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1 **Threat management priorities for conserving Antarctic biodiversity**

2

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59 **Abstract:**

60 Antarctic terrestrial biodiversity faces multiple threats, from invasive species to climate
61 change. Yet no large-scale assessments of threat management strategies exist. Applying a
62 structured participatory approach, we demonstrate that existing conservation efforts are
63 insufficient in a changing world, estimating that 65% (at best 37%, at worst 97%) of native
64 terrestrial taxa and land-associated seabirds are likely to decline by 2100 under current
65 trajectories. Emperor penguins are identified as the most vulnerable taxon, followed by other
66 seabirds and dry soil nematodes. We find that implementing 10 key threat management
67 strategies in parallel, at an estimated present-day equivalent annual cost of US\$23 million,
68 could benefit up to 84% of Antarctic taxa. Climate change is identified as the most pervasive
69 threat to Antarctic biodiversity and influencing global policy to effectively limit climate
70 change is the most beneficial conservation strategy. However, minimising impacts of human
71 activities and improved planning and management of new infrastructure projects are cost-
72 effective and will help to minimise regional threats. Simultaneous global and regional efforts
73 are critical to secure Antarctic biodiversity for future generations.

74 **Introduction**

75

76 Conserving Antarctic species for future generations is in the interest of all humankind.
77 Designated as a natural reserve, devoted to peace and science, Antarctica is home to numerous
78 endemic species (Chown and Convey 2007). Charismatic emperor and Adélie penguins capture
79 the world's imagination, whilst the nematode *Scottinema lindsayae* survives in saline soils that
80 are inhospitable to other eukaryotic life forms (Adams et al. 2007). These endemic species
81 possess distinctive adaptations that allow them to survive Antarctica's extreme conditions
82 (Convey 1996; Convey and Peck 2019). Some of them may even be key for developing new
83 technologies or medicines, including sustainable biomanufacturing processes, uses in the
84 frozen food industry (Muñoz et al. 2017), and biodiesel production (Lv et al. 2019).
85 Furthermore, Antarctica and the Southern Ocean provide essential ecosystem services, in
86 particular regulating global climate via processes driving atmospheric circulation and ocean
87 currents, and the absorption of anthropogenic heat and CO₂ (Turner et al. 2009; Rintoul et al.
88 2018). Finally, Antarctica is one of the few places on the planet that can still be considered
89 largely unspoilt by the industrial development of humanity (Leihy et al. 2020).

90

91 Although Antarctica is relatively free from many of the environmental threats that beset the
92 rest of the world, e.g., deforestation to generate land for agriculture, threats to Antarctic
93 biodiversity are intensifying at an unprecedented rate (Chown et al. 2017). The Antarctic
94 Peninsula was one of the most rapidly warming regions globally in the second half of the
95 Twentieth Century (Turner et al. 2009). This trend has recently paused (Turner et al. 2016), but
96 many locations have still experienced short term extreme events, such as heat waves with
97 record high air temperatures (18.3 °C; Robinson et al. 2020, or +40 °C above average;
98 Bergstrom et al. 2022), and recent studies report evidence of a strong warming trend re-

99 establishing (e.g., on the South Orkney Islands; Cannone et al. 2022). Scientific activities and
100 associated infrastructure are expanding (Brooks et al. 2019) and annual tourist numbers have
101 increased more than eightfold since the 1990s, to nearly 75,000 in 2019/2020 (Bender et al.
102 2016; IAATO 2020), although then experiencing a temporary hiatus as a result of the global
103 COVID-19 pandemic (Hughes and Convey 2020). The current suite of Antarctic protected
104 areas do not represent the continent's full range of biodiversity and some are experiencing
105 anthropogenic pressures (Hughes et al. 2013; 2021; Shaw et al. 2014; Wauchope et al. 2019).
106 Although Antarctica's geographic isolation and extreme climate have historically afforded
107 some protection to the continent, the combination of increasing human activity and warming
108 is also lowering the barriers to the arrival and establishment of non-native species (Hughes et
109 al. 2006; 2020; Duffy et al. 2017).

110

111 The threats to Antarctic species and ecosystems are increasingly well documented, however,
112 species vulnerability to threats is poorly understood, and decision-makers also lack the
113 information required to prioritise, develop and implement threat management responses
114 (Chown et al. 2017). Understanding how vulnerable species are to threats, and how varying
115 conservation actions would benefit those species, is important for tailoring appropriate
116 conservation responses across time and space (Lee et al. 2015; Tulloch et al. 2015). A number
117 of studies examine vulnerability of a particular species or taxa to a specific threat (e.g., open
118 top chamber experiments indicate the springtail *Cryptopygus antarcticus* is vulnerable to
119 warming; Bokhorst et al. 2008), though there have been limited efforts to undertake broad scale
120 quantifications of vulnerability across terrestrial groups. Species that are not vulnerable are less
121 likely to require investment of conservation resources.

122

123 Resources for conservation are often finite and it is important to understand how and where
124 time and effort should be invested to achieve the best outcomes (Murdoch et al. 2007; Bottrill
125 et al. 2008). Cost-effectiveness approaches have been demonstrated to provide conservation
126 solutions that create greater benefits for biodiversity with limited resources, compared to when
127 cost-effectiveness is not considered (Balmford et al. 2000; Murdoch et al. 2010; Auerbach et
128 al. 2014). Identifying the conservation strategies that provide the highest expected benefit can
129 also be useful when cost estimates are uncertain or when cost is not a barrier (Murdoch et al.
130 2010). Despite the interest in conserving Antarctic biodiversity, there is no comprehensive
131 assessment of the costs of effective conservation in Antarctica, or the expected benefits and
132 cost-effectiveness of applying various conservation strategies. Some specific examples exist,
133 e.g., Raymond and Snape (2016), who use triage to identify potential candidate sites for
134 undertaking remediation.

135

136

137 Antarctic Treaty Parties recognise the importance of drawing on the best available science to
138 inform decisions, yet key questions regarding where and how conservation resources should
139 be invested remain unanswered. Here we seek to answer three of the most pressing questions:
140 *1) Which terrestrial Antarctic taxa are most vulnerable to threats? 2) What management*
141 *actions and resource investment will provide the greatest benefit to biodiversity and ensure*
142 *persistence across all terrestrial biodiversity groups? 3) Which management strategies should*
143 *we focus on to provide the highest conservation return on investment?* We answer these
144 questions by undertaking a comprehensive quantification of the relative importance and return
145 on investment of existing and potential management actions and strategies for reducing threats
146 and securing Antarctica's biodiversity. We also provide crucial first estimates of the costs of
147 these strategies.

148

149 **Our Approach**

150

151 Antarctica's size, isolation and extreme environmental conditions make research challenging.
152 Our understanding of Antarctica's biodiversity is hampered by a lack of quantitative data,
153 especially on species interactions, taxonomy and baseline data on abundance and distributions.
154 In this context, expert knowledge, together with available empirical data, can significantly
155 improve the foundation on which conservation plans and management actions are based
156 (Martin et al. 2012a). Antarctic experts have accumulated decades of experience in the region
157 and hold unique knowledge encompassing most terrestrial biodiversity groups. Using this
158 knowledge, we apply a structured, participatory decision-science approach (Carwardine et al.
159 2012, 2019) to quantify and prioritise cost-effective and complementary strategies for
160 achieving biodiversity conservation in terrestrial Antarctica (see Materials and methods).

161

162 First, experts collectively defined a set of management strategies with the aim of safeguarding
163 Antarctic biodiversity until 2100 (Table 1), for both the Antarctic Peninsula and continental
164 Antarctic regions (see Fig. 1b). It was important to consider these regions separately because
165 they are climatically and biologically distinct (Chown and Convey 2007) and the threats and
166 the species responses to threats are likely to be different between the two regions. Each
167 management strategy was targeted towards abating local threats (e.g., remediating
168 contaminated sites), except for the '*Influence external policy*' strategy which was unique in
169 being targeted towards reducing global threats (namely climate change). Each management
170 strategy is made up of multiple conservation actions which, when implemented together, will
171 achieve the strategy's objectives (Table 1). Experts estimated the cost and feasibility for
172 undertaking each action (see Materials and methods). For example, developing a best practice

173 manual for remediation of contaminated sites was estimated to require one full-time equivalent
174 employee (FTE) for the first year and an ongoing 0.25 FTE each year to update and maintain
175 the manual, with a likelihood of uptake of 100%. This is the equivalent of 21.75 FTE and would
176 cost \$1.7 M over the 83-year timeframe. The conservation actions, and cost and feasibility of
177 each action, are detailed in S1 Data. Because the '*Influence external policy*' strategy is targeted
178 toward reducing global threats, whilst we identified costs and actions, they are focused only on
179 the tasks that can be undertaken directly by the Antarctic community (i.e., public and policy
180 engagement; see S1 Data). In consequence the estimated costing does *not* represent the full
181 global cost (nor the full global benefits) of reducing emissions to limit warming to 2 °C
182 (UNFCCC 2015) and we therefore did not include '*Influence external policy*' in the cost-
183 effectiveness or complementarity analyses.

184

185 Conservation benefits were quantified at the strategy level, where the benefit was estimated
186 using the difference between current and predicted future levels of intactness of biota. We
187 defined intactness as a measure of how 'intact' a taxon will be compared to 2017 levels (see
188 Materials and methods). A score of 100 indicates - 'intactness same as today', 0 - 'taxon is
189 completely degraded', and 200 - 'taxon is doing twice as well'. A metric based on extinction
190 risk or persistence probability was considered inappropriate for Antarctic biodiversity given
191 that very few species are predicted to be at risk of extinction by the end of the century. As per
192 expert elicitation protocols (Hemming et al. 2018), biodiversity experts provided a best
193 estimate, and lower (worst case scenario) and upper (best case scenario) bounds of predicted
194 future intactness of each taxon in response to each management strategy and for a 'business as
195 usual' baseline (Table 1). They also provided a confidence estimate to capture uncertainty,
196 which together with the bounds were used in a sensitivity analysis (McBride et al. 2012;

197 Carwardine et al. 2019). They also identified knowledge shortfalls for each taxon (S1 and S2
198 Tables; Hortal et al. 2015).

199

200 Using the cost, feasibility and benefit estimates we assessed the expected benefit, cost-
201 effectiveness and complementarity of strategies for conserving Antarctic biodiversity to the
202 end of the Twenty-first Century under IPCC climate change scenarios (IPCC 2013). For the
203 *'Influence external policy'* strategy we assessed the option of influencing global climate
204 policy to abate the threat of climate change, where an outcome of the successful
205 implementation of this strategy is that greenhouse gas emissions are reduced sufficiently to
206 meet the 2 °C Paris Climate Agreement, limiting warming to <2 °C above pre-industrial
207 levels and ideally to 1.5 °C (UNFCCC 2015). Thus, *'Influence external policy'* was assessed
208 under the Representative Concentration Pathway (RCP) 2.6 scenario adopted by the
209 Intergovernmental Panel on Climate Change (IPCC), the only RCP scenario that keeps global
210 warming to <2 °C (Meinshausen et al. 2011; IPCC 2013). All other strategies were assessed
211 under RCP4.5 and RCP8.5, where RCP4.5 represents moderate carbon emissions and RCP8.5
212 a more severe scenario (IPCC 2013).

213 **Table 1.** Overview of proposed management strategies for conserving Antarctic biodiversity.
 214 Shorthand strategy names are given in brackets. ‘Current’ refers to the state of the Antarctic
 215 environment and associated management actions in 2017. Grey shading identifies global
 216 strategies or a combination of regional and global strategies. More details on specific actions,
 217 costs and feasibility are provided in S1 Data.

Strategy Name	Objectives and details
Business as usual (<i>Baseline</i>)	<i>Continue with actions and strategies currently in use, but neither expand on these strategies nor employ new strategies.</i> Baseline against which to measure other strategies.
Remediation (<i>Remediate</i>)	<i>Increase amount of, or improve, quality of habitat available to biodiversity in comparison to habitat currently available.</i> By remediating 20 environmentally damaged (physically, chemically, biologically) sites (including freshwater) that will provide the greatest benefit to biodiversity, including remediation of legacy waste sites if necessary.
Manage existing infrastructure (<i>Exist infra.</i>)	<i>Reduce and minimise impacts of existing infrastructure compared to current levels.</i>
Manage new infrastructure (<i>New infra.</i>)	<i>Prevent, reduce and minimise impacts of new infrastructure.</i>
Transport management (<i>Transport</i>)	<i>Reduce and minimise impacts of transport compared to current levels.</i>
Manage non-native species and disease (<i>Non-native</i>)	<i>Reduce impacts of non-native species and disease on native biodiversity.</i> Where possible prevent establishment of new populations of non-native species. Eradicate or, if not possible, minimise impacts of established non-native species.
Protect vegetation from physical impacts (<i>Protect vegetation</i>)	<i>Reduce physical impacts of human activities and native vertebrate activities on vegetation.</i> Halt the decline (or loss) of vegetation and associated taxa due to direct physical damage/impact at key sites in the Antarctic Peninsula (e.g. animal damage).
Protecting areas (<i>Protecting areas</i>)	<i>Reduce impacts of human activities on biodiversity by increasing the amount and representation of habitat in protected areas.</i> Develop the Antarctic Specially Protected Area (ASPA) system to improve representation of the values specified in the Environmental Protocol and ensure the network incorporates contemporary systematic conservation planning pillars.
Managing and protecting species (<i>Protecting species</i>)	<i>Reduce threatening impacts on taxa identified as threatened by 2100.</i> 1. Identify and protect threatened species (assume 10 - 15 species to be identified and listed under this strategy) 2. Prevent extinction of native species in-situ.
Minimise impacts of human activity (<i>Human activities</i>)	<i>Prevent and minimise physical impacts on biodiversity and habitats compared to current levels that stem from human activities in Antarctica</i> (e.g. fieldwork, tourism, station activities). Relevant where improving education and training, and implementing standard practices, on-ground operating procedures and compliance is likely to reduce impacts through changes in human behaviour.
Influence external policy (<i>Influence ext. policy</i>)	<i>Minimise or reduce impacts of threats (primarily climate change) on Antarctic biodiversity that originate externally via engagement with appropriate policy bodies and raising public awareness.</i> Note: Outcome of strategy is an assumption that the Paris Climate Agreement of <2 °C warming is achieved. Use RCP2.6 instead of 4.5/8.5.
All strategies excluding ‘influence external policy’ (<i>All strats. excl IEP</i>)	All management strategies combined except ‘Influence external policy’.
All strategies combined (<i>All strategies</i>)	All management strategies combined.

218

219 **Results and Discussion**

220

221 **Threat vulnerability**

222

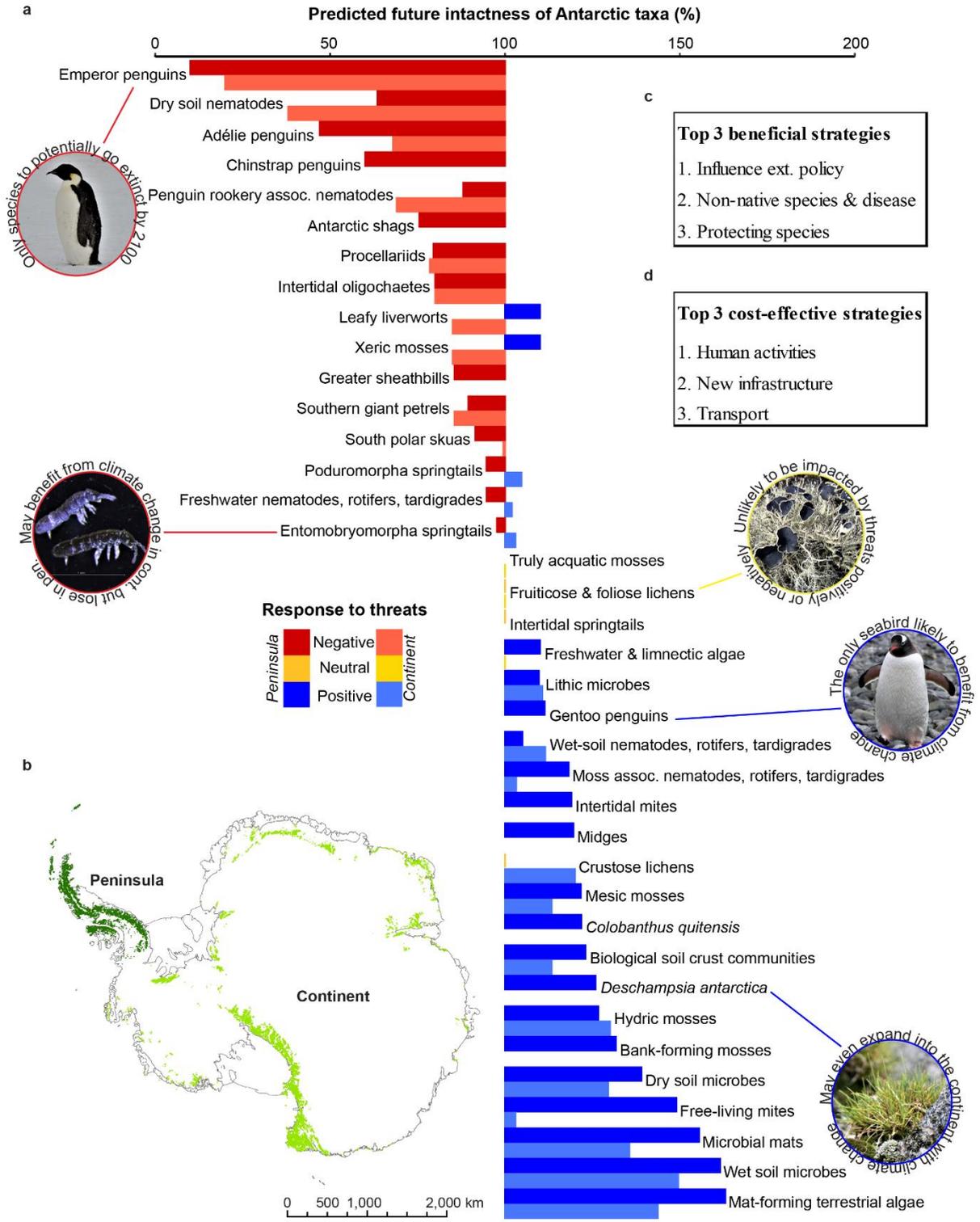
223 Taxa varied in their expected vulnerability to threats by 2100 (Fig. 1a, see raw values on the
224 Australian Antarctic Data Centre; <https://doi.org/10.26179/5da8f8e7a2256>). Some species are
225 predicted to decline under future conditions, whilst others are expected to benefit, with climate
226 change likely to be the primary factor driving these responses. Emperor penguins (*Aptenodytes*
227 *forsteri*) were identified as the most vulnerable taxon, and the only one at risk of possible
228 extinction (see worst-case scenario/lower bound: <https://doi.org/10.26179/5da8f8e7a2256>),
229 followed by dry soil nematodes and Adélie (*Pygoscelis adeliae*) and chinstrap (*P. antarcticus*)
230 penguins. Recent declines in dry soil nematodes in the McMurdo Dry Valleys have been linked
231 to a changing climate (Andriuzzi et al. 2018), as have declines among Adélie penguins in the
232 Atlantic sector (Lynch et al. 2012). Up to 80% of emperor penguin colonies are projected to be
233 quasi-extinct by 2100 (decline by >90%) with business-as-usual increases in greenhouse gas
234 emissions (Jenouvrier et al. 2020). However, if Paris Climate Agreement measures to limit
235 warming to <2 °C are met, this estimate reduces to 31% (Jenouvrier et al. 2020). Several taxa
236 are predicted to be vulnerable in only one region while increasing intactness in the other (e.g.,
237 xeric mosses), though the taxa may be classed as vulnerable overall when averaged. Research
238 targeted to better understand why some taxa are more vulnerable than others (i.e., sensitivity
239 and exposure; Williams et al. 2008) and the spatial patterns of these drivers across taxa, can
240 inform conservation actions for particular taxa or regions (Lee et al. 2015). Some of the most
241 vulnerable taxa may also warrant special protection through designation under Annex II of the

242 Environmental Protocol as Specially Protected Species, as has already been suggested for
243 emperor penguins (Trathan et al. 2020).

244

245 Some taxa were not predicted to be sensitive to climate change or other threats and their
246 intactness is expected to remain similar to current levels. Others may expand their
247 distribution and/or abundance due to future changes in the region, including those that are
248 primarily constrained by climate-related abiotic factors such as temperature and limited water
249 availability (Convey and Peck 2019). Indeed, evidence suggests this is already occurring –
250 the increase in growth rate of bank-forming moss on the Antarctic Peninsula (Amesbury et al.
251 2017), rapid expansion in some populations of the two native flowering plant species
252 *Colobanthus quitensis* and *Deschampsia antarctica* (Cannone et al. 2016; 2022), and
253 southward range extensions of gentoo penguins (*P. papua*; Lynch et al. 2012). However,
254 these species will not continue expanding indefinitely and the longer-term impacts of
255 environmental change for all species remain uncertain and complex. The expansion of some
256 taxa may also negatively impact other native species at a competitive disadvantage (Lee et al.
257 2017). Some experimental evidence suggests that the invasive grass *Poa annua* is likely to
258 compete with, and possibly outcompete, the two native flowering plants (Molina-Montenegro
259 et al. 2012; 2019).

Antarctica in 2100



261 **Fig. 1.** Vulnerability of terrestrial Antarctic biodiversity to all threats under climate forcing
262 scenario RCP8.5 and the most beneficial and cost-effective conservation management
263 strategies. **a,** Regional vulnerability of biodiversity groups to all potential threats, where
264 colours represent each taxon's expected response to threats, with darker/lighter shadings
265 denoting the regional delineation as peninsula or continent, respectively. Bars represent
266 experts' best estimate of the future intactness of each taxon relative to current (100%)
267 intactness if no additional conservation strategies are implemented. Taxa with values below
268 100% are predicted to be vulnerable, whilst taxa with values beyond 100% are predicted to
269 benefit. **b,** The two main Antarctic regions considered in this study **c,** The top three individual
270 management strategies that would provide the highest total benefit to biodiversity. **d,** The top
271 three most cost-effective strategies for conserving biodiversity. The data underlying this
272 Figure can be found in S2 Data. The Antarctic coastline file for the map has been
273 downloaded from the Antarctic Digital Database (ADD Version 7; <http://www.add.scar.org>).

274
275

276 **Benefits of management strategies**

277

278 Under the current management scenario and if global greenhouse gas emissions continue to
279 track above 2 °C warming (Höhne et al. 2020), approximately 65% (at best 37% and at worst
280 97%) of taxa will decline by 2100 (Fig. 2a – 'Baseline'; S1 Fig.). These results demonstrate
281 that current conservation actions under the provisions of the Protocol on Environmental
282 Protection to the Antarctic Treaty are insufficient to conserve Antarctic biodiversity in a
283 warmer future. If comprehensive management is implemented (*'All strategies combined'*
284 approach) approximately 63% (minimum 37%, maximum 84%) of taxa will benefit and the
285 number of taxa declining compared to their current intactness could be reduced to 42% (Fig.

286 2a). However, 53 – 61%, and up to 68%, of taxa would benefit if the single '*Influence external*
287 *policy*' strategy aimed at reducing global climate change was successful. If climate change
288 cannot be mitigated, all regional strategies combined ('*All strategies combined excluding*
289 *policy influence*') will still benefit 53 – 55%, and up to 74% of taxa (Fig. 2a), though the total
290 amount of benefit achieved is reduced (Fig. 2b). The individual strategy benefitting the next
291 most taxa is '*Manage non-native species and disease*' (47% for both RCP4.5 and RCP8.5), and
292 then both '*Managing and protecting species*' and '*Protecting areas*' for RCP4.5 (45%) and
293 '*Protecting areas*' for RCP8.5 (40%).

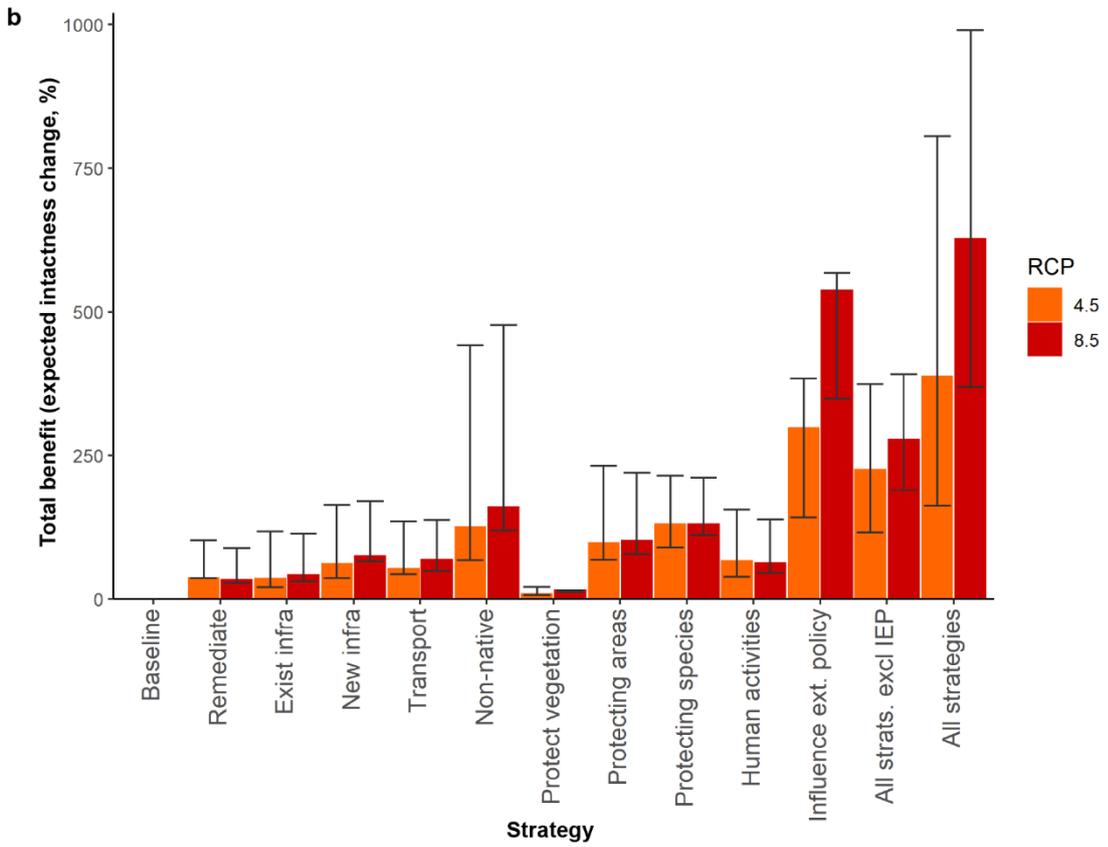
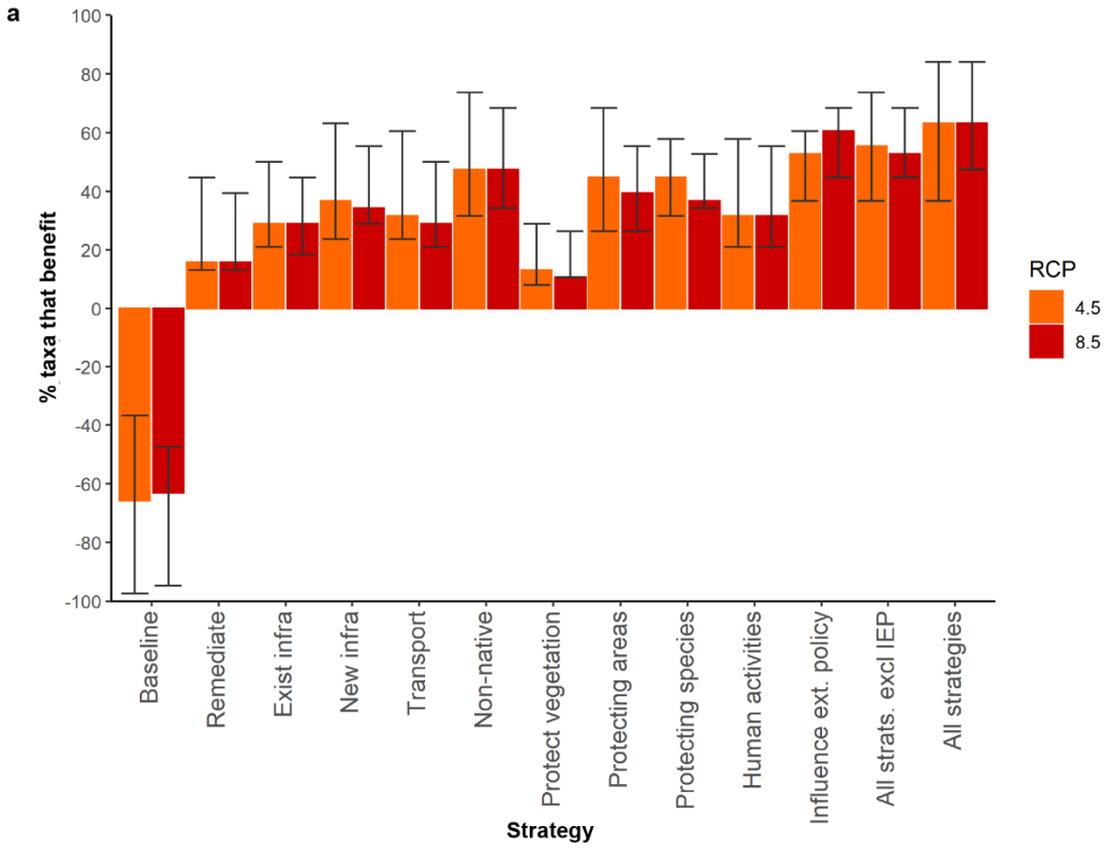
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295 The strategies that provide the highest total expected benefits, when combined for all taxa and
296 both regions, are almost the same regardless of climate forcing scenario (Fig. 2b; Table 2). '*All*
297 *strategies combined*', unsurprisingly, provides the highest total benefit. The second highest
298 total benefit is '*Influence external policy*' followed by '*All strategies combined excluding*
299 *policy influence*'. For RCP4.5 the next best strategy is '*Managing and protecting species*',
300 whilst for RCP8.5 it is '*Manage non-native species and disease*' (Fig. 2b; Table 2). Regionally,
301 the same three strategies deliver the greatest benefit, though higher benefits are generally
302 predicted for the Antarctic Peninsula region than the continent (S2 Fig.), possibly due to the
303 greater projected changes there.

304

305 While the above summarises the number of taxa that would benefit and the total amount of
306 benefit predicted under each management strategy for all taxa, it does not provide information
307 on the amount of benefit to an individual taxon (where some taxa may benefit far more from a
308 management strategy than others). Responses to management strategies vary amongst taxa in
309 both scale and direction (see benefits for individual taxa shown on the Australian Antarctic

310 Data Centre; <https://doi.org/10.26179/5da8f8e7a2256>), for example Adélie penguins are predicted
311 to increase intactness by ~45% with the *'Influencing external policy'* strategy (RCP8.5), whilst
312 Antarctic shags are predicted to benefit by ~10%. Most strategies reduce predicted declines.
313 However, for those species that are predicted to benefit with climate change, at least initially
314 (e.g., gentoo penguins), they benefit less with the milder RCP2.6 scenario in contrast to RCP4.5
315 or RCP8.5. Thus, it appears that they have reduced intactness with the RCP2.6 *'Influence*
316 *external policy'* strategy compared to the baseline RCP4.5 or RCP8.5 values.



319

320 **Fig. 2.** Response of Antarctic terrestrial biodiversity to various conservation management
321 strategies by the end of 2100 under two climate forcing scenarios (RCP4.5, RCP8.5). **a,**
322 Percentage of taxonomic groups likely to benefit. **b,** Total expected benefit of strategies
323 summed for all taxa and both regions combined. Bars represent the experts' best estimates
324 when assessing benefit, whilst error bars represent upper (best case scenario) and lower (worst
325 case scenario) bounds. An outcome of the '*Influence external policy*' (IEP) and '*All strategies*
326 *combined*' strategies is that carbon emissions are reduced globally (in line with the milder
327 RCP2.6); however, benefits are still calculated relative to the baselines of RCP4.5 and RCP8.5.
328 Values used to calculate benefit were capped at current (100%) intactness (see S1 Fig. for
329 inclusion of benefits beyond current intactness). The data underlying this Figure can be found
330 in S2 Data.

331

332

333 **Feasibility and costs**

334

335 The relationships between expected benefit, estimated cost and feasibility are illustrated in S3
336 Fig. *All strategies combined*' and '*All strategies combined excluding policy influence*' are both
337 high cost, high benefit strategies (S3 Fig. a), whereas '*Influence external policy*' is low cost (in
338 terms of direct cost to Antarctic decision-makers and managers), high benefit (S3 Fig. a).
339 However, '*Influence external policy*' has the lowest feasibility of all strategies, where the
340 experts estimated it to have a 'likelihood of success' of 5% in the short term and 45% from
341 year 30 onwards (averaged at 12% over the 83 years when incorporating the 'likelihood of
342 uptake' estimates), reflecting the uncertainty around the socio-political dynamics of climate
343 action and also noting global governments' so far unsuccessful efforts to drastically reduce

344 carbon emissions (Raftery et al. 2017). For the other strategies, *'Minimise impacts of human*
345 *activities'* has the second lowest feasibility. *'Transport management'* and *'Protecting areas'*
346 have the highest feasibility after the baseline (Table 2, S3 Fig. b).

347

348 Combining all strategies was consistently estimated to be the most expensive strategy, closely
349 followed by *'All strategies combined excluding policy influence'* (S4 Fig. a). Implementing all
350 conservation strategies combined excluding *'Influence external policy'* is estimated, using a
351 2% discount rate (where future costs are discounted to present day values; PVs), to cost an
352 average of US\$23 million annually until 2100 if costs were borne evenly across years (in
353 practice, a higher investment would be needed in earlier years and less in later years). In total
354 this equates to ~US\$1.92 billion (US\$3.69 billion with 0% discount; S4 Fig. a). This equates
355 to 0.004% of the global GDP in 2019 (US\$87.75 trillion; World Bank 2019), which is a
356 comparably small investment in the context of *i*) the timeframe and large number of nations
357 committed to protecting the Antarctic environment and *ii*) the future benefits to Antarctica's
358 terrestrial and seabird biodiversity. However, determining how strategies will be funded is not
359 straightforward due to Antarctica's governance arrangements, and costs would need to be
360 shared across Treaty Parties and National Antarctic Programmes.

361

362 The third and fourth most expensive strategies were *'Managing existing infrastructure'* and
363 *'Managing non-native species and disease'*, respectively. Both managing non-native species
364 and managing and protecting individual species were estimated to be relatively expensive
365 (approximately US\$763 and \$216 million respectively) as they include baseline biodiversity
366 surveys and could require intensive on-ground action, such as translocating individuals (e.g.,
367 as has been done for moss beds on King George Island; Câmara et al. 2021) or eradicating non-
368 native species (S1 Data). Yet if climate change was reduced or largely prevented, the risk of

369 non-native species invasion and necessary management of individual species is likely to be
370 reduced in comparison to what would otherwise be necessary due to the synergistic effect of
371 climate change on non-native species survival and expansion (Chown et al. 2012; Duffy et al.
372 2017; Duffy and Lee 2019). Some established non-native species are, however, already
373 expanding their ranges (Hughes et al. 2015; Bartlett et al. 2020). Consequences of milder
374 climates, such as reduced sea ice extent, may also increase accessibility for science and tourism,
375 thereby increasing the potential inadvertent transfer of non-native species. The cheapest
376 strategy was '*Minimise impacts of human activity*' (~US\$11.5 million), followed by '*Influence*
377 *external policy*' (~US\$14 million) and '*Protect vegetation from physical impacts*' (~US\$32
378 million). However, as noted above, the '*Influence external policy*' strategy does *not* include the
379 global costs of reducing emissions and thus we have excluded it from the cost-effectiveness
380 and complementarity analyses below.

381
382 Regionally, it would be more expensive to implement management strategies in the Antarctic
383 Peninsula (S4 Fig. b). This is due to rapid environmental change and the concentration of
384 human activity in the region resulting in a larger effort needed for strategies to be successful
385 (S3 Table). The largest cost components varied depending on the strategy (see S1 Data), but
386 overall, the major elements were funding long summer Antarctic berths (living costs and
387 transport), followed by the costs of Antarctic full-time equivalent salaries (S4 Fig. c).

388

389 **Cost-effective strategies**

390

391 Strategies varied in their cost-effectiveness, though the highest ranked strategies were
392 consistent across regions and RCP's (Table 2; S5 Table a), demonstrating our analyses are
393 robust to alternative future climate warming scenarios. Several strategies were identified as

394 providing the highest conservation return on investment, specifically: minimising impacts of
395 human activities, improved planning and management of new infrastructure projects, and
396 improving transport management (e.g., reducing pollution and disturbance caused by vessels
397 and aircraft; Table 2). Regionally, and with analyses using the upper and lower bound
398 estimates, the same three strategies were consistently ranked as the most cost-effective, though
399 their order varied (S4 and S5 Tables). Two of these three strategies (‘*Minimise impacts of*
400 *human activity*’ and ‘*Manage new infrastructure*’) were also identified as complementary (Fig.
401 3). These strategies offer opportunities for rapid and cost-effective improvements that can
402 support the more expensive, and already prioritised, management of non-native species
403 (Chown et al. 2017). For individual taxa, cost-effectiveness ranking of strategies varied (S6 –
404 S9 Tables), indicating that several strategies that rank lower for biodiversity overall may be
405 key for maintaining intactness in some taxa or locations, such as ‘*Protect vegetation from*
406 *physical impacts*’ for bank-forming mosses in the Antarctic Peninsula (S8 and S9 Tables).

407 **Table 2.** Evaluation of key management strategies for Antarctic biodiversity until 2100 under
408 two climate forcing scenarios (RCP4.5, RCP8.5). Including estimated total cost over the next
409 83 years (present value; using social discount rate of 2%), estimated feasibility, total expected
410 benefit (% change combined for all taxa), and cost-effectiveness rank. Ranked in order of cost-
411 effectiveness (CE) for RCP4.5. Benefits of strategies are calculated using best estimates of
412 improved intactness provided by experts (see S4 Table for calculations using upper and lower
413 bounds) and were capped at current (100%) intactness.

Strategy	Cost (US\$ M)	Feasibility	RCP4.5		RCP8.5	
			Benefit	CE Rank	Benefit	CE Rank
Minimise impacts of human activity	11.48	0.31	66.0	1	62.1	1
Manage new infrastructure	31.81	0.60	60.5	2	74.3	2
Transport management	39.08	0.72	52.3	3	68.3	3
Protecting areas	99.82	0.70	96.7	4	101.1	4
Managing and protecting species	215.94	0.53	129.6	5	130.2	5
Remediation	109.85	0.54	35.8	6	32.9	7

Protect vegetation from physical impacts	31.72	0.37	8.3	7	13.8	6
Manage non-native species and disease	762.62	0.58	124.9	8	159.3	8
All strategies excl influence ext. policy	1923.84	0.56	224.7	9	277.3	9
Manage existing infrastructure	811.43	0.60	34.8	10	40.8	10
Baseline	0	1.00	0	11	0	11

414

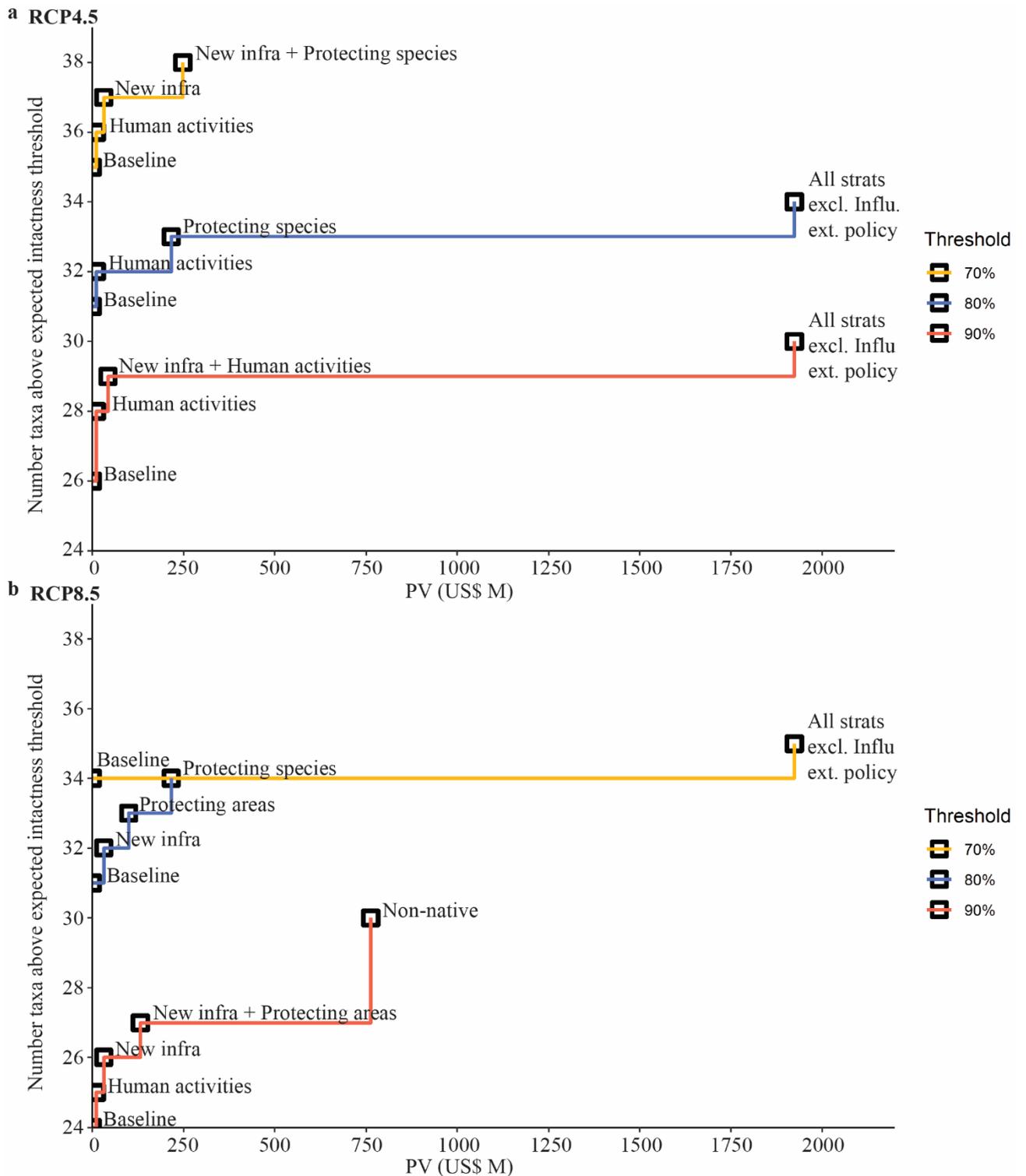
415

416 **Complementary strategies**

417

418 Sets of complementary strategies, which benefit as many taxa as possible under a given budget,
419 varied depending on the intactness threshold and climate forcing scenario (Fig. 3). However,
420 generally the most cost-effective strategies were also identified as complementary.
421 Combinations of ‘*Minimise impacts of human activity*’, and ‘*Manage new infrastructure*’ were
422 often identified for smaller budgets of less than US\$35 million, whilst ‘*Protecting areas*’ was
423 incorporated with an increased budget of around \$100 million and ‘*Managing and protecting*
424 *species*’ with a budget of \$216 million. If funding is not a barrier, then the \$1.92 billion ‘*All*
425 *strategies combined excluding external policy*’ will maximise the number of intact taxa in some
426 scenarios (Fig. 3). Our analysis also identified eight taxa that, in some scenarios (e.g., a 90%
427 threshold under RCP8.5), are unable to reach the target intactness thresholds and may require
428 increased attention from policymakers (Fig. 3). These taxa include Adélie penguins, chinstrap
429 penguins, Antarctic shags (*Leucocarbo bransfieldensis*), dry soil nematodes, emperor
430 penguins, leafy liverworts, penguin-rookery associated nematodes and xeric mosses. However,
431 most taxa will retain a 70% intactness threshold even under the baseline, and all taxa can reach
432 a 70% threshold under RCP4.5 with the implementation of several management strategies
433 (‘*Minimise impacts of human activities*’, ‘*Manage new infrastructure*’ and ‘*Managing and*
434 *protecting species*’) highlighting the lower predicted threats to Antarctic biodiversity in
435 comparison to many regions globally (Maxwell et al. 2016), at least in this century. Given the

436 generally lower abundance and the smaller growth windows for many Antarctic species
 437 (Convey 1996), any reduction in intactness is considered substantial though.



438
 439 **Fig. 3.** Complementary solutions for conserving Antarctic terrestrial biodiversity for any given
 440 budget under three intactness thresholds and where there is no possibility of reducing climate

441 scenario to the milder RCP2.6 through implementation of the *'Influence external policy'*
442 strategy. **a**, RCP4.5 climate forcing scenario. **b**, RCP8.5 climate forcing scenario. The steps
443 represent the optimal strategies to invest in to ensure the maximum number of taxa possible
444 reach an intactness threshold under any given budget. For example, if a budget of \$250 M were
445 available under RCP8.5, then the optimal strategy to invest in for an 80% threshold is
446 *'Managing and protecting species'*, whilst for a 90% threshold it is *'Manage new*
447 *infrastructure'* and *'Protecting areas'*. Strategy names used here are abbreviated, and
448 abbreviations are given in Table 1. Budget (over 83 years) is given as present value (PV), where
449 costs are discounted to equivalent present-day 2017 values using a 2% discount rate. Values
450 used to calculate benefit, used in complementarity analysis, were capped at current (100%)
451 intactness (An1). The data underlying this Figure can be found in S2 Data.

452

453 **Implementation of threat management strategies**

454

455 Climate change is the key threat to Antarctic life and it is clear that substantial conservation
456 benefits could be achieved if climate change were reduced to less than 2 °C warming, in line
457 with the Paris Climate Agreement. Further limiting the warming trajectory to 1.5 °C will
458 likely provide even greater benefits, as predicted for emperor penguins (Jenouvrier et al.
459 2020; 2021) as well as biodiversity globally (Smith et al. 2018). This highlights an urgent
460 need to address the significant threats to Antarctic biodiversity arising from activities outside
461 the Antarctic region, in particular climate change. Antarctic Treaty Consultative Parties
462 (ATCPs) could proactively address this through enhanced engagement with relevant
463 government bodies and intergovernmental processes (Antarctic Treaty, Article III.2, 1959),
464 such as the IPCC and the United Nations Framework Convention on Climate Change
465 (UNFCCC), to highlight the Antarctic implications of climate change and inform and support

466 global climate action (ATCM XXXV, WP32, 2012; ATCM XLIII, Resolution D, 2021).
467 Climate change and associated environmental implications continue to be a major point of
468 discussion at recent Antarctic meetings (e.g., Chown et al 2022 at ATCM XLIV - CEP
469 XXIV), and ACTPs are well placed to represent these implications more broadly across other
470 fora. Parties to the UNFCCC need to strengthen efforts to respond to the threat of climate
471 change by meeting their obligations under the Paris Climate Agreement. A global threat
472 cannot be abated by one region alone, and all regions and sectors have a role to play in
473 addressing climate change. Antarctica provides essential ecosystem services for the entire
474 planet and humanity cannot afford to ignore potential impacts to these systems (Rintoul et al.
475 2018). Mitigating climate change will help to stabilise these Antarctic processes, which drive
476 global ocean and atmospheric circulation, and which will play a critical role in future global
477 sea-level rise (IPCC 2018; Rintoul et al. 2018). Anthropogenic impacts on any of these
478 processes could fundamentally change life on Earth (Rintoul et al. 2018).

479
480 Although we found that working towards global climate action will provide the largest
481 conservation benefit and will help to ensure persistence of Antarctic terrestrial biodiversity, it
482 is also essential to continue advancing Antarctic-centric conservation measures (Bennett et al.
483 2015; Chown et al. 2017). There is now an opportunity for ATCPs, and other stakeholders, to
484 rapidly implement the most cost-effective and complementary regional strategies. In
485 comparison to other regions globally (e.g., meeting restoration targets in the Brazilian
486 Atlantic Forest hotspot is estimated to cost upwards of US\$20 billion; Strassburg et al. 2019,
487 or recovering Australia's threatened species is likely to cost more than US\$1.2 billion/year;
488 Wintle et al. 2019), the costs of implementing regional conservation actions in the Antarctic
489 are relatively modest and should receive increased international attention. Minimising the
490 impacts of human activity through influencing behaviour change and improving technology

491 could provide substantial benefit to native species at an estimated cost of only US\$11.5
492 million. Actions such as improving education for all visitors, optimising fieldwork to
493 minimise research footprint, and developing and utilising remote sensing technology where
494 possible, to reduce the number of field parties, will help to reduce impacts on biodiversity
495 and habitats. Improved planning for and management of new infrastructure (~US\$32 million)
496 can help to prevent and reduce unnecessary impacts of National Antarctic Programs (NAPs).
497 Carefully considering the locations and the need to establish such infrastructure is essential
498 (Chown et al. 2017; Brooks et al. 2019). National operators could also commit to further
499 sharing infrastructure and logistics where possible (Brooks et al. 2019) to reduce both carbon
500 and spatial footprint, as well as costs (ATCM XL, Resolution 4, 2017). The initial success of
501 a logistic-sharing trial in the Antarctic Peninsula, organised by the Council of Managers of
502 National Antarctic Programs (COMNAP), demonstrates the potential of such approaches
503 (COMNAP 2020), though noting that the use of some infrastructure is already
504 oversubscribed. Improving transport management by better utilising transport infrastructure
505 and technology to reduce transport or black carbon pollution (Graf et al. 2010; Cordero et al.
506 2022), and by optimising routes and timing to minimise wildlife disturbance (Coetzee &
507 Chown 2016) is another feasible and low-cost strategy. The International Association of
508 Antarctica Tour Operators (IAATO) has commenced taking steps in this direction by
509 establishing two ‘go-slow’ whale zones in the Antarctic Peninsula region (ATCM XLII, IP97,
510 2019).

511

512 Simultaneously, ATCPs could prioritise further efforts toward enacting some of the more
513 ambitious conservation strategies, with a focus on providing the highest benefits to
514 biodiversity. Managing and protecting threatened species, whilst costly, is expected to deliver
515 substantial benefits to these species through designation as Specially Protected Species (CEP

516 VIII, Annex 8, 2005) and by developing and implementing recovery plans and on-ground
517 management (including *ex-situ* conservation, if necessary). Improving management of non-
518 native species and disease by preventing new establishment events and eradicating or, if that
519 is not possible, managing established populations is increasingly important to reduce a threat
520 that is likely to act synergistically with climate change (Bennett et al. 2015; Duffy et al. 2017;
521 Convey and Peck 2019; Hughes et al. 2020). Currently, national programs differ substantially
522 in their implementation of environmental management strategies (such as the degree of
523 biosecurity for vessels and staff; Hughes et al. 2015, 2020), and in some cases there may be
524 large benefits in promoting standard (or at least compatible) levels of conservation
525 management across programs. COMNAP has an opportunity to make further substantial
526 contributions toward resolving this issue.

527

528 **Uncertainty**

529

530 Expert based assessments are valuable for informed and precautionary decision-making in
531 Antarctica, where there is often a lack of comprehensive quantitative data. This is highlighted
532 by the >30 taxa for which the experts identified Eltonian (lack of knowledge on ecological
533 interactions) and/or Prestonian (lack of understanding of species abundance and population
534 dynamics) knowledge shortfalls (Hortal et al. 2015; Fig. 4; shortfall definitions in S1 Table;
535 shortfalls for individual taxa in S2 Table). Utilising the collective knowledge of experts to
536 help bridge these gaps, as we did here, is a useful and appropriate alternative, though
537 uncertainty also arises from expert assessments (Burgman 2004; McBride et al. 2012;
538 Hemming et al. 2018; 2020). In some studies, experts have also been found to be
539 overconfident and to underestimate the uncertainty around their estimates (Speirs-Bridge et
540 al. 2010; Hemming et al. 2020), which should be considered in interpretation of results.

541

542 We captured some of the uncertainties of the expert's assessments by eliciting a range of
543 lower to upper bounds for expected benefit (e.g., Fig. 2), and in the confidence estimates.
544 Utilising these estimates in sensitivity analyses helped us to determine whether results are
545 robust in light of expert's uncertainties (McBride et al. 2012; Ponce Reyes et al. 2016;
546 Carwardine et al. 2019). A sensitivity analysis of the cost, feasibility and benefit values
547 provided by the experts indicated that the strategies cost-effectiveness rankings were
548 reasonably robust to all sources of uncertainty considered here (see S5, S6 Figs.). While there
549 was some overlap of the most pessimistic bounds of the optimal strategies with the most
550 optimistic bounds of the mid-level strategies (e.g., if the most optimistic bound of *'Protecting*
551 *areas'* and the most pessimistic bound of *'Managing transport'* represented true values, then
552 *'Protecting areas'* would be the more cost-effective of the two), the same strategies were still
553 consistently highlighted as the most cost-effective (S5, S6 Figs.). Thus, despite the
554 uncertainties in expert's estimates, our results suggest the top three most beneficial
555 (*'Influence external policy'*, *'Manage non-native species and disease'*, *'Managing and*
556 *protecting species'*), or most cost-effective strategies (*'Minimise impacts of human activity'*,
557 *'Manage new infrastructure'*, *'Transport management'*) are the same regardless of RCP,
558 region or whether upper or lower bound is used (see Table 2; S5, S6 Figs.; S4, S5 Tables).
559 Future research targeting the identified knowledge shortfalls (S2 Table), as well as increased
560 accessibility of cost and feasibility information for implemented Antarctic management
561 options, could help to reduce data gaps and uncertainty in future analyses (Nicol et al. 2019).

562

563 A lack of empirical data need not hinder conservation decisions and the implementation of
564 management strategies, especially in an era of rapid global change (Martin et al. 2012a,b;
565 Maxwell et al. 2015; CEP XXIII, Final Report, Para. 172, 2021). The cost-effectiveness

566 approach employed here provides robust decision support based on expert judgement.
 567 Acknowledging uncertainties is important but deferring decisions whilst filling quantitative
 568 data gaps can result in worse conservation outcomes (Martin et al. 2012b; Bennett et al.
 569 2018). Making no decision is still a decision (as represented here by the baseline '*Business as*
 570 *usual*' strategy) and our results unequivocally suggest that continuing with business-as-usual
 571 will lead to declines for some Antarctic taxa. Antarctic Treaty Parties must continue to
 572 advance Antarctic conservation using the best science available today.
 573

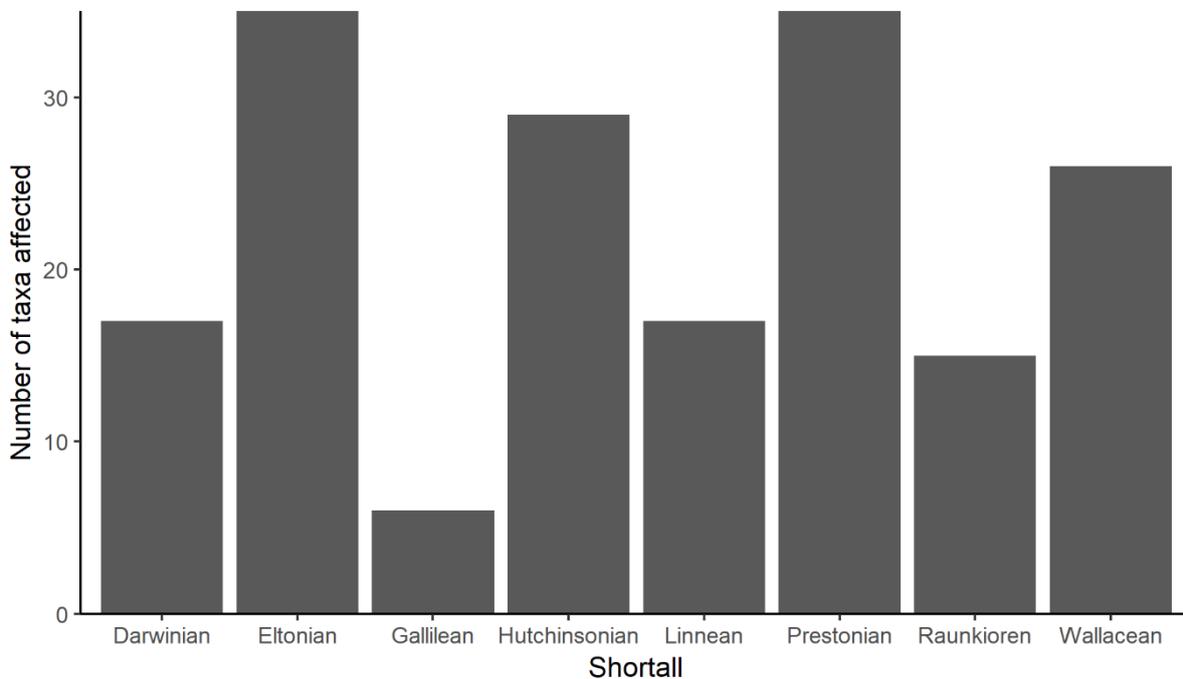


Fig. 4. Number of taxa for which each of eight knowledge shortfalls were identified that limit understanding and assessment of Antarctic terrestrial biodiversity. See S1 Table for a definition of each of the eight shortfalls and S2 Table that lists the shortfalls identified for each biodiversity taxon individually. The data underlying this Figure can be found in S2 Data.

574
 575
 576
 577

Conclusions

578 Conserving Antarctic biodiversity for future generations requires political commitment and
579 practical action both within the Antarctic region and globally. Our analysis identifies and
580 prioritises the management strategies and resources required to promote the continued
581 persistence of Antarctic terrestrial biodiversity and represents a significant advance in the
582 ‘best available science’ to inform decision-making and management. The ATCPs reaffirmed
583 their commitment to comprehensive protection of the Antarctic environment and dependent
584 and associated ecosystems through the Paris Declaration of 2021 (Environmental Protocol,
585 Article II, 1991; ATCM XLIII, Paris Declaration, 2021). Parties reaffirmed their commitment
586 *“to take account of best available scientific and technical advice in the planning and conduct*
587 *of their activities in Antarctica”, “to work together to better understand changes to the*
588 *Antarctic climate and to implement actions consistent with the Paris Agreement’s goals”, and*
589 *“to safeguard the Antarctic environment and dependent and associated ecosystems and to*
590 *remain vigilant and continue to identify and effectively address current and future Antarctic*
591 *environmental challenges by taking effective and timely action”*. Our work demonstrates that
592 securing the future of Antarctic biodiversity will require the Antarctic Treaty Parties to
593 implement regional conservation actions, while simultaneously working through relevant
594 global frameworks to encourage all nations to deliver the aims of the Paris Climate
595 Agreement.

596 **Materials and methods**

597

598 Priority threat management (PTM) is a structured decision science approach that combines
599 expert elicitation and scientific data to identify optimal and cost-efficient threat management
600 strategies for conserving biodiversity across a region (Carwardine et al. 2012, 2019). It has
601 been successfully applied in regions around Australia (Chadés et al. 2015; Firm et al. 2015),
602 Canada (Martin et al. 2018) and Indonesia (Utami et al. 2020). The method brings together
603 relevant stakeholders in a workshop to define appropriate biodiversity features, management
604 strategies, costs and feasibility, and utilises expert knowledge to derive predicted benefits to
605 biodiversity for each management strategy. Further details of the PTM background and method
606 are described in Carwardine et al. (2019), and see definitions of PTM terms in S10 Table.

607

608 PTM is an ideal tool for the Antarctic as the remoteness and comparatively young nature of
609 Antarctic science result in the region being data poor. This is especially prominent in the
610 biological sciences, where remote areas of unsurveyed wilderness and severe logistic and
611 funding constraints have resulted in a lack of quantitative data on comprehensive species
612 taxonomy and distributions, and limited understanding of physiology and ecology. Where data
613 and expert knowledge on biodiversity and potential conservation strategies do exist, they are
614 often held in disparate sources, including the separation of expertise by subject matter. Thus, a
615 process for bringing together expert knowledge is crucial for underpinning conservation plans
616 and prioritisations alongside empirical data.

617

618 We followed the PTM approach, adapting it as required to suit the Antarctic biodiversity threat
619 management problem. This consisted of defining the region, timeframe and climate change
620 scenarios pre-workshop, using expert elicitation during the workshop to define the threats,

621 taxonomic groups, management strategies, costs and feasibility of each strategy, and to assess
622 the benefit of each strategy for each selected taxon. Post-workshop, we quality checked the
623 data and undertook cost-effectiveness, complementarity, and sensitivity analyses. Ethical
624 clearance for this project was granted by the Commonwealth Scientific and Industrial Research
625 Organisation (066/17).

626

627 *Region, timeframe, and climate scenarios*

628

629 The Antarctic region was defined as the area subject to Antarctic Treaty governance, which
630 includes all ocean, ice and landmass south of 60°S (Antarctic Treaty 1959). The end of the
631 current century, i.e., 2100, was selected as the timeframe for the project, 83 years from the time
632 of the workshop.

633

634 Two IPCC Representative Concentration Pathway (RCP) climate forcing scenarios (RCP4.5,
635 8.5) were selected for the assessments and analysis (IPCC 2013). The RCP4.5 pathway is based
636 on moderate carbon emissions, and RCP8.5 represents more severe emissions, without climate
637 mitigation policies (IPCC 2013). Whilst the RCPs were the current climate forcing scenarios
638 in use at the time of this research by the IPCC, recent research has suggested that RCP8.5
639 represents an unlikely future scenario as emissions have fallen over the last decade (Hausfather
640 and Peters 2020), with the uncertainty around climate forcing scenarios highlighting the
641 importance of comparing multiple scenarios. For comparison, the RCPs are succeeded by the
642 Shared Socioeconomic Pathways (SSPs) in the latest IPCC AR6 synthesis, where RCP8.5 is
643 replaced by SSP5-8.5, RCP4.5 by SSP2-4.5, and RCP2.6 by SSP1-2.6 (Hausfather and Peters
644 2020; IPCC 2022). We did not use a scenario representing ‘no climate change’ as this was
645 considered unrealistic (Gasser et al. 2015). However, one of the outcomes of the successful

646 implementation of the *'Influence external policy'* strategy would be sufficient reductions in
647 global carbon emissions to achieve the Paris Climate Agreement target of less than 2 °C by
648 2100 (UNFCCC 2015). Therefore, RCP2.6, the low emissions scenario and the only one to
649 keep global warming to <2 °C (IPCC 2013; Gasser et al. 2015), was used to assess the
650 *'Influence external policy'* and *'All Strategies Combined'* strategies, instead of RCP4.5 or 8.5.

651

652 We divided the assessment area into two regions – the Antarctic Peninsula (including the South
653 Shetland and South Orkney archipelagos) and continental Antarctica (where biodiversity is
654 primarily concentrated around the coasts). These regions are climatically (Trusel et al. 2015;
655 Lee et al. 2017) and biologically (Convey 2017) distinct and represent a broad biogeographical
656 division (Chown and Convey 2007, Terauds and Lee 2016). They also have largely (but not
657 completely) distinct logistic and operational considerations (Hughes et al. 2019).

658

659 ***Expert participants and elicitation***

660

661 The participants in the PTM process included 29 diverse experts (four participated remotely),
662 all of which were invited to be co-authors on this paper. We aimed to ensure that their expertise
663 covered a variety of National Antarctic Programs (NAPs) operating in different regions of the
664 continent, with comprehensive knowledge in at least one of the following subjects:
665 biodiversity, policymaking, logistics, tourism or conservation. The experts were drawn from
666 12 different countries, with representatives from every continent. The group had balanced
667 gender representation and included early career researchers. The expert elicitation was
668 primarily carried out during a two-day workshop held at Katholieke Universiteit Leuven in
669 Belgium in July 2017, though extensive preparatory work and follow up was required.
670 Participation involved structured sessions at the workshop, as well as pre-workshop and follow

671 up communication: to enable the definition and parameterisation of biodiversity features,
672 threats, time frame, spatial units, scenarios, as well as the finalisation of the list of management
673 strategies and their costs, feasibility and benefits (S1 Data). An independent facilitator with no
674 Antarctic affiliation helped to run the workshop and ensured all the experts' contributions were
675 heard and accounted for.

676

677 *Selection of taxonomic groups*

678

679 We focused on Antarctic terrestrial biodiversity, which includes microbes, terrestrial algae,
680 various invertebrate groups (nematodes, tardigrades, rotifers, enchytraeid worms, springtails,
681 mites and two insects), mosses and liverworts, lichens, and two vascular plants (Convey 2017;
682 Chown et al. 2015). A number of marine seabirds, including four species of penguin, were also
683 included as they rely on ice-free areas for breeding (Schrimpf et al. 2020), or in the case of
684 most colonies of the emperor penguin, fast ice (Trathan et al. 2020).

685

686 The biodiversity experts (a subset of all experts) selected a total of 38 biodiversity taxonomic
687 groups to include in the exercise (hereafter 'taxon/taxa'), which ranged from single species to
688 broader functional taxa (S11 Table). Each taxon contained species that were expected to
689 respond similarly and by similar magnitudes to threatening processes and management
690 strategies. The taxonomic resolution of groups differed depending on their predicted response
691 and level of species-specific knowledge available. For example, most seabird species were
692 considered as individual taxa, whilst soil microfauna were grouped based on habitat
693 requirements (e.g., moss-associated tardigrades, rotifers and nematodes formed a single group
694 containing multiple higher taxa). Seabirds in the procellariid taxa were grouped as experts felt
695 they would respond in similar ways to threats, though Southern Giant Petrels were kept separate

696 as there is more information available. A further seven taxa identified were not included in the
697 analyses as none of the participating experts felt sufficiently knowledgeable to assess them.
698 These included: thalloid liverworts, snow algae, freshwater decapods and copepods, non-
699 marine aquatic system plankton, sea-ice dependent and sea-ice independent seals.

700

701 *Threats*

702

703 Prior to the workshop, experts identified multiple threatening processes that could impact
704 terrestrial Antarctic biodiversity by 2100, including direct and indirect impacts of climate
705 change, human activity (science and tourism), non-native species and pollution (S12 Table).
706 Some marine-based threats, such as fishing and ocean acidification, were considered in the
707 study due to their potential direct (e.g. krill dependant penguins impacted by fisheries) or
708 indirect (e.g. redistribution of penguin colonies can impact distribution of vegetation via
709 nutrient inputs) impacts on terrestrial ecosystems, including marine seabirds. Background
710 information on, and predictions for, some of these threats on a 2100 timeframe were provided
711 to the experts to assist with their decisions, including maps of projected changes in temperature,
712 precipitation, ice-free areas and non-native species for RCP4.5 and RCP 8.5 across the
713 Antarctic continent (Duffy et al. 2017; Lee et al. 2017).

714

715 *Management strategies*

716

717 Experts agreed on a total of 13 strategies for managing and conserving Antarctic terrestrial
718 biodiversity to 2100 (Table 1; S1 Data). A quantifiable aim was determined for each strategy
719 (Table 1). Whilst differing aims may result in a different prioritisation, a large amount of time
720 was spent carefully defining these aims as this is paramount to ensuring useful outcomes, as it

721 is in any conservation planning exercise (Game et al. 2013). Strategies had to be stand-alone,
722 providing a substantial benefit to biodiversity, without being contingent on the implementation
723 of another strategy to successfully meet their aims. If strategies were considered to be too
724 interdependent, they were amalgamated (for example, managing individual species on the
725 ground and protecting individual species via policy were combined to form the '*Manage and*
726 *protecting species*' strategy). All of the strategies applied to both regions, except for '*Protect*
727 *vegetation from physical impacts*' which only applied in the Antarctic Peninsula, where
728 trampling of vegetation by seal species occurs.

729

730 The first strategy defined was '*Business as usual*', where conservation actions currently in
731 place are continued, but no new actions are added. The regularity of implementing current
732 conservation actions was not considered to change over the timeframe in the '*Business as*
733 *usual*' strategy as current conservation actions, such as biosecurity or designating a new
734 protected area, are already irregularly implemented and any change (increase) in the frequency
735 of implementation would constitute one of the new management strategies. This strategy
736 represented a baseline against which other strategies could be evaluated. The other strategies
737 included managing infrastructure, transport, human activity, vegetation, and non-native
738 species, area protection and protecting species. The '*Influence external policy*' strategy
739 objective aimed to influence global policy to reduce pressures on Antarctica from external
740 threats, i.e. primarily climate change, but also including other threats, such as microplastics
741 and persistent organic pollutants (POPs). The final two strategies '*All strategies combined*
742 *excluding policy influence*', and '*All strategies combined*' are a combination of the other
743 strategies, used to assess whether the expected benefits from strategy combinations are greater
744 than the sum of their parts. Because the '*All strategies combined*' strategy includes '*Influence*
745 *external policy*', it was also assessed under the RCP2.6 climate forcing scenario. The

746 combination strategy ‘*All strategies combined excluding policy influence*’ was utilised in order
747 to assess the benefits of all the other strategies if the ‘*Influence external policy*’ strategy was
748 not implemented, or not successful, and the world were committed to >2 °C warming (i.e.,
749 RCP4.5 or RCP8.5).

750

751 Each strategy consisted of a suite of actions determined by the experts which, when
752 implemented together, ensure the strategy can successfully meet its objective/s. The actions are
753 detailed in S1 Data.

754

755 ***Feasibility and cost***

756

757 Feasibility consisted of two aspects: ‘likelihood of uptake’ and ‘likelihood of success’, which
758 were estimated by the experts using a scale of 0 – 100%, where: 0 = *Impossible*, 15 =
759 *Improbable*, 25 = *Unlikely*, 50 = *Fifty-fifty*, 75 = *Likely*, 85 = *Probable*, 100 = *Certain*.

760 Likelihood of uptake was estimated for each action and represents the likelihood that
761 policymakers will agree to implement this action considering social and political factors,
762 assuming that cost is not a barrier. The likelihood of uptake estimates were averaged for all
763 actions in the strategy to obtain an overall estimate per strategy, which will be lower overall
764 for strategies that include one or more actions that are more socio-politically challenging.

765 Likelihood of success was estimated per strategy and represents the likelihood that the strategy
766 will meet its objectives in reducing impacts of threats, assuming that all actions have been
767 implemented. Overall feasibility per strategy was calculated as a product of the two likelihoods
768 and is provided as a probability (S3 Fig.; S1 Data).

769

770 Experts estimated the cost for each action over the 83-year time horizon being considered (the
771 costs are outlined in detail in S1 Data). Where available, they used existing cost information to
772 help inform their estimates. Costs typically consisted of: number of Full Time Equivalent
773 (FTE) employees, number of Antarctic berths required (researcher living costs and transport)
774 and other costs (e.g. number of workshops, laboratory analyses, etc). The cost of FTEs (in
775 Antarctica and not in Antarctica), berths (short summer, long summer, and winter) and other
776 costs that were used multiple times (such as workshops) were standardised across strategies
777 using the average USD value of cost estimates given from multiple NAPs (S13 Table). Cost
778 estimates used 30 operating NAPs, including 35 seasonal and 45 year-round operational
779 stations. Costs were estimated assuming all actions are successfully implemented.

780

781 The total costs of the strategies over the whole timeframe were converted to present-day values
782 (present value: PV) using a conservative social discount rate of 2%, where future costs are
783 discounted to present-day values. Discounting costs is important to allow for fair comparison
784 of strategies costs when the payment schedule of actions differ over time. For example, some
785 strategies have large start-up costs or require substantial investment for only part of the
786 timeframe (e.g., *'Remediation'* has a large start-up cost and ongoing investment for the first 50
787 years, before teetering off when the remediation is finished), whilst others have recurring costs
788 distributed more regularly across the years (e.g., *'Minimise impacts of human activity'* has costs
789 distributed much more evenly and recurring actions every two, three and five years). PVs were
790 also compared using discount rates of 0 and 5% (S4 Fig. a). PVs were calculated prior to the
791 COVID-19 pandemic and do not incorporate the likely impacts and expected economic
792 recession (World Bank 2020), which are likely to impact both governmental and non-
793 governmental Antarctic operations well beyond the short term (Frame and Hemmings 2020;
794 Hughes and Convey 2020).

795

796 The magnitude of costs remained the same regardless of the discount rate applied and it had
797 little impact on the order of top-ranking cost-effective strategies (S4 Fig. a). However, the
798 management intensity and scale of the actions underlying each strategy, and hence their costs,
799 may be considered subjective. In some cases, higher investments would achieve additional
800 benefits. For example, in managing non-native species, a larger investment in biosecurity is
801 likely to increase biodiversity benefits. Some management strategies also include large
802 amounts of preparatory work to optimally make decisions and take appropriate actions. The
803 primary example is baseline biodiversity surveys undertaken in the '*Manage non-native species*
804 *and disease*' strategy and '*Managing and protecting species*' strategy, which substantially
805 increase the cost of these strategies, and highlight that our current understanding is limited by
806 uncertainty and data-deficiency. Also, this was an Antarctic priority threat management
807 exercise, and the goal was to prioritise strategies and actions that can be undertaken in the
808 Antarctic and where Antarctic policy can have an influence. Thus, whilst we identified a
809 strategy to influence global external policy, the actions were targeted at the Antarctic
810 stakeholders' contributions and did not include the global costs of reducing carbon emissions,
811 such as increasing use of renewable energy sources, carbon sequestration or negative emissions
812 technologies (Smith et al. 2016; Griscom et al. 2017). However, the strategies were consistently
813 costed as the actions required to meet their aims, and the experts revised them several times to
814 ensure this.

815

816 To simplify the process, and because the experts already had a laborious task, it was assumed
817 that costs and feasibility would remain the same for both RCP4.5 and RCP8.5. Costs were
818 adjusted for regional analysis in proportion to the regional strategy effort required, where

819 experts estimated the percentage effort of each overall strategy that should be targeted towards
820 each region (S3 Table).

821

822 *Benefit assessments*

823

824 To assess the predicted benefits of each management strategy we needed an appropriate metric.
825 Often in PTM, and in other conservation assessments, this metric is probability of persistence
826 or extinction risk, where the predicted benefit of a strategy is the estimated reduction in
827 extinction risk to the species (Carwardine et al. 2012; 2019). The experts determined that
828 extinction risk is not relevant to most Antarctic terrestrial species on a 2100 timeframe as
829 populations change slowly. Thus, we defined a more flexible metric for use in this study –
830 ‘intactness’ – which represents how intact or unharmed the taxonomic group is relative to a
831 baseline. Experts were encouraged to conceptualise intactness in an appropriate way for each
832 taxonomic group, for example extinction risk, population decline, or functional persistence
833 might be appropriate for vertebrates, but range contraction, ground cover, or density might be
834 more appropriate for vegetation or invertebrates, which are more unlikely to become extinct by
835 2100.

836

837 To estimate the benefits of each management strategy, biodiversity experts individually
838 predicted the intactness of each biodiversity taxon at 2100, first under the ‘*Business as usual*’
839 baseline strategy and then again under each of the 12 strategies, assuming each strategy had
840 been successfully implemented and would meet its objectives to reduce the impacts of threats.
841 Intactness values were always estimated relative to the intactness of the taxon today (2017, at
842 the time of the workshop), where a value of 100 indicates that the ‘intactness for the taxon is
843 the same as today’, a value of 0 represents that the ‘taxon is completely degraded relative to

844 today', and a value of 200 represents that the 'taxon is doing twice as well as today'. The
845 experts considered a scale of 0 to 200 necessary for Antarctic taxa, as some groups are predicted
846 or already observed to benefit from climate warming (e.g., Chown and Convey 2007; Convey
847 2011; Cannone et al. 2016; Convey and Peck 2019). Such taxa expanding beyond current
848 intactness may also have consequential negative impacts on other species, such as the grass
849 *Deschampsia antarctica*'s predicted ability to outcompete native mosses due to more efficient
850 nitrogen acquisition (Hill et al. 2011).

851

852 Intactness estimates were recorded by biodiversity experts using an online tool created with
853 JavaScript and HTML and hosted by a NodeJS web server on Amazon Web Services. The tool
854 effectively functioned as a survey where biodiversity experts could select the taxon they wished
855 to assess and then proceed through the questions estimating the benefits for both regions
856 (Antarctic Peninsula and continental Antarctica) and for both climate forcing scenarios
857 (RCP4.5 and RCP8.5) using a slider. The experts provided a best guess, lower bound, and
858 upper bound for each question, as is standard for structured expert elicitation (Hemming et al.
859 2018). The lower bound represented what the experts believe to be the lowest possible
860 (pessimistic) intactness value for the taxon by 2100, the upper bound represented the highest
861 possible (optimistic) intactness value, and the best guess represented their best estimate of the
862 true value. They also provided a confidence value, which represented their confidence that the
863 true value lay within the range of the lower to upper bound (Speirs-Bridge et al. 2010). Experts
864 were also able to enter comments and identify sources of uncertainty in their estimates,
865 categorised as knowledge shortfalls.

866

867 Every effort was made to ensure each taxon was assessed by multiple biodiversity experts.
868 Nevertheless, six taxa had only one assessor while some had as many as seven, as the

869 biodiversity experts only assessed taxa they felt they had sufficient expertise to undertake the
870 assessment for. After the workshop, the biodiversity experts' intactness values were
871 anonymised and all estimates (for each taxon) were circulated to allow opportunity for revision
872 of values in the light of the judgements of the expert group as a whole, as per the modified
873 Delphi method (Speirs-Bridge et al. 2010; McBride et al. 2012). Expert values were then
874 averaged for use in the analysis.

875

876 Because some taxa were predicted to expand under climate change (i.e. increase intactness
877 beyond the 100% values of today), we performed all analyses twice: first using expert values
878 capped at 100% before averaging, so that the benefits of taxa expanding above 100% intactness
879 were excluded from the totals (Analysis 1 – 'An1'), and second including all benefits (Analysis
880 2 – 'An2'). The primary results of this paper focus on An1 as by definition, conservation is
881 concerned with abating biodiversity loss or impact, so species that increase intactness with
882 climate change do not necessarily require conservation. Thus, we chose to focus analyses on
883 those taxa predicted to decline (decrease intactness) by the end of 2100 (though results also
884 including benefits for those taxa for which climate change may have a positive impact are
885 provided in the Supporting information).

886

887 Expert's values of predicted future baseline intactness allowed us to identify which taxa are
888 likely to be vulnerable to future changes in the region. Some taxa that are predicted to have
889 future intactness values similar to current (100%) levels are classified as vulnerable in Analysis
890 1, but as benefiting in Analysis 2. This occurs when the averaged expert intactness value is
891 below 100% when the values are capped, but where the average might be above 100% when
892 uncapped (see S14 Table, and raw values on the Australian Antarctic Data Centre;
893 <https://doi.org/10.26179/5da8f8e7a2256>). These results highlight some of the uncertainty in

894 predicting future responses to global change of some taxa, though we consider identifying them
895 as potentially vulnerable to be appropriately conservative from a conservation perspective.

896

897 Some experts predicted that the two vascular plants, *Colobanthus quitensis* and *Deschampsia*
898 *antarctica*, may expand into the continental region of Antarctica (from the Peninsula region)
899 as climate changes. These benefits were included for the Analysis 2 benefits calculations,
900 though were excluded from vulnerability assessments.

901

902 ***Knowledge shortfalls***

903

904 Seven knowledge shortfalls were identified by Hortal et al. (2015) that represent gaps in our
905 understanding of biodiversity data and hinder our abilities to answer hypotheses or make
906 decisions, such as a limited understanding of species distributions (defined as a ‘Wallacean’
907 shortfall). An eighth shortfall was identified prior to the workshop by Peter Fretwell (British
908 Antarctic Survey) and colleagues, representing a technological shortfall (termed a ‘Galilean’
909 shortfall) where the data are available, but where we do not yet possess the skills or computing
910 power to understand or interpret them adequately. The shortfalls are outlined in S1 Table. The
911 experts identified relevant shortfalls for each biodiversity taxon in an effort to better understand
912 the drivers of uncertainty in benefit estimates (S2 Table). The shortfalls also provide useful
913 information for directing future research to reduce data gaps and uncertainty.

914

915 ***Total potential benefits***

916

917 The potential benefit per strategy was calculated as the difference between the best estimate
918 intactness value of the strategy and the intactness value of the baseline (error bars were

919 generated giving the difference between the upper/lower bound intactness values and the
920 baseline values). The benefit calculations thus use the arithmetic, or absolute, difference to
921 calculate benefit. An alternative method would be to use percentage change, which would class
922 increases in intactness for those with a lower baseline (e.g., intactness baseline value of 5%
923 increasing to 30% with strategy, percentage change of 500%) as more significant than those
924 with a higher baseline (e.g., intactness baseline value of 70% increasing to 95% with strategy,
925 percentage change of 35.7%), whereas this increase (25%) is the same using arithmetic
926 difference. Percentage change could be useful if prioritising individual taxa for management
927 as it gives more weight to vulnerable taxa. We used arithmetic difference in this analysis as we
928 focused on conservation outcomes overall and did not want to weight vulnerable taxa as more
929 important.

930

931 It should be noted that, because the amount of benefit from implementing a strategy does not
932 have to be the same for all three bounds, the benefits calculated for the upper and lower bounds
933 can end up being both higher or lower than the benefit calculated for the best guess estimate.
934 The potential benefit for *'Influencing external policy'* and *'All strategies combined'* was
935 calculated in the same way as for all the other strategies, noting the assumption that the future
936 with the strategy in place (an outcome of the successful strategy implementation) was a
937 reduction in climate forcing scenario to RCP2.6 relative to the RCP4.5 or RCP8.5 baseline.

938

939 Benefits were summarised at different scales, including potential benefits per taxon, per region
940 and per climate scenario, and then summed to give regional and overall potential benefits for
941 all biodiversity taxa combined. We assume that benefits accrue over time at a similar rate up
942 to the maximum improvement estimated for each action. Hence for ease of interpretation, we
943 do not discount the benefit metric over time as we do for costs.

944

945 *Cost-effectiveness*

946

947 The cost-effectiveness of each strategy i (CE_i) was calculated as the total potential benefit (sum
948 benefits across all taxa) (B_i) divided by the expected cost (C_i), and multiplied by feasibility (F_i):

949

950

951
$$CE_i = \frac{B_i F_i}{C_i}.$$

952

953 The CE score provides an indication of the total expected benefit that is likely to be achieved
954 per unit cost spent, for each strategy that decision makers choose to attempt to implement.

955 Strategies were ranked according to cost-effectiveness score, and rankings compared across
956 regions, climate scenarios and taxa.

957

958 The primary results of the cost-effectiveness analysis presented in the main text use the best
959 guess estimates provided by the experts, though results for the upper and lower bounds are
960 available in S4 Table. Because the '*Influence external policy*' strategy includes only the
961 Antarctic component of working toward climate mitigation, and not the full global cost of
962 reducing emissions, it was excluded from the primary cost-effectiveness and complementarity
963 analyses.

964

965 *Complementarity analysis*

966

967 While cost-effectiveness analyses are a convenient tool to rank strategies independently,
968 complementarity analyses are more suitable for identifying and prioritising subsets of strategies

969 to guide conservation investment under different budgets. A complementarity analysis ensures
970 a maximum coverage of biodiversity benefits by identifying sets of strategies that complement
971 each other in order to achieve equity of benefits across taxa and avoid redundancy (i.e., one
972 taxon receiving maximum benefits and another taxon receiving none). This is achieved by
973 solving a combinatorial optimisation problem also termed a complementarity analysis (Tulloch
974 et al. 2013; Carwardine et al. 2019).

975

976 Complementarity analyses rely on setting appropriate persistence (intactness) thresholds for
977 biodiversity, to ensure as many taxa as possible reach the designated threshold. We used 70%,
978 80% and 90% of expected intactness as our designated thresholds, where a value of 100%
979 represents the taxon's current intactness. We considered these values appropriate for Antarctic
980 biodiversity, which does not face the same levels of extinction and rapid human impacts as
981 global biodiversity, and for which any decline in intactness is considered substantial.

982

983 We used the best guess estimates of biodiversity intactness provided by the experts, capped at
984 100% to exclude benefits to those taxa expected to benefit from climate change, and a 2%
985 social discount rate on PV to undertake the complementarity analysis. The expected intactness
986 P_{ij} for each taxon j under a given strategy i can be calculated as follows:

987

$$P_{ij} = \bar{P}_{baselinej} + F_i \bar{B}_{ij},$$

988

989 with $\bar{P}_{baselinej}$ the mean intactness across contributing experts assuming the baseline strategy
990 applies to taxon j , F_i the feasibility of strategy i , and \bar{B}_{ij} the mean potential benefit across
991 contributing experts of applying strategy i for taxon j . Conveniently the P_{ij} can be assessed
992 under different persistence thresholds and provide a binary matrix T such that an element T_{ij}
993 takes value 1 if the expected persistence of taxon j under strategy i (P_{ij}) is above the

994 designated threshold and 0 otherwise. Note that the baseline represents the future intactness
 995 of a taxon subject to *all* threats (and only current conservation actions), thus inaction in
 996 addressing one threat may be negatively affecting intactness, whilst a strategy that addresses
 997 a different threat may be simultaneously positively affecting intactness. Therefore, a strategy
 998 must increase intactness of a taxon enough to reach the persistence threshold whilst
 999 potentially still being negatively affected by other threats.

1000

1001 The complementarity problem is usually formulated as maximising the number of taxa above
 1002 the designated threshold for a given budget (Carwardine et al. 2019). Here, we chose to
 1003 minimise the cost of securing a given number of taxa above threshold. Both problems are
 1004 equally difficult to solve - classified as NP-hard in the complexity scale for decision problems
 1005 (Bruker 1979). In our case, the aim was to generate a complete investment profile to secure as
 1006 many taxa as possible. Because we had a finite number of taxa, it was computationally
 1007 advantageous to formulate the complementarity problem as a variant of a minimum set
 1008 coverage problem, i.e. minimise the cost of securing a given number of taxa above threshold
 1009 (Moilanen et al. 2009). This combinatorial problem can be formulated as an integer linear
 1010 program (ILP; Williams 2013; Tulloch et al. 2016). Here we define S as the finite set of
 1011 strategies and R the finite set of taxa. Formally, we sought to minimise the cost of selected
 1012 strategies:

1013

	minimize $\sum_{i \in S} y_i C_i$	
Subject to		
$\forall i \in S, \forall j \in R,$	$x_{ij} \leq y_i$	(c1)
$\forall j \in R,$	$\sum_{i \in S} x_{ij} \leq 1$	(c2)

	$\sum_{i \in S} \sum_{j \in R} x_{ij} T_{ij} \geq Target$	(c3)
	$y_i \in \{0,1\}, x_{ij} \in \{0,1\}, i \in S, j \in R$	(c4)

1014

1015 Solving this ILP requires finding the values of two sets of binary decision variables. The first
 1016 set of decision variables y_i determines if a strategy $i \in S$ is selected ($y_i = 1$) or not ($y_i = 0$).

1017 If strategy i is selected, the taxon j with values of $T_{ij}=1$ is assumed secured. The second set of
 1018 auxiliary decision variables x_{ij} identifies the taxon j secured by strategy i – these decision
 1019 variables ensure we reach the target of a given number of taxa to secure (identified by Target).

1020 We sought to minimise the cost of implementing strategies while respecting four constraints:

- 1021 • (c1): A strategy is selected ($y_i = 1$), if at least one taxon is secured by strategy i ;
- 1022 • (c2): For the purpose of the optimisation, only one strategy can count towards securing
 1023 a taxon above the threshold. Therefore, the sum of the $\sum_j x_{ij}$ represents the total
 1024 number of taxa secured.
- 1025 • (c3): The number of taxa secured must be greater or equal to the given target number
 1026 (Target).
- 1027 • (c4): The decision variables are defined as binary.

1028

1029 Running this ILP using Target values ranging from 1 taxon to 38 taxa and two RCP scenarios,
 1030 generated Fig. 3.

1031

1032 As only one strategy can count toward securing a taxon above a threshold, strategies are
 1033 considered independently of one another (except for ‘*All strategies combined excl. IEP*’) and
 1034 interactions between strategies are not considered (i.e., if multiple strategies provide benefits
 1035 to a taxon, the benefits are not considered cumulative). If two or more strategies help to secure
 1036 the *same* taxa above the threshold, then the one that is cheaper is selected (because selecting

1037 more than one would be redundant as those particular taxa can reach the threshold under either
1038 strategy). If multiple strategies help to secure *different* taxa above the threshold, then they are
1039 complementary (because they increase the number of taxa that can reach the threshold). If two
1040 or more strategies help to secure some of the *same* and some *different* taxa, then whilst there
1041 may be some redundancy of benefits for those individual *same* taxa (because they can reach
1042 the threshold under either strategy), overall, for all taxa, there is no redundancy as both
1043 strategies are still required to secure the *different* taxa.

1044

1045 In reality, there may be some interactions between strategies, and benefits might be cumulative
1046 or redundant when multiple strategies are implemented together. For example, a taxon may not
1047 be able to reach a threshold if either strategy *a* or strategy *b* were implemented but might be
1048 able to reach the threshold if strategy *a* and *b* are implemented together because the benefits
1049 are cumulative. Accounting for these factors in complementarity analysis would require the
1050 experts to estimate the expected benefits of not just each individual strategy, but every possible
1051 combination of strategies, whilst considering whether there was redundancy or not between
1052 each combination. We deemed this too complex and too laborious a task and instead utilised
1053 the combined strategies '*All strategies combined*' and '*All strategies combined excl. IEP*' to
1054 provide estimates of the maximum total benefits that can be achieved if all strategies were to
1055 be implemented.

1056

1057 *Sensitivity analyses*

1058

1059 We performed sensitivity analyses to examine the impact of uncertainty on the cost-
1060 effectiveness rankings. The experts provided four values for each intactness estimate they
1061 made: an upper bound, a lower bound, a best estimate, and a confidence estimate representing

1062 their confidence that the true value lay within the range of the lower to upper bound. Because
1063 the experts did not provide the same confidence estimates, we standardised the intactness
1064 estimates using linear extrapolation of the lower, best, and upper bounds, and confidence
1065 interval to fit 80% credible bounds (confidence) around individuals' best estimates (as per
1066 Bedford and Cooke 2001; McBride et al. 2012). The absolute minimum and maximum
1067 bounds computed from the linear extrapolation (representing the 10th and 90th percentile
1068 respectively), together with the best estimates, were used to constrain beta-pert distributions
1069 for each expert's estimates per taxa. Monte Carlo simulations with 10,000 iterations, seeded
1070 with a random number, sampled values from the constrained beta-pert distribution for each
1071 taxon (as per Ponce Reyes et al. 2016; Carwardine et al. 2019), which were used to examine
1072 uncertainty of the intactness estimates (converted to benefits) when incorporated into cost-
1073 effectiveness analysis (Fig. S5 a.; using the original estimates of cost and feasibility). To
1074 avoid experts' fatigue, lower or upper bounds for the cost or feasibility estimates were not
1075 elicited. Instead we used 70% and 130% of the original values (Firn et al. 2015) to produce
1076 uniform distributions of cost and feasibility for each strategy, from which the 10,000 samples
1077 were drawn for examining uncertainty of cost and feasibility (Fig. S5 b,c). Finally, we
1078 combined the 10,000 samples of intactness, cost and feasibility to examine cost-effectiveness
1079 robustness in light of all three components of uncertainty combined (Fig. S6).

1080

1081 **Additional information:** Antarctic priority threat management database containing
1082 intactness values, benefits and uncertainties for each biodiversity taxon has been made
1083 available through the Australian Antarctic Data Centre (AADC;
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1085

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1104

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1419

1420 **Supporting information**

1421 **S1 Data.** Table of Proposed management strategies for conserving Antarctic biodiversity to
1422 the end of this century, detailing strategy objectives, specific actions that make up the
1423 strategy, costs and feasibility of each action.

1424

1425 **S2 Data.** Workbook containing the numerical values underlying the Figures in the Main text
1426 and Supporting information. The values for each Figure are provided in separate worksheets.

1427 These values were calculated from the raw values using the methods described in the

1428 'Materials and methods' section of the Main text. The cost and feasibility values are available

1429 in S1 Data. The averaged expert intactness and benefit values are available on the Australian
1430 Antarctic Data Centre: <https://doi.org/10.26179/5da8f8e7a2256>

1431

1432 **S1 Fig.** Response of Antarctic terrestrial biodiversity to various conservation management
1433 strategies by the end of 2100 under two climate forcing scenarios (RCP4.5, RCP8.5). **a**,
1434 Percentage of taxa likely to benefit. **b**, Expected total benefit of strategies summed for all
1435 taxa and both regions combined. Bars represent the experts' best estimates when assessing
1436 benefit, whilst error bars represent upper (best case scenario) and lower (worst case scenario)
1437 bounds. An outcome of the '*Influence external policy (IEP)*' and '*All strategies combined*'
1438 strategies is that carbon emissions are reduced globally (in line with the milder RCP2.6);
1439 however, benefits are still calculated relative to the baselines of RCP4.5 and RCP8.5. Values
1440 used to calculate benefit include benefits to taxa expected to expand beyond current (100%)
1441 intactness (An2).

1442

1443 **S2 Fig.** Expected total benefit by region (continent and peninsula) of various conservation
1444 management strategies summed for all Antarctic taxa combined, at the end of 2100 under two
1445 climate forcing scenarios (RCP4.5, RCP8.5). Bars represent the experts' best estimates when
1446 assessing benefit, whilst error bars represent upper (best case scenario) and lower (worst case
1447 scenario) bounds. An outcome of the '*Influence external policy*' (IEP) and '*All strategies*
1448 *combined*' strategies is that carbon emissions are reduced globally (in line with the milder
1449 RCP2.6); however, benefits are still calculated relative to the baselines of RCP4.5 and
1450 RCP8.5. Values used to calculate benefit were capped at current (100%) intactness (An1).

1451

1452 **S3 Fig.** Expected benefit, estimated cost and feasibility of various conservation management
1453 strategies for Antarctic biodiversity by the end of 2100 under two climate forcing scenarios

1454 (RCP4.5, RCP8.5). **a**, Expected total benefit and estimated present value (PV), **b**, Expected
1455 total benefit and estimated feasibility, **c**, Estimated feasibility and estimated present value.
1456 Expected total benefit is summed for all taxa and both regions combined and is calculated
1457 using biodiversity experts' best estimates when assessing benefit. An outcome of the
1458 *'Influence external policy'* (IEP) and *'All strategies combined'* strategies is that carbon
1459 emissions are reduced globally (in line with the milder RCP2.6); however, benefits are still
1460 calculated relative to the baselines of RCP4.5 and RCP8.5. Values used to calculate benefit
1461 were capped at current (100%) intactness (An1).

1462

1463 **S4 Fig.** Cost comparison and contribution to costs of various conservation management
1464 strategies for Antarctic biodiversity. **a**, Estimated present value using three different social
1465 discount rates. Ordered from most to least expensive using a 2% discount rate. **b**, Estimated
1466 present value across two different regions. **c**, Percentage breakdown of primary cost items for
1467 various conservation management strategies for Antarctic biodiversity. OFC FTE – Office
1468 full-time equivalent employees, ANT FTE – Antarctic based full-time equivalent employees,
1469 SSUM – short summer Antarctic berths (6 weeks), LSUM Antarctic berths (3 months), LAB
1470 – lab analysis costs post field sample collection per event, OTHER – other costs, such as
1471 captive breeding programs, remediation, flights, combined.

1472

1473 **S5 Fig.** Output from the sensitivity analysis examining sources of expert uncertainty on the
1474 cost-effectiveness ranking of strategies under two climate forcing scenarios (RCP4.5,
1475 RCP8.5). Sources of uncertainty include: *a*) expected benefit, *b*) cost, *c*) feasibility. While
1476 each of the sources was considered independently, the other two variables/sources used the
1477 experts original best-estimates in the cost-effectiveness equation. The whiskers of the

1478 boxplots can be considered to represent the most optimistic (maximum) and most pessimistic
1479 (minimum) outcomes possible for each strategy.

1480

1481 **S6. Fig.** Output from the sensitivity analysis examining sources of expert uncertainty on the
1482 cost-effectiveness ranking of strategies, whilst varying all three sources of expert uncertainty
1483 (expected benefits, cost, feasibility) together. The whiskers of the boxplots can be considered
1484 to represent the most optimistic (maximum) and most pessimistic (minimum) outcomes
1485 possible for each strategy. Outcomes under two climate forcing scenarios (RCP4.5, RCP8.5)
1486 are represented.

1487

1488 **S1 Table.** The Seven (8) shortfalls of biodiversity knowledge as defined by Hortal et al.
1489 2015, with the addition of an 8th strategy (Galilean).

1490

1491 **S2 Table.** Shortfalls identified per taxon that limit understanding and assessment of 38
1492 Antarctic taxa. Presence of shortfall indicated by a tick.

1493

1494 **S3 Table.** Average expert estimation of effort (%) required to implement conservation
1495 strategies for Antarctic terrestrial biodiversity split across two regions in Antarctica
1496 (continent and peninsula).

1497

1498 **S4 Table.** Evaluation of key management strategies for Antarctic biodiversity until 2100 under
1499 two climate forcing scenarios (RCP4.5, RCP8.5). Benefit calculated using a, upper bound
1500 values and b, lower bound values given by experts. Including estimated total cost over the next
1501 83 years (present value; using social discount rate of 2%), estimated feasibility, total expected
1502 benefit (% change combined for all taxa), and cost-effectiveness rank. Ranked in order of cost-

1503 effectiveness (CE) for RCP4.5. Values used to calculate benefit were capped at current (100%)
1504 intactness (An1).

1505

1506 **S5 Table.** Evaluation of key management strategies for Antarctic biodiversity until 2100
1507 under two climate forcing scenarios (RCP4.5, RCP8.5) in two regions a, continent, b,
1508 peninsula. Including estimated total cost over the next 83 years (present value; using social
1509 discount rate of 2%), estimated feasibility, total expected benefit (% change combined for all
1510 taxa), and cost-effectiveness rank. Ranked in order of cost-effectiveness (CE) for RCP4.5.
1511 Benefits of strategies are calculated using best estimates of improved intactness provided by
1512 experts. Values used to calculate benefit were capped at current (100%) intactness (An1).

1513

1514 **S6 Table.** The three most cost-effective conservation management strategies for Antarctic
1515 taxa under climate forcing scenario RCP8.5; identified in order of significance as 1, 2, 3.
1516 Benefits of strategies are calculated using best estimates of improved intactness provided by
1517 experts and were capped at current (100%) intactness (An1; if a taxon only has benefits
1518 beyond 100% no strategies have been identified; see Supplementary Table 4 including these
1519 benefits). The cost-effectiveness values were calculated using a discount rate of 2% for the
1520 present value.

1521

1522 **S7 Table.** The three most cost-effective conservation management strategies for Antarctic
1523 taxa under climate forcing scenario RCP4.5; identified in order of significance as 1, 2, 3.
1524 Benefits of strategies are calculated using best estimates of improved intactness provided by
1525 experts and were capped at current (100%) intactness (An1; if a taxon only has benefits
1526 beyond 100% no strategies have been identified; see Supplementary Table 5 including these

1527 benefits). The cost-effectiveness values were calculated using a discount rate of 2% for the
1528 present value.

1529

1530 **S8 Table.** The three most cost-effective conservation management strategies for Antarctic
1531 taxa under climate forcing scenario RCP8.5; identified in order of significance as 1, 2, 3.

1532 Benefits of strategies are calculated using best estimates of improved intactness provided by
1533 experts and include benefits to taxa expected to expand beyond current (100%) intactness
1534 (An2). The cost-effectiveness values were calculated using a discount rate of 2% for the
1535 present value.

1536

1537 **S9 Table.** The three most cost-effective conservation management strategies for Antarctic
1538 taxa under climate forcing scenario RCP4.5; identified in order of significance as 1, 2, 3.

1539 Benefits of strategies are calculated using best estimates of improved intactness provided by
1540 experts and include benefits to taxa expected to expand beyond current (100%) intactness
1541 (An2). The cost-effectiveness values were calculated using a discount rate of 2% for the
1542 present value.

1543

1544 **S10 Table.** Methodological terms relating to priority threat management.

1545

1546 **S11 Table.** The 38 taxa used in Antarctic priority threat management; where species were
1547 grouped based on a similar predicted response to threats and management strategies.

1548

1549 **S12 Table.** Identified threats that may impact Antarctic terrestrial biodiversity by 2100.

1550

1551 **S13 Table.** Estimates for common priority threat management costs averaged from various
1552 National Antarctic Program estimates of cost; see table S4 for further details.

1553

1554 **S14 Table.** Percentage of Antarctic biodiversity taxa likely to decline, remain neutral, or
1555 benefit with future changes regionally and overall by 2100, under two analyses: **a**, when
1556 intactness values were capped at current (100%) intactness (An1), and **b**, when intactness
1557 values include benefits to taxa expected to expand beyond current (100%) intactness (An2).
1558 The values given represent biodiversity experts best estimate of the true intactness value.
1559 Estimates given under two climate forcing scenarios: RCP4.5 and RCP8.5.