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1 **Managing consequences of climate-driven species**
2 **redistribution requires integration of ecology, conservation**
3 **and social science**

4
5 Timothy C. Bonebrake^{1,*}, Christopher J. Brown², Johann D. Bell^{3,4}, Julia L.
6 Blanchard^{5,6}, Alienor Chauvenet^{7,8}, Curtis Champion⁵, I-Ching Chen⁹,
7 Timothy D. Clark^{5,10}, Robert K. Colwell^{11,12,13,14}, Finn Danielsen¹⁵, Anthony
8 I. Dell^{16,17}, Jennifer M. Donelson^{18,19}, Birgitta Evengård²⁰, Simon Ferrier²¹,
9 Stewart Frusher^{5,6}, Raquel A. Garcia^{22,23}, Roger B. Griffis²⁴, Alistair J.
10 Hobday^{6,25}, Marta A. Jarzyna²⁶, Emma Lee⁶, Jonathan Lenoir²⁷, Hlif
11 Linnetved²⁸, Victoria Y. Martin²⁹, Phillipa C. McCormack³⁰, Jan
12 McDonald^{6,30}, Eve McDonald-Madden^{8,31}, Nicola Mitchell³², Tero
13 Mustonen³³, John M. Pandolfi³⁴, Nathalie Pettorelli³⁵, Hugh Possingham^{8,36},
14 Peter Pulsifer³⁷, Mark Reynolds³⁸, Brett R. Scheffers³⁹, Cascade J. B.
15 Sorte⁴⁰, Jan M. Strugnell⁴¹, Mao-Ning Tuanmu⁴², Samantha Twiname⁵,
16 Adriana Vergés⁴³, Cecilia Villanueva⁵, Erik Wapstra⁴⁴, Thomas
17 Wernberg^{32,45} and Gretta T. Pecl^{5,6}

18
19 ¹*School of Biological Sciences, The University of Hong Kong, Pokfulam Rd, Hong Kong*
20 *SAR, China*

21 ²*Australian Rivers Institute, Griffith University, Nathan, 4111, Australia*

22 ³*Australian National Centre for Ocean Resources and Security, University of*
23 *Wollongong, NSW 2522, Australia*

24 ⁴*Conservation International, Arlington, VA 22202, USA*

25 ⁵*Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS 7001,*
26 *Australia*

27 ⁶*Centre for Marine Socioecology, University of Tasmania, Hobart, TAS 7001, Australia*

28 ⁷*Centre for Biodiversity and Conservation Science, University of Queensland, St Lucia,*
29 *QLD 4072, Australia*

30 ⁸*ARC Centre of Excellence for Environmental Decisions, School of Biological Sciences,*
31 *The University of Queensland, Brisbane, QLD, Australia*

32 ⁹*Department of Life Sciences, National Cheng Kung University, Tainan 701, Taiwan,*
33 *Republic of China*

34 ¹⁰*CSIRO Agriculture and Food, Hobart, TAS 7000, Australia*

35 ¹¹*Center for Macroecology, Evolution and Climate, University of Copenhagen, Natural*
36 *History Museum of Denmark, 2100 Copenhagen, Denmark*

37 ¹²*Department of Ecology and Evolutionary Biology, University of Connecticut, Storrs,*
38 *CT 06269, USA*

39 ¹³*University of Colorado Museum of Natural History, Boulder, CO 80309, USA*

40 ¹⁴*Departamento de Ecologia, Universidade Federal de Goiás, CP 131, 74.001-970*
41 *Goiânia, Goiás, Brazil*

42 ¹⁵*Nordic Foundation for Development and Ecology (NORDECO), Copenhagen DK-1159,*
43 *Denmark*

44 ¹⁶*National Great Rivers Research and Education Center (NGRREC), One Confluence*
45 *Way, East Alton, IL 62024, USA*

46 ¹⁷*Department of Biology, Washington University in St. Louis, St. Louis, MO, USA*

47 ¹⁸*School of Life Sciences, University of Technology, Sydney, NSW, Australia*

48 ¹⁹*ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville,*
49 *QLD, Australia*

50 ²⁰*Division of Infectious Diseases, Department of Clinical Microbiology, Umea*
51 *University, 90187 Umea, Sweden*

52 ²¹*CSIRO Land and Water, Canberra, ACT 2601, Australia*

53 ²²*Centre for Statistics in Ecology, the Environment and Conservation, Department of*
54 *Statistical Sciences, University of Cape Town, Rondebosch 7701, Cape Town, South*
55 *Africa*

56 ²³*Centre for Invasion Biology, Department of Botany and Zoology, Faculty of Science,*
57 *Stellenbosch University, Matieland 7602, South Africa*

58 ²⁴*NOAA National Marine Fisheries Service, Office of Science and Technology, Silver*
59 *Spring, Maryland 20910, USA*

60 ²⁵*CSIRO, Oceans and Atmosphere, Hobart, Tasmania, 7000, Australia*

61 ²⁶*Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT*
62 *06511, USA*

63 ²⁷*UR « Ecologie et dynamique des systèmes anthropisés » (EDYSAN, FRE 3498 CNRS-*
64 *UPJV), Université de Picardie Jules Verne, 1 Rue des Louvels, FR-80037 Amiens Cedex*
65 *1, France*

66 ²⁸*Institute of Food and Resource Economics, Faculty of Science, University of*
67 *Copenhagen, Rolighedsvej 25, DK-1958 Frederiksberg C, Denmark*

68 ²⁹*Cornell Lab of Ornithology, Cornell University, Ithaca, NY 14850, USA*

69 ³⁰*Faculty of Law, University of Tasmania, Hobart, TAS 7001, Australia*

70 ³¹*School of Geography, Planning and Environmental Management, The University of*
71 *Queensland, Brisbane, Queensland, Australia*

72 ³²*School of Biological Sciences, University of Western Australia, Crawley WA 6009,*
73 *Australia*

74 ³³*Snowchange Cooperative, University of Eastern Finland, 80130 Joensuu, Finland*

75 ³⁴*School of Biological Sciences, ARC Centre of Excellence for Coral Reef Studies, The*
76 *University of Queensland, Brisbane, QLD 4072, Australia*

77 ³⁵*Institute of Zoology, Zoological Society of London, Regent's Park, NW1 4RY London,*
78 *UK*

79 ³⁶*Grand Challenges in Ecosystems and the Environment, Silwood Park, Imperial*
80 *College, London, UK*

81 ³⁷*National Snow and Ice Data Center, University of Colorado Boulder, 449 UCB,*
82 *Boulder, Colorado 80309, USA*

83 ³⁸*The Nature Conservancy, 201 Mission St, 4th Floor, San Francisco, CA 94105, USA*

84 ³⁹*Department of Wildlife Ecology and Conservation, University of Florida/IFAS,*
85 *Gainesville, FL 32611, USA*

86 ⁴⁰*Department of Ecology and Evolutionary Biology, University of California, Irvine, CA*
87 *92697, USA*

88 ⁴¹*Centre for Sustainable Tropical Fisheries and Aquaculture, College of Science and*
89 *Engineering, James Cook University, Townsville, 4811 QLD, Australia*

90 ⁴²*Biodiversity Research Center, Academia Sinica, Taipei 115, Taiwan, Republic of China*

91 ⁴³*Centre for Marine Bio-Innovation and Evolution & Ecology Research Centre, School of*
92 *Biological, Earth and Environmental Sciences, University of New South Wales, Sydney,*
93 *NSW 2052, Australia*

94 ⁴⁴*School of Biological Sciences, University of Tasmania, Tasmania 7001, Australia*

95 ⁴⁵*UWA Oceans Institute, University of Western Australia, Perth, WA 6009, Australia*

96

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98 Running head: Research directions in species redistribution

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101 * Author for correspondence (E-mail: tbone@hku.hk; Tel.: +852 2299 0675).

102

103 ABSTRACT

104 Climate change is driving a pervasive global redistribution of the planet's species.

105 Species redistribution poses new questions for the study of ecosystems, conservation

106 science and human societies that require a coordinated and integrated approach. Here we

107 review recent progress, key gaps and strategic directions in this nascent research area,

108 emphasising emerging themes in species redistribution biology, the importance of

109 understanding underlying drivers and the need to anticipate novel outcomes of changes in

110 species ranges. We highlight that species redistribution has manifest implications across

111 multiple temporal and spatial scales and from genes to ecosystems. Understanding range
112 shifts from ecological, physiological, genetic and biogeographical perspectives is
113 essential for informing changing paradigms in conservation science and for designing
114 conservation strategies that incorporate changing population connectivity and advance
115 adaptation to climate change. Species redistributions present challenges for human well-
116 being, environmental management and sustainable development. By synthesising recent
117 approaches, theories and tools, our review establishes an interdisciplinary foundation for
118 the development of future research on species redistribution. Specifically, we
119 demonstrate how ecological, conservation and social research on species redistribution
120 can best be achieved by working across disciplinary boundaries to develop and
121 implement solutions to climate change challenges. Future studies should therefore
122 integrate existing and complementary scientific frameworks while incorporating social
123 science and human-centred approaches. Finally, we emphasise that the best science will
124 not be useful unless more scientists engage with managers, policy makers and the public
125 to develop responsible and socially acceptable options for the global challenges arising
126 from species redistributions.

127

128 *Key words:* adaptive conservation, climate change, food security, health, managed
129 relocation, range shift, sustainable development, temperature.

130

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156 **I. INTRODUCTION**

157 Species across the globe, in all ecosystems, are shifting their distributions in response to
158 recent and ongoing climate change (Parmesan & Yohe, 2003; Sorte, Williams & Carlton,
159 2010; Pinsky *et al.*, 2013; Alofs, Jackson & Lester, 2014; Lenoir & Svenning, 2015;
160 Poloczanska *et al.*, 2016; Scheffers *et al.*, 2016). These shifts are faster at greater levels
161 of warming (Chen *et al.*, 2011) and are projected to accelerate into the future with
162 continued changes in the global climate system (Urban, 2015). Thus, there is a clear need
163 to understand the impacts and consequences of global species redistribution for
164 ecosystem dynamics and functioning, for conservation and for human societies (Pecl *et*
165 *al.*, 2017).

166 Species range dynamics and climate have an intertwined history in ecological research
167 going back centuries (Grinnell, 1917; Parmesan, 2006). However, research on species
168 range shifts driven by contemporary climate change is relatively recent, dating back only
169 20 years (Southward, Hawkins & Burrows, 1995). In the past decade, research on the
170 subject has increased dramatically (Fig. 1). While coverage is far from complete
171 methodologically, geographically or taxonomically (Lenoir & Svenning, 2015; Brown *et*
172 *al.*, 2016; Feeley, Stroud & Perez, 2016), this increased research effort highlights
173 growing awareness that species are moving in response to climate change, worldwide
174 (IPCC, 2014).

175 We believe that ‘species redistribution science’ has emerged as a field in its own right.
176 However, to date the field has lacked strategic direction and an interdisciplinary
177 consideration of research priorities. Historically, researchers have used ‘species range
178 shifts’ or ‘species distribution shifts’ as favoured descriptive terms for climate-driven

179 species movements. Here we use the term ‘species redistribution’ to encapsulate not only
180 species movement, but also its consequences for whole ecosystems and linked social
181 systems. Despite accumulating evidence of recent climate-driven species redistributions
182 (Lenoir & Svenning, 2015; Poloczanska *et al.*, 2016; Scheffers *et al.*, 2016), integrated
183 and interdisciplinary frameworks that can effectively predict the ecological, conservation
184 and societal consequences of these changes remain uncommon [but see Williams *et al.*
185 (2008) for a framework highlighting species vulnerability and potential management
186 responses]. A long-term strategy for the field of species redistribution research is required
187 to capitalise on, and respond to, the ‘global experiment’ of large-scale changes in our
188 natural and managed ecosystems. What can be implemented now to build scientific and
189 social capacity for adaptation to species redistribution over the next decade, the next
190 century and beyond (IPCC, 2014)?

191 The ‘Species on the Move’ conference (held in Hobart, Australia, 9–12 February
192 2016) brought together scientists from across the physical, biological and social sciences.
193 Here, we build on the outcomes of this conference by identifying key research directions
194 to meet the global challenge of preparing for the impacts of climate-driven species
195 redistribution on the biosphere and human society. We focus on directions and needs
196 around three focal points for understanding species redistribution and its impacts: (1)
197 species redistribution ecology, (2) conservation actions, and (3) social and economic
198 impacts and responses. For each focal point we summarise recent trends in the field and
199 propose priority questions for future research. We identify promising research directions
200 and approaches for addressing these questions, placing emphasis on the potential benefits
201 from integrating approaches across multiple disciplines and sub-disciplines. In so doing,

202 we argue that greater interdisciplinary synthesis is fundamental to ensuring that species
203 redistribution research continues to advance beyond simple documentation of species
204 range shifts, to develop research programs and achieve outcomes that will inform policy
205 and management decisions.

206

207 **II. SPECIES REDISTRIBUTION AS A FIELD OF RESEARCH**

208 To support our synthesis of future directions, we first establish how the research field of
209 climate-driven species redistributions has evolved and quantify, bibliometrically, the
210 prevailing research foci. To understand this history in the context of the broader scientific
211 literature, we analysed publication trends in the peer-reviewed literature on species range
212 shifts over the past 25 years. In total we extracted 1609 publications from Thompson
213 Reuters *Web of Science* that contained search terms relating to distribution change or
214 range shift (see online Supporting Information, Appendix S1 for details).

215 In 2006, both the proportion of range shift publications in the ‘environmental sciences’
216 and the diversity of journals publishing research on range shifts showed a clear increase
217 (Fig. 1). At the same time, citation rates dropped relative to the discipline’s baseline
218 heralding that publications about range shifts had shifted from a few high-profile
219 publications to mainstream ecological science (Fig. 1).

220 We analysed this corpus to identify research trends in two ways. First, we identified
221 ‘trending’ terms. Terms were defined based on word stems, and trending terms were
222 those that showed a significant increase in use in titles, abstracts or key words since 1995.
223 Second, we identified ‘high-impact’ terms, i.e. those associated with higher than average
224 citation rates, once we had accounted for the confounding effect of publication year. The

225 trends analysis indicated that range shift science has become increasingly
226 interdisciplinary over time. Terms associated with socioeconomic approaches, such as
227 ‘ecosystem services’ have also become increasingly prevalent and tend to be associated
228 with high-impact papers (Fig. 2). Management-oriented studies, with terms including
229 ‘priority’ (referring to management priorities) are also increasing in use. Both
230 socioeconomic (‘social’, ‘socioeconomic’) and management-related terms
231 (‘complement*’ referring to complementary protection) were associated with higher than
232 average citation rates during the period 2010–2015 (Fig. 2). Thus, we find clear evidence
233 for the emergence of a new field that is generating increasing interest, while expanding to
234 link with other existing and emerging fields.

235

236 **III. SPECIES REDISTRIBUTION ECOLOGY**

237 Species redistribution has been widely documented (Scheffers *et al.*, 2016) and well-
238 developed theories have been proposed to explain how and why range shifts occur (Bates
239 *et al.*, 2014) and how future species redistribution may proceed under global climate
240 change (Urban *et al.*, 2016). Hence, we can consider the ecology of species redistribution
241 under two broad and complementary areas: explanatory ecology and anticipatory
242 ecology. Explanatory ecology generally aims to evaluate models and theory to enhance
243 scientific understanding of the processes that drive species redistribution. For detailed
244 reviews on subject areas specific to explanatory ecology we refer the reader to Somero
245 (2010) (physiological factors), Blois *et al.* (2013) (biotic interactions), Maguire *et al.*
246 (2015) (historical ecology), and Garcia *et al.* (2014) (climate trends/extreme events).
247 Anticipatory ecology, by contrast, intends to forecast future states by inferring possible

248 trajectories or behaviours of the system, based on parameters likely to be impacted by
249 anthropogenic factors, such as predicting the effects of climate change on species,
250 communities and ecosystems. For detailed reviews of anticipatory ecology we
251 recommend Urban *et al.* (2016) and Cabral, Valente & Hartig (2016).

252 In this section, we do not duplicate former reviews of the explanatory and anticipatory
253 ecology of species redistribution. Our review focuses, instead, on gaps in explanatory and
254 anticipatory ecology (Table 1) that need to be filled in order to predict the impacts of
255 species redistribution on biodiversity and human well-being. To achieve this aim, we
256 examine multiple elements of explanatory ecology, including the physiological and
257 ecological factors underpinning species redistribution, biotic interactions and historical
258 ecology, as well as climate trends and extreme events. We conclude this section with a
259 discussion of the challenges of anticipatory ecology.

260

261 **(1) Physiological and ecological factors underpinning species redistribution**

262 Climate change is causing pervasive impacts on ectothermic animals because of their
263 reliance on environmental temperature to regulate body temperature (Deutsch *et al.*,
264 2008; Kearney & Porter, 2009). Thermal performance curves, which quantify how an
265 ectotherm's body temperature affects its performance or fitness, are used to understand
266 range shifts and to predict future distributions (Sunday, Bates & Dulvy, 2012; Sunday *et*
267 *al.*, 2014). While thermal tolerance and performance patterns have been well studied for
268 ectothermic taxa (Dell, Pawar & Savage, 2011), similar trends in large-scale patterns of
269 climatic niche, e.g. heat tolerance conserved across lineages, are also apparent for
270 endotherms and plants (Araújo *et al.*, 2013). The use of thermal performance curves in

271 predicting species distributions often disregards ecological interactions (e.g. competition,
272 predation, mutualism) that may be critical to population establishment and persistence
273 (but see Urban, Tewksbury & Sheldon, 2012). In addition, the form of each species'
274 performance curve has important effects on species interactions, with asymmetries in the
275 thermal performance curves between interacting species likely having important impacts
276 on the strength and outcome of interactions (Dell *et al.*, 2011; Dell, Pawar & Savage,
277 2014). Physiological plasticity (e.g. thermal acclimation), resource specialisation,
278 competitive interactions and behavioural thermoregulation (Thomas *et al.*, 2001; Burton,
279 Phillips & Travis, 2010; Feary *et al.*, 2014; Sunday *et al.*, 2014; Tunney *et al.*, 2014;
280 Tedeschi *et al.*, 2016) are additional factors that can modify thermal performance curves
281 and/or impact the nature and outcome of species range shifts.

282 Future research would therefore benefit from approaches that connect mechanistic
283 processes across biological levels of organisation, from genes to ecosystems. For
284 example, because selection acts on individual genotypes/phenotypes, an understanding of
285 intraspecific variation in key functional traits will help in forecasting species' breadth of
286 tolerance and capacity for range shifts (Norin, Malte & Clark, 2016). In general, both low
287 and high variability in thermal tolerances can exist within and among populations and
288 may vary with extrinsic factors such as environmental filtering, which causes a
289 convergence in tolerance (i.e. heat hardening; Phillips *et al.*, 2015), or intrinsic factors
290 such as body size or life-history stages, which might result in thermal tolerance
291 dispersion (Ray, 1960; Angilletta, Steury & Sears, 2004; Daufresne, Lengfellner &
292 Sommer, 2009; Scheffers *et al.*, 2013; Cheung *et al.*, 2013).

293 The mechanistic basis behind variability in thermal tolerance remains poorly
294 understood (Clark, Sandblom & Jutfelt, 2013) but may be revealed through new genetic
295 tools (Bentley *et al.*, 2017). Measuring genetic diversity as organisms expand their range
296 and documenting genetic structure during and after colonisation can provide a wealth of
297 information on evolutionary dynamics of range shifts (McInerny *et al.*, 2009; Sexton,
298 Strauss & Rice, 2011; Duputié *et al.*, 2012), but requires new, dedicated research
299 programs and/or careful analysis of historical museum collections. Knowledge of the
300 genetics underpinning thermal tolerance can directly inform species conservation and
301 ecosystem restoration through assisted evolution applications (Van Oppen *et al.*, 2015).

302 The magnitude of range shifts can be population, species, and ecosystem dependent,
303 suggesting determinants or mediators of species redistribution other than climate
304 (Rapacciuolo *et al.*, 2014; Rowe *et al.*, 2015). Species redistribution studies have
305 commonly sought to identify ecological traits that explain species responses (see Fig. 2;
306 McGill *et al.*, 2006; Sunday *et al.*, 2015; Pacifici *et al.*, 2015). However, trait-based
307 studies have had mixed success at identifying predictors of range shifts, with thermal
308 niches and climate trends remaining in general the strongest explanatory variables
309 (Buckley & Kingsolver, 2012; Pinsky *et al.*, 2013; Sommer *et al.*, 2014; Sunday *et al.*,
310 2015). Key traits may include those related to dispersal and establishment (Angert *et al.*,
311 2011; Sunday *et al.*, 2015; Estrada *et al.*, 2016), local persistence, such as intrinsic ability
312 to tolerate changing climate (physiological specialisation; Bertrand *et al.*, 2016),
313 phenotypic plasticity (Valladares *et al.*, 2014), micro-evolutionary processes (genetic
314 adaptation; Duputié *et al.*, 2012), capacity to utilise microhabitat buffering effects
315 (Scheffers *et al.*, 2013), fossorial habits (Pacifici *et al.*, 2017), and tolerance to habitat

316 fragmentation (Hodgson *et al.*, 2012). Determining the contexts and conditions under
317 which different traits mediate species redistribution, and to what degree those traits
318 determine redistribution, is an important avenue of future research.

319

320 **(2) Biotic interactions**

321 In general, biotic interactions remain under-measured in range-shift studies, yet they
322 likely play a key role in mediating many climate-induced range shifts (Davis *et al.*, 1998;
323 HilleRisLambers *et al.*, 2013; Ockendon *et al.*, 2014). Shifts in species interactions will
324 occur as a result of differential responses to climate by individual species that can lead to
325 asynchronous migrations within communities and creation of novel assemblages (Pörtner
326 & Farrell, 2008; Hobbs, Higgs, & Harris, 2009; Gilman *et al.*, 2010; Urban *et al.*, 2012;
327 Kortsch *et al.*, 2015; Barceló *et al.*, 2016). Asynchronous shifts can also cause decoupling
328 of trophic interactions, for example when symbiont–host interactions break down
329 (Hoegh-Guldberg *et al.*, 2007) through mismatches in the phenology between consumers
330 and their resources (Winder & Schindler, 2004; Durant *et al.*, 2005; Post &
331 Forchhammer, 2008; Thackeray *et al.*, 2016) or through differential thermal sensitivity of
332 consumers and their resources (Dell *et al.*, 2014). Conversely, climate change and species
333 distribution shifts can create novel species interactions through range expansions, as
334 species that have evolved in isolation from one another come into contact for the first
335 time (Vergés *et al.*, 2014; Sánchez-Guillén *et al.*, 2015).

336 Some of the most dramatic impacts of community change are likely to arise through
337 the assembly of novel species combinations following asynchronous range shifts
338 associated with climate change (Urban *et al.*, 2012; Alexander, Diez & Levine, 2015).

339 These predictions are supported by palaeoecological studies that show how novel species
340 interactions resulting from past climatic changes drove profound community-level
341 change (Blois *et al.*, 2013). The emergence of novel ecological communities will pose
342 significant conservation and societal challenges, because most management paradigms
343 are insufficient to cope with major reorganisation of ecosystems (Morse *et al.*, 2014;
344 Radeloff *et al.*, 2015). Studies of the response of linked social-ecological systems to
345 historical climatic changes are needed to inform the management of ecosystems under
346 ongoing and future climate change (e.g. Hamilton, Brown & Rasmussen, 2003).

347 Contemporary observations of extreme events suggest that shifts in species
348 interactions are particularly important when redistribution occurs in foundation (i.e.
349 habitat-forming) or keystone species. Shifts in foundation species can initiate cascading
350 effects on other species and act as biotic multipliers of climate change (Zarnetske, Skelly
351 & Urban, 2012). For example, many of the greatest ecosystem impacts of climate change
352 in marine systems have been caused by the loss of habitat-forming species such as corals,
353 kelp forests and seagrasses (Hoegh-Guldberg & Bruno, 2010; Thomson *et al.*, 2015;
354 Wernberg *et al.*, 2016; Vergés *et al.*, 2016).

355 Explanatory ecology is now shifting its focus from single species to the role of biotic
356 interactions in mediating range shifts. A key research priority is to identify the
357 importance of biotic interactions relative to species traits, geographic context and
358 physical rates of change (Sunday *et al.*, 2015). A limiting factor has been the lack of
359 multi-species ‘climate change experiments’ (Wernberg, Smale & Thomsen, 2012) and
360 long time-series data that follow multiple trophic levels (Brown *et al.*, 2016). Thus, there
361 is a need to join multiple data sets in order to understand how biotic interactions shape

362 range shifts. Understanding the role of biotic interactions in species redistribution is
363 important to inform conservation and societal challenges. For instance, models of three
364 interacting invasive pests (potato tuber moths) in the Andes predicted that their
365 redistribution would alter biotic interactions, which would in turn impact the level of crop
366 damage (Crespo-Pérez *et al.*, 2015).

367

368 **(3) Community redistribution and historical ecology**

369 Despite species redistribution science being born of ecology, we are still a long way from
370 understanding how species redistribution will drive changes in ecological communities
371 (Marzloff *et al.*, 2016). Historical ecology suggests that climate change can result in
372 dramatic alterations in community structure. For example, the equatorial dip in diversity
373 evident in modern marine communities (Tittensor *et al.*, 2010) was most pronounced for
374 reef corals during the warmer intervals of the last interglacial period (125 ka), indicating
375 that both leading and trailing edges of species ranges were responding to increases in
376 ocean temperature (Kiessling *et al.*, 2012). Pleistocene reef records suggest that species
377 and communities are relatively robust to climate change and that ecological structure
378 generally has persisted within reef coral communities over multiple climatic cycles
379 (Pandolfi, 1996; Pandolfi & Jackson, 2006). By contrast, many North American tree
380 species have shifted their individual distributions and adapted genetically to Quaternary
381 climatic changes (Davis & Shaw, 2001). Human migrations, settlement patterns, and
382 species use have also been linked to environmental change (Graham, Dayton &
383 Erlandson, 2003). However, the rate of contemporary climate change, genetic constraints
384 on rapid adaptation and dramatic land cover changes over the past century will challenge

385 'natural' species redistribution in the Anthropocene (Hoffmann & Sgro, 2011; Moritz &
386 Agudo, 2013) and complicate human responses to these changes.

387 A key question for historical ecology is to determine the extent to which community
388 change is driven by multiple species-specific responses to climate, *versus* shifts in key
389 species driving cascading community change. Historical ecology can fill an important
390 gap in our understanding, given that it focuses on systems that were, in most cases, far
391 less influenced by humans than occur presently. Furthermore, studies in deep time allow
392 us a glimpse into the outcome of processes similar to those that we are watching in their
393 infancy today.

394

395 **(4) Climate trends, scale mismatch and extreme events**

396 Climate trends are a key predictor of range shifts due to the importance of climatic
397 tolerances (or thermal performance curves) in controlling species ranges. Observational
398 evidence of the direction of range shifts in terrestrial and aquatic environments are
399 overwhelmingly consistent with expectations required for species to track temperature
400 changes (Sorte *et al.*, 2010; Chen *et al.*, 2011; Comte *et al.*, 2013; Poloczanska *et al.*,
401 2013). Longitudinal range shifts, as well as shifts towards the tropics or lower elevations
402 (which run counter to intuitive expectations), can be attributed to the complex mosaic of
403 regional climate changes expected under global change that involve not only temperature
404 but also other factors such as precipitation and land-use changes (Lenoir *et al.*, 2010;
405 Crimmins *et al.*, 2011; McCain & Colwell, 2011; Tingley *et al.*, 2012; VanDerWal *et al.*,
406 2013; Pinsky *et al.*, 2013).

407 Multi-directional distribution shifts stem partly from the spatial arrangement of
408 mountain ranges on land and continental shelves in the ocean, which are important
409 physiographic features constraining (as barriers) or enhancing (as corridors) species
410 redistribution (VanDerWal *et al.*, 2013; Burrows *et al.*, 2014). For example, the ranges of
411 some forest plants are shifting equatorward and upward as the climate warms in France,
412 likely due to the fact that the main mountain ranges in France are located in the south
413 (Alps, Massif Central and Pyrenees; Kuhn *et al.*, 2016). Such geographic features may
414 thus represent potential climatic traps or ‘cul-de-sacs’ for living organisms facing climate
415 change. The northern Mediterranean Sea, for example, will likely act as a cul-de-sac for
416 endemic fishes under future climate change (Lasram *et al.*, 2010).

417 A challenge in using climate variables to explain species redistribution is that species
418 may respond to different climate variables than those available from historical
419 measurements, due to a spatial mismatch between the size of the studied organisms and
420 the scale at which climate data are collected and modelled (Potter, Woods &
421 Pincebourde, 2013). For instance, relationships between climate velocity and marine
422 species redistribution are weak or non-existent using global sea-surface temperature data
423 sets to calculate climate velocity (Brown *et al.*, 2016), but can be strong using locally
424 measured temperatures that coincide with organism sampling (Pinsky *et al.*, 2013).
425 Therefore, we consider it a research priority to find ways to reconstruct high spatial- and
426 temporal-resolution temperature histories that are relevant to the organisms under study
427 (Franklin *et al.*, 2013; Kearney, Isaac & Porter, 2014; Levy *et al.*, 2016). This objective
428 requires better communication and more collaboration among climatologists, remote
429 sensing specialists and global change biologists to produce climatic grids at spatial and

430 temporal resolutions that match organism size and thus are more meaningful for
431 forecasting species redistribution under anthropogenic climate change.

432 The study of extreme events has been instrumental to species redistribution research,
433 because punctuating events provide distinct natural experiments for the study of
434 biological responses to climate change. The frequency and amplitude of extreme events is
435 increasing with climate change (IPCC, 2013), placing increasing emphasis on studying
436 extreme events in the context of longer-term change. Impacts of climate change on
437 biological communities are often mediated by extreme events (Fraser *et al.*, 2014;
438 Thomson *et al.*, 2015; Wernberg *et al.*, 2016). For example, ocean temperatures along the
439 western Australian coast increased for over 40 years, with kelp forests exhibiting little
440 noticeable ecological change, but a marine heat wave drove a 100 km kelp forest range
441 contraction in only two years (Wernberg *et al.*, 2016). The infrequent nature of extreme
442 events means that long time series are required to document the cumulative impacts on
443 ecosystems. For example, in Australia, severe wildfires in quick succession brought about
444 an ecosystem regime shift in mountain ash forests (Bowman *et al.*, 2014). A research
445 priority is therefore to extend studies that document changes arising from a short-term
446 extreme event into longer time series that may allow us to understand the cumulative
447 effects of changes in frequency of extreme events.

448

449 **(5) Anticipating future redistributions**

450 The urgency of responding to anthropogenic climate change has stimulated a shift
451 towards anticipatory ecology that aims to predict future ecological change. The shift to
452 anticipatory ecology is indicated by our literature analysis, which found an increased

453 frequency of terms related to prediction [Fig. 2; terms ‘sdm’ (species distribution model)
454 and ‘maxent’ (a popular tool for such modeling); Phillips & Dudík (2008)]. Approaches
455 to predicting the consequences of climate change for biodiversity are varied and include
456 correlative species distribution models (SDMs; Guisan & Zimmermann, 2000) as well as
457 mechanistic and hybrid SDMs that account for physiological constraints, demographic
458 processes or environmental forecasts (Kearney & Porter, 2009; Hartog *et al.*, 2011;
459 Webber *et al.*, 2011; Dullinger *et al.*, 2012; Cheung *et al.*, 2015; Table 1). The emergence
460 of the study of species redistributions during the era of rapidly increasing computing
461 power and growing availability of climate data has also contributed to the dominance of
462 spatial modelling techniques. The emphasis on forecasting has been paralleled by a
463 development of predictive techniques, including machine-learning algorithms such as
464 maxent (Phillips & Dudík, 2008).

465 Anticipatory models have recently been progressing on two fronts. First, mechanistic
466 and process-based models, often including physiology, biotic interactions, and/or extreme
467 events, are increasingly being used and developed for biogeographic prediction (Kearney
468 & Porter 2009; Cabral *et al.*, 2016). Bioenergetics models, for example, can overcome
469 traditional species distribution model limitations when making predictions under novel
470 climates, modelling extreme events and understanding the importance of timing of
471 weather events (e.g. Briscoe *et al.*, 2016). Mechanistic models tend to be data intensive
472 and have so far been little used in conservation planning despite significant potential
473 (Evans, Diamond & Kelly, 2015; Mitchell *et al.*, 2016). However, prospects for process-
474 based models integrating conservation and society are positive, as models become more
475 flexible, accurate, and accessible (Kearney & Porter, 2009).

476 The second trend with predictive models has been an increasing focus on physical
477 drivers at appropriate spatial and temporal scales (Potter *et al.*, 2013). In this regard, a
478 key perspective in species redistribution is the velocity of climate change – which
479 measures the geographic movement of temperature isotherms (Loarie *et al.*, 2009;
480 Burrows *et al.*, 2011) to project changes in species ranges and community composition
481 (Hamann *et al.*, 2015). Climate velocity trajectories (Burrows *et al.*, 2014) based on sea
482 surface temperatures, for example, were recently combined with information on thermal
483 tolerances and habitat preferences of more than 12,000 marine species to project that
484 range expansions will outnumber range contractions up to the year 2100. Broadened
485 ranges, in turn, are projected to yield a net local increase in global species richness, with
486 widespread invasions resulting in both homogenised and novel communities (Molinos *et*
487 *al.*, 2015). However, velocity measures have limitations and can underestimate climate
488 change exposure for some communities (Dobrowski & Parks, 2016). For marine systems,
489 changes in the speed and direction of currents can potentially influence dispersal and
490 therefore population connectivity, and may also need to be considered for a more
491 complete understanding of the relationship between climate drivers and rates and
492 magnitudes of range shifts (Sorte, 2013; Cetina-Heredia *et al.*, 2015). High-resolution
493 particle-transport Lagrangian models may be useful in this context (van Gennip *et al.*,
494 2017). Ultimately, examining multiple climate change metrics and linking them to the
495 threats and opportunities they represent for species could overcome the limitations of
496 individual metrics and provide more-robust impact estimates (Garcia *et al.*, 2014).
497

498 **IV. CONSERVATION ACTIONS**

499 Faced with climate change as a novel and substantial threat, a new species-management
500 paradigm has emerged (Stein *et al.*, 2013): to be effective, conservation strategies must
501 account for both present and future needs and must be robust to future climate change.
502 Such strategies will require integration of species redistribution science with
503 consideration of the social and economic consequences (Table 1). Managers have several
504 options for conserving species and ecosystems faced with range shifts: adapt
505 conservation management in current landscapes and seascapes; facilitate natural species
506 movement; manage resources to support species redistribution; and/or move species as a
507 conservation intervention, i.e. managed relocation. Important reviews on conservation
508 under climate change, such as Heller & Zavaleta (2009) and Mawdsley, O'Malley &
509 Ojima, (2009), provide context for adaptation strategies under warming. In this section
510 we specifically aim to synthesise recent advances in species redistribution science and
511 conservation actions that attempt to accommodate species redistributions, requiring the
512 involvement of multiple stakeholders for effective implementation.

513

514 **(1) Adapting management in current conservation landscapes and seascapes**

515 Mitigating the impacts of climate change on species and ecosystems *in situ* is
516 challenging, because it requires management decisions that are robust to future change
517 and the development of adaptive solutions for specific populations (e.g. providing shelter
518 or supplemental food; Correia *et al.*, 2015). Systematic conservation planning efforts are
519 increasingly incorporating the principles of climate change adaption into the protected-
520 area design process (Carvalho *et al.*, 2011; Groves *et al.*, 2012), ensuring that existing

521 protected areas are resilient to climate change by maintaining and increasing the area of
522 high-quality habitats, prioritising areas that have high environmental heterogeneity, and
523 controlling other anthropogenic threats (Hodgson *et al.*, 2009). Habitat engineering may
524 also be required to provide effective recovery and maintenance of populations, for
525 example, through the installation of microclimate and microhabitat refuges or
526 enhancement and restoration of breeding sites (Shoo *et al.*, 2011). Identification of
527 microrefugia, small areas robust to warming impacts over long time periods, will also be
528 key for long-term planning (Lenoir, Hattab & Pierre, 2017). In many countries, the legal
529 and governance framework underpinning protected-area management may not yet allow
530 for these types of active management interventions (McDonald *et al.*, 2016a), so legal
531 reform may be needed.

532

533 **(2) Facilitating natural species movement**

534 As the most suitable habitat conditions for species are shifting geographically under
535 climate change and species redistribute themselves, forward planning is increasingly
536 essential, both temporally and spatially (Mawdsley *et al.*, 2009). Although most
537 palaeoecological studies (e.g. Williams & Jackson, 2007) indicate that range shifts alone
538 do not drive widespread extinction events [but see Nogués-Bravo *et al.* (2010) who did
539 find evidence for extinctions], range-restricted species potentially face high climate-
540 driven extinction risks (Finnegan *et al.*, 2015; Urban, 2015).

541 Reserve networks must consider current biodiversity, probable patterns of future
542 biodiversity, corridors suitable for projected range shifts, and cost (Scriven *et al.*, 2015;
543 Lawler *et al.*, 2015), anticipating the need for protected-area establishment in newly

544 suitable areas (Carvalho *et al.*, 2011). Climate-velocity methods (Burrows *et al.*, 2014) or
545 the analysis of fine-scaled climatic grids (Ashcroft *et al.*, 2012) can be used to identify
546 climate refugia – places where microclimates are decoupled from macroclimatic
547 fluctuations and are thus more stable and less likely to change quickly – as potentially
548 good candidates for future protected areas. Information on future habitat suitability for
549 threatened species (e.g. obtained using SDMs) can be coupled with information on
550 climate refugia to target areas likely to maximise conservation benefits (see Hannah *et*
551 *al.*, 2014; Slavich *et al.*, 2014). To assess landscape or seascape connectivity with greater
552 realism, patterns of habitat fragmentation (McGuire *et al.*, 2016) and flow must be
553 considered, i.e. wind and oceanic currents (van Gennip *et al.*, 2017; Péron *et al.*, 2010;
554 Sorte, 2013).

555 In some cases, facilitating species redistribution can be achieved through the
556 expansion or realignment of existing protected area boundaries. Where public
557 conservation funding is limited, it may be necessary in some circumstances to release
558 protection of some areas in order to secure others of higher priority (Alagador, Cerdiera
559 & Araújo, 2014). In addition to maintaining connectivity through reserve network design,
560 market-based instruments and public–private partnerships can be harnessed to
561 accommodate species redistribution. Conservation easements, for example, while popular
562 and potentially effective in environmental protection of private land, rarely consider
563 climate change impacts or species redistribution (Rissman *et al.*, 2015). New mechanisms
564 for private land stewardship and management, including Indigenous Protected Area (IPA)
565 agreements, will also be needed.

566 Conservation interventions designed to meet contemporary environmental challenges
567 can conflict with climate change planning objectives. For example, fences in Africa
568 around wildlife reserves have been good for minimising human–wildlife conflict but poor
569 for maintaining landscape connectivity (Durant *et al.*, 2015). Similarly, shifts in
570 agriculturally suitable areas in the Albertine region of Africa, as a result of changing
571 climate, may cause a displacement of agriculture into protected areas, significantly
572 complicating climate-driven species redistribution impacts on conservation plans for the
573 region (Watson & Segan, 2013).

574

575 **(3) Resource-management systems for species redistribution**

576 Some existing resource-management systems can be extended for adaptive management
577 of species on the move. For example, a real-time management system is used in eastern
578 Australia to predict the distribution of a tuna species over the cycle of a fishing season
579 (Hobday & Hartmann, 2006; Hobday *et al.*, 2011). The changing distribution of the fish
580 requires dynamic responses to zones that restrict fishing activity. While this example of
581 species redistribution is on a seasonal timescale, the management system can also
582 respond to long-term species redistribution, based on regular updates of the management
583 zones. Such real-time management responses to changing species distributions are
584 relatively advanced in marine systems and are being formalised in the field of dynamic
585 ocean management (Hobday *et al.*, 2014; Lewison *et al.*, 2015; Maxwell *et al.*, 2015).

586 Conservation strategies for mobile and range-shifting species can also utilise
587 innovative market-based instruments and develop new partnerships involving private
588 landholders. A promising example is The Nature Conservancy’s California pop-up

589 wetland initiative, which involves seasonal land ‘rentals’, in which farmers agree to flood
590 their fields to facilitate water bird migration (McColl *et al.*, 2016). Predictive habitat
591 modelling of bird migration is used to earmark different land parcels, and landholders
592 submit bids to participate in each year’s habitat creation program. As in this example,
593 local and regional conservation planning for multiple uses requires good-quality data,
594 plus resources for monitoring and implementation. Researchers also need to understand
595 what information land-owners, planners and policy makers actually need to aid decision-
596 making, which requires considerable engagement and knowledge exchange (Cvitanovic
597 *et al.*, 2015).

598 As part of this engagement, structured decision-making processes can inject both
599 values and scientific data into the development of management strategies for ecosystem-
600 based marine management, as proposed for development of high seas protected areas
601 (Maxwell, Ban & Morgan, 2014). Options for managers and policy makers can be
602 evaluated with quantitative modelling tools, such as models of intermediate complexity
603 (Plagányi *et al.*, 2014), while management strategy evaluation (Bunnefeld, Hoshino &
604 Milner-Gulland, 2016) can be used to test climate-smart management strategies that
605 include socio-ecological criteria. In addition to novel dynamic management approaches,
606 existing tools in development and conservation law, such as biodiversity offsets, will
607 need to be modified to promote adaptive conservation planning for species redistribution
608 (McDonald, McCormack & Foerster, 2016*b*) and to allow management responses on
609 appropriate timescales (Hobday *et al.*, 2014).

610

611 **(4) Managed relocation**

612 Given numerous decision frameworks for managed relocation, the science required to
613 inform any decision to relocate a species is defined by knowledge gaps in local species
614 ecology and management (e.g. Richardson *et al.*, 2009; McDonald-Madden *et al.*, 2011;
615 Rout *et al.*, 2013 and see Article 9 in Glowka *et al.*, 1994). Trial introductions of the
616 critically endangered western swamp turtle (*Pseudemydura umbrina*) to the south-
617 western corner of Australia (300 km south of its native range), in 2016, serve as a useful
618 example. For the turtle, persistence in the wild is constrained by severe habitat loss and
619 fragmentation and by a rapid reduction in winter rainfall. Correlative SDMs based on
620 coarse-grained climatic data have created a challenge for translocation planning, as the
621 turtle historically occupies just two wetlands 5 km apart (Mitchell *et al.*, 2013). The
622 solution has been to build mechanistic SDMs that are based on detailed knowledge of the
623 turtle's physiological limits, behaviour, and the ecohydrology of their ephemeral wetland
624 habitats (Mitchell *et al.*, 2013, 2016). Forcing these process-based SDMs with future
625 drier and warmer climates has illustrated where suitable habitat might exist into the
626 future, and when complemented with spatially explicit multiple criteria analysis (Dade,
627 Pauli & Mitchell, 2014) has identified candidate wetlands for future attempts to establish
628 outside-of-range populations.

629 The primary challenge for practicing managed relocation is identifying ways to
630 overcome any social barriers to relocation. Relocating species for conservation can
631 challenge deeply held values and beliefs about human intervention in nature, and what
632 constitutes appropriate and desirable environmental stewardship. Particular challenges
633 may arise for Indigenous peoples, for whom connection to landscapes and historically,

634 culturally and spiritually significant species is of great importance. Formal mechanisms
635 for engaging with local communities and stakeholders, including consideration of the
636 cultural effects and drivers of proactive conservation management under climate change,
637 will be critical. Issues include cultural nuances, such as the terminology used in
638 management proposals and policy. For example the term ‘assisted colonisation’, adopted
639 in the guidelines of the International Union for Conservation of Nature (IUCN) for
640 species introductions outside of the known range to prevent extinction, has historical and
641 colonial connotations with the word ‘colonisation’ that may create barriers to
642 participation. In this case, an alternative, culturally considerate phrase to encourage
643 broader inclusion might be ‘managed relocation’ (see Schwartz *et al.*, 2012).

644 The IUCN guidelines for conservation translocations (IUCN/SSC, 2013) provide a
645 complete framework to assess the need for managed relocation, including the risks
646 associated with translocations for the species of interest and for the ecosystem that
647 receives the new species. Potential damage to the ecosystem from managed relocation is
648 the worst-case scenario, and this issue forces decision-makers to ask themselves what
649 they value most. Is the survival of a particular species that is threatened by human actions
650 sometimes worth the risk of profound change to the recipient ecosystem? If we aim for a
651 species to thrive, when does it become invasive? These are questions that will need to be
652 answered as managed relocation for conservation becomes more frequent. Legislative
653 reform is also required to change the regional and domestic laws and policies that guide
654 practical implementation of managed relocations. Many jurisdictions around the world
655 have no explicit legal mechanisms for relocating species across jurisdictional borders, a
656 regulatory gap that is likely to become more problematic under rapid climate change

657 (Schwartz *et al.*, 2012). Law and policy should incorporate collaborative mechanisms for
658 cross-tenure, local, regional and international species relocations, and should facilitate
659 species relocation to support broader ecological processes, not just to preserve
660 charismatic threatened species.

661

662 **V. SOCIAL AND ECONOMIC IMPACTS OF SPECIES REDISTRIBUTION**

663 Changing distributions of economically and socially important species under climate
664 change are affecting a wide range of peoples and communities. Understanding the
665 ecology of species on the move and the development of conservation tools for species
666 redistribution responses will, together, contribute to an integrated approach to managing
667 social impacts (Table 1). Consequences will likely include exacerbated food security
668 issues; challenges for Indigenous and local livelihoods, governance and cultures; and
669 human health problems. Facing these challenges will require an interdisciplinary,
670 participatory approach (O'Brien, Marzano & White, 2013) that will include not only
671 scientists and professionals from different fields but also managers, governments and
672 communities.

673

674 **(1) Food security**

675 Since the spike in food prices in 2008, much thought has gone into how to feed nine
676 billion people by 2050 (World Bank, 2008; Evans, 2009; Royal Society of London,
677 2009). A key to producing 70–100% more food by 2050 will be filling the yield gap for
678 agriculture (Godfray *et al.*, 2010), i.e. the difference between potential and actual yields.
679 For fisheries and aquaculture, the challenge is to provide an additional 75 Mt of fish by

680 2050 to supply 20% of the dietary protein needed by the human population (Rice &
681 Garcia, 2011). Given that yields from capture fisheries have already plateaued, most of
682 the additional fish will need to come from aquaculture (FAO, 2014).

683 The challenges of enhancing agricultural and fisheries productivity to meet global
684 food demand (Godfray *et al.*, 2010; FAO, 2014) are exacerbated by species
685 redistribution. Increased agricultural productivity will depend in part on keeping weeds,
686 diseases and pests in check where they increase in abundance and disperse to new areas.
687 As fish species migrate in search of optimal thermal conditions, the locations of
688 productive fisheries will change (Cheung *et al.*, 2010), resulting in gains for some
689 communities and losses for others (Bell *et al.*, 2013). Changes in the distributions and
690 relative abundances of harmful marine algae, pathogens and pests, will also create new
691 hurdles for fisheries and aquaculture (Bell *et al.*, 2016).

692 A key short-term priority for food-security research is the development of new global
693 models of fishery production that account for climate change. Several models are now
694 being used to inform large-scale policy on global change in marine fishery production
695 (e.g. Cheung *et al.*, 2010, Barange *et al.*, 2014). However, a single approach (Cheung *et*
696 *al.*, 2010) has been dominant in representing species redistributions. While this model has
697 been repeatedly updated (Cheung *et al.*, 2016, Cheung & Reygondeau 2016),
698 considerable structural uncertainty remains in our ability to predict change in fishery
699 production, as production depends critically on uncertain future fishery-management
700 arrangements (Brander, 2015). The extent to which structural uncertainty afflicts global
701 production estimates needs to be evaluated with alternative modelling approaches. These
702 issues are beginning to be addressed by model ensemble initiatives such as through the

703 Inter-sectoral Model Intercomparison Project (<https://www.isimip.org/>) and through the
704 inclusion of more detailed bio-economic processes (Galbraith *et al.*, 2017).

705

706 **(2) Indigenous livelihoods, governance and cultures**

707 The distributions and relative abundances of species within their historic ranges have
708 been central to the knowledge of Indigenous peoples, including not only sedentary
709 communities, but also mobile communities such as nomads, pastoralists, shifting
710 agriculturalists and hunter-gatherers (Kawagley, 2006; Sheridan & Longboat, 2006;
711 Arctic Council, 2013; Mustonen & Lehtinen, 2013). Maintaining relatively intact
712 ecosystems is crucial to the preservation of livelihoods, cosmologies, cultures and
713 languages of these groups, and many have developed governance systems for their
714 biological resources based on holistic observations and checks-and-balances to prevent
715 overharvesting (Huntington, 2011; Mustonen, 2015; Mustonen & Mustonen, 2016).
716 Alterations in species ranges and relative abundances due to climate change will have
717 profound consequences for these governance systems.

718 Leaders of these societies also recognise that changes in relative abundances of
719 species are caused by other drivers, such as extraction of natural resources and
720 development of infrastructure (Arctic Council, 2013), and have called for a paradigm
721 shift in governance to address the profound changes underway (Kawagley, 2006;
722 Huntington, 2011). This paradigm shift requires partnership approaches with non-
723 Indigenous institutions to respond to the scale and significance of impacts on livelihoods
724 (Huntington, 2011). Culturally safe and respectful language spoken by scientists, and
725 teaching of science for Indigenous, traditional and mobile peoples are an essential part of

726 this approach. Otherwise, opportunities to effectively integrate the often deep and diverse
727 knowledge of these people into strategies to cope with change will be lost (Lee *et al.*,
728 2016).

729

730 **(3) Human health**

731 The risk of increases in infectious diseases due to species redistributions, potentially
732 exacerbated by food insecurity crises, is also a significant concern (Altizer *et al.*, 2013)
733 and a key research challenge. History is full of examples of climate-driven species
734 movements and human distribution shifts, resulting in infectious disease outbreaks
735 (McMichael, 2012). For example, bubonic plague outbreaks caused by the bacterium
736 *Yersinia pestis* during the Black Death – the great pandemic originating in Asia and
737 spreading throughout Europe between 1347 and 1353 – have been shown to occur
738 roughly 15 years after a warmer and wetter period (Schmid *et al.*, 2015). Even the
739 contemporary dynamics of bubonic plague, which still occurs in Central Asia, have been
740 clearly linked to climate change (Stenseth *et al.*, 2006).

741 In the Arctic, many interconnected factors such as climate, wildlife populations, and
742 health have triggered infectious disease outbreaks. Although the health of Indigenous
743 peoples of the circumpolar region has improved over the last 50 years, certain zoonotic
744 and parasitic infections remain higher in Arctic Indigenous populations compared to
745 respective national population rates (Parkinson & Evengård, 2009). Evidence for
746 associations between climate and infectious disease in the Arctic is clear, but the
747 relationship between climate change and vector-borne disease rates is poorly explored,
748 owing to the small number of studies on the subject (Hedlund, Blomstedt & Schumann,

749 2014). However, the case of increasing incidence of tick-borne encephalitis in Sweden
750 since the 1980s is instructive: mild winters have increased tick population densities in the
751 country, leading to increased disease incidence (Lindgren & Gustafson, 2001). A key
752 component of prevention and control of climate-mediated infectious diseases is
753 surveillance.

754

755 **(4) Need for monitoring**

756 More modelling is needed to understand the cascading effects of climatic changes on the
757 species that we rely on for food and livelihoods and those whose spread can adversely
758 affect human health. Such modelling will help identify practical adaptations and the
759 policies needed to support them.

760 Collection of the information needed to validate these models can be enhanced by
761 community-based monitoring and citizen science, engaging the agriculture, fishing and
762 aquaculture industries and Indigenous and local communities (Mayer, 2010; Johnson *et*
763 *al.*, 2015; Robinson *et al.*, 2015). These groups are well placed to monitor changes in the
764 relative abundance and distribution of species that they rely on or regularly interact with.
765 For many Indigenous and local communities, monitoring is central to the preservation of
766 their sea- and land-use patterns and sustainable development (Sheridan & Longboat,
767 2006; Mustonen, 2015). Moreover, rapidly developing tools and networks in citizen
768 science may enhance large-scale monitoring (Chandler *et al.*, 2016). For example, citizen
769 science has already contributed approximately half of what we know about migratory
770 birds and climate change (Cooper, Shirk & Zuckerberg, 2014). Broad stakeholder
771 engagement has the added benefit of increasing awareness of the effects of climate

772 change on human well-being, while empowering communities to effect changes in
773 environmental behaviour and policies.

774 Involving local stakeholders in monitoring also enhances management responses at the
775 local spatial scale, and increases the speed of decision-making to tackle environmental
776 challenges at operational levels of resource management (Danielsen *et al.*, 2010). The
777 promptness of decision-making in community-based monitoring and the focus of the
778 decisions at the operational level of species and resource management make community-
779 based monitoring approaches particularly suitable when species are rapidly shifting
780 ranges. Community-based monitoring is also likely to provide information about crucial
781 new interactions between species (Alexander *et al.*, 2011; Huntington, 2011). One
782 potential challenge to community-based monitoring is that, in situations in which
783 constraints or demands on resources may condition quotas or financial payments to
784 communities, the local stakeholders might have an incentive to report false positive
785 trends in those natural resources so they can continue to harvest the resources or continue
786 to be paid, even though the resources may actually be declining (Danielsen *et al.*, 2014).
787 Systems ensuring triangulation and periodic review of the community-based monitoring
788 results will therefore be required, whether the monitoring is implemented by
789 communities, governments or the private sector.

790 Increased monitoring may also increase understanding of the spatial and temporal
791 impacts on human societies posed by changes in the distribution and abundance of
792 species. The effects of climate change on species needs to be mainstreamed into routine
793 food-production assessments so that society is prepared and can adapt to predicted
794 changes. Technological improvements have increased the potential for citizen scientists

795 to engage in the necessary monitoring (Brammer *et al.*, 2016) and for industries to
796 capture essential data as part of routine field operations (Ewing & Frusher, 2015). On a
797 broader scale, co-ordination of monitoring to obtain data that can be compared across
798 diverse regions is needed. Identification of hotspots, where range changes and impacts
799 are expected to be seen earlier (Hobday & Pecl, 2014; Pecl *et al.*, 2014), can aid in the
800 early development of broad-based practical adaptive strategies. Moreover, technological
801 advances are making it possible to not just monitor the location of organisms, but
802 understand the physiological and behavioural processes underlying their movement
803 patterns (Block *et al.*, 2001; Clark *et al.*, 2008, 2010). An integrated understanding of the
804 drivers of species movement will greatly strengthen our capacity to plan for species
805 redistributions in the future.

806

807 **VI. INTERDISCIPLINARY APPROACHES TO ADDRESS SPECIES**

808 **REDISTRIBUTION CHALLENGES**

809 Species redistribution is a complex phenomenon dependent upon multiple and interacting
810 multiscale climatic variation, as well as social and ecological/evolutionary processes (Fig.
811 3). The formation of novel species assemblages as a consequence of this redistribution
812 brings significant new challenges for governments, resource users and communities,
813 particularly when dependence on natural resources is high or where present or future
814 species ranges cross jurisdictional boundaries (Pecl *et al.*, 2011). Identifying the
815 mechanisms and processes driving species redistributions is critically important for
816 improving our capacity to predict future biological change, managing proactively for

817 changes in resource-based human livelihoods and addressing conservation objectives
818 (Pinsky & Fogarty, 2012).

819 In recent years, the scientific study of climate-driven species redistribution has
820 matured significantly (Fig. 1). Although research continues to focus on modelling and
821 prediction of distribution shifts, researchers have increasingly incorporated management
822 and socio-economic considerations explicitly (Fig. 2). As this review has highlighted,
823 biological studies and management and social science research on species redistribution
824 have provided a wealth of insights into global change, and have supported several
825 innovative management responses (i.e. managed relocation, real-time management
826 systems). Nevertheless, many challenges and key questions require answers (Table 1).
827 Further integrated development will require working across disciplines to find innovative
828 solutions (Bjurström & Polk, 2011).

829 Long-term interdisciplinary research programs that integrate the natural and social
830 sciences are needed to study, understand and model the impact of climate-driven species
831 redistribution on ecosystem functioning. More specifically, interdisciplinary research is
832 needed on changes to multiple ecosystem services (e.g. food) and disservices (e.g.
833 diseases) delivered to society, as climate changes, particularly as interdisciplinary
834 approaches are not well represented in climate research (Bjurström & Polk, 2011).
835 Simultaneous socio-ecological time series often reveal that people respond to ecosystem
836 change in surprising ways. For example, a climate regime shift around 1960–1990 drove
837 declines of a cod fishery, but opened up opportunities for a new shrimp fishery off
838 Greenland (Hamilton *et al.*, 2003). However, only communities with sufficient capital to
839 invest in new fishing gear, and entrepreneurial individuals who were willing to invest in a

840 new fishery were able to adapt to the ecosystem change. Thus, societal responses to
841 species redistributions can be highly dependent on a few individuals, and human
842 responses and natural changes must be considered in combination (Pinsky & Fogarty,
843 2012).

844 Many challenges must be overcome to execute a successful long-term interdisciplinary
845 research program. Even within fields such as ecology, disciplinary barriers threaten to
846 limit advances in species redistribution research. For example, communication and
847 collaboration between marine and terrestrial researchers (Webb, 2012) has the potential
848 to spark key developments. Unfortunately, research proposals with the highest degree of
849 interdisciplinarity currently have the lowest probability of being funded (Bromham,
850 Dinnage & Hua, 2016). Although long-term monitoring programs provide the essential
851 foundation for tracking and understanding the causes and consequences of species
852 redistributions, they also encounter funding difficulties due to the long time span of
853 funding required and a bias in grant agencies away from studies perceived as simply
854 observational research and towards hypothesis-driven research (Lovett *et al.*, 2007).
855 Institutional change in funding agencies and an emphasis on prioritising interdisciplinary
856 and long-term projects could lead to important, high-impact climate change research
857 (Green *et al.*, 2017). In the meantime, global change scientists also need to explore
858 multiple options to support long-term and interdisciplinary studies, such as harnessing
859 citizen science and engaging in large-scale collaborative efforts.

860 In fact, citizen science may help to fill the knowledge gap in long-term and spatially
861 extensive studies (Breed, Stichter & Crone, 2013). Citizen science approaches typically
862 involve recruiting observers to be part of a formal program, a method for recording

863 meaningful data, and a means of making those data accessible and discoverable for later
864 use. In addition, successful programs often include data-vetting and data-management
865 practices to ensure the integrity and long-term availability of data, providing data
866 products to contributors and other interested parties, and interpreting the results of these
867 efforts to tell a story of environmental functioning or change to larger audiences. Further
868 work is needed, however, to find suitable ways to connect citizen science and
869 community-based monitoring programs with international biodiversity data repositories
870 (Chandler *et al.*, 2016).

871 Growing recognition of the important role of Indigenous, traditional and mobile
872 peoples in protected area management is one positive change in recent years. The
873 creation of a fourth type of governance (in addition to government, shared and private
874 governance) in the IUCN's Protected Area Guidelines specifically addresses IPAs and
875 Indigenous peoples' and Community-Conserved territories and Areas (ICCAs). In this
876 case, the nature–culture binary is being dismantled to incorporate a range of worldviews
877 that promote sustainable development, governance vitality and management devolution
878 (delegation of power) (Borrini-Feyerabend *et al.*, 2013; Lee, 2016). Acknowledging the
879 legitimacy of traditional knowledge systems can be instrumental in understanding species
880 redistribution and provides a mechanism by which local communities can monitor and
881 manage impacts (Eicken *et al.*, 2014; Tengö *et al.*, 2017).

882 Examples of on-ground management responses to shifting species are few, to date, and
883 those that have been reported are based on seasonal or short-term responses to changes in
884 species distribution (Hobday *et al.*, 2011, 2014; McColl *et al.*, 2016). These few
885 examples do illustrate how long-term change might be accommodated, but such

886 approaches may not support management responses for the transformational level of
887 change that may be needed in some regions. In these cases, development of long-term
888 adaptive pathways (sensu Wise *et al.*, 2014) for species on the move is required. These
889 pathways can include decision points at which switching of strategies is required, for
890 example defining at what point a habitat-creation strategy should be changed to a
891 translocation strategy.

892

893 **VII. CONCLUSIONS**

894 (1) Until recently, species redistribution was seen as something that would happen in the
895 future rather than an immediate issue. However, it is happening now, with serious
896 ecological and societal implications and impacts already being observed.

897 (2) The cross-cutting nature of species redistribution calls for the integration of multiple
898 scientific disciplines, from climate science to ecology, palaeoecology, physiology,
899 macroecology, and more. We further suggest that research on contemporary species
900 redistribution needs to span process-based studies, observational networks by both
901 scientists and community members, historical data synthesis and modelling over a variety
902 of scales.

903 (3) Species redistribution defies conservation paradigms that focus on restoring systems
904 to a baseline and challenges environmental management strategies, which are often static
905 and based on human-dictated boundaries drawn in the past. Climate-driven species
906 redistribution therefore presents both fundamental philosophical questions and urgent
907 issues relevant to conservation and society.

908 (4) For species redistribution research to support development of relevant adaptive
909 strategies and policy decisions adequately, studies need to take an interdisciplinary
910 approach and must recognise and value stakeholders. Involving stakeholders in
911 monitoring and collection of data offers an opportunity to help guide effective adaptation
912 actions across sectors.

913

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933

934 **IX. REFERENCES**

935 ALAGADOR, D., CERDEIRA, J.O. & ARAÚJO, M.B. (2014). Shifting protected areas:
936 scheduling spatial priorities under climate change. *Journal of Applied Ecology* **51**,
937 703–713.

938 ALBOUY, C., LEPRIEUR, F., LE LOC'H, F., MOUQUET, N., MEYNARD, C.N., DOUZERY,
939 E.J.P. & MOUILLOT, D. (2015). Projected impacts of climate warming on the
940 functional and phylogenetic components of coastal Mediterranean fish biodiversity.
941 *Ecography* **38**, 681–689.

942 ALEXANDER, C., BYNUM, N., JOHNSON, E., KING, U., MUSTONEN, T., NEOFOTIS, P.,
943 OETTLÉ, N., ROSENZWEIG, C., SAKAKIBARA, C., SHADRIN, V., VICARELLI, M.,
944 WATERHOUSE, J. & WEEKS, B. (2011). Linking indigenous and scientific knowledge
945 of climate change. *BioScience* **61**, 477–484.

946 ALEXANDER, J.M., DIEZ, J.M. & LEVINE, J.M. (2015). Novel competitors shape species'
947 responses to climate change. *Nature* **525**, 515–518.

948 ALOFS, K.M., JACKSON, D.A. & LESTER, N.P. (2014). Ontario freshwater fishes
949 demonstrate differing range-boundary shifts in a warming climate. *Diversity and*
950 *Distributions* **20**, 123–136.

951 ALTIZER, S., OSTFELD, R.S., JOHNSON, P.T.J., KUTZ, S. & HARVELL, C.D. (2013). Climate
952 change and infectious diseases: from evidence to a predictive framework. *Science*
953 **341**, 514–519.

954 ANGERT, A.L., CROZIER, L.G., RISSLER, L.J., GILMAN, S.E., TEWKSBURY, J.J. & CHUNCO,
955 A.J. (2011). Do species' traits predict recent shifts at expanding range edges?
956 *Ecology Letters* **14**, 677–689.

957 ANGILLETTA, M.J., STEURY, T.D. & SEARS, M.W. (2004). Temperature, growth rate, and
958 body size in ectotherms: fitting pieces of a life-history puzzle. *Integrative and*
959 *Comparative Biology* **44**, 498–509.

960 ARAÚJO, M.B., FERRI-YÁÑEZ, F., BOZINOVIC, F., MARQUET, P.A., VALLADARES, F. &
961 CHOWN, S.L. (2013). Heat freezes niche evolution. *Ecology Letters* **16**, 1206–1219.

962 ARCTIC COUNCIL (2013). *Arctic Biodiversity Assessment*. www.arcticbiodiversity.is

963 ASHCROFT, M.B., GOLLAN, J.R., WARTON, D.I. & RAMP, D. (2012). A novel approach to
964 quantify and locate potential microrefugia using topoclimate, climate stability, and
965 isolation from the matrix. *Global Change Biology* **18**, 1866–1879.

966 AZZURRO, E., TUSET, V.M., LOMBARTE, A., MAYNOU, F., SIMBERLOFF, D., RODRÍGUEZ-
967 PÉREZ, A. & SOLÉ, R. V. (2014). External morphology explains the success of
968 biological invasions. *Ecology Letters* **17**, 1455–1463.

969 BARANGE, M., MERINO, G., BLANCHARD, J.L., SCHOLTENS, J., HARLE, J., ALLISON, E.H.,
970 ALLEN, J.I., HOLT, J., & JENNINGS, S. (2014). Impacts of climate change on marine
971 ecosystem production in societies dependent on fisheries. *Nature Climate Change* **4**,
972 211–216.

973 BARCELÓ, C., CIANNELLI, L., OLSEN, E.M., JOHANNESSEN, T. & KNUTSEN, H. (2016).
974 Eight decades of sampling reveal a contemporary novel fish assemblage in coastal
975 nursery habitats. *Global Change Biology* **22**, 1155–1167.

976 BATES, A.E., PECL, G.T., FRUSHER, S., HOBDAJ, A.J., WERNBERG, T., SMALE, D.A.,

977 DULVY, N., SUNDAY, J.M., HILL, N., DULVY, N.K., COLWELL, R. (2014). Defining
978 and observing stages of climate-mediated range shifts in marine systems. *Global*
979 *Environmental Change*, **26**, 27–38.

980 BELL, J., CHEUNG, W., SILVA, S. DE, GASALLA, M., FRUSHER, S., HOBDAY, A., LAM, V.,
981 LEHODEY, P., PECL, G., SAMOILYS, M. & SENINA, I. (2016). Impacts and effects of
982 ocean warming on the contributions of fisheries and aquaculture to food security. In
983 *Explaining Ocean Warming: Causes, scale, effects and consequences* (eds D.
984 LAFFOLEY & J.M. BAXTER), pp. 409–437. IUCN, Gland, Switzerland.

985 BELL, J.D., GANACHAUD, A., GEHRKE, P.C., GRIFFITHS, S.P., HOBDAY, A.J., HOEGH-
986 GULDBERG, O., JOHNSON, J.E., LE BORGNE, R., LEHODEY, P., LOUGH, J.M.,
987 MATEAR, R.J., PICKERING, T.D., PRATCHETT, M.S., GUPTA, A. SEN, *et al.* (2013).
988 Mixed responses of tropical Pacific fisheries and aquaculture to climate change.
989 *Nature Climate Change* **3**, 591–599.

990 BENNETT, S.T., WERNBERG, T., ARACKAL JOY, B., DE BETTIGNIES, T., & CAMPBELL, A.H.
991 (2015). Central and rear-edge populations can be equally vulnerable to warming.
992 *Nature Communications* **6**, 10280.

993 BENTLEY, B.P., HAAS, B.J., TEDESCHI, J.N., & BERRY, O. (2017). Loggerhead sea turtle
994 embryos (*Caretta caretta*) regulate expression of stress-response and developmental
995 genes when exposed to a biologically realistic heat stress. *Molecular Ecology*
996 DOI:10.1111/mec.14087

997 BERTRAND, R., RIOFRIO-DILLON, G., LENOIR, J., DRAPIER, J., DE RUFFRAY, P., GEGOUT,
998 J.-C. & LOREAU, M. (2016). Ecological constraints increase the climatic debt in
999 forests. *Nature Communications* **7**, doi:10.1038/ncomms12643.

1000 BJURSTRÖM, A. & POLK, M. (2011). Climate change and interdisciplinarity: a co-citation
1001 analysis of IPCC Third Assessment Report. *Scientometrics* **87**, 525–550.

1002 BLOCK, B.A., DEWAR, H., BLACKWELL, S.B., WILLIAMS, T.D., PRINCE, E.D., FARWELL,
1003 C.J., BOUSTANY, A., TEO, S.L.H., SEITZ, A., WALLI, A. & FUDGE, D. (2001).
1004 Migratory movements, depth preferences, and thermal biology of Atlantic bluefin
1005 tuna. *Science* **293**, 1310–1314.

1006 BLOIS, J.L., ZARNETSKE, P.L., FITZPATRICK, M.C. & FINNEGAN, S. (2013). Climate
1007 change and the past, present, and future of biotic interactions. *Science* **341**, 499–504.

1008 BONEBRAKE, T.C., SYPHARD, A.D., FRANKLIN, J.F., ANDERSON, K.E., AKÇAKAYA, H.R.,
1009 MIZEREK, T., WINCHELL, C., REGAN, H.M. (2014). Fire management, managed
1010 relocation, and land conservation options for long-lived obligate seeding plants
1011 under global changes in climate, urbanization, and fire regime. *Conservation*
1012 *Biology* **28**, 1057–1067.

1013 BORRINI-FEYERABEND, G., DUDLEY, N., JAEGER, T., LASSEN, B., PATHAK BROOME, N.,
1014 PHILLIPS, A. & SANDWITH, T. (2013). Governance of Protected Areas: from
1015 understanding to action. *Best Practice Protected Area Guidelines Series No. 20*.
1016 Gland, Switzerland.

1017 BOWMAN, D.M.J.S., MURPHY, B.P., NEYLAND, D.L.J., WILLIAMSON, G.J. & PRIOR, L.D.
1018 (2014). Abrupt fire regime change may cause landscape-wide loss of mature
1019 obligate seeder forests. *Global Change Biology* **20**, 1008–1015.

1020 BRADLEY, B.A., ESTES, L.D., HOLE, D.G., HOLNESS, S., OPPENHEIMER, M., TURNER,
1021 W.R., BEUKES, H., SCHULZE, R.E., TADROSS, M.A. & WILCOVE, D.S. (2012).
1022 Predicting how adaptation to climate change could affect ecological conservation:

1023 Secondary impacts of shifting agricultural suitability. *Diversity and Distributions*
1024 **18**, 425–437.

1025 BRAMMER, J.R., BRUNET, N.D., BURTON, A.C., CUERRIER, A., DANIELSEN, F., DEWAN,
1026 K., HERRMANN, T.M., JACKSON, M., KENNETT, R., LAROCQUE, G., MULRENNAN, M.,
1027 PRATHAST, A.K., SAINT-ARNAUD, M., SCOTT, C. & HUMPHRIES, M.M. (2016). The
1028 role of digital data entry in participatory environmental monitoring. *Conservation*
1029 *Biology* doi: 10.1111/cobi.12727

1030 BRANDER, K. (2015). Improving the reliability of fishery predictions under climate
1031 change. *Current Climate Change Reports* **1**, 40–48.

1032 BREED, G.A., STICHTER, S. & CRONE, E.E. (2013). Climate-driven changes in
1033 northeastern US butterfly communities. *Nature Climate Change* **3**, 142–145.

1034 BRISCOE, N.J., KEARNEY, M.R., TAYLOR, C.A. & WINTLE, B.A. (2016). Unpacking the
1035 mechanisms captured by a correlative species distribution model to improve
1036 predictions of climate refugia. *Global Change Biology* **22**, 2425–2439.

1037 BROMHAM, L., DINNAGE, R. & HUA, X. (2016). Interdisciplinary research has
1038 consistently lower funding success. *Nature* **534**, 684–687.

1039 BROWN, C.J., O’CONNOR, M.I., POLOCZANSKA, E.S., SCHOEMAN, D.S., BUCKLEY, L.B.,
1040 BURROWS, M.T., DUARTE, C.M., HALPERN, B.S., PANDOLFI, J.M., PARMESAN, C. &
1041 RICHARDSON, A.J. (2016). Ecological and methodological drivers of species’
1042 distribution and phenology responses to climate change. *Global Change Biology* **22**,
1043 1548–1560.

1044 BUCKLEY, L.B. & KINGSOLVER, J.G. (2012). Functional and phylogenetic approaches to
1045 forecasting species’ responses to climate change. *Annual Review of Ecology*,

1046 *Evolution, and Systematics* **43**, 205–226.

1047 BUISSON, L., GRENOUILLET, G., VILLÉGER, S., CANAL, J. & LAFFAILLE, P. (2013).

1048 Toward a loss of functional diversity in stream fish assemblages under climate

1049 change. *Global Change Biology* **19**, 387–400.

1050 BUNNEFELD, N., HOSHINO, E. & MILNER-GULLAND, E.J. (2016). Management strategy

1051 evaluation: a powerful tool for conservation? *Trends in Ecology & Evolution* **26**,

1052 441–447.

1053 BURROWS, M.T., SCHOEMAN, D.S., BUCKLEY, L.B., MOORE, P., POLOCZANSKA, E.S.,

1054 BRANDER, K.M., BROWN, C., BRUNO, J.F., DUARTE, C.M., HALPERN, B.S., HOLDING,

1055 J., KAPPEL, C.V., KIESSLING, W., O’CONNOR, M.I., PANDOLFI, J.M., *et al.* (2011).

1056 The pace of shifting climate in marine and terrestrial ecosystems. *Science* **334**, 652–

1057 655.

1058 BURROWS, M.T., SCHOEMAN, D.S., RICHARDSON, A.J., MOLINOS, J.G., HOFFMANN, A.,

1059 BUCKLEY, L.B., MOORE, P.J., BROWN, C.J., BRUNO, J.F., DUARTE, C.M., HALPERN,

1060 B.S., HOEGH-GULDBERG, O., KAPPEL, C.V., KIESSLING, W., O’CONNOR, M.I., *et al.*

1061 (2014). Geographical limits to species-range shifts are suggested by climate

1062 velocity. *Nature* **507**, 492–495.

1063 BURTON, O.J., PHILLIPS, B.L., & TRAVIS, J.M.J. (2010). Trade-offs and the evolution of

1064 life-histories during range expansion. *Ecology* **13**, 1210–1220.

1065 CABRAL, J. S., VALENTE, L., & HARTIG, F. (2016). Mechanistic simulation models in

1066 macroecology and biogeography: state-of-art and prospects. *Ecography* doi:

1067 10.1111/ecog.02480

1068 CARVALHO, S.B., BRITO, J.C., CRESPO, E.G., WATTS, M.E. & POSSINGHAM, H.P. (2011).

1069 Conservation planning under climate change: toward accounting for uncertainty in
1070 predicted species distributions to increase confidence in conservation investments in
1071 space and time. *Biological Conservation* **144**, 2020–2030.

1072 CETINA-HEREDIA, P., ROUGHAN, M., VAN SEBILLE, E., FENG, M., COLEMAN, M.A.
1073 (2015). Strengthened currents override the effect of warming on lobster larval
1074 dispersal and survival. *Global Change Biology*, **21**, 4377–4386.

1075 CHANDLER, M., SEE, L., COPAS, K., Bonde, A.M.Z., Lopez, B.C., DANIELSEN, F.,
1076 LEGIND, J.K., MASINDE, S., MILLER RUSHING, A.J., NEWMAN, G., ROSEMARTIN, A.,
1077 TURAK, E. (2016). Contribution of citizen science towards international biodiversity
1078 monitoring. *Biological Conservation* doi: 10.1016/j.biocon.2016.09.004

1079 CHEN, I.-C., HILL, J.K., OHLEMÜLLER, R., ROY, D.B. & THOMAS, C.D. (2011). Rapid
1080 range shifts of species associated with high levels of climate warming. *Science* **333**,
1081 1024–1026.

1082 CHEUNG, W.W.L., BRODEUR, R.D., OKEY, T.A. & PAULY, D. (2015). Projecting future
1083 changes in distributions of pelagic fish species of Northeast Pacific shelf seas.
1084 *Progress in Oceanography* **130**, 19–31.

1085 CHEUNG, W.W.L., JONES, M.C., REYGONDEAU, G., STOCK, C.A., LAM, V.W.Y. &
1086 FRÖLICHER, T.L. (2016). Structural uncertainty in projecting global fisheries catches
1087 under climate change. *Ecological Modelling* **325**, 57–66.

1088 CHEUNG, W.W.L., LAM, V.W.Y., SARMIENTO, J.L., KEARNEY, K., WATSON, R., ZELLER,
1089 D. & PAULY, D. (2010). Large-scale redistribution of maximum fisheries catch
1090 potential in the global ocean under climate change. *Global Change Biology* **16**, 24–
1091 35.

1092 CHEUNG, W.W.L. & REYGONDEAU, G. (2016). Large benefits to marine fisheries of
1093 meeting the 1.5°C global warming target. *Science* **354**, 1591–1594.

1094 CHEUNG, W.W.L., SARMIENTO, J.L., DUNNE, J., FROLICHER, T.L., LAM, V.W.Y., DENG
1095 PALOMARES, M.L., WATSON, R. & PAULY, D. (2013). Shrinking of fishes
1096 exacerbates impacts of global ocean changes on marine ecosystems. *Nature Climate*
1097 *Change* **3**, 254–258.

1098 CLARK, T.D., SANDBLOM, E., HINCH, S.G., PATTERSON, D.A., FRAPPELL, P.B. &
1099 FARRELL, A.P. (2010). Simultaneous biologging of heart rate and acceleration, and
1100 their relationships with energy expenditure in free-swimming sockeye salmon
1101 (*Oncorhynchus nerka*). *Journal of Comparative Physiology B* **180**, 673–684.

1102 CLARK, T.D., SANDBLOM, E. & JUTFELT, F. (2013). Aerobic scope measurements of
1103 fishes in an era of climate change: respirometry, relevance and recommendations.
1104 *The Journal of Experimental Biology* **216**, 2771–2782.

1105 CLARK, T.D., TAYLOR, B.D., SEYMOUR, R.S., ELLIS, D., BUCHANAN, J., FITZGIBBON, Q.P.
1106 & FRAPPELL, P.B. (2008). Moving with the beat: heart rate and visceral temperature
1107 of free-swimming and feeding bluefin tuna. *Proceedings of the Royal Society B:*
1108 *Biological Sciences* **275**, 2841–2850.

1109 COMTE, L., BUISSON, L., DAUFRESNE, M. & GRENOUILLET, G. (2013). Climate-induced
1110 changes in the distribution of freshwater fish: Observed and predicted trends.
1111 *Freshwater Biology* **58**, 625–639.

1112 COOPER, C.B., SHIRK, J., ZUCKERBERG, B. (2014). The invisible prevalence of citizen
1113 science in global research: migratory birds and climate change. *PloS one*, **9**,
1114 e106508.

1115 CORREIA, D.L.P., CHAUVENET, A.L.M., ROWCLIFFE, J.M. & EWEN, J.G. (2015). Targeted
1116 management buffers negative impacts of climate change on the hihi, a threatened
1117 New Zealand passerine. *Biological Conservation* **192**, 145–153.

1118 CRESPO-PEREZ, V., REGNIERE, J., CHUINE, I., REBAUDO, F., & DANGLES, O. (2015).
1119 Changes in the distribution of multispecies pest assemblages affect levels of crop
1120 damage in warming tropical Andes. *Global Change Biology* **21**, 82-96.

1121 CRIMMINS, S.M., DOBROWSKI, S.Z., GREENBERG, J.A., ABATZOGLOU, J.T. &
1122 MYNSBERGE, A.R. (2011). Changes in climatic water balance drive downhill shifts
1123 in plant species' optimum elevations. *Science* **331**, 324–327.

1124 CVITANOVIC, C., HOBDAY, A.J., KERKHOFF, L. VAN, WILSON, S.K. & DOBBS, K. (2015).
1125 Improving knowledge exchange among scientists and decision- makers to facilitate
1126 the adaptive governance of marine resources : a review of knowledge and research
1127 needs. *Ocean and Coastal Management* **112**, 25–35.

1128 DADE, M.C., PAULI, N. & MITCHELL, N.J. (2014). Mapping a new future: using spatial
1129 multiple criteria analysis to identify novel habitats for assisted colonization of
1130 endangered species. *Animal Conservation* **17**, 4–17.

1131 DANIELSEN, F., BURGESS, N.D., JENSEN, P.M. & PIRHOFFER-WALZL, K. (2010).
1132 Environmental monitoring: the scale and speed of implementation varies according
1133 to the degree of peoples involvement. *Journal of Applied Ecology* **47**, 1166–1168.

1134 DANIELSEN, F., JENSEN, P.M., BURGESS, N.D., ALTAMIRANO, R., ALVIOLA, P.A.,
1135 ANDRIANANDRASANA, H., BRASHARES, J.S., BURTON, A.C., CORONADO, I., CORPUZ,
1136 N., ENGHOFF, M., FJELDSÅ, J., FUNDER, M., HOLT, S., HÜBERTZ, H., *et al.* (2014). A
1137 multicountry assessment of tropical resource monitoring by local communities.

1138 *BioScience* **64**, 236–251.

1139 DAUFRESNE, M., LENGFELLNER, K. & SOMMER, U. (2009). Global warming benefits the
1140 small in aquatic ecosystems. *Proceedings of the National Academy of Sciences* **106**,
1141 12788–12793.

1142 DAVIS, A.J., JENKINSON, L.S., LAWTON, J.H., SHORROCKS, B. & WOOD, S. (1998).
1143 Making mistakes when predicting shifts in species range in response to global
1144 warming. *Nature* **391**, 783–786.

1145 DAVIS, M.B. & SHAW, R.G. (2001). Range shifts and adaptive responses to Quaternary
1146 climate change. *Science* **292**, 673–679.

1147 DELL, A.I., PAWAR, S. & SAVAGE, V.M. (2011). Systematic variation in the temperature
1148 dependence of physiological and ecological traits. *Proceedings of the National*
1149 *Academy of Sciences* **108**, 10591–10596.

1150 DELL, A.I., PAWAR, S. & SAVAGE, V.M. (2014). Temperature dependence of trophic
1151 interactions are driven by asymmetry of species responses and foraging strategy.
1152 *Journal of Animal Ecology* **83**, 70–84.

1153 DEUTSCH, C.A., TEWKSBURY, J.J., HUEY, R.B., SHELDON, K.S., GHALAMBOR, C.K.,
1154 HAAK, D.C. & MARTIN, P.R. (2008). Impacts of climate warming on terrestrial
1155 ectotherms across latitude. *Proceedings of the National Academy of Sciences* **105**,
1156 6668–6672.

1157 DOBROWSKI, S.Z. & PARKS, S.A. (2016). Climate change velocity underestimates climate
1158 change exposure in mountainous regions. *Nature Communications* **7**,
1159 doi:10.1038/ncomms12349.

1160 DULLINGER, S., GATTRINGER, A., THULLER, W., MOSER, D., ZIMMERMANN, N.E.,

1161 GUISAN, A., WILLNER, W., PLUTZAR, C., LEITNER, M., MANG, T., CACCIANIGA, M.,
1162 DIRNBÖCK, T., ERTL, S., FISCHER, A., LENOIR, J., *et al.* (2012). Extinction debt of
1163 high-mountain plants under twenty-first-century climate change. *Nature Climate*
1164 *Change* **2**, 619–622.

1165 DUPUTIÉ, A., MASSOL, F., CHUINE, I., KIRKPATRICK, M. & RONCE, O. (2012). How do
1166 genetic correlations affect species range shifts in a changing environment? *Ecology*
1167 *Letters* **15**, 251–259.

1168 DURANT, J.M., HJERMANN, D.Ø., ANKER-NILSSEN, T., BEAUGRAND, G., MYSTERUD, A.,
1169 PETTORELLI, N., STENSETH, N.C. (2005). Timing and abundance as key mechanisms
1170 affecting trophic interactions in variable environments. *Ecology Letters*, **8**, 952–958.

1171 DURANT, S.M., BECKER, M.S., CREEL, S., BASHIR, S., DICKMAN, A.J., BEUDELS-JAMAR,
1172 R.C., LICHTENFELD, L., HILBORN, R., WALL, J., WITTEMYER, G., BADAMJAV, L.,
1173 BLAKE, S., BOITANI, L., BREITENMOSER, C., BROEKHUIS, F., *et al.* (2015).
1174 Developing fencing policies for dryland ecosystems. *Journal of Applied Ecology* **52**,
1175 544–551.

1176 EICKEN, H., KAUFMAN, M., KRUPNIK, I., PULSIFER, P., APANGALOOK, L., APANGALOOK,
1177 P., WEYAPUK, W. & LEAVITT, J. (2014). A framework and database for community
1178 sea ice observations in a changing Arctic: an Alaskan prototype for multiple users.
1179 *Polar Geography* **37**, 5–27.

1180 ESTRADA, A., MORALES-CASTILLA, I., CAPLAT, P. & EARLY, R. (2016). Usefulness of
1181 species traits in predicting range shifts. *Trends in Ecology & Evolution* **31**, 190–203.

1182 EVANS, A. (2009). *The Feeding of the Nine Billion: Global Food Security for the 21st*
1183 *Century*. London, UK.

1184 EVANS, T. G., DIAMOND, S. E., & KELLY, M. W. (2015). Mechanistic species distribution
1185 modelling as a link between physiology and conservation. *Conservation Physiology*
1186 **3**, cov056.

1187 EWING, G. & FRUSHER, S. (2015). New puerulus collector design suitable for fishery-
1188 dependent settlement monitoring. *ICES Journal of Marine Science* **72**, i225–i231.

1189 FAO (2014). *State of the World Fisheries and Aquaculture. Opportunities and*
1190 *challenges*. Rome.

1191 FEARY, D.A., PRATCHETT, M.S., EMSLIE, M.J., FOWLER, A.M., FIGUEIRA, W.F., LUIZ,
1192 O.J., NAKAMURA, Y. & BOOTH, D.J. (2014). Latitudinal shifts in coral reef fishes:
1193 why some species do and others do not shift. *Fish and Fisheries* **14**, 593–615.

1194 FEELEY, K. J., STROUD, J. T., & PEREZ, T. M. (2016). Most ‘global’ reviews of species’
1195 responses to climate change are not truly global. *Diversity and Distributions* doi:
1196 10.1111/ddi.12517

1197 FEINERER, I., HORNIK, K. & MEYER, D. (2008). Text Mining Infrastructure in R. *Journal*
1198 *of Statistical Software* **25**, 1–54.

1199 FERRIER, S., MANION, G., ELITH, J. & RICHARDSON, K. (2007). Using generalized
1200 dissimilarity modelling to analyse and predict patterns of beta diversity in regional
1201 biodiversity assessment. *Diversity and Distributions* **13**, 252–264.

1202 FINNEGAN, S., ANDERSON, S.C., HARNIK, P.G., SIMPSON, C., TITTENSOR, D.P., BYRNES,
1203 J.E., FINKEL, Z. V, LINDBERG, D.R., LIOW, L.H., LOCKWOOD, R., LOTZE, H.K.,
1204 McCLAIN, C.R., MCGUIRE, J.L., O’DEA, A. & PANDOLFI, J.M. (2015).
1205 Paleontological baselines for evaluating extinction risk in the modern oceans.
1206 *Science* **348**, 567–570.

1207 FITZPATRICK, M.C., SANDERS, N.J., NORMAND, S., SVENNING, J.-C., FERRIER, S., GOVE,
1208 A.D. & DUNN, R.R. (2013). Environmental and historical imprints on beta diversity:
1209 insights from variation in rates of species turnover along gradients. *Proceedings of*
1210 *the Royal Society B: Biological Sciences* **280**.

1211 FORDHAM, D.A., WIGLEY, T.M.L. & BROOK, B.W. (2011). Multi-model climate
1212 projections for biodiversity risk assessments. *Ecological Applications* **21**, 1939–
1213 5582.

1214 FRANKLIN, J., DAVIS, F.W., IKEGAMI, M., SYPHARD, A.D., FLINT, L.E., FLINT, A.L. &
1215 HANNAH, L. (2013). Modeling plant species distributions under future climates: how
1216 fine scale do climate projections need to be? *Global Change Biology* **19**, 473–483.

1217 FRASER, M.W., KENDRICK, G.A., STATTON, J., HOVEY, R.K., ZAVALA-PEREZ, A. &
1218 WALKER, D.I. (2014). Extreme climate events lower resilience of foundation
1219 seagrass at edge of biogeographical range. *Journal of Ecology* **102**, 1528–1536.

1220 GALBRAITH, E.D., CAROZZA, D.A. & BIANCHI, D (2017). A coupled human-Earth model
1221 perspective on long-term trends in the global marine fishery. *Nature*
1222 *Communications* **8**, 14884.

1223 GARCIA, R.A., CABEZA, M., RAHBEK, C. & ARAÚJO, M.B. (2014). Multiple dimensions of
1224 climate change and their implications for biodiversity. *Science* **344**, 1247579.

1225 GARCIA, S.M. & ROSENBERG, A.A. (2010). Food security and marine capture fisheries:
1226 characteristics, trends, drivers and future perspectives. *Philosophical Transactions*
1227 *of the Royal Society B: Biological Sciences* **365**, 2869–2880.

1228 GILMAN, S.E., URBAN, M.C., TEWKSBURY, J., GILCHRIST, G.W. & HOLT, R.D. (2010). A
1229 framework for community interactions under climate change. *Trends in Ecology &*

1230 *Evolution* **25**, 325–331.

1231 GLOWKA, L., BURHENNE-GUILMIN, F., SYNGE, H., MCNEELY, J.A. & GÜNDLING, L.
1232 (1994). *A Guide to the Convention on Biological Diversity*. IUCN, Gland and
1233 Cambridge.

1234 GODFRAY, H.C.J., BEDDINGTON, J.R., CRUTE, I.R., HADDAD, L., LAWRENCE, D., MUIR,
1235 J.F., PRETTY, J., ROBINSON, S., THOMAS, S.M. & TOULMIN, C. (2010). Food
1236 security: the challenge of feeding 9 billion people. *Science* **327**, 812–818.

1237 GRAHAM, M.H., DAYTON, P.K. & ERLANDSON, J.M. (2003). Ice ages and ecological
1238 transitions on temperate coasts. *Trends in Ecology & Evolution* **18**, 33–40.

1239 GREEN, D., PITMAN, A., BARNETT, A., KALDOR, J., DOHERTY, P., STANLEY, F. (2017).
1240 Advancing Australia's role in climate change and health research. *Nature Climate*
1241 *Change*, **7**, 103–106.

1242 GRINNELL, J. (1917). Field tests of theories concerning distributional control. *The*
1243 *American Naturalist* **51**, 115–128.

1244 GROFFMAN, P.M., STYLINSKI, C., NISBET, M.C., DUARTE, C.M., JORDAN, R., BURGIN,
1245 A., PREVITALI, M.A. COLOSO, J. (2010). Restarting the conversation: challenges at
1246 the interface between ecology and society. *Frontiers in Ecology and the*
1247 *Environment*, **8**, 284–291.

1248 GROVES, C.R., GAME, E.T., ANDERSON, M.G., CROSS, M., ENQUIST, C., FERDAÑA, Z.,
1249 GIRVETZ, E., GONDOR, A., HALL, K.R., HIGGINS, J., MARSHALL, R., POPPER, K.,
1250 SCHILL, S. & SHAFER, S.L. (2012). Incorporating climate change into systematic
1251 conservation planning. *Biodiversity and Conservation* **21**, 1651–1671.

1252 GUISAN, A. & ZIMMERMANN, N.E. (2000). Predictive habitat distribution models in

1253 ecology. *Ecological Modelling* **135**, 147–186.

1254 HAMANN, A., ROBERTS, D.R., BARBER, Q.E., CARROLL, C. & NIELSEN, S.E. (2015).

1255 Velocity of climate change algorithms for guiding conservation and management.

1256 *Global Change Biology* **21**, 997–1004.

1257 HAMILTON, L.C., BROWN, B.C. & RASMUSSEN, R.O. (2003). West Greenland's cod-to-

1258 shrimp transition: local dimensions of climatic change. *Arctic* **56**, 271–282.

1259 HANNAH, L., FLINT, L., SYPHARD, A.D., MORITZ, M.A., BUCKLEY, L.B. &

1260 MCCULLOUGH, I.M. (2014). Fine-grain modeling of species' response to climate

1261 change: holdouts, stepping-stones, and microrefugia. *Trends in Ecology & Evolution*

1262 **29**, 390–397.

1263 HANNAH, L., ROEHRDANZ, P.R., IKEGAMI, M., SHEPARD, A. V, SHAW, M.R., TABOR, G.,

1264 ZHI, L., MARQUET, P.A. & HIJMANS, R.J. (2013). Climate change, wine, and

1265 conservation. *Proceedings of the National Academy of Sciences* **110**, 6907–6912.

1266 HARRIGAN, R.J., THOMASSEN, H.A., BUERMANN, W. & SMITH, T.B. (2014). A continental

1267 risk assessment of West Nile virus under climate change. *Global Change Biology*

1268 **20**, 2417–2425.

1269 HARTOG, J.R., HOBDAY, A.J., MATEAR, R. & FENG, M. (2011). Habitat overlap between

1270 southern bluefin tuna and yellowfin tuna in the east coast longline fishery -

1271 implications for present and future spatial management. *Deep-Sea Research Part II:*

1272 *Topical Studies in Oceanography* **58**, 746–752.

1273 HEDLUND, C., BLOMSTEDT, Y. & SCHUMANN, B. (2014). Association of climatic factors

1274 with infectious diseases in the Arctic and subarctic region – a systematic review.

1275 *Global Health Action* **7**, 24161.

1276 HELLER, N. E. & ZAVALETA, E. S. (2009). Biodiversity management in the face of climate
1277 change: a review of 22 years of recommendations. *Biological Conservation* **142**, 14–
1278 32.

1279 HIGA, M., NAKAO, K., TSUYAMA, I., NAKAZONO, E., YASUDA, M., MATSUI, T. &
1280 TANAKA, N. (2013). Indicator plant species selection for monitoring the impact of
1281 climate change based on prediction uncertainty. *Ecological Indicators* **29**, 307–315.

1282 HILLERISLAMBERS, J., HARSCH, M.A., ETTINGER, A.K., FORD, K.R. & THEOBALD, E.J.
1283 (2013). How will biotic interactions influence climate change–induced range shifts?
1284 *Annals of the New York Academy of Sciences* **1297**, 112–125.

1285 HOBBS, R.J., HIGGS, E. & HARRIS, J.A. (2009). Novel ecosystems: implications for
1286 conservation and restoration. *Trends in Ecology & Evolution* **24**, 599–605.

1287 HOBDAY, A.J. & HARTMANN, K. (2006). Near real-time spatial management based on
1288 habitat predictions for a longline bycatch species. *Fisheries Management and*
1289 *Ecology* **13**, 365–380.

1290 HOBDAY, A.J., HARTOG, J.R., SPILLMAN, C.M. & ALVES, O. (2011). Seasonal forecasting
1291 of tuna habitat for dynamic spatial management. *Canadian Journal of Fisheries and*
1292 *Aquatic Sciences* **68**, 898–911.

1293 HOBDAY, A.J., MAXWELL, S.M., FORGIE, J., MCDONALD, J., DARBY, M., SESTO, K., ET AL.
1294 (2014). Dynamic ocean management: integrating scientific and technological
1295 capacity with law, policy and management. *Stanford Environmental Law Journal*
1296 **33**, 125–165.

1297 HOBDAY, A.J. & PECL, G.T. (2014). Identification of global marine hotspots: sentinels for
1298 change and vanguards for adaptation action. *Reviews in Fish Biology and Fisheries*

1299 **24**, 415–425.

1300 HODGSON, J.A., THOMAS, C.D., DYTHAM, C., TRAVIS, J.M.J. & CORNELL, S.J. (2012).

1301 The speed of range shifts in fragmented landscapes. *PLoS ONE* **7**, e47141.

1302 HODGSON, J.A., THOMAS, C.D., WINTLE, B.A. & MOILANEN, A. (2009). Climate change,

1303 connectivity and conservation decision making: back to basics. *Journal of Applied*

1304 *Ecology* **46**, 964–969.

1305 HOEGH-GULDBERG, O. & BRUNO, J.F. (2010). The impact of climate change on the

1306 world’s marine ecosystems. *Science* **328**, 1523–1528.

1307 HOEGH-GULDBERG, O., MUMBY, P.J., HOOTEN, A.J., STENECK, R.S., GREENFIELD, P.,

1308 GOMEZ, E., HARVELL, C.D., SALE, P.F., EDWARDS, A.J., CALDEIRA, K., KNOWLTON,

1309 N., EAKIN, C.M., IGLESIAS-PRIETO, R., MUTHIGA, N., BRADBURY, R.H., *et al.*

1310 (2007). Coral reefs under rapid climate change and ocean acidification. *Science* **318**,

1311 1737–1742.

1312 HOFFMANN, A.A. & SGRO, C.M. (2011). Climate change and evolutionary adaptation.

1313 *Nature* **470**, 479–485.

1314 HOFFMANN, A.A., GRIFFIN, P., DILLON, S., CATULLO, R., RANE, R., BYRNE, M., JORDAN,

1315 R., OAKESHOTT, J., WEEKS, A., JOSEPH, L., LOCKHART, P., BOREVITZ, J., & SRGÒ, C.

1316 (2015). A framework for incorporating evolutionary genomics into biodiversity

1317 conservation and management. *Climate Change Responses* **2**, 1.

1318 HUNTINGTON, H.P. (2011). Arctic science: The local perspective. *Nature* **478**, 182–183.

1319 IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of*

1320 *Working Group I to the Fifth Assessment Report of the Intergovern- mental Panel on*

1321 *Climate Change*. Cambridge University Press, Cambridge, UK and New York,

1322 USA.

1323 IPCC (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B:*
1324 *Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report*
1325 *of the Intergovernmental Panel on Climate Change.* Cambridge University Press,
1326 Cambridge, UK and New York, USA.

1327 IUCN/SSC (2013). *Guidelines for Reintroductions and Other Conservation*
1328 *Translocations.* Version 1.0. Gland, Switzerland.

1329 JETZ, W., WILCOVE, D.S. & DOBSON, A.P. (2007). Projected impacts of climate and land-
1330 use change on the global diversity of birds. *PLoS Biology* **5**, e157.

1331 JOHNSON, N., ALESSA, L., BEHE, C., DANIELSEN, F., GEARHEARD, S., GOFMAN-
1332 WALLINGFORD, V., KLISKEY, A., KRÜMMEL, E.-M., LYNCH, A., MUSTONEN, T.,
1333 PULSIFER, P. & SVOBODA, M. (2015). The contributions of community-based
1334 monitoring and traditional knowledge to arctic observing networks: reflections on
1335 the state of the field. *Arctic* **68**, 28–40.

1336 JORDAN, R., SINGER, F., VAUGHAN, J. & BERKOWITZ, A. (2009). What should every
1337 citizen know about ecology? *Frontiers in Ecology and the Environment* **7**, 495–500.

1338 KAWAGLEY, O. (2006). *A Yupiaq Worldview: A Pathway to Ecology and Spirit* Second.
1339 Waveland Press.

1340 KAYS, R., CROFOOT, M.C., JETZ, W. & WIKELSKI, M. (2015). Terrestrial animal tracking
1341 as an eye on life and planet. *Science* **348**, aaa2478.

1342 KEARNEY, M. & PORTER, W. (2009). Mechanistic niche modelling: combining
1343 physiological and spatial data to predict species' ranges. *Ecology Letters* **12**, 334–
1344 350.

1345 KEARNEY, M.R., ISAAC, A.P. & PORTER, W.P. (2014). microclim: global estimates of
1346 hourly microclimate based on long-term monthly climate averages. *Scientific Data*
1347 **1**, 140006.

1348 KENNICUTT, M.C., CHOWN, S.L., CASSANO, J.J., LIGGETT, D., PECK, L.S., MASSOM, R.,
1349 RINTOUL, S.R., STOREY, J., VAUGHAN, D.G., WILSON, T.J., ALLISON, I., AYTON, J.,
1350 BADHE, R., BAESEMAN, J., BARRETT, P.J., *et al.* (2015). A roadmap for Antarctic and
1351 Southern Ocean science for the next two decades and beyond. *Antarctic Science* **27**,
1352 3–18.

1353 KEPPEL, G., VAN NIEL, K.P., WARDELL-JOHNSON, G.W., YATES, C.J., BYRNE, M.,
1354 MUCINA, L., SCHUT, A.G.T., HOPPER, S.D. & FRANKLIN, S.E. (2012). Refugia:
1355 identifying and understanding safe havens for biodiversity under climate change.
1356 *Global Ecology and Biogeography* **21**, 393–404.

1357 KIESSLING, W., SIMPSON, C., BECK, B., MEWIS, H. & PANDOLFI, J.M. (2012). Equatorial
1358 decline of reef corals during the last Pleistocene interglacial. *Proceedings of the*
1359 *National Academy of Sciences* **109**, 21378–21383.

1360 KLEIN, J.A., HOPPING, K.A., YEH, E.T., NYIMA, Y., BOONE, R.B., Galvin, K.A. (2014).
1361 Unexpected climate impacts on the Tibetan Plateau: Local and scientific knowledge
1362 in findings of delayed summer. *Global Environmental Change* **28**, 141–152.

1363 KORTSCH, S., PRIMICERIO, R., FOSSHEIM, M., DOLGOV, A. V & ASCHAN, M. (2015).
1364 Climate change alters the structure of arctic marine food webs due to poleward shifts
1365 of boreal generalists. *Proceedings of the Royal Society B: Biological Sciences* **282**,
1366 20151546.

1367 KUHN, E., LENOIR, J., PIEDALLU, C. & GÉGOUT, J.C. (2016). Early signs of range

1368 disjunction of submountainous plant species: An unexplored consequence of future
1369 and contemporary climate changes. *Global Change Biology* **22**, 2094–2105.

1370 LASRAM, F.B.R., GUILHAUMON, F., ALBOUY, C., SOMOT, S., THUILLER, W. & MOUILLOT,
1371 D. (2010). The Mediterranean Sea as a ‘cul-de-sac’ for endemic fishes facing
1372 climate change. *Global Change Biology* **16**, 3233–3245.

1373 LAWLER, J.J., ACKERLY, D.D., ALBANO, C.M., ANDERSON, M.G., DOBROWSKI, S.Z.,
1374 GILL, J.L., HELLER, N.E., PRESSEY, R.L., SANDERSON, E.W. & WEISS, S.B. (2015).
1375 The theory behind, and the challenges of, conserving nature’s stage in a time of
1376 rapid change. *Conservation Biology* **29**, 618–629.

1377 LEE, E. (2016). Protected areas, country and value: the nature-culture tyranny of the
1378 IUCN’s Protected Area Guidelines for Indigenous Australians. *Antipode* **48**, 355–
1379 374.

1380 LEE, E., MCCORMACK, P., MICHAEL, P., MOLLOY, S., MUSTONEN, T. & POSSINGHAM, H.
1381 (2016). The language of science: essential ingredients for indigenous participation.
1382 *Square Brackets* **10**, 22–23.

1383 LENOIR, J., HATTAB, T., PIERRE, G. (2017). Climatic microrefugia under anthropogenic
1384 climate change: implications for species redistribution. *Ecography* **40**, 253–266.

1385 LENOIR, J., GÉGOUT, J.-C., GUIBAN, A., VITTOZ, P., WOHLGEMUTH, T., ZIMMERMANN,
1386 N.E., DULLINGER, S., PAULI, H., WILLNER, W. & SVENNING, J.-C. (2010). Going
1387 against the flow: potential mechanisms for unexpected downslope range shifts in a
1388 warming climate. *Ecography* **33**, 295–303.

1389 LENOIR, J. & SVENNING, J.C. (2015). Climate-related range shifts - a global
1390 multidimensional synthesis and new research directions. *Ecography* **38**, 15–28.

1391 LE ROUX, P.C., AALTO, J. & LUOTO, M. (2013). Soil moisture's underestimated role in
1392 climate change impact modelling in low-energy systems. *Global Change Biology*
1393 **19**, 2965–2975.

1394 LEVY, O., BUCKLEY, L.B., KEITT, T.H., ANGILLETTA, M.J. (2016). A dynamically
1395 downscaled projection of past and future microclimates. *Ecology*, **97**, 1888–1888.

1396 LEWISON, R., HOBDAY, A.J., MAXWELL, S., HAZEN, E., HARTOG, J.R., DUNN, D.C.,
1397 BRISCOE, D., FOSSETTE, S., O'KEEFE, C.E., BARNES, M., ABECASSIS, M., BOGRAD,
1398 S., BETHONEY, N.D., BAILEY, H., WILEY, D., *et al.* (2015). Dynamic ocean
1399 management: identifying the critical ingredients of dynamic approaches to ocean
1400 resource management. *BioScience* **65**, 486–498.

1401 LIAW, A. & WIENER, M. (2002). Classification and regression by randomForest. *R News*
1402 **2**, 18–22.

1403 LINDGREN, E. & GUSTAFSON, R. (2001). Tick-borne encephalitis in Sweden and climate
1404 change. *The Lancet* **358**, 16–18.

1405 LOARIE, S.R., DUFFY, P.B., HAMILTON, H., ASNER, G.P., FIELD, C.B. & ACKERLY, D.D.
1406 (2009). The velocity of climate change. *Nature* **462**, 1052–1055.

1407 LOVETT, G.M., BURNS, D. A, DRISCOLL, C.T., JENKINS, J.C., MITCHELL, M.J., RUSTAD,
1408 L., SHANLEY, J.B., LIKENS, G.E. & HAEUBER, R. (2007). Who needs environmental
1409 monitoring? *Frontiers in Ecology and the Environment* **5**, 253–260.

1410 MAGUIRE, K.C., NIETO-LUGILDE, D., BLOIS, J.L., FITZPATRICK, M.C., WILLIAMS, J.W.,
1411 FERRIER, S., LORENZ, D.J. (2016). Controlled comparison of species-and
1412 community-level models across novel climates and communities. *Proceedings of the*
1413 *Royal Society B: Biological Sciences* **283**, 20152817.

1414 MAGUIRE, K.C., NIETO-LUGILDE, D., FITZPATRICK, M.C., WILLIAMS, J.W., BLOIS, J.L.
1415 (2015). Modeling species and community responses to past, present, and future
1416 episodes of climatic and ecological change. *Annual Review of Ecology, Evolution,*
1417 *and Systematics* **46**, 343–368.

1418 MARZLOFF, M.P., MELBOURNE-THOMAS, J., HAMON, K.G., HOSHINO, E., JENNINGS, S.,
1419 VAN PUTTEN, I.E. & PECL, G.T. (2016). Modelling marine community responses to
1420 climate-driven species redistribution to guide monitoring and adaptive ecosystem-
1421 based management. *Global Change Biology* **22**, 2462–2474.

1422 MAWDSLEY, J.R., O’MALLEY, R. & OJIMA, D.S. (2009). A review of climate-change
1423 adaptation strategies for wildlife management and biodiversity conservation.
1424 *Conservation Biology* **23**, 1080–1089.

1425 MAXWELL, S.M., BAN, N.C. & MORGAN, L.E. (2014). Pragmatic approaches for effective
1426 management of pelagic marine protected areas. *Endangered Species Research* **26**,
1427 59–74.

1428 MAXWELL, S.M., HAZEN, E.L., LEWISON, R.L., DUNN, D.C., BAILEY, H., BOGRAD, S.J.,
1429 BRISCOE, D.K., FOSSETTE, S., HOBDAY, A.J. (2015). Dynamic ocean management:
1430 defining and conceptualizing real-time management of the ocean. *Marine Policy* **58**,
1431 42–50.

1432 MAYER, A. (2010). Phenology and citizen science: volunteers have documented seasonal
1433 events for more than a century, and scientific studies are benefiting from the data.
1434 *BioScience* **60**, 172–175.

1435 MCCAIN, C., & COLWELL, R.K. (2011). Assessing the threat to montane biodiversity
1436 from discordant shifts in temperature and precipitation in a changing climate.

1437 *Ecology Letters* **14**, 1236–1245.

1438 MCCOLL, C., ANDREWS, K., REYNOLDS, M., GOLET, G. (2016). Pop-up wetland habitats
1439 benefit migrating birds and farmers. *ERSI-ARCUser summer 2016*.
1440 <http://www.esri.com/esri-news/arcuser/summer-2016/popup-wetland-habitats>

1441 McDONALD, J., MCCORMACK, P.C., FLEMING, A.J., HARRIS, R.M.B. & LOCKWOOD, M.
1442 (2016a). Rethinking legal objectives for climate-adaptive conservation. *Ecology and*
1443 *Society* **21**, 25.

1444 McDONALD, J., MCCORMACK, P.C. & FOERSTER, A. (2016b). Promoting resilience to
1445 climate change in Australian conservation law: the case of biodiversity offsets.
1446 *University of New South Wales Law Journal* **39**, 1612–1651.

1447 McDONALD-MADDEN, E., RUNGE, M.C., POSSINGHAM, H.P. & MARTIN, T.G. (2011).
1448 Optimal timing for managed relocation of species faced with climate change. *Nature*
1449 *Climate Change* **1**, 261–265.

1450 MCGILL, B.J., ENQUIST, B.J., WEIHER, E. & WESTOBY, M. (2006). Rebuilding
1451 community ecology from functional traits. *Trends in Ecology & Evolution* **21**, 178–
1452 185.

1453 MCGUIRE, J.L., LAWLER, J.J., MCRAE, B.H., NUÑEZ, T.A. & THEOBALD, D.M. (2016).
1454 Achieving climate connectivity in a fragmented landscape. *Proceedings of the*
1455 *National Academy of Sciences* **113**, 7195–7200.

1456 MCINERNEY, G.J., TURNER, J.R.G., WONG, H.Y., TRAVIS, J.M.J. & BENTON, T.G. (2009).
1457 How range shifts induced by climate change affect neutral evolution. *Proceedings of*
1458 *the Royal Society B: Biological Sciences* **276**, 1527–1534.

1459 MCMICHAEL, A.J. (2012). Insights from past millennia into climatic impacts on human

1460 health and survival. *Proceedings of the National Academy of Sciences of the United*
1461 *States of America* **109**, 4730–4737.

1462 MITCHELL, N., HIPSEY, M.R., ARNALL, S., MCGRATH, G., TAREQUE, H. BIN, KUCHLING,
1463 G., VOGWILL, R., SIVAPALAN, M., PORTER, W.P. & KEARNEY, M.R. (2013). Linking
1464 eco-energetics and eco-hydrology to select sites for the assisted colonization of
1465 Australia's rarest reptile. *Biology* **2**, 1–25.

1466 MITCHELL, N.J., RODRIGUEZ, N., KUCHLING, G., ARNALL, S.G. & KEARNEY, M.R.
1467 (2016). Reptile embryos and climate change: Modelling limits of viability to inform
1468 translocation decisions. *Biological Conservation* **204**, 134–147.

1469 MOLINOS, J.G., HALPERN, B.S., SCHOEMAN, D.S., BROWN, C.J., KIESSLING, W., MOORE,
1470 P.J., PANDOLFI, J.M., POLOCZANSKA, E.S., RICHARDSON, A.J. & BURROWS, M.T.
1471 (2015). Climate velocity and the future global redistribution of marine biodiversity.
1472 *Nature Climate Change* **6**, 83–88.

1473 MOOR, H., HYLANDER, K. & NORBERG, J. (2015). Predicting climate change effects on
1474 wetland ecosystem services using species distribution modeling and plant functional
1475 traits. *Ambio* **44**, 113–126.

1476 MORITZ, C. & AGUDO, R. (2013). The future of species under climate change: resilience
1477 or decline? *Science* **341**, 504–508.

1478 MORSE, N.B., PELLISSIER, P.A., CIANCIOLA, E.N., BRERETON, R.L., SULLIVAN, M.M.,
1479 SHONKA, N.K., WHEELER, T.B. & MCDOWELL, W.H. (2014). Novel ecosystems in
1480 the Anthropocene: a revision of the novel ecosystem concept for pragmatic
1481 applications. *Ecology and Society* **19**, 12.

1482 MUSTONEN, T. (2015). Communal visual histories to detect environmental change in

1483 northern areas: Examples of emerging North American and Eurasian practices.
1484 *Ambio* **44**, 766–777.

1485 MUSTONEN, T. & LEHTINEN, A. (2013). Arctic earthviews: cyclic passing of knowledge
1486 among the indigenous communities of the Eurasian North. *Sibirica* **12**, 39–55.

1487 MUSTONEN, T. & MUSTONEN, K. (2016). *Life in the cyclic world: a compendium of*
1488 *traditional knowledge from the Eurasian North*. Kontiolahti: Snowchange
1489 Cooperative.

1490 NOGUÉS-BRAVO, D., OHLEMÜLLER, R., BATRA, P. & ARAÚJO, M.B. (2010). Climate
1491 predictors of late quaternary extinctions. *Evolution* **64**, 2442–2449.

1492 NORIN, T., MALTE, H. & CLARK, T.D. (2016). Differential plasticity of metabolic rate
1493 phenotypes in a tropical fish facing environmental change. *Functional Ecology* **30**,
1494 369–378.

1495 O'BRIEN, L., MARZANO, M. & WHITE, R.M. (2013). 'Participatory interdisciplinarity':
1496 Towards the integration of disciplinary diversity with stakeholder engagement for
1497 new models of knowledge production. *Science and Public Policy* **40**, 51–61.

1498 OCKENDON, N., BAKER, D.J., CARR, J.A., WHITE, E.C., ALMOND, R.E.A., AMANO, T.,
1499 BERTRAM, E., BRADBURY, R.B., BRADLEY, C., BUTCHART, S.H.M., DOSWALD, N.,
1500 FODEN, W., GILL, D.J.C., GREEN, R.E., SUTHERLAND, W.J., *et al.* (2014).
1501 Mechanisms underpinning climatic impacts on natural populations: altered species
1502 interactions are more important than direct effects. *Global Change Biology* **20**,
1503 2221–2229.

1504 PACIFICI, M., FODEN, W.B., VISCONTI, P., WATSON, J.E.M., BUTCHART, S.H.M., KOVACS,
1505 K.M., SCHEFFERS, B.R., HOLE, D.G., MARTIN, T.G., AKÇAKAYA, H.R., CORLETT,

1506 R.T., HUNTLEY, B., BICKFORD, D., CARR, J.A., HOFFMANN, A.A., *et al.* (2015).
1507 Assessing species vulnerability to climate change. *Nature Climate Change* **5**, 215–
1508 224.

1509 PACIFICI, M., VISCONTI, P., BUTCHART, S.H.M., WATSON, J.E.M., CASSOLA, F.M.,
1510 RONDININI, C. (2017). Species' traits influenced their response to recent climate
1511 change. *Nature Climate Change*, **7**, 205–208.

1512 PANDOLFI, J.M. (1996). Limited membership in Pleistocene reef coral assemblages from
1513 the Huon Peninsula, Papua New Guinea: constancy during global change.
1514 *Paleobiology* **22**, 152–176.

1515 PANDOLFI, J.M. & JACKSON, J.B.C. (2006). Ecological persistence interrupted in
1516 Caribbean coral reefs. *Ecology Letters* **9**, 818–826.

1517 PARKINSON, A.J. & EVENGÅRD, B. (2009). Climate change, its impact on human health in
1518 the Arctic and the public health response to threats of emerging infectious diseases.
1519 *Global Health Action* **2**.

1520 PARMESAN, C. (2006). Ecological and evolutionary responses to recent climate change.
1521 *Annual of Ecology, Evolution and Systematics* **37**, 637–669.

1522 PARMESAN, C. & YOHE, G. (2003). A globally coherent fingerprint of climate change
1523 impacts across natural systems. *Nature* **421**, 37–42.

1524 PECL, G.T., ARAÚJO, M.B., BELL, J.D., BLANCHARD, J., BONEBRAKE, T.C., CHEN I.C.,
1525 CLARK, T.D., COLWELL, R.K., DANIELSON, F., EVENGÅRD, B., FALCONI, L.,
1526 FERRIER, S., FRUSHER, S., GARCIA, R.A., GRIFFIS, R., *et al.* (2017) Biodiversity
1527 redistribution under climate change: impacts on ecosystems and human well-being.
1528 *Science* **355**, eaai9214.

1529 PECL, G.T., HOBDAJ, A.J., FRUSHER, S., SAUER, W.H.H. & BATES, A.E. (2014). Ocean
1530 warming hotspots provide early warning laboratories for climate change impacts.
1531 *Reviews in Fish Biology and Fisheries* **24**, 409–413.

1532 PECL, G.T., TRACEY, S.R., DANYUSHEVSKY, L., WOTHERSPOON, S. &
1533 MOLTSCHANIWSKYJ, N.A. (2011). Elemental fingerprints of southern calamary
1534 (*Sepioteuthis australis*) reveal local recruitment sources and allow assessment of the
1535 importance of closed areas. *Canadian Journal of Fisheries and Aquatic Sciences* **68**,
1536 1351–1360.

1537 PÉRON, C., AUTHIER, M., BARBRAUD, C., DELORD, K., BESSON, D. & WEIMERSKIRCH, H.
1538 (2010). Interdecadal changes in at-sea distribution and abundance of subantarctic
1539 seabirds along a latitudinal gradient in the Southern Indian Ocean. *Global Change*
1540 *Biology* **16**, 1895–1909.

1541 PETTORELLI, N., LAURANCE, W.F., O'BRIEN, T.G., WEGMANN, M., NAGENDRA, H. &
1542 TURNER, W. (2014). Satellite remote sensing for applied ecologists: opportunities
1543 and challenges. *Journal of Applied Ecology* **51**, 839–848.

1544 PHILLIPS, B.L., MUÑOZ, M.M., HATCHER, A., MACDONALD, S.L., LLEWELYN, J., LUCY,
1545 V. & MORITZ, C. (2015). Heat hardening in a tropical lizard: geographic variation
1546 explained by the predictability and variance in environmental temperatures.
1547 *Functional Ecology* **30**, 1161–1168.

1548 PHILLIPS, S.J. & DUDÍK, M. (2008). Modeling of species distributions with Maxent: new
1549 extensions and a comprehensive evaluation. *Ecography* **31**, 161–175.

1550 PINSKY, M.L. & FOGARTY, M. (2012). Lagged social-ecological responses to climate and
1551 range shifts in fisheries. *Climatic Change* **115**, 883–891.

1552 PINSKY, M.L., WORM, B., FOGARTY, M.J., SARMIENTO, J.L. & LEVIN, S.A. (2013).
1553 Marine taxa track local climate velocities. *Science* **341**, 1239–1242.

1554 PLAGÁNYI, É.E., PUNT, A.E., HILLARY, R., MORELLO, E.B., THÉBAUD, O., HUTTON, T.,
1555 PILLANS, R.D., THORSON, J.T., FULTON, E.A., SMITH, A.D.M., SMITH, F., BAYLISS,
1556 P., HAYWOOD, M., LYNE, V. & ROTH LISBERG, P.C. (2014). Multispecies fisheries
1557 management and conservation: tactical applications using models of intermediate
1558 complexity. *Fish and Fisheries* **15**, 1–22.

1559 POLOCZANSKA, E.S., BROWN, C.J., SYDEMAN, W.J., KIESSLING, W., SCHOEMAN, D.S.,
1560 MOORE, P.J., BRANDER, K., BRUNO, J.F., BUCKLEY, L.B., BURROWS, M.T., DUARTE,
1561 C.M., HALPERN, B.S., HOLDING, J., KAPPEL, C.V., O’CONNOR, M.I., *et al.* (2013).
1562 Global imprint of climate change on marine life. *Nature Climate Change* **3**, 919–
1563 925.

1564 POLOCZANSKA, E.S., BURROWS, M.T., BROWN, C.J., GARCIA, J., HALPERN, B.S., HOEGH-
1565 GULDBERG, O., KAPPEL, C. V, MOORE, P.J., RICHARDSON, A.J., SCHOEMAN, D.S. &
1566 SYDEMAN, W.J. (2016). Responses of marine organisms to climate change across
1567 oceans. *Frontiers in Marine Science* **3**, 1–21.

1568 PÖRTNER, H.O. & FARRELL, A.P. (2008). Physiology and climate change. *Science* **322**,
1569 690–692.

1570 POST, E. & FORCHHAMMER, M.C. (2008). Climate change reduces reproductive success
1571 of an Arctic herbivore through trophic mismatch. *Philosophical Transactions of the*
1572 *Royal Society B: Biological Sciences* **363**, 2367 LP-2373.

1573 POTTER, K. A., WOODS, H.A., & PINCEBOURDE, S. (2013). Microclimatic challenges in
1574 global change biology. *Global Change Biology* **19**, 2932–2939.

1575 RADELOFF, V.C., WILLIAMS, J.W., BROOKE, B.L., BURKE, K.D., CARTER, S.K.,
1576 CHILDRESS, E.S., CROMWELL, K.J., GRATTON, C., HASLEY, A.O., KRAERMER, B.M.,
1577 LATZKA, A.W., MARIN-SPIOTTA, E., MEINE, C.D., MUNOZ, S.E., NEESON, T.M., *et al.*
1578 (2015). The rise of novelty in ecosystems. *Ecological Applications* **25**, 2051–2068.

1579 RAPACCIUOLO, G., MAHER, S.P., SCHNEIDER, A.C., HAMMOND, T.T., JABIS, M.D.,
1580 WALSH, R.E., IKNAYAN, K.J., WALDEN, G.K., OLDFATHER, M.F., ACKERLY, D.D. &
1581 BEISSINGER, S.R. (2014). Beyond a warming fingerprint: individualistic
1582 biogeographic responses to heterogeneous climate change in California. *Global*
1583 *Change Biology* **20**, 2841–2855.

1584 RAY, C. (1960). The application of Bergmann’s and Allen’s rules to the poikilotherms.
1585 *Journal of Morphology* **106**, 85–108.

1586 RICE, J.C. & GARCIA, S.M. (2011). Fisheries, food security, climate change, and
1587 biodiversity: characteristics of the sector and perspectives on emerging issues. *ICES*
1588 *Journal of Marine Science* **68**, 1343–1353.

1589 RICHARDSON, D.M., HELLMANN, J.J., MCLACHLAN, J.S., SAX, D.F., SCHWARTZ, M.W.,
1590 GONZALEZ, P., BRENNAN, E.J., CAMACHO, A., ROOT, T.L., SALA, O.E., SCHNEIDER,
1591 S.H., ASHE, D.M., CLARK, J.R., EARLY, R., ETTERTSON, J.R., *et al.* (2009).
1592 Multidimensional evaluation of managed relocation. *Proceedings of the National*
1593 *Academy of Sciences* **106**, 9721–9724.

1594 RISSMAN, A.R., OWLEY, J., SHAW, M.R. & THOMPSON, B.B. (2015). Adapting
1595 conservation easements to climate change. *Conservation Letters* **8**, 68–76.

1596 ROBINSON, L.M., GLEDHILL, D.C., MOLTSCHANIWSKYJ, N.A., HOBDAY, A.J., FRUSHER,
1597 S., BARRETT, N., STUART-SMITH, J. & PECL, G.T. (2015). Rapid assessment of an

1598 ocean warming hotspot reveals ‘high’ confidence in potential species’ range
1599 extensions. *Global Environmental Change* **31**, 28–37.

1600 ROHR, J.R., RAFFEL, T.R., ROMANSIC, J.M., MCCALLUM, H., HUDSON, P.J. (2008).
1601 Evaluating the links between climate, disease spread, and amphibian declines.
1602 *Proceedings of the National Academy of Sciences*, **105**, 17436–17441.

1603 ROUT, T.M., McDONALD-MADDEN, E., MARTIN, T.G., MITCHELL, N.J., POSSINGHAM,
1604 H.P. & ARMSTRONG, D.P. (2013). How to decide whether to move species
1605 threatened by climate change. *PLoS ONE* **8**, e75814.

1606 ROWE, K.C., ROWE, K.M.C, TINGLEY, M.W., KOO, M.S., PATTON, J.L., CONROY, C.J., LE
1607 PERRINE, J.D., BEISSINGER, S.R., & MORITZ, C. (2015). Spatially heterogeneous
1608 impact of climate change on small mammals of montane California. *Proceedings of*
1609 *the Royal Society of London B: Biological Sciences* **282**, 20141857.

1610 ROYAL SOCIETY OF LONDON (2009). Reaping the benefits: science and the sustainable
1611 intensification of global agriculture. London, UK.

1612 RUSSELL, B.D., THOMPSON, J.A.I., FALKENBERG, L.J. & CONNELL, S.D. (2009).
1613 Synergistic effects of climate change and local stressors: CO₂ and nutrient-driven
1614 change in subtidal rocky habitats. *Global Change Biology* **15**, 2153–2162.

1615 SALE, P.F., AGARDY, T., AINSWORTH, C.H., FEIST, B.E., BELL, J.D., CHRISTIE, P., HOEGH-
1616 GULDBERG, O., MUMBY, P.J., FEARY, D.A., SAUNDERS, M.I., DAW, T.M., FOALE,
1617 S.J., LEVIN, P.S., LINDEMAN, K.C., LORENZEN, K., *et al.* (2014). Transforming
1618 management of tropical coastal seas to cope with challenges of the 21st century.
1619 *Marine Pollution Bulletin* **85**, 8–23.

1620 SÁNCHEZ-GUILLÉN, R.A., CÓRDOBA-AGUILAR, A., HANSSON, B., OTT, J. &

1621 WELLENREUTHER, M. (2015). Evolutionary consequences of climate-induced range
1622 shifts in insects. *Biological Reviews* **91**, 1050–1064.

1623 SCHEFFERS, B.R., BRUNNER, R.M., RAMIREZ, S.D., SHOO, L.P., DIOSMOS, A. &
1624 WILLIAMS, S.E. (2013). Thermal buffering of microhabitats is a critical factor
1625 mediating warming vulnerability of frogs in the Philippine biodiversity hotspot.
1626 *Biotropica* **45**, 628–635.

1627 SCHEFFERS, B.R., DE MEESTER, L., BRIDGE, T.C., HOFFMANN, A.A., PANDOLFI, J.M.,
1628 CORLETT, R.T., BUTCHART, S.H., PEARCE- KELLY, P., KOVACS, K.M., DUDGEON,
1629 D., PACIFICI, M., RONDININI, C., SCHEFFERS, FODEN, W.B., MARTIN, T.G., MORA, C.,
1630 BICKFORD, D., WATSON, J.E.M. (2016). The broad footprint of climate change from
1631 genes to biomes to people. *Science* **354**, aaf7671.

1632 SCHMID, B. V, BÜNTGEN, U., EASTERDAY, W.R., GINZLER, C., WALLØE, L., BRAMANTI,
1633 B. & STENSETH, N.C. (2015). Climate-driven introduction of the Black Death and
1634 successive plague reintroductions into Europe. *Proceedings of the National*
1635 *Academy of Sciences* **112**, 3020–3025.

1636 SCHWARTZ, M.W., HELLMANN, J.J., MCLACHLAN, J.M., SAX, D.F., BOREVITZ, J.O.,
1637 BRENNAN, J., CAMACHO, A.E., CEBALLOS, G., CLARK, J.R., DOREMUS, H., EARLY,
1638 R., ETTERTSON, J.R., FIELDER, D., GILL, J.L., GONZALEZ, P., *et al.* (2012). Managed
1639 relocation: integrating the scientific, regulatory, and ethical challenges. *BioScience*
1640 **62**, 732–743.

1641 SCRIVEN, S.A., HODGSON, J.A., MCCLEAN, C.J. & HILL, J.K. (2015). Protected areas in
1642 Borneo may fail to conserve tropical forest biodiversity under climate change.
1643 *Biological Conservation* **184**, 414–423.

1644 SEXTON, J.P., STRAUSS, S.Y. & RICE, K.J. (2011). Gene flow increases fitness at the
1645 warm edge of a species' range. *Proceedings of the National Academy of Sciences*
1646 **108**, 11704–11709.

1647 SHERIDAN, J. & LONGBOAT, R.D. (2006). The Haudenosaunee imagination and the
1648 ecology of the sacred. *Space and Culture* **9**, 365–381.

1649 SHOO, L.P., HOFFMANN, A.A., GARNETT, S., PRESSEY, R.L., WILLIAMS, Y.M., TAYLOR,
1650 M., FALCONI, L., YATES, C.J., SCOTT, J.K., ALAGADOR, D. & WILLIAMS, S.E.
1651 (2013). Making decisions to conserve species under climate change. *Climatic*
1652 *Change* **119**, 239–246.

1653 SHOO, L.P., OLSON, D.H., MCMENAMIN, S.K., MURRAY, K.A., VAN SLUYS, M.,
1654 DONNELLY, M.A., STRATFORD, D., TERHIVUO, J., MERINO-VITERI, A., HERBERT,
1655 S.M., BISHOP, P.J., CORN, P.S., DOVEY, L., GRIFFITHS, R.A., LOWE, K, *et al.* (2011).
1656 Engineering a future for amphibians under climate change. *Journal of Applied*
1657 *Ecology* **48**, 487–492.

1658 SHRESTHA, U.B., BAWA, K.S. (2014). Impact of climate change on potential distribution
1659 of Chinese caterpillar fungus (*Ophiocordyceps sinensis*) in Nepal Himalaya. *PloS*
1660 *one* **9**, e106405.

1661 SLAVICH, E., WARTON, D.I., ASHCROFT, M.B., GOLLAN, J.R. & RAMP, D. (2014).
1662 Topoclimate versus macroclimate: how does climate mapping methodology affect
1663 species distribution models and climate change projections? *Diversity and*
1664 *Distributions* **20**, 952–963.

1665 SMITH, T.B., KINNISON, M.T., STRAUSS, S.Y., FULLER, T.L. & CARROLL, S.P. (2014).
1666 Prescriptive evolution to conserve and manage biodiversity. *Annual Review of*

1667 *Ecology, Evolution, and Systematics* **45**, 1–22.

1668 SOMERO, G. N. (2010). The physiology of climate change: how potentials for
1669 acclimatization and genetic adaptation will determine ‘winners’ and ‘losers’.
1670 *Journal of Experimental Biology* **213**, 912–920.

1671 SOMMER, B., HARRISON, P.L., BEGER, M. & PANDOLFI, J.M. (2014). Trait-mediated
1672 environmental filtering drives assembly at biogeographic transition zones. *Ecology*
1673 **95**, 1000–1009.

1674 SORTE, C.J.B. (2013). Predicting persistence in a changing climate: flow direction and
1675 limitations to redistribution. *Oikos* **122**, 161–170.

1676 SORTE, C.J.B., WILLIAMS, S.L. & CARLTON, J.T. (2010). Marine range shifts and species
1677 introductions: Comparative spread rates and community impacts. *Global Ecology*
1678 *and Biogeography* **19**, 303–316.

1679 SOUTHWARD, A.J., HAWKINS, S.J. & BURROWS, M.T. (1995). Effects of rising
1680 temperature on the ecology and physiology of aquatic organisms. Seventy years’
1681 observations of changes in distribution and abundance of zooplankton and intertidal
1682 organisms in the western English Channel in relation to rising sea temperature.
1683 *Journal of Thermal Biology* **20**, 127–155.

1684 STEIN, B.A., STAUDT, A., CROSS, M.S., DUBOIS, N.S., ENQUIST, C., GRIFFIS, R., HANSEN,
1685 L.J., HELLMANN, J.J., LAWLER, J.J., NELSON, E.J. & PAIRIS, A. (2013). Preparing for
1686 and managing change: climate adaptation for biodiversity and ecosystems. *Frontiers*
1687 *in Ecology and the Environment* **11**, 502–510.

1688 STENSETH, N.C., SAMIA, N.I., VILJUGREIN, H., KAUSRUD, K.L., BEGON, M., DAVIS, S.,
1689 LEIRS, H., DUBYANSKIY, V.M., ESPER, J., AGEYEV, V.S., KLASSOVSKIY, N.L., POLE,

1690 S.B. & CHAN, K.-S. (2006). Plague dynamics are driven by climate variation.
1691 *Proceedings of the National Academy of Sciences* **103**, 13110–13115.

1692 SUNDAY, J.M., BATES, A.E. & DULVY, N.K. (2012). Thermal tolerance and the global
1693 redistribution of animals. *Nature Climate Change* **2**, 686–690.

1694 SUNDAY, J.M., BATES, A.E., KEARNEY, M.R., COLWELL, R.K., DULVY, N.K., LONGINO,
1695 J.T. & HUEY, R.B. (2014). Thermal-safety margins and the necessity of
1696 thermoregulatory behavior across latitude and elevation. *Proceedings of the*
1697 *National Academy of Sciences* **111**, 5610–5615.

1698 SUNDAY, J.M., PECL, G.T., FRUSHER, S., HOBDAY, A.J., HILL, N., HOLBROOK, N.J.,
1699 EDGAR, G.J., STUART-SMITH, R., BARRETT, N., WERNBERG, T., WATSON, R.A.,
1700 SMALE, D.A., FULTON, E.A., SLAWINSKI, D., FENG, M., *et al.* (2015). Species traits
1701 and climate velocity explain geographic range shifts in an ocean-warming hotspot.
1702 *Ecology Letters* **18**, 944–953.

1703 TEDESCHI, J.N., KENNINGTON, W.J., TOMKINS, J.L., BERRY, O., WHITING, S., MEEKAN,
1704 M.G. & MITCHELL, N.J. (2016). Heritable variation in heat shock gene expression: a
1705 potential mechanism for adaptation to thermal stress in embryos of sea turtles.
1706 *Proceedings of the Royal Society B: Biological Sciences* **283**, 20152320.

1707 TENGÖ, M., HILL, R., MALMER, P., RAYMOND, C.M., SPIERENBURG, M., DANIELSEN, F.,
1708 ELMQVIST, T., & FOLKE, C., (2017). Weaving knowledge systems in IPBES, CBD
1709 and beyond – lessons learned for sustainability. *Current Opinions in Environmental*
1710 *Sustainability* **26-7**, 17–25.

1711 THACKERAY, S.J., HENRYS, P.A., HEMMING, D., BELL, J.R., BOTHAM, M.S., BURTHE, S.,
1712 HELAOUET, P., JOHNS, D.G., JONES, I.D., LEECH, D.I., MACKAY, MASSIMINO, D.,

1713 ATKINSON, S., BACON, P.J., BRERETON, T.M., CARVALHO, L., *et al.* (2016).
1714 Phenological sensitivity to climate across taxa and trophic levels. *Nature* **535**, 241–
1715 245.

1716 THOMAS, C.D., BODSWORTH, E.J., WILSON, R.J., SIMMONS, A.D., DAVIES, Z.G., MUSCHE,
1717 M. & CONRADT, L. (2001). Ecological and evolutionary processes at expanding
1718 range margins. *Nature* **411**, 577–581.

1719 THOMSON, J.A., BURKHOLDER, D.A., HEITHAUS, M.R., FOURQUREAN, J.W., FRASER,
1720 M.W., STATTON, J. & KENDRICK, G.A. (2015). Extreme temperatures, foundation
1721 species, and abrupt ecosystem change: an example from an iconic seagrass
1722 ecosystem. *Global Change Biology* **21**, 1463–1474.

1723 TINGLEY, M.W., KOO, M.S., MORITZ, C., RUSH, A.C. & BEISSINGER, S.R. (2012). The
1724 push and pull of climate change causes heterogeneous shifts in avian elevational
1725 ranges. *Global Change Biology* **18**, 3279–3290.

1726 TITTENSOR, D.P., MORA, C., JETZ, W., LOTZE, H.K., RICARD, D., BERGHE, E. VANDEN &
1727 WORM, B. (2010). Global patterns and predictors of marine biodiversity across taxa.
1728 *Nature* **466**, 1098–1101.

1729 TØTTRUP, A.P., THORUP, K., RAINIO, K., YOSEF, R., LEHIKONEN, E. & RAHBK, C.
1730 (2008). Avian migrants adjust migration in response to environmental conditions en
1731 route. *Biology Letters* **4**, 685–688.

1732 TUNNEY, T.D., MCCANN, K.S., LESTER, N.P. & SHUTER, B.J. (2014). Effects of
1733 differential habitat warming on complex communities. *Proceedings of the National*
1734 *Academy of Sciences of the United States of America* **111**, 8077–8082.

1735 URBAN, M.C. (2015). Accelerating extinction risk from climate change. *Science* **348**,

1736 571–573.

1737 URBAN, M.C., BOCEDI, G., HENDRY, A.P., MIHOUB, J.B., PE'ER, G., SINGER, A., BRIDLE,
1738 J.R., CROZIER, L.G., DE MEESTER, L., GODSOE, W. & GONZALEZ, A. (2016).
1739 Improving the forecast for biodiversity under climate change. *Science* **353**, aad8466.

1740 URBAN, M.C., TEWKSBURY, J.J. & SHELDON, K.S. (2012). On a collision course:
1741 competition and dispersal differences create no-analogue communities and cause
1742 extinctions during climate change. *Proceedings of the Royal Society B: Biological*
1743 *Sciences*, **279**, 2072–2080.

1744 VALLADARES, F., MATESANZ, S., GUILHAUMON, F., ARAÚJO, M.B., BALAGUER, L.,
1745 BENITO-GARZON, M., CORNWELL, W., GIANOLI, E., VAN KLEUNEN, M., NAYA, D.E.,
1746 NICOTRA, A.B., POORTER, H. & ZAVALA, M.A. (2014). The effects of phenotypic
1747 plasticity and local adaptation on forecasts of species range shifts under climate
1748 change. *Ecology Letters* **17**, 1351–1364.

1749 VAN OPPEN, M.J.H., OLIVER, J.K., PUTNAM, H.M. & GATES, R.D. (2015). Building coral
1750 reef resilience through assisted evolution. *Proceedings of the National Academy of*
1751 *Sciences* **112**, 2307–2313.

1752 VANDERWAL, J., MURPHY, H.T., KUTT, A.S., PERKINS, G.C., BATEMAN, B.L., PERRY, J.J.
1753 & RESIDE, A.E. (2013). Focus on poleward shifts in species' distribution
1754 underestimates the fingerprint of climate change. *Nature Climate Change* **3**, 239–
1755 243.

1756 VAN GENNIP, S.J., POPOVA, E.E., YOOL, A., PECL, G.T., HOBDAY, A.J. & SORTE, C.J.B.
1757 (2017). Going with the flow: the role of ocean circulation in global marine
1758 ecosystems under a changing climate. *Global Change Biology* doi:

1759 10.1111/gcb.13586

1760 VERGÉS, A., STEINBERG, P.D., HAY, M.E., POORE, A.G.B., CAMPBELL, A.H.,
1761 BALLESTEROS, E., HECK, K.L., BOOTH, D.J., COLEMAN, M.A., FEARY, D.A.,
1762 FIGUEIRA, W., LANGLOIS, T., MARZINELLI, E.M., MIZEREK, T., MUMBY, P.J., *et al.*
1763 (2014). The tropicalization of temperate marine ecosystems: climate-mediated
1764 changes in herbivory and community phase shifts. *Proceedings of the Royal Society*
1765 *B: Biological Sciences*, **281**, 20140846.

1766 VERGÉS, A., DOROPOULOS, C., MALCOLM, H.,A., SKYE, M., GARCIA-PIZA, M.,
1767 MARZINELLI, E.M., CAMPBELL, A.H., BALLESTEROS, E., HOEY, A.S., VILA-
1768 CONCEJO, A., BOZEC, Y.M., STEINBERG, P.D. (2016). Long-term empirical evidence
1769 of ocean warming leading to tropicalization of fish communities, increased
1770 herbivory and loss of kelp. *Proceedings of the National Academy of Sciences*, **48**,
1771 13791–13796.

1772 WATSON, J.E.M. & SEGAN, D.B. (2013). Accommodating the human response for
1773 realistic adaptation planning: response to Gillson et al. *Trends in Ecology &*
1774 *Evolution* **28**, 573–574.

1775 WEBB, T.J. (2012). Marine and terrestrial ecology: unifying concepts, revealing
1776 differences. *Trends in Ecology & Evolution* **27**, 535–541.

1777 WEBBER, B.L., YATES, C.J., LE MAITRE, D.C., SCOTT, J.K., KRITICOS, D.J., OTA, N.,
1778 MCNEILL, A., LE ROUX, J.J. & MIDGLEY, G.F. (2011). Modelling horses for novel
1779 climate courses: insights from projecting potential distributions of native and alien
1780 Australian acacias with correlative and mechanistic models. *Diversity and*
1781 *Distributions* **17**, 978–1000.

1782 WERNBERG, T., SMALE, D.A., THOMSEN, M.S. (2012). A decade of climate change
1783 experiments on marine organisms: procedures, patterns and problems. *Global*
1784 *Change Biology* **18**, 1491–1498.

1785 WERNBERG, T., BENNETT, S., BABCOCK, R.C., DE BETTIGNIES, T., CURE, K., DEPCZYNSKI,
1786 M., DUFOIS, F., FROMONT, J., FULTON, C.J., HOVEY, R.K., HARVEY, E.S., HOLMES,
1787 T.H., KENDRICK, G.A., RADFORD, B., SANTANA-GARCON, J., *et al.* (2016). Climate-
1788 driven regime shift of a temperate marine ecosystem. *Science* **353**, 169–172.

1789 WILLIAMS, J.W. & JACKSON, S.T. (2007). Novel climates, no-analog communities, and
1790 ecological surprises. *Frontiers in Ecology and the Environment* **5**, 475–482.

1791 WILLIAMS, S.E., SHOO, L.P., ISAAC, J.L., HOFFMANN, A.A. & LANGHAM, G. (2008).
1792 Towards an integrated framework for assessing the vulnerability of species to
1793 climate change. *PLoS Biology* **6**, e325.

1794 WINDER, M. & SCHINDLER, D.E. (2004). Climate change uncouples trophic interactions
1795 in an aquatic ecosystem. *Ecology* **85**, 2100–2106.

1796 WINKLER, D. (2008). Yartsa Gunbu (*Cordyceps sinensis*) and the fungal commodification
1797 of Tibet's rural economy. *Economic Botany* **62**, 291–305.

1798 WISE, R.M., FAZEY, I., STAFFORD SMITH, M., PARK, S.E., EAKIN, H.C., ARCHER VAN
1799 GARDEREN, E.R.M. & CAMPBELL, B. (2014). Reconceptualising adaptation to
1800 climate change as part of pathways of change and response. *Global Environmental*
1801 *Change* **28**, 325–336.

1802 WISZ, M.S., POTTIER, J., KISSLING, W.D., PELLISSIER, L., LENOIR, J., DAMGAARD, C.F.,
1803 DORMANN, C.F., FORCHHAMMER, M.C., GRYTNES, J-A., GUISAN, A., HEIKKINEN,
1804 R.K., HØYE, T.T., KÜHN, I., LUOTO, M., MAIORANO, L., *et al.* (2013). The role of

1805 biotic interactions in shaping distributions and realised assemblages of species:
1806 implications for species distribution modelling. *Biological Reviews* **88**, 15–30.
1807 WORLD BANK (2008). World development report 2008: agriculture for development.
1808 Washington DC, USA.
1809 YAN, Y., LI, Y., WANG, W.J., HE, J.S., YANG, R.H., WU, H.J., WANG, X-L., LEI, J.,
1810 TANG, Z. & YAO, Y.J. (2017). Range shifts in response to climate change of
1811 *Ophiocordyceps sinensis*, a fungus endemic to the Tibetan Plateau. *Biological*
1812 *Conservation* **206**, 143–150.
1813 ZARNETSKE, P.L., SKELLY, D.K. & URBAN, M.C. (2012). Biotic multipliers of climate
1814 change. *Science* **336**, 1516–1518.
1815 ZIMMERMANN, N.E., YOCCOZ, N.G., EDWARDS, T.C., MEIER, E.S., THULLER, W.,
1816 GUISAN, A., SCHMATZ, D.R. & PEARMAN, P.B. (2009). Climatic extremes improve
1817 predictions of spatial patterns of tree species. *Proceedings of the National Academy*
1818 *of Sciences* **106**, 19723–19728.

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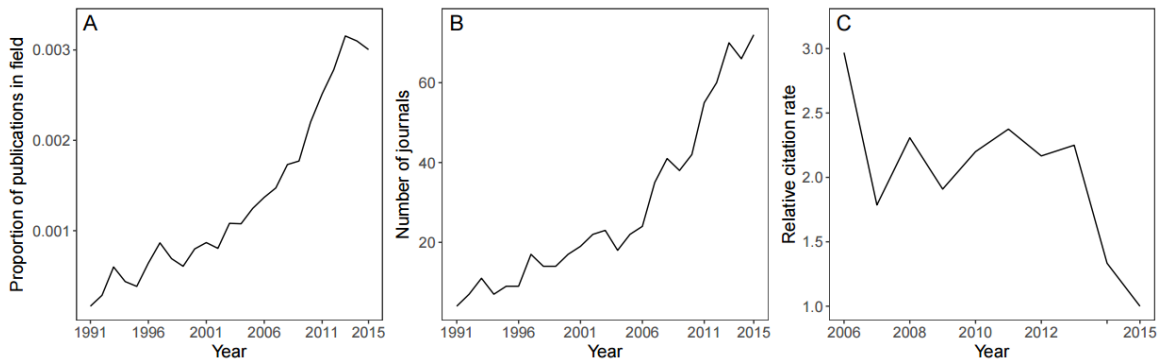
1820 **X. SUPPORTING INFORMATION**

1821 Additional supporting information may be found in the online version of this article.

1822 **Appendix S1.** Details of extraction and analysis of research foci in the field of species
1823 redistribution.

1824 **Table S1.** List of 109 ‘trending’ terms defined as word stems that significantly increased
1825 in annual frequency of appearance in publications on species redistribution since 1995.

1826 **Table S2.** List of 49 ‘high-impact’ terms defined as word stems associated with higher
1827 than average citation rates, accounting for publication year.



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1829 **Fig. 1.** Publication trends for papers on species range shifts. (A) Proportion of
 1830 publications addressing species redistribution over a time, as a fraction of all papers in
 1831 environmental sciences/ecology fields. (B) Number of journals publishing species
 1832 redistribution papers over time. (C) Median annual citation rate of species redistribution
 1833 papers decreases to the median annual citation rate of papers in the general environmental
 1834 sciences/ecology field.

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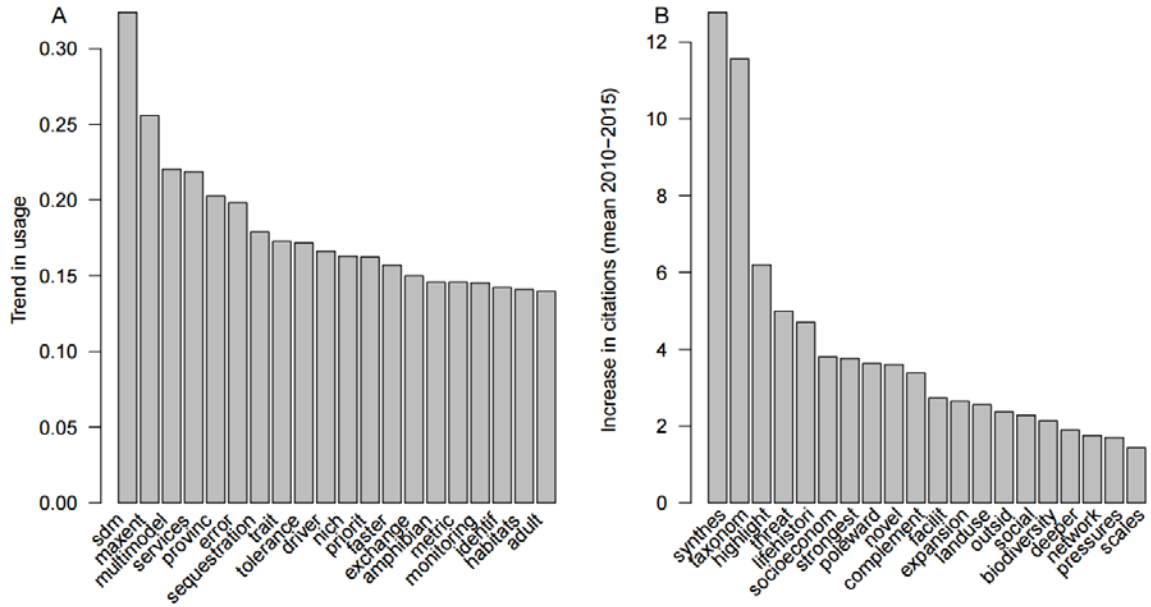
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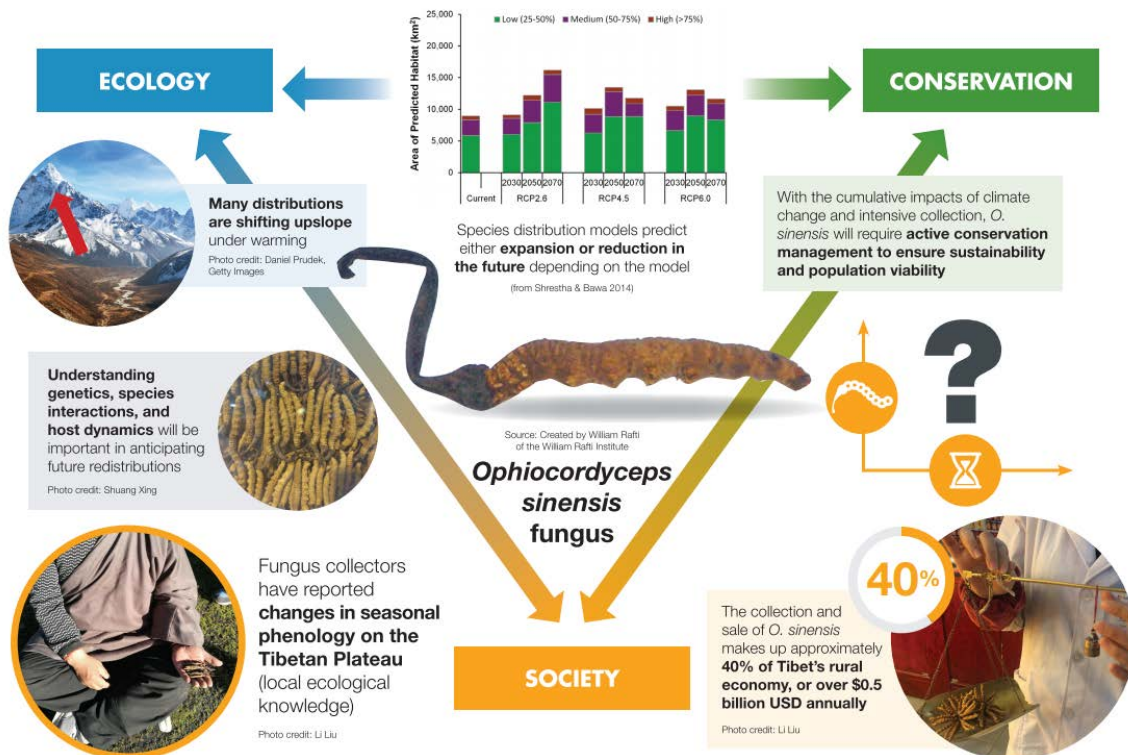
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1845 **Fig. 2.** Analysis of trends used within the species redistribution literature: (A) top 20
 1846 trending words that increased significantly in usage, and (B) top 20 high-impact words
 1847 that correspond with increased citation rates of papers published between 2010 and 2015.
 1848 See Supporting Information for details of the analysis. sdm, species redistribution model.

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1854 **Fig. 3.** *Ophiocordyceps sinensis*, a caterpillar-feeding fungus of the Tibetan plateau,
 1855 presents a useful case study for the importance of an integrated and interdisciplinary
 1856 approach to species redistribution. The species is widely consumed throughout China,
 1857 largely for medicinal purposes. Distribution shifts of the species in recent decades have
 1858 been observed, but models under future climates have yielded divergent outcomes (both
 1859 range expansion and reduction) based on different sets of data and approaches (Yan *et al.*,
 1860 2017). Open questions remain about the physiology of the species and, particularly
 1861 critical in this case, how interactions with the host caterpillar species might change under
 1862 warming. *O. sinensis* is a critical part of the Tibetan economy (Winkler, 2008) but is also
 1863 vulnerable to extinction given intensive collecting pressure and possible climate change
 1864 impacts (Yan *et al.*, 2017). Greater understanding of the ecology of the species will assist

1865 in addressing economic and conservation challenges. But, equally importantly, the
1866 Indigenous populations that depend upon *O. sinensis* for income can also provide
1867 invaluable insights into complex ecological systems and how climate change might be
1868 changing these systems (Klein *et al.*, 2014).

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1871 Table 1. Key questions posed by attendees of the 2016 *Species on the Move* conference
 1872 and additional questions developed for each research focus: Ecology, Conservation and
 1873 Society. Also included for each key question are cross-cutting themes (*sensu* Kennicutt *et*
 1874 *al.*, 2015). ECO, Ecology; CONS, Conservation; SOC, Society; SDM, species
 1875 redistribution model.

Key questions and topics	Approaches and interdisciplinary cross-cutting	References
Ecology		
To what extent will novel species combinations impact future change to ecological communities? CONS/SOC	Experimental manipulation Modelling	Urban <i>et al.</i> (2012) Alexander <i>et al.</i> (2015)
How much do biotic interactions affect range shifts, compared to the effects on ranges from species traits, geographic context and physical rates of change? CONS	Incorporation of species interactions into SDMs Palaeoecological methods	Ferrier <i>et al.</i> (2007) Wisz <i>et al.</i> (2013) Blois <i>et al.</i> (2013) Fitzpatrick <i>et al.</i> (2013)
How can we predict species responses to extreme events? Much empirical physical research is focused on extreme events, but most biological/ecological modelling evaluates slow long-term change. CONS/SOC	Incorporate extreme climatic events into modelling/predictions Measure key mechanistic processes	Zimmermann <i>et al.</i> (2009) Azzurro <i>et al.</i> (2014) Briscoe <i>et al.</i> (2016)
What is the role of plasticity (physiological, behavioural) in mediating species responses within and between populations, and how does plasticity affect modelling predictions? CONS	Accounting for intraspecific differences in realised niche	Valladares <i>et al.</i> (2014) Bennett <i>et al.</i> (2015)

What are the main determinants of time lags in biotic responses to climate change (the climatic debt)? CONS	Explaining magnitude of lags in response to climate change in addition to the magnitude of the shift	Bertrand <i>et al.</i> (2016)
How will uncertainty in climate change projections affect predictions of species redistribution? CONS	Multi-model ensemble averaging	Fordham <i>et al.</i> (2011)
How can co-occurring taxa/communities best be modelled under changing climates? CONS	Community-level models	Maguire <i>et al.</i> (2016)
Conservation		
How can we integrate uncertainty into the conservation planning process? What time frame allows for robust actions while minimising uncertainty? SOC	Decision science	Shoo <i>et al.</i> (2013)
How can we monitor large-scale landscapes and seascapes and complex natural and social interactions best across regions? ECO/SOC	Monitoring to adjust (adaptive) conservation actions continuously Interpretation of satellite remote-sensing, population surveys	Tøttrup <i>et al.</i> (2008) Pettorelli <i>et al.</i> (2014) Kays <i>et al.</i> (2015)
What are the values and risks associated with novel communities that arise from individual species range shifts? What are the effects of invasive species on the maintenance of phylogenetic and functional diversity? ECO	Assessing functional and phylogenetic diversity Palaeoecological methods	Buisson <i>et al.</i> (2013) Albouy <i>et al.</i> (2015)

How do we apply prescriptive/assisted evolution to accommodate species redistribution? ECO	Molecular ecology Conservation genomics	Smith <i>et al.</i> (2014) Hoffmann <i>et al.</i> (2015)
How can we build dynamic conservation management strategies that cope with changes in species distributions? SOC	Sequential dynamic optimisation	Alagador <i>et al.</i> (2014)
How does climate change interact with other drivers of biodiversity change (e.g. invasive species, land use and fire) to influence outcomes for biodiversity (all species)? ECO/SOC	Management of local stressors Coupled population and SDMs	Russell <i>et al.</i> (2009) Bonebrake <i>et al.</i> (2014) Jetz <i>et al.</i> (2007)
Will microrefugia allow species to persist locally as climate changes? If so, where are they? ECO	Climate change metrics Fine-scale grids	Keppel <i>et al.</i> (2012) Ashcroft <i>et al.</i> (2012)
Society		
How do species redistributions impact ecosystem services through biodiversity reshuffling? ECO	Coupled SDM and trait-based methods	Moor <i>et al.</i> (2015)
What are the key messages we need to communicate to the public about shifting distribution of marine and terrestrial species? How do we communicate them effectively? ECO	Creating opportunities for respectful dialogue between scientists and the public Improving ecological and science literacy	Jordan <i>et al.</i> (2009) Groffman <i>et al.</i> (2010)
How can people and communities contribute further to monitoring the impacts of changes in the distributions and relative abundances of species caused by climate change? ECO/CONS	Community-based observation systems	Higa <i>et al.</i> (2013) Chandler <i>et al.</i> (2016)

What is the effect of climate change on soil biodiversity, and how does climate change affect soil health and agriculture? ECO/CONS	SDMs and soil science	Hannah <i>et al.</i> (2013) le Roux <i>et al.</i> (2013)
How can marine spatial planning be reorganised to reconcile biodiversity conservation and food security? ECO/CONS	Adaptive management Restoration	Garcia & Rosenberg (2010) Rice & Garcia (2011) Sale <i>et al.</i> (2014)
What practical adaptations for agriculture, fisheries and aquaculture can be promoted to minimise the risks to food security and maximise the opportunities that are expected to arise from altered species distributions? ECO/CONS	Adaptive management Restoration	Bradley <i>et al.</i> (2012) Bell <i>et al.</i> (2013)
How will climate change impact the redistribution of disease-associated species and influence infectious disease dynamics? ECO	Host and vector SDMs	Rohr <i>et al.</i> (2008) Harrigan <i>et al.</i> (2014)
How can international environmental agreements that influence resource-management decisions incorporate local community observations and insights into their guidance and policy-making objectives? CONS	Evidence-based legal processes Multiple evidence-based frameworks	Tengö <i>et al.</i> (2017)

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