2
3
4 Mary I. O'Connor, Akira Hori, Andrew Gonzalez, Michel Loreau, Meghan Avolio, Jarrett Byrnes,
5 Jane Cowles, Adam Clark, Laura Dee, Yann Hautier, Andy Hector, Kim LaParo, Tim Newbold,
6 Charlie Outhwaite, Peter Reich, Eric Seabloom, Laura Williams, Alexandra Wright, Forest Isbell.
7 *(please correct this list, I'm sure it's missing people!)*
8
9
10
11
12
13

14 *Possible venues:*

15 *Current Opinions in The Environment and Sustainability (these are really short <2000 words,*
16 *and invited; there is a longer version (<3000 words) and we can inquire). I'd like to know if, after*
17 *reading this, you think we should aim for super-concise and the shorter version, or explain in*
18 *more detail and aim for something longer - Bioscience perhaps?]*
19
20
21

22 **Abstract** [100-200 words]:

23
24 Humans **have become a** major component of global biodiversity; our well-being depends on
25 sustainable biodiversity and ecosystem services, and our actions drive changes in biodiversity
26 and ecosystem services at local and global scales. Ecological science has demonstrated how
27 feedbacks between biodiversity and ecosystem function govern the consequences of
28 biodiversity change. Yet, major policy platforms are still catching up to this integrated
29 perspective, at times treating biodiversity, ecosystem functions and services separately,
30 ignoring feedbacks between them. Seven knowledge gaps impede integration of feedbacks into
31 policy and research platforms. These include the need for more comprehensive theory for how
32 people interact with biodiversity – function feedbacks across scales, **theory** for how to relate
33 observations of biodiversity to dynamic change in the biodiversity-ecosystem function system,
34 and how ecosystem services depend on feedbacks at different scales of the biosphere. To meet
35 these challenges, we outline a 5-point agenda for action based on collaboration and connection
36 among scientists and policy-makers that emphasizes open and international access to data,
37 projects and products. We argue that efforts to protect biodiversity require the best possible
38 scientific understanding of biodiversity trends, ecosystem functions, and - critically - the
39 feedbacks between them across spatial scales.
40
41
42


43

44 **I. Global science and policy efforts require scientific understanding of biodiversity and**
45 **ecosystem functioning feedbacks across scales**

46 

47 Minimizing irreversible biodiversity change and identifying sustainable limits to ecosystem
48 changes are two of the greatest ecological challenges of our time (Watson and Zakri 2005,
49 Ceballos et al. 2017, Diaz et al. 2019). Achieving sustainable levels of biodiversity change is a
50 primary motivation of international agreements and targets aimed at biodiversity and ecosystem
51 functions (United Nations 1992). Policies and conservation efforts guided by these agreements
52 require robust scientific models that allow identification of solutions and visualization of possible
53 futures to guide decisions about how people can best influence drivers of change in biodiversity
54 and its functions and services (IPBES:uq). These models must integrate scientific
55 understanding of the complex nature of biodiversity and ecosystem function feedbacks at
56 multiple spatial, temporal and biological scales.

57

58 The conceptual framework of the IPBES (Diaz:2015ja; Diaz et al. 2019) outlines some of the
59 pathways through which nature contributes to people (Box 1). ~~This framework is offered with the~~
60 ~~purpose of aligning assessments of change and scientific knowledge development with policy~~
61 ~~needs (Pascual et al. 2017, Díaz et al. 2018).~~ The IPBES framework is also offered to the
62 broader community as a system for understanding how biodiversity, inclusive of humanity and
63 human diversity (Box 1, Glossary), are related to a sustainable biosphere (Pascual et al. 2017).
64 While this framework does incorporate interactions between people and nature (Box 1), it does
65 not yet fully reflect our knowledge (and limits to knowledge) of the feedbacks between
66 biodiversity and function that underlie the human well-being and biodiversity that are central to
67 the framework (Mace 2019). 

68

69 Biodiversity, ecosystem function and human well-being are intricately related in a complex living
70 system defined by feedbacks within and between these elements (see Glossary for definitions)
71 (Ross et al 2017 Eco Letts), yet the characterization of these elements in the policy frameworks
72 that guide high-level assessments does not fully incorporate feedbacks. Biodiversity science
73 has demonstrated biodiversity - ecosystem function feedbacks (Odorico et al. 2013)(good
74 refs?), as well as feedbacks between people, biodiversity and function (Isbell et al. 2017, Dee et
75 al. 2017a). Most evidence supporting these feedbacks comes from theory and empirical
76 evidence that builds on our understanding of how ecosystem processes generate and maintain
77 biodiversity, and biodiversity in turn increases stability of ecosystem functions such as
78 productivity (Schindler et al. 2010, Wang and Loreau 2014), provides of food and nutrition to
79 people (Frison et al. 2011), and responds to conservation decisions (Dee et al. 2017b).

80

81 Failure to consider biodiversity (inclusive of people, Box 1) and ecosystem functions as a
82 system of interactions and feedbacks at multiple scales likely underestimates the severity of the
83 sustainability challenges we face and risks missing key opportunities for mitigation and
84 solutions. Furthermore, if policy frameworks that do not fully integrate the current state of
85 scientific knowledge guide major investments in scientific research, they may limit the scope of

86 efforts to understand of nature as the diverse, complex adaptive system we know it to be. We
87 cannot afford this just when we need science urgently to guide our planning for the future.

88
89 As scientists concerned with understanding nature and seeing this understanding applied in
90 efforts to make decisions, we identify two current challenges. First, we argue that the current
91 understanding of feedbacks between biodiversity and ecosystem functions can be more
92 effectively integrated into existing conceptual frameworks, models and assessments. Second,
93 the absence of emphasis on feedbacks in the current IPBES framework implies that we need a
94 deeper and more applicable understanding of the feedbacks between biodiversity and
95 ecosystem functioning across scales. Overcoming these challenges requires targeting these
96 feedbacks as scientific research goals, and considering how assessments and policies can best
97 reflect this knowledge development and subsequent gain.

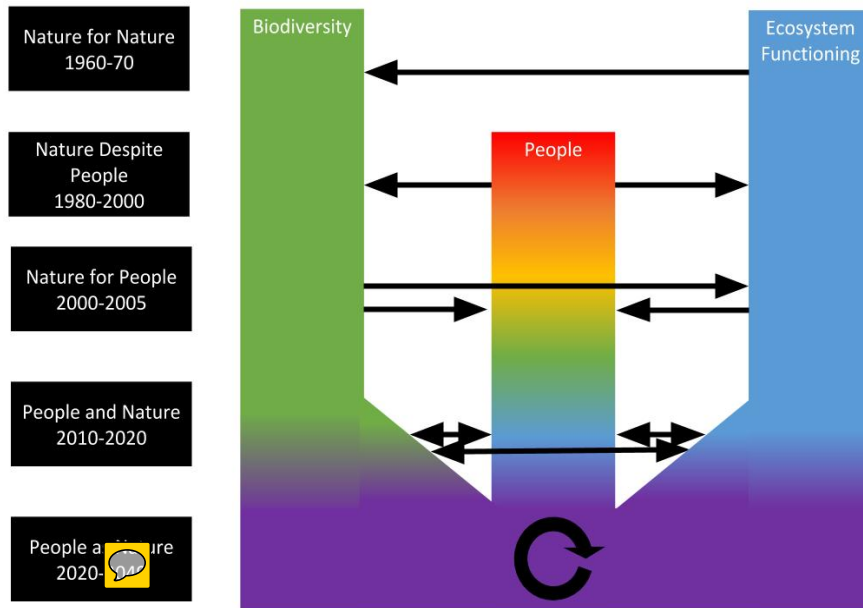
98
99 Here, we outline a research agenda to meet the second challenge. We begin by highlighting
100 knowledge gaps in our current scientific understanding of biodiversity ecosystem function
101 feedbacks when humans are an integral part of the dynamic system [Box 1]. Then we outline
102 seven major scientific challenges that deserve organized and collaborative investment for rapid
103 progress. Finally, we outline an agenda for action to meet these challenges to support policy-
104 relevant science in a changing world, as our understanding of that world also changes.

105
106 **--- Box 1--- Conceptualizations of the biodiversity - function system and its inclusion of**
107 **humans have evolved over time in western science -----**

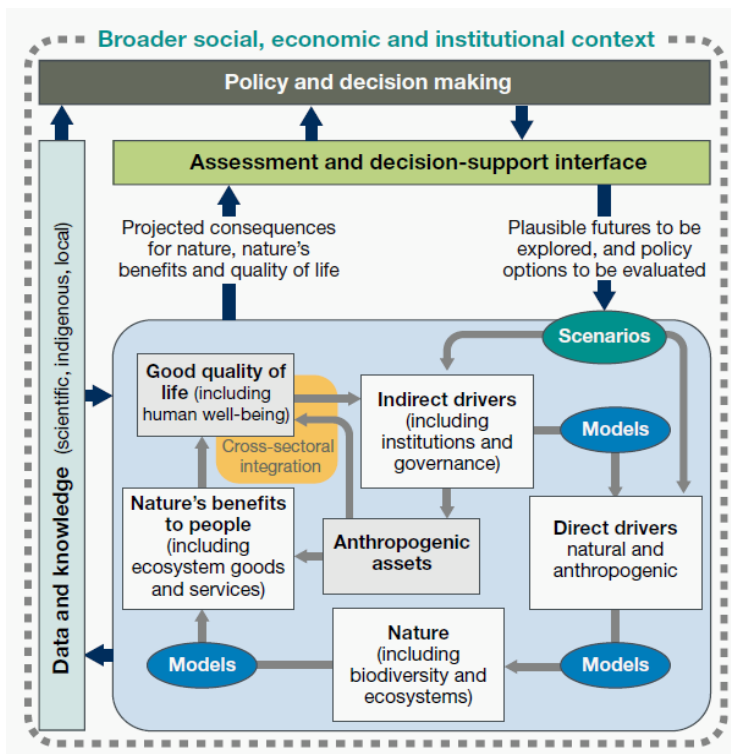
108 ~~The way biodiversity and ecosystem function feedbacks have been considered in the context of~~
109 ~~humanity's relationship with nature has changed over the last half century. Though early leaders~~
110 in ecology and biodiversity science noted biodiversity and ecosystem functioning feedbacks
111 (Hector:2002; ~~Mace:2014a~~), they did not feature in the dominant paradigm of the
112 1950s to 1980s of conservation of nature for itself (Figure 1A). Biodiversity-functioning
113 relationships were raised in the 1990s, with the realization that extinctions of species might
114 reduce ecosystem functioning (the Ehrlich's analogy of species loss as the popping of rivets in
115 spaceship Earth; (Mace:2014b)). In the 1990s, biodiversity and ecosystem functioning and
116 ecosystem services became a formal field of research. This 'nature for people' framing rapidly
117 led to the integration of ecology and environmental economics. In contemporary framings, the
118 emphasis on biodiversity function feedbacks is mixed, with some approaches that include a link
119 between diversity and function (e.g. ecosystem stability) while others treat biodiversity as purely
120 responsive to global change drivers (the resilience and planetary boundary frameworks). The
121 most recent scientific developments converge with themes in many cultures that envision
122 biodiversity as inclusive of people and human behaviour (United Nations 2015, Diaz et al. 2019)
123 (Figure 1B) [glossary]. The current IPBES framework maps biodiversity, function and people in
124 ways that do not capture the important feedbacks within and among these elements of the
125 biosphere (Figure 1B). The agenda we propose aims to frame the relationships among
126 biodiversity – inclusive of people - and function to emphasize a strong scientific understanding
127 of feedbacks across scales. [maybe give letters to the levels in the color figure].

128

129 **Figure 1A:** Progression of framings for the conservation of biodiversity over time (developed
 130 from (Mace 2014)) showing those that include the link between diversity and function (COLOUR
 131 arrows) versus the introduction and emphasis of other relationships (COLOUR arrows). Later
 132 framings complement (not replace) earlier ones, although some do not include the link between
 133 diversity and function. People and human activities were absent from earlier framings and have
 134 increasing prominence in more recent ones. Figure 1B: IPBES framework (Díaz et al. 2015).
 135



136
137



138

139
140 ---- end Box 1----

141
142
143 **Glossary:**

- 144 - **Biodiversity:** variety of life. We use the concept to include people in the living earth
145 system; biodiversity is measured at many scales and in many ways, from genetic
146 diversity to functional diversity to behavioral or cultural diversity (ref).
- 147 - **Beta diversity:** spatial or temporal variation in the composition of biodiversity
- 148 - **Ecosystems:** joint biotic/abiotic systems of life, characterized by dynamic stocks and
149 fluxes of energy, materials and information in the form of biodiversity.
- 150 - **Biodiversity-ecosystem function (BEF) relationship:** refers to the relationship
151 between diversity *per se* and the magnitude and stability of an ecosystem function.
152 Biodiversity-ecosystem functioning (BEF) relationships, when broadly defined, are
153 inclusive of the total biomass of living organisms, as well as the identities or importance
154 of specific organisms. BEF defined more narrowly refers to the role diversity plays in an
155 ecosystem function that is over and above the importance of total abundance, biomass
156 or composition of the biological assemblage.
- 157 - **Ecosystem functions:** the processes of energy flow (e.g., primary production), material
158 cycling (e.g., carbon cycling) and information processing (e.g., evolution) done by living
159 systems. Functions are understood to reflect interaction networks involving multiple
160 genetic and functional elements of biodiversity.
- 161 - **Ecosystem services:** the value of ecosystem functions to people (MA). Value can be
162 assessed in a variety of ways, from economic values to cultural values, in intrinsic,
163 instrumental or relational systems (Chan et al. 2016).
- 164 - **Natures contributions to people** = inclusive of ecosystem services as defined in MA,
165 but also includes other ways to conceptualize nature and people (Folgar et al. 2017).

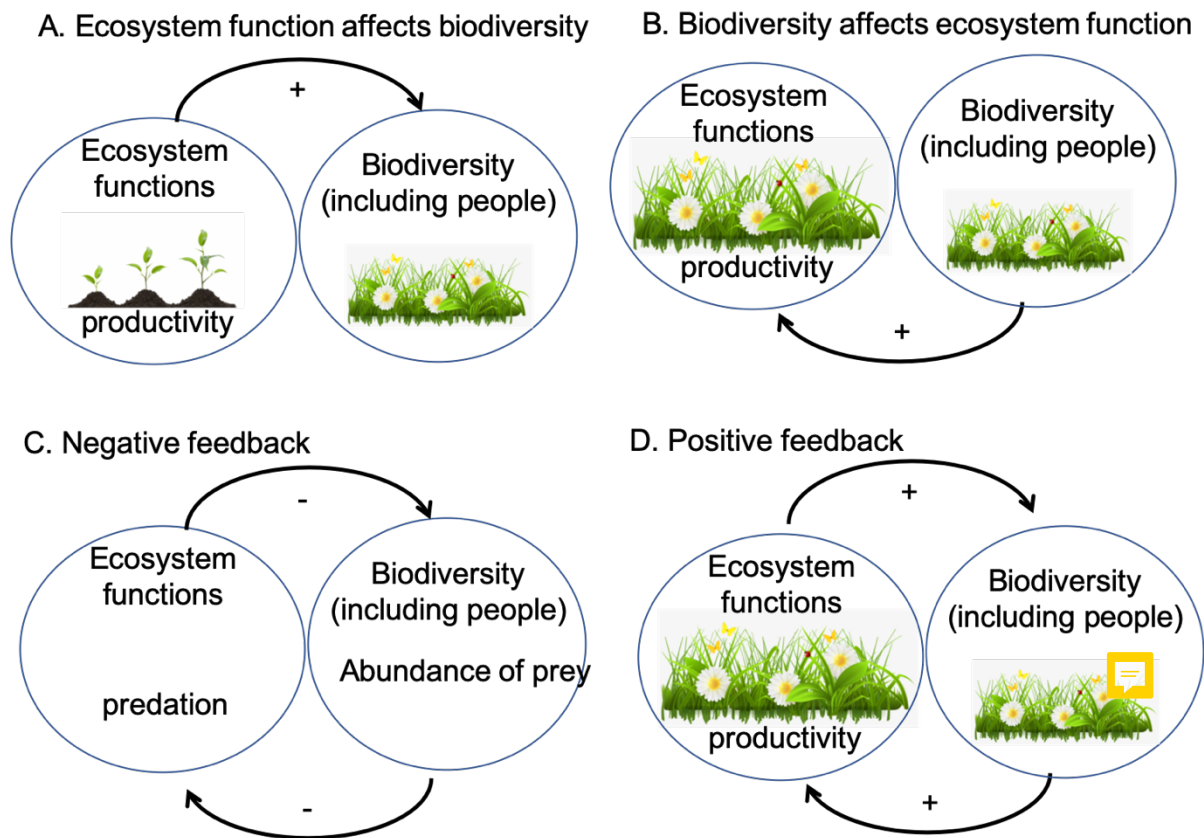
166
167
168 **II. Primary biodiversity and ecosystem function feedbacks**

169 Feedbacks are sets of interactions that can determine the stability and future trajectories
170 of living systems (Figure 2). Negative feedbacks are self-damping and stabilizing, and can
171 buffer systems against change. Negative feedbacks between consumer diversity and prey
172 abundance can lead to short-term increases in prey consumption that ultimately lead to declines
173 in prey or nest abundance, and consequently predator abundance allowing prey to recover
174 (good example). In contrast, positive feedbacks are self-reinforcing and can be destabilizing.
175 For example, productive grasslands can shift to deserts in a process called 'desertification'
176 when positive feedbacks between plant diversity and function (productivity, biomass, moisture
177 retention in the system) are disrupted by diversity loss or climate change, and soils dry (ref). As
178 the ecosystem desertifies, functions of plant production and moisture retention are lost, and
179 biodiversity cannot recover, in a negative feedback between soil drying and plant diversity (see
180 Sasaki et al. 2009, Ecology for the influences of wind erosion). The ultimate consequence of this
181 positive feedback is a shift in ecosystem state to a state less desirable to humans (Odorico et al.

182 2013) – a landscape scale change mediated by the balance of feedbacks between plants and
183 their environment at finer spatial scales.

184 Feedbacks can occur among all elements of the biosphere, and are response for rapid
185 changes in living systems that may not be anticipated by simple one-way relationships. For
186 example, a perception that people affect biodiversity but that there is no feedback from
187 biodiversity to people is increasingly recognized as dangerous for human well-being in short and
188 long-term thinking (United Nations 2015, Diaz et al. 2019). Feedbacks in socio-economic-
189 ecological systems are affected by the fast recent and current growth of the global human
190 population and economic activities. In turn, human growth and activities feed back to affect
191 human population dynamics and economic activities in the long run through changes in
192 ecosystem functioning, and thereby in the provision of ecosystem services and human
193 wellbeing.
194

195 **Figure 2. illustration of one-way effects (A, B) and two feedback loops (C, D).**



196

197

198

199 **III. Feedbacks are more than the sum of their parts**

200 While biodiversity, ecosystem functions and human systems each change and affect the others
201 (Figure 2), the feedbacks between these elements of complex living systems create ecological
202 and social dynamics across scales that are still not well understood. For example, we have science-
203 based support for a general understanding of how humans affect biodiversity (Butchart et al.
204 2010, Dirzo et al. 2014, Newbold et al. 2015, Ceballos et al. 2017)(Ripple et al 2019
205 conservation biology), how humans affect ecosystem function (IPCC, other good refs), how
206 biodiversity affects ecosystem functioning (Cardinale et al. 2011, Liang et al. 2016, Isbell et al.
207 2017) and how ecosystem functions affect humans (e.g., nature's contributions to people)
208 (Balvanera et al. 2013, Isbell et al. 2014, Pascual et al. 2017) (Figure 2). These one-way effects
209 are essential but incomplete representations of change in our biosphere.

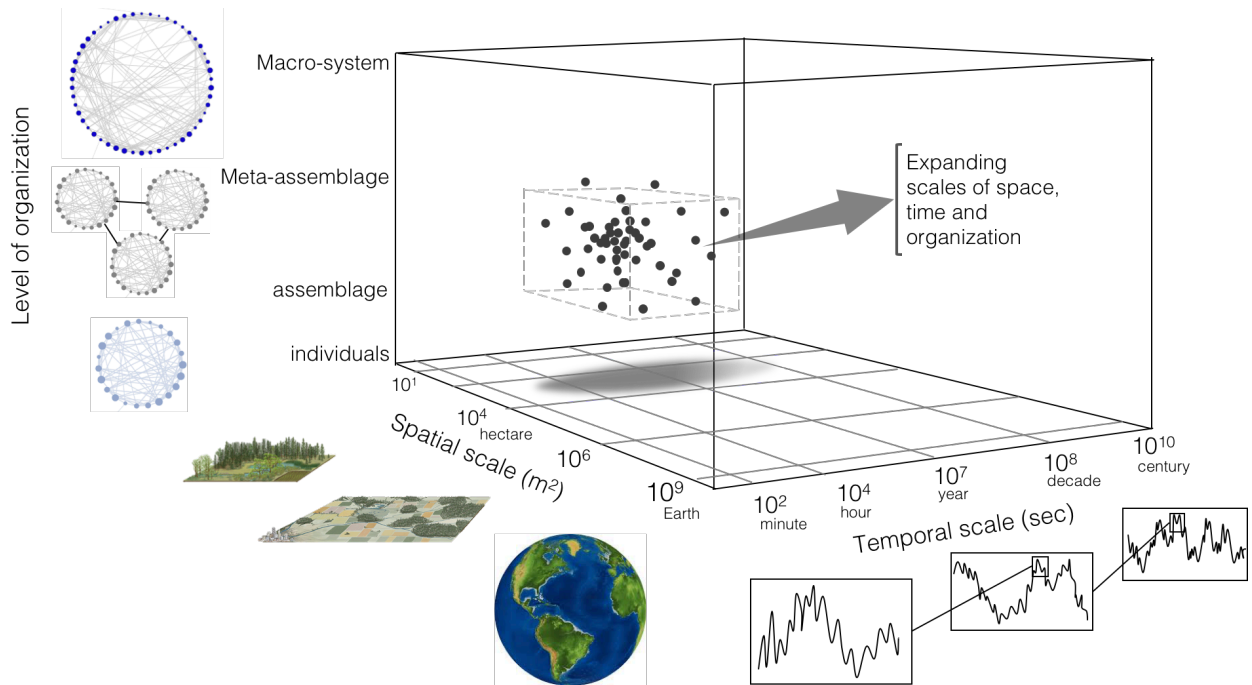
210
211 One pervasive consequence of the persistent decoupling of biodiversity and function is that
212 most of the biodiversity observations being assembled for assessments do not have
213 accompanying measures of ecosystem processes. As a result, future trajectories of diversity,
214 function or human well-being are impossible to project with only observations of biodiversity.
215 Similarly, observations of ecosystem functions such as production, carbon storage or nutrient
216 uptake in the absence of biodiversity estimates from the same places and times are difficult to
217 project forward with confidence, given the inability to project changes in the diversity-function
218 feedbacks.

219
220 Feedbacks cause behavior in systems that can differ radically from what is predicted based on
221 simpler models without feedbacks. Because feedbacks inherently introduce nonlinear
222 relationships between elements and states of systems (Peters et al. 2004), observations of
223 biodiversity without related observations of function in the same time and space, together with
224 an understanding of feedbacks, cannot reliably predict future or unobserved states. In scientific,
225 social and policy contexts, we often rely on a combination of our intuition and model projections
226 of scenarios or context we cannot directly observe (observation may be impossible because we
227 are in a different place or time, or because the size or scope of what we want to observe is
228 beyond our direct abilities). Without considering feedbacks in these elements of living systems,
229 efforts to project future states may be limited, even with large amounts of observations in hand
230 (Peters et al. 2004). This mismatch between biodiversity data and the theory and concepts that
231 allow projections of future states is amounting to a crisis of knowledge for sustainability
232 scenarios.

233
234 **Figure 2b.** Biodiversity across dimensions of life affect the abiotic environment and ecosystem
235 function via the metabolism, behavior and activities of individual organisms, associated with the
236 traits they express. Feedbacks exist between the abiotic environment, ecosystem functions,
237 people, ecosystem services and biodiversity. We observe biodiversity and functions, and we
238 value services, but we are still learning about how to observe and monitor the feedbacks that
239 determine the ultimate stability and change of the entire system.

240 A. Lifted from Gonzalez et al in review; placeholder here for a figure that illustrates the
241 hierarchical nature of diversity – species > populations > OTUs > genotypes /
242 phenotypes (for challenge 3) and spatial and temporal variation (for challenge 4).

243

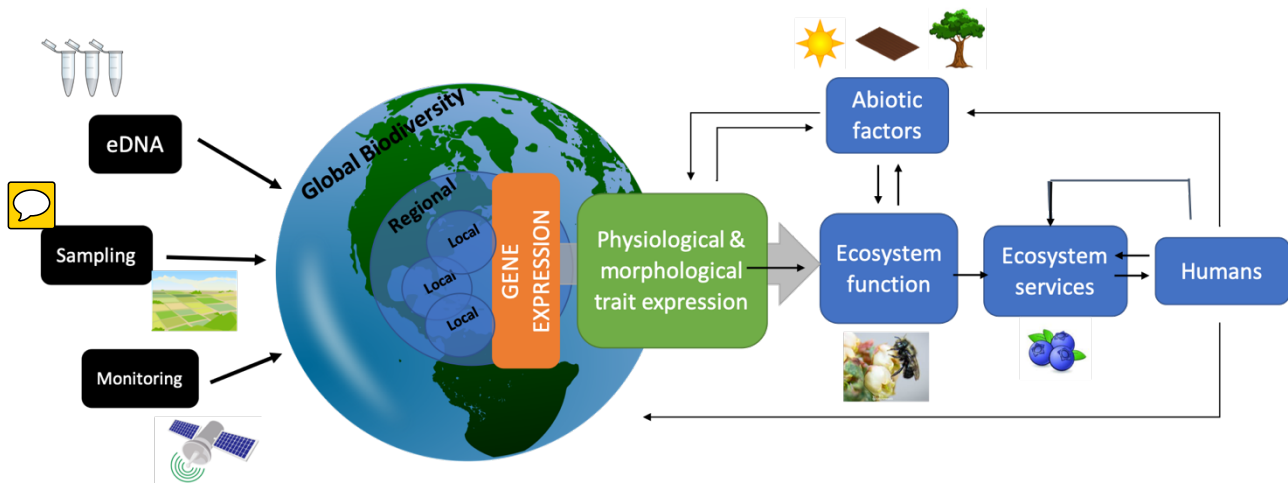


244

245

246 B.

247



248

249

250

251 ----

252

253

254

255

III. Grand challenges in Biodiversity Research. All existing knowledge points to unprecedented changes to the Earth system, the biosphere and human societies in the coming decades as a result of changes in biodiversity-function feedbacks. Here, we outline 7 scientific

256 challenges that are top priorities for major investment to enhance our knowledge frameworks to
257 support biodiversity policies and to realize sustainability goals.

258

259 **1. What are the feedbacks between biodiversity, and in particular its human component,**
260 **and ecosystem function?** A major ~~future~~ challenge ~~will be to account~~ for the indirect effects of
261 changes in biodiversity on human societies and for the resulting feedbacks these effects have
262 on biodiversity and ecosystems. A research agenda should aim toward an ultimate goal of fully
263 including the multiple human (behavioral, demographic, social, political, economic, institutional)
264 components of these feedbacks. There is growing recognition of the importance of the
265 feedbacks that couple natural and social systems; some authors now even argue that the
266 dynamics of either natural or human systems cannot be understood without considering these
267 feedbacks explicitly. This is especially true at the global scale, where long-term feedbacks play
268 a prominent role, but there is evidence that these feedbacks can be critical for projections of
269 regional or local development or sustainability. Accounting for these feedbacks will be a
270 particularly critical challenge for predictive models of BEF that aim to predict changes in
271 biodiversity and ecosystems at large spatial scales. *This challenge is both scientific and*
272 *perhaps philosophical, fully including human systems in our understanding of the biosphere.*
273

274

275 **2. What are the major feedbacks between diversity and ecosystem function across**
276 **scales?** ~~Many approaches to date have aimed to minimize feedbacks and isolate directional~~
277 ~~effects (e.g., effect of diversity on function) to gain clear~~ understanding of *parts* of biodiversity-
278 function feedbacks at a particular scale of space, time or biological organization (Figure 3A). We
279 now require new theory and experimental tests that allow us to understand feedbacks between
280 diversity change and ecosystem function, and how these are linked across scales of space, time
281 and organization (Figure 3A). For example, we do not have a robust model to allow us to
282 understand how changes in biodiversity at large scales (e.g., global or continental) interact with
283 changes at fine spatial scales (e.g., locally operating processes such as disturbance, invasion or
284 restoration) to influence biodiversity and function. Such theory and experimental work would be
285 explicit about temporal patterns in biodiversity and function, would identify links between
286 feedbacks involving ecosystem function and multiple scales of diversity (see challenge 3), and
287 would integrate evolutionary processes of biodiversity change. ~~It might help to resolve~~
288 ~~challenges associated with how to~~ interpret static measures of diversity in a single place or one
time to the dynamics that underlie the diversity-function feedbacks.

289 **3. How do different dimensions of biodiversity feedback on diversity, and with function?**

290 Biodiversity ~~is hierarchical in nature~~ (Seibold et al 2018, TREE) (Figure 3A). Much of our current
291 and future estimates of biodiversity and its change will be based on observations of alleles,
292 genes, traits, species (or OTUs), and even phylogenies. Yet, we lack the scientific knowledge to
293 relate changes in observed diversity in the environment at different levels of this hierarchy to
294 changes in ecosystem function, and feedbacks between biodiversity and function. One key
295 element of BEF feedbacks is trait expression, which links biodiversity contained in genes and
296 genomes to biodiversity of traits, and also plays a role in which genes and genomes persist in
297 communities. We lack theory and empirical understanding of how the aspects of diversity that
298 are realized through the expression of traits is related to the diversity present in genes and

299 alleles, and why patterns of trait expression vary in space and time. Until we meet this
300 challenge, the rapidly accumulating data on biodiversity cannot be used to estimate future
301 states of the biosphere.

302 **4. What is the role of spatial and temporal variation in BEF feedbacks?** Biodiversity is
303 dynamic in time, and changes over space, reflecting both biotic and abiotic processes including
304 the direct and indirect behaviors of people. As human activities continue to change the physical
305 and temporal structure of landscapes, our limited understanding of how biodiversity and function
306 feedbacks depend on spatial and temporal environmental variability remains a major challenge to
307 developing models and forecasts for patterns of diversity and function for future scenarios. We
308 need new theory for how spatial variation in biodiversity (beta-diversity) affects ecosystem
309 functioning. Even when we can improve our understanding of causes of change in beta diversity
310 (Glossary), we additionally need to understand what causes spatial and temporal variation in
311 population dynamics - this synchrony or asynchrony among populations in an ecosystem is a
312 key component of the feedback between biodiversity and stability of ecosystem function. We
313 also still lack theory to explain how landscape change, homogenization of diversity, and
314 changing patterns of asynchrony would affect feedbacks between diversity and function.

315 **5. How do ecosystem services depend on ecosystem functions and biodiversity-function**
316 **feedbacks?** One-way interactions between biodiversity and ecosystem functions, and
317 ecosystem functions and services, are well-established. It is also well-recognized that many
318 ecosystem services depend on the presence of specific species or functional groups (Balvanera
319 et al. 2013, Pascual et al. 2017), thus implicating biodiversity-ecosystem function feedbacks as
320 broadly defined (glossary). However, the strengths of interactions between biodiversity and
321 services remains less established for many services, especially with respect to the role of
322 biodiversity-ecosystem function feedbacks as defined more strictly to be additional to the
323 contributions of particular species (Glossary) (Balvanera et al. 2013). It remains unclear how
324 ecosystem functions, or related sets of functions (sometimes called 'multifunctionality'), confer
325 ecosystem services that are relevant for human wellbeing (Gamfeldt et al. 2013, Renard et al.
326 2015). For example, although some services likely map directly to commonly studied functions -
327 e.g. carbon sequestration - for others, the link is less straightforward - e.g. existence value of
328 conservation land or of particular species (Graves et al. 2017). Furthermore, the dependence of
329 services upon feedbacks between biodiversity and ecosystem functions is not well
330 characterized.

331 **6. How can we identify critical thresholds for stability, resilience, sustainability?** We
332 currently face high uncertainty about how biodiversity and ecosystem functioning feedbacks will
333 respond increasing dominance of humans (Steffen et al. 2004, Nature). The challenge is to
334 understand the capacity of ecosystems and biodiversity feedbacks to remain in the states
335 needed to ensure vital levels of ecosystem services supplies. Consideration of feedbacks
336 suggests the possibility of nonlinear change and critical thresholds that could cause rapid and
337 possibly irreversible shifts in ecosystem states, as invoked in the 'planetary boundaries'
338 paradigm (). However, existing theory for biodiversity-ecosystem function feedbacks does not
339 allow us yet to apply this global concept of tipping points at local and regional scales. It is likely
340 that critical thresholds and state shifts occur differently between spatial scales and it is therefore

341 highly uncertain how local changes and potential shifts to an undesired state could be related
342 from local to large scales.

343 **7. How can we ensure emerging technologies produce information that can be used to**
344 **deepen our understanding of biodiversity-function feedbacks?** Technological tools for
345 observing biodiversity allow high throughput and remote sensing of dimensions of biodiversity
346 (Bush et al 2017 NEL). In addition to the challenges of building a knowledge framework for
347 relating dimensions of biodiversity to ecosystem functions, we face the additional challenges of
348 understanding how to interpret these observations. With the tidal waves of new information
349 about diversity comes new forms of uncertainty in how well a data point actually represents
350 what it attempted to observe. For eDNA, it is unclear how much of the diversity in the
351 environment is sampled, and over what time period. If diversity is sampled (to an unknown
352 extent) over a spatial - temporal window, how can we use that information to understand
353 function. Without knowing how close observations are to the current state of nature, it is difficult
354 to relate these observations to models of feedbacks. (current limitations are that we don't know
355 the area sampled, or how long the DNA donor was present for, how observed DNA
356 concentrations relate to abundance, etc.)

357
358 **IV. Agenda for action.** We have outlined 7 gaps in scientific knowledge that limit our current
359 capacity to assess changes to the biosphere. Resolving these knowledge gaps will require
360 investment in scientific research by research teams worldwide, who employ diverse and
361 multidisciplinary approaches in the field, lab, and **in silico**. Here, we outline five 'action items' for
362 implementing the research agenda to maximize benefits to the science-policy community.

- 363
364 1. **Collaborate and connect** scientists and non-scientists from the beginning, as
365 observers, knowledge users, and decision makers about scientific activities at the local
366 scale.
- 367
368 2. **Develop multi-scale PBEF models** to estimate what has happened over recent
369 centuries, and forecast future patterns under various human development scenarios.
- 370
371 3. **Observe biodiversity, ecosystem function and human activity change together** at
372 different spatial scales with worldwide coverage, going beyond the *ad hoc* approaches to
373 sampling of biodiversity throughout the world that has produced a set of observations of
374 diversity that is highly biased to developed countries and terrestrial habitats.
- 375
376 4. **Experimentally and interactively test the model.** Observatories must be intimately
377 linked with experimental programs that provide information for the models to help with
378 understanding and projection.
- 379
380 5. **Identify and support a leadership team.** A leadership team must assemble, must be
381 able to draw on existing scientific knowledge and work with the research community to
382 develop research programs.

383

384 Along the way, the research community will need to confront additional logistical challenges that
385 currently limit rapid scientific advances. These include i) the current lack of open science and
386 the fact that data for biodiversity and ecosystem function knowledge from many places is not
387 curated or made available in a central database (like GenBank), ii) limited technology integration
388 such that observations from different methods not spatially coordinated, and ii) the clear need
389 for more balanced engagement from global community (through research and citizen science).

390

391 **Conclusion**

392 Scientific progress over the last 30 years has led to recognition of the importance of
393 feedbacks among biodiversity, function and people across scales. Despite this understanding,
394 and major progress with models, experiments and observations, major challenges remain to
395 integrate this knowledge with new capabilities to meet the challenges of the coming decades.
396 As major policy-guiding scientific assessments grow in importance, it is essential to keep
397 striving for the scientific advances, and in particular theoretical advances, that will foster
398 integration of state-of-the-art scientific understanding with international and local policy
399 objectives.

400 Meeting these knowledge challenges will lead to a deeper and truer understanding of
401 our biosphere. As our technological capacity to observe our world and influence accelerates, we
402 must harness these abilities to also understand the complex feedbacks and interactions that
403 govern the dynamics of biodiversity and ecosystem functioning. By investing in science and
404 supporting collaborative and interdisciplinary partnerships we can realize the fullest potential of
405 a collective knowledge system to project possible futures and act on our understanding of those
406 projects in the best possible way for our planet.

407

408

409 **Acknowledgments**

410 NCEAS LTER 

411 **References**

- 412 Balvanera, P., I. Siddique, L. Dee, A. Paquette, F. Isbell, A. Gonzalez, J. Byrnes, M. I.
 413 O'Connor, B. A. Hungate, and J. N. Griffin. 2013. Linking Biodiversity and Ecosystem
 414 Services: Current Uncertainties and the Necessary Next Steps. *Bioscience* 64:49–57.
- 415 Butchart, S. H. M., M. Walpole, B. Collen, A. van Strien, J. P. W. Scharlemann, R. E. A. Almond,
 416 J. E. M. Baillie, B. Bomhard, C. Brown, J. Bruno, K. E. Carpenter, G. M. Carr, J. Chanson,
 417 A. M. Chenery, J. Csirke, N. C. Davidson, F. Dentener, M. Foster, A. Galli, J. N. Galloway,
 418 P. Genovesi, R. D. Gregory, M. Hockings, V. Kapos, J.-F. Lamarque, F. Leverington, J. Loh,
 419 M. A. McGeoch, L. McRae, A. Minasyan, M. Hernández Morcillo, T. E. E. Oldfield, D. Pauly,
 420 S. Quader, C. Revenga, J. R. Sauer, B. Skolnik, D. Spear, D. Stanwell-Smith, S. N. Stuart,
 421 A. Symes, M. Tierney, T. D. Tyrrell, J.-C. Vié, and R. Watson. 2010. Global biodiversity:
 422 indicators of recent declines. *Science* 328:1164–1168.
- 423 Cardinale, B. J., K. L. Matulich, D. U. Hooper, J. E. Byrnes, E. Duffy, L. Gamfeldt, P. Balvanera,
 424 M. I. O'Connor, and A. Gonzalez. 2011. The functional role of producer diversity in
 425 ecosystems. *American Journal of Botany* 98:572–592.
- 426 Ceballos, G., P. R. Ehrlich, and R. Dirzo. 2017. Biological annihilation via the ongoing sixth
 427 mass extinction signaled by vertebrate population losses and declines. *Proceedings of the*
 428 *National Academy of Sciences* 114:E6089–E6096.
- 429 Chan, K. M. A., P. Balvanera, K. Benessaiah, M. Chapman, S. Díaz, E. Gómez-Baggethun, R.
 430 Gould, N. Hannahs, K. Jax, S. Klain, G. W. Luck, B. Martin-Lopez, B. Muraca, B. Norton, K.
 431 Ott, U. Pascual, T. Satterfield, M. Tadaki, J. Taggart, and N. Turner. 2016. Opinion: Why
 432 protect nature? Rethinking values and the environment. *Proceedings of the National*
 433 *Academy of Sciences* 113:1462–1465.
- 434 Dee, L. E., M. De Lara, C. Costello, and S. D. Gaines. 2017a. To what extent can ecosystem
 435 services motivate protecting biodiversity? *Ecology Letters* 20:935–946.
- 436 Dee, L. E., M. De Lara, C. Costello, and S. D. Gaines. 2017b. To what extent can ecosystem
 437 services motivate protecting biodiversity? *Ecology Letters* 20:935–946.
- 438 Diaz, S., J. Settele, E. Brondizio, H. T. Ngo, M. Gueze, J. Agard, A. Arneeth, P. Balvanera, K.
 439 Brauman, S. Butchart, K. Chan, L. Garibaldi, K. Ichii, J. Liu, P. Miloslavich, Z. Molnár, D.
 440 Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, R. Roy Chowdhury, Y.-J. Shin, I.
 441 Visseren-Hamakers, K. Willis, and C. Zayas. 2019. Summary for policymakers of the global
 442 assessment report on biodiversity and ecosystem services of the Intergovernmental
 443 Science-Policy Platform on Biodiversity and Ecosystem Services. Pages 1–39.
- 444 Dirzo, R., H. S. Young, M. Galetti, G. Ceballos, N. J. B. Isaac, and B. Collen. 2014. Defaunation
 445 in the Anthropocene. *Science* 345:401–406.
- 446 Díaz, S., S. Demissew, J. Carabias, C. Joly, M. Lonsdale, N. Ash, A. Larigauderie, J. R.
 447 Adhikari, S. Arico, A. Báldi, A. Bartuska, I. A. Baste, A. Bilgin, E. Brondizio, K. M. Chan, V.
 448 E. Figueroa, A. Duraiappah, M. Fischer, R. Hill, T. Koetz, P. Leadley, P. Lyver, G. M. Mace,
 449 B. Martin-Lopez, M. Okumura, D. Pacheco, U. Pascual, E. S. Pérez, B. Reyers, E. Roth, O.
 450 Saito, R. J. Scholes, N. Sharma, H. Tallis, R. Thaman, R. Watson, T. Yahara, Z. A. Hamid,
 451 C. Akosim, Y. Al-Hafedh, R. Allahverdiyev, E. Amankwah, S. T. Asah, Z. Asfaw, G. Bartus,
 452 L. A. Brooks, J. Caillaux, G. Dalle, D. Darnaedi, A. Driver, G. Erpul, P. Escobar-Eyzaguirre,
 453 P. Failler, A. M. M. Fouda, B. Fu, H. Gundimeda, S. Hashimoto, F. Homer, S. Lavorel, G.
 454 Lichtenstein, W. A. Mala, W. Mandivenyi, P. Matczak, C. Mbizvo, M. Mehrdadi, J. P.
 455 Metzger, J. B. Mikissa, H. Moller, H. A. Mooney, P. Mumby, H. Nagendra, C. Nesshover, A.
 456 A. Oteng-Yeboah, G. Pataki, M. Roué, J. Rubis, M. Schultz, P. Smith, R. Sumaila, K.
 457 Takeuchi, S. Thomas, M. Verma, Y. Yeo-Chang, and D. Zlatanova. 2015. ScienceDirect
 458 The IPBES Conceptual Framework — connecting nature and people. *Current Opinion in*
 459 *Environmental Sustainability* 14:1–16.
- 460 Díaz, S., U. Pascual, M. Stenseke, B. Martin-Lopez, R. T. Watson, Z. Molnár, R. Hill, K. M. A.
 461 Chan, I. A. Baste, K. A. Brauman, S. Polasky, A. Church, M. Lonsdale, A. Larigauderie, P.

462 W. Leadley, A. P. E. van Oudenhoven, F. van der Plaat, M. Schröter, S. Lavorel, Y.
463 Aumeeruddy-Thomas, E. Bukvareva, K. Davies, S. Demissew, G. Erpul, P. Failler, C. A.
464 Guerra, C. L. Hewitt, H. Keune, S. Lindley, and Y. Shirayama. 2018. Assessing nature's
465 contributions to people. *Science* 359:270–272.

466 Frison, A. E., J. Cherfas, and T. Hodgkin. 2011. Agricultural biodiversity is essential for a
467 sustainable improvement in food and nutrition security. *Sustainability* 3:238–253.

468 Gamfeldt, L., T. Snäll, R. Bagchi, M. Jonsson, L. Gustafsson, P. Kjellander, M. C. Ruiz-Jaen, M.
469 Fröberg, J. Stendahl, C. D. Philipson, G. Mikusiński, E. Andersson, B. Westerlund, H.
470 Andrén, F. Moberg, J. Moen, and J. Bengtsson. 2013. Higher levels of multiple ecosystem
471 services are found in forests with more tree species. *Nature Communications* 4:59–8.

472 Graves, R. A., S. M. Pearson, and M. G. Turner. 2017. Species richness alone does not predict
473 cultural ecosystem service value. *Proceedings of the National Academy of Sciences*
474 114:3774–3779.

475 Isbell, F., A. Gonzalez, M. Loreau, J. Cowles, S. Díaz, A. Hector, G. M. Mace, D. A. Wardle, M.
476 I. O'Connor, J. E. Duffy, L. A. Turnbull, P. L. Thompson, and A. Larigauderie. 2017. Linking
477 the influence and dependence of people on biodiversity across scales. *Nature* 546:65–72.

478 Isbell, F., D. Tilman, S. Polasky, and M. Loreau. 2014. The biodiversity-dependent ecosystem
479 service debt. *Ecology Letters* 18:119–134.

480 Liang, J., T. W. Crowther, N. Picard, S. Wiser, M. Zhou, G. Alberti, E. D. Schulze, A. D.
481 McGuire, F. Bozzato, H. Pretzsch, S. de-Miguel, A. Paquette, B. Herault, M. Scherer-
482 Lorenzen, C. B. Barrett, H. B. Glick, G. M. Hengeveld, G. J. Nabuurs, S. Pfautsch, H. Viana,
483 A. C. Vibrans, C. Ammer, P. Schall, D. Verbyla, N. Tchebakova, M. Fischer, J. V. Watson,
484 H. Y. H. Chen, X. Lei, M. J. Schelhaas, H. Lu, D. Gianelle, E. I. Parfenova, C. Salas, E. Lee,
485 B. Lee, H. S. Kim, H. Bruelheide, D. A. Coomes, D. Piotta, T. Sunderland, B. Schmid, S.
486 Gourlet-Fleury, B. Sonke, R. Tavani, J. Zhu, S. Brandl, J. Vayreda, F. Kitahara, E. B.
487 Searle, V. J. Neldner, M. R. Ngugi, C. Baraloto, L. Frizzera, R. Ba azy, J. Oleksyn, T. Zawi
488 a-Nied wiecki, O. Bouriaud, F. Bussotti, L. Finer, B. Jaroszewicz, T. Jucker, F. Valladares,
489 A. M. Jagodzinski, P. L. Peri, C. Gonmadje, W. Marthy, T. OBrien, E. H. Martin, A. R.
490 Marshall, F. Rovero, R. Bitariho, P. A. Niklaus, P. Alvarez-Loayza, N. Chamuya, R.
491 Valencia, F. Mortier, V. Wortel, N. L. Engone-Obiang, L. V. Ferreira, D. E. Odeke, R. M.
492 Vasquez, S. L. Lewis, and P. B. Reich. 2016. Positive biodiversity-productivity relationship
493 predominant in global forests. *Science* 354:aaf8957–aaf8957.

494 Mace, G. M. 2014. Ecology. Whose conservation? *Science* 345:1558–1560.

495 Mace, G. M. 2019. The ecology of natural capital accounting. *Oxford Review of Economic Policy*
496 35:54–67.

497 Newbold, T., L. N. Hudson, S. L. L. Hill, S. Contu, I. Lysenko, R. A. Senior, L. Börger, D. J.
498 Bennett, A. Choimes, B. Collen, J. Day, A. De Palma, S. Díaz, S. Echeverria-Londoño, M. J.
499 Edgar, A. Feldman, M. Garon, M. L. K. Harrison, T. Alhousseini, D. J. Ingram, Y. Itescu, J.
500 Kattge, V. Kemp, L. Kirkpatrick, M. Kleyer, D. L. P. Correia, C. D. Martin, S. Meiri, M.
501 Novosolov, Y. Pan, H. R. P. Phillips, D. W. Purves, A. Robinson, J. Simpson, S. L. Tuck, E.
502 Weiher, H. J. White, R. M. Ewers, G. M. Mace, J. P. W. Scharlemann, and A. Purvis. 2015.
503 Global effects of land use on local terrestrial biodiversity. *Nature* 520:45–50.

504 Odorico, P. D., A. Bhattachan, K. F. Davis, S. Ravi, and C. W. Runyan. 2013. Global
505 desertification: Drivers and feedbacks. *Advances in Water Resources* 51:326–344.

506 Pascual, U., P. Balvanera, S. Díaz, G. Pataki, E. Roth, M. Stenseke, R. T. Watson, E. B.
507 Dessane, M. Islar, E. Kelemen, V. Maris, M. Quaas, S. M. Subramanian, H. Wittmer, A.
508 Adlan, S. Ahn, Y. S. Al-Hafedh, E. Amankwah, S. T. Asah, P. Berry, A. Bilgin, S. J. Breslow,
509 C. Bullock, D. Cáceres, H. Daly-Hassen, E. Figueroa, C. D. Golden, E. Gómez-Baggethun,
510 D. González-Jiménez, J. Houdet, H. Keune, R. Kumar, K. Ma, P. H. May, A. Mead, P.
511 O'Farrell, R. Pandit, W. Pengue, R. Pichis-Madruga, F. Popa, S. Preston, D. Pacheco-
512 Balanza, H. Saarikoski, B. B. Strassburg, M. van den Belt, M. Verma, F. Wickson, and N.

513 Yagi. 2017. ScienceDirect Valuing nature's contributions to people: the IPBES approach.
514 Current Opinion in Environmental Sustainability 26-27:1–10.
515 Peters, D. P. C., R. A. Pielke, B. T. Bestelmeyer, C. D. Allen, S. Munson-McGee, and K. M.
516 Havstad. 2004. Cross-scale interactions, nonlinearities, and forecasting catastrophic events.
517 Proceedings of the National Academy of Sciences 101:15130–15135.
518 Renard, D., J. M. Rhemtulla, and E. M. Bennett. 2015. Historical dynamics in ecosystem service
519 bundles. Proceedings of the National Academy of Sciences 112:13411–13416.
520 Schindler, D. E., R. Hilborn, B. Chasco, C. P. Boatright, T. P. Quinn, L. A. Rogers, and M. S.
521 Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature
522 465:609–612.
523 United Nations. 1992. Convention on biological diversity. Pages 1–30.
524 United Nations. 2015. Transforming our world: the 2030 agenda for sustainable development.
525 Pages 1–41.
526 Wang, S., and M. Loreau. 2014. Ecosystem stability in space: α , β and γ variability. Ecology
527 Letters 17:891–901.
528 Watson, R. T., and A. H. Zakri. 2005. Ecosystems and Human Well-Being. Pages 1–155.
529