

Threat management priorities for conserving Antarctic biodiversity

Jasmine R. Lee, Aleks Terauds, Josie Carwardine, Justine D. Shaw, Richard A. Fuller, Hugh Possingham, Steven L Chown, Peter Convey, Neil Gilbert, Kevin A. Hughes, et al.

▶ **To cite this version:**

Jasmine R. Lee, Aleks Terauds, Josie Carwardine, Justine D. Shaw, Richard A. Fuller, et al.. Threat management priorities for conserving Antarctic biodiversity. PLoS Biology, 2022, 20 (12), pp.e3001921. 10.1371/journal.pbio.3001921 . hal-03906003

HAL Id: hal-03906003
https://hal.science/hal-03906003

Submitted on 19 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Threat management priorities for conserving Antarctic biodiversity

Jasmine R. Lee[1,2,3,4*], Aleks Terauds[5], Josie Carwardine[2], Justine D. Shaw[1], Richard A. Fuller[1], Hugh P. Possingham[1,6], Steven L. Chown[7], Peter Convey[4,8], Neil Gilbert[9], Kevin A. Hughes[4], Ewan McIvor[5], Sharon A. Robinson[10,11], Yan Ropert-Coudert[12], Dana M. Bergstrom[5,10], Elisabeth M. Biersma[4,13], Claire Christian[14], Don A. Cowan[15], Yves Frenot[16], Stéphanie Jenouvrier[17], Lisa Kelley[18], Michael J. Lee[19], Heather J. Lynch[20], Birgit Njåstad[21], Antonio Quesada[22], Ricardo M. Roura[14], E. Ashley Shaw[23], Damon Stanwell-Smith[18,24], Megumu Tsujimoto[25,26], Diana H. Wall[27], Annick Wilmotte[28], Iadine Chadès[2]

[1.] School of Biological Sciences, The University of Queensland, Brisbane, QLD 4072, Australia.

[2.] CSIRO, Dutton Park, QLD 4102, Australia.

[3.] School of Biological Sciences, Monash University, Melbourne, VIC 3800, Australia.

[4.] British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 0ET, United Kingdom.

[5.] Australian Antarctic Division, Kingston, TAS 7050, Australia.

[6.] The Nature Conservancy, Arlington, VA 22203, United States.

[7.] Securing Antarctica's Environmental Future, School of Biological Sciences, Monash University, Melbourne, VIC 3800, Australia.

[8.] Department of Zoology, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa.

[9.] Constantia Consulting Ltd, 310 Papanui Road, Christchurch 8052, New Zealand.

[10.] Centre for Sustainable Ecosystem Solutions, School of Earth, Atmosphere and Life Sciences and Global Challenges Program, University of Wollongong, Wollongong, NSW 2522, Australia.

[11.] Securing Antarctica's Environmental Future, University of Wollongong, Wollongong, NSW 2522, Australia.

[12.] Centre d'Etudes Biologiques de Chizé, La Rochelle Université − CNRS, UMR 7372, 79360 Villiers en Bois, France.

[13.] Natural History Museum of Denmark, University of Copenhagen, Øster Farimagsgade 5, DK-1353 Copenhagen, Denmark.

[14.] Antarctic and Southern Ocean Coalition, 1320 19th St. NW, Fifth Floor, Washington, DC 20036, USA.

[15.] Centre for Microbial Ecology and Genomics, Department of Biochemistry, Genetics and Microbiology, University of Pretoria, Pretoria 0002, South Africa.

[16.] University of Rennes 1, CNRS, EcoBio (Ecosystèmes, biodiversité, évolution) - UMR 6553, 35000 Rennes, France.

[17.] Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA.

[18.] International Association of Antarctica Tour Operators (IAATO), South Kingstown, RI 02879, USA.

[19.] Reel Time Gaming, Taringa, QLD 4068, Australia.

[20.] Department of Ecology and Evolution, Stony Brook University, Stony Brook, NY 11794-5245, USA.

[21.] Norwegian Polar Institute, Fram Centre, 9296 Tromsø, Norway.

[22.] Department of Biology, Universidad Autónoma de Madrid. 28049 Madrid. Spain.

[23.] Institute of Ecology and Evolution, University of Oregon, Eugene, OR 97403, USA.

[24.] Viking Expeditions, Schäferweg 20, 4057 Basel, Switzerland.

[25.] Faculty of Environment and Information Studies, Keio University, Fujisawa, Kanagawa 252-0882, Japan.

[26.] National Institute of Polar Research, Tachikawa, Tokyo 190-8518, Japan.

[27.] Department of Biology and School of Global Environmental Sustainability, Colorado State University, Fort Collins, CO 80523, USA.

[28.] InBios-Centre for Protein Engineering, University of Liège, Liège, Belgium.

*** Jasmine R Lee**

Email: jasmine.lee1@uqconnect.edu.au

Abstract:

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

Introduction

Conserving Antarctic species for future generations is in the interest of all humankind. Designated as a natural reserve, devoted to peace and science, Antarctica is home to numerous endemic species (Chown and Convey 2007). Charismatic emperor and Adélie penguins capture the world's imagination, whilst the nematode *Scottnema lindsayae* survives in saline soils that are inhospitable to other eukaryotic life forms (Adams et al. 2007). These endemic species possess distinctive adaptations that allow them to survive Antarctica's extreme conditions (Convey 1996; Convey and Peck 2019). Some of them may even be key for developing new technologies or medicines, including sustainable biomanufacturing processes, uses in the frozen food industry (Muñoz et al. 2017), and biodiesel production (Lv et al. 2019). Furthermore, Antarctica and the Southern Ocean provide essential ecosystem services, in particular regulating global climate via processes driving atmospheric circulation and ocean currents, and the absorption of anthropogenic heat and CO_2 (Turner et al. 2009; Rintoul et al. 2018). Finally, Antarctica is one of the few places on the planet that can still be considered largely unspoilt by the industrial development of humanity (Leihy et al. 2020).

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

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

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

Our Approach

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

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

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

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

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

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

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

Strategy Name	**Objectives and details**
Business as usual *(Baseline)*	*Continue with actions and strategies currently in use, but neither expand on these strategies nor employ new strategies*. Baseline against which to measure other strategies.
Remediation *(Remediate)*	*Increase amount of, or improve, quality of habitat available to biodiversity in comparison to habitat currently available*. 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 *(Exist infra.)*	*Reduce and minimise impacts of existing infrastructure compared to current levels*.
Manage new infrastructure *(New infra.)*	*Prevent, reduce and minimise impacts of new infrastructure.*
Transport management *(Transport)*	*Reduce and minimise impacts of transport compared to current levels.*
Manage non-native species and disease *(Non-native)*	*Reduce impacts of non-native species and disease on native biodiversity.* 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 *(Protect vegetation)*	*Reduce physical impacts of human activities and native vertebrate activities on vegetation*. 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 *(Protecting areas)*	*Reduce impacts of human activities on biodiversity by increasing the amount and representation of habitat in protected areas.* 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 *(Protecting species)*	*Reduce threatening impacts on taxa identified as threatened by 2100*. 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 *(Human activities)*	*Prevent and minimise physical impacts on biodiversity and habitats compared to current levels that stem from human activities in Antarctica* (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 *(Influence ext. policy)*	*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.* **Note:** Outcome of strategy is an assumption that the Paris Climate Agreement of <2 °C warming is avhieved. Use RCP2.6 instead of 4.5/8.5.
All strategies excluding 'influence external policy' *(All strats. excl IEP)*	All management strategies combined except 'Influence external policy'.
All strategies combined *(All strategies)*	All management strategies combined.

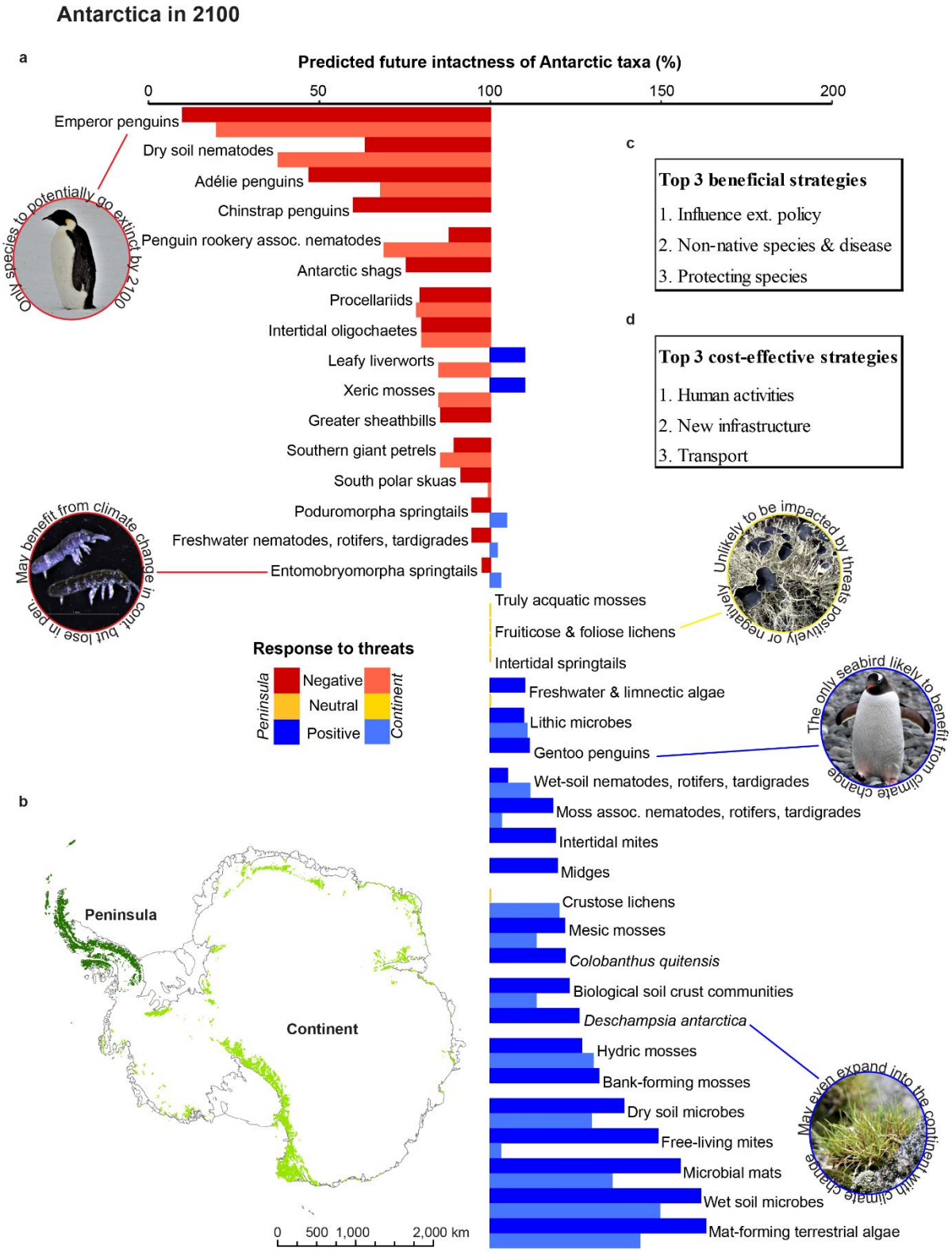
Results and Discussion

Threat vulnerability

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

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

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


Antarctica in 2100
a
Predicted future intactness of Antarctic taxa (%)
0
50
100
150
200
Emperor penguins
Dry soil nematodes
Adélie penguins
Chinstrap penguins
Penguin rookery assoc. nematodes
Antarctic shags
Procellariids
Intertidal oligochaetes
Leafy liverworts
Xeric mosses
Greater sheathbills
Southern giant petrels
South polar skuas
Poduromorpha springtails
Freshwater nematodes, rotifers, tardigrades
Entomobryomorpha springtails
Truly acquatic mosses
Fruiticose & foliose lichens
Intertidal springtails
Freshwater & limnectic algae
Lithic microbes
Gentoo penguins
Wet-soil nematodes, rotifers, tardigrades
Moss assoc. nematodes, rotifers, tardigrades
Intertidal mites
Midges
Crustose lichens
Mesic mosses
Colobanthus quitensis
Biological soil crust communities
Deschampsia antarctica
Hydric mosses
Bank-forming mosses
Dry soil microbes
Free-living mites
Microbial mats
Wet soil microbes
Mat-forming terrestrial algae
Only species to potentially go extinct by 2100
May benefit from climate change in cont. but lose in pen.
Unlikely to be impacted by threats positively or negatively
The only seabird likely to benefit from climate change
May even expand into the continent with climate change
Response to threats
Peninsula
Negative
Neutral
Positive
Continent
b
Peninsula
Continent
0 500 1,000 2,000 km
c
Top 3 beneficial strategies
1. Influence ext. policy
2. Non-native species & disease
3. Protecting species
d
Top 3 cost-effective strategies
1. Human activities
2. New infrastructure
3. Transport

260

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

Benefits of management strategies

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

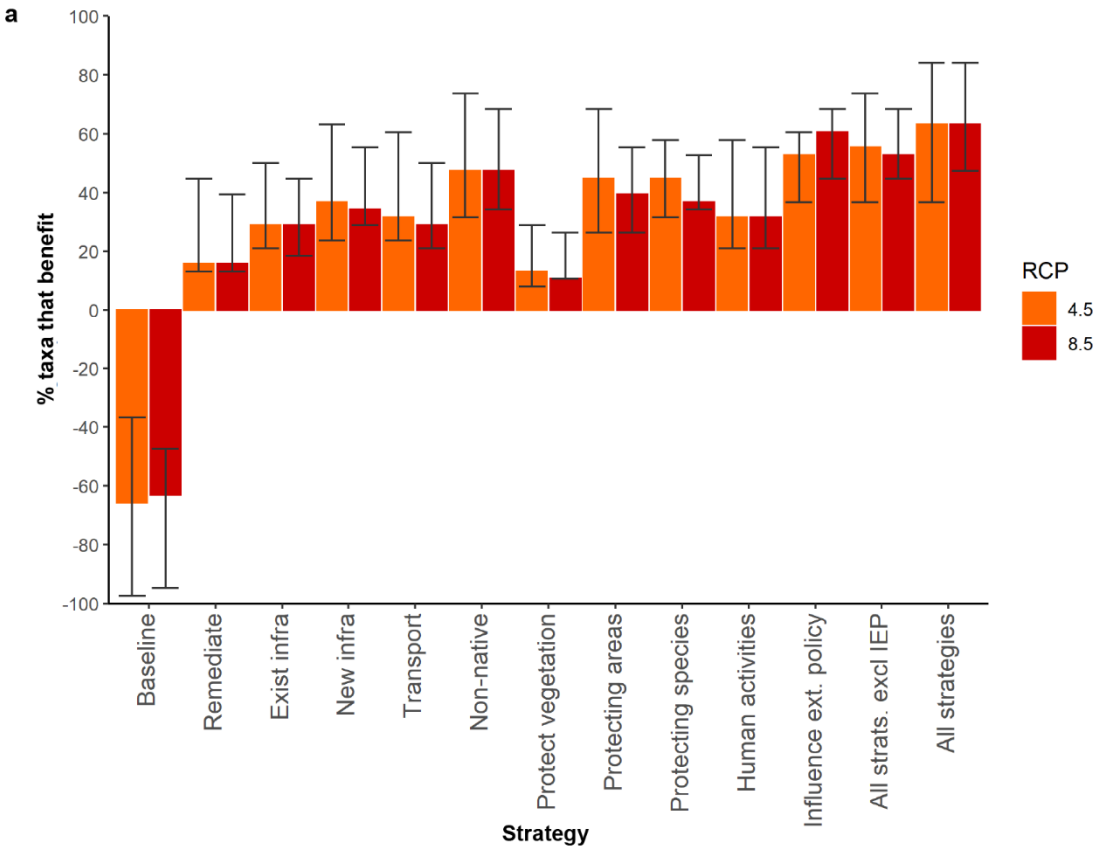
2a). However, 53 – 61%, and up to 68%, of taxa would benefit if the single '*Influence external policy'* strategy aimed at reducing global climate change was successful. If climate change cannot be mitigated, all regional strategies combined (*'All strategies combined excluding policy influence')* will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

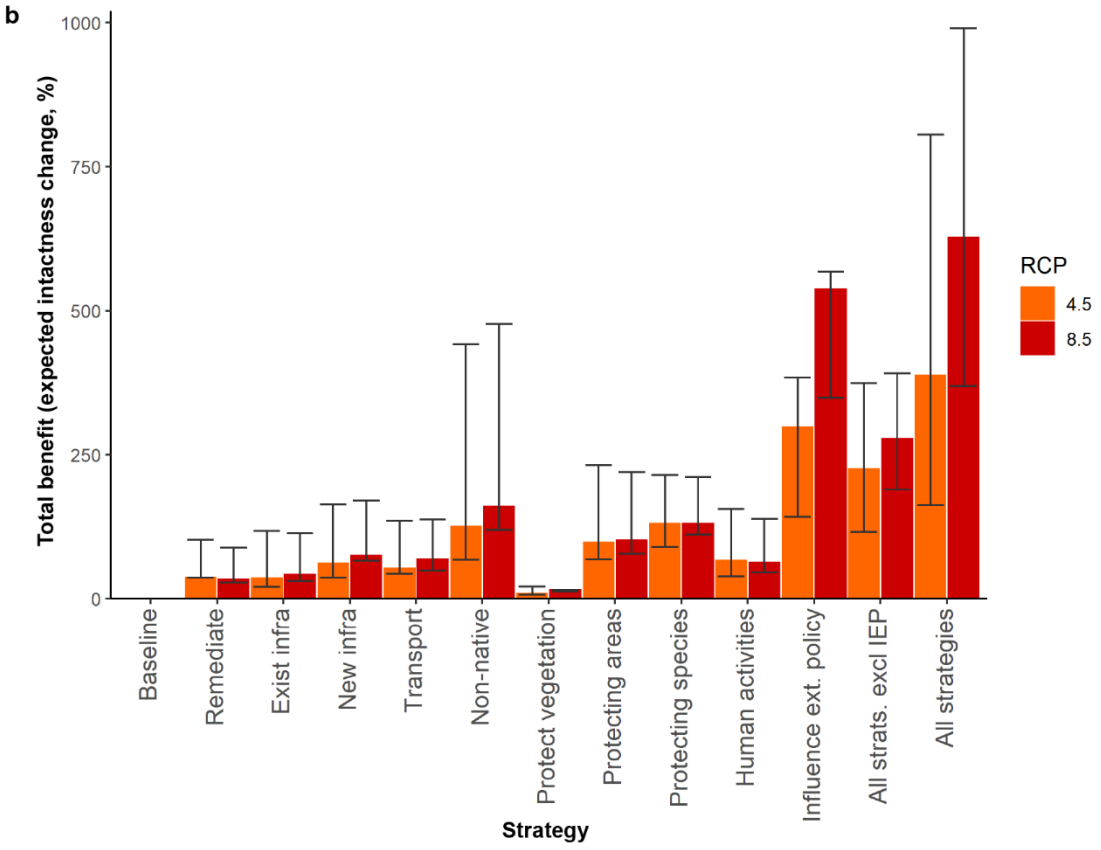
The strategies that provide the highest total expected benefits, when combined for all taxa and both regions, are almost the same regardless of climate forcing scenario (Fig. 2b; Table 2). *'All strategies combined',* unsurprisingly, provides the highest total benefit. The second highest total benefit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

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

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

317


a
% taxa that benefit
100
80
60
40
20
0
-20
-40
-60
-80
-100
Baseline
Remediate
Exist infra
New infra
Transport
Non-native
Protect vegetation
Protecting areas
Protecting species
Human activities
Influence ext. policy
All strats. excl IEP
All strategies
Strategy
RCP
4.5
8.5


b
Total benefit (expected intactness change, %)
1000
750
500
250
0
Baseline
Remediate
Exist infra
New infra
Transport
Non-native
Protect vegetation
Protecting areas
Protecting species
Human activities
Influence ext. policy
All strats. excl IEP
All strategies
Strategy
RCP
4.5
8.5

318

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

Feasibility and costs

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

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

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

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

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

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

Cost-effective strategies

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

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

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

			RCP4.5		RCP8.5	
Strategy	**Cost (US$ M)**	**Feasibility**	**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

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

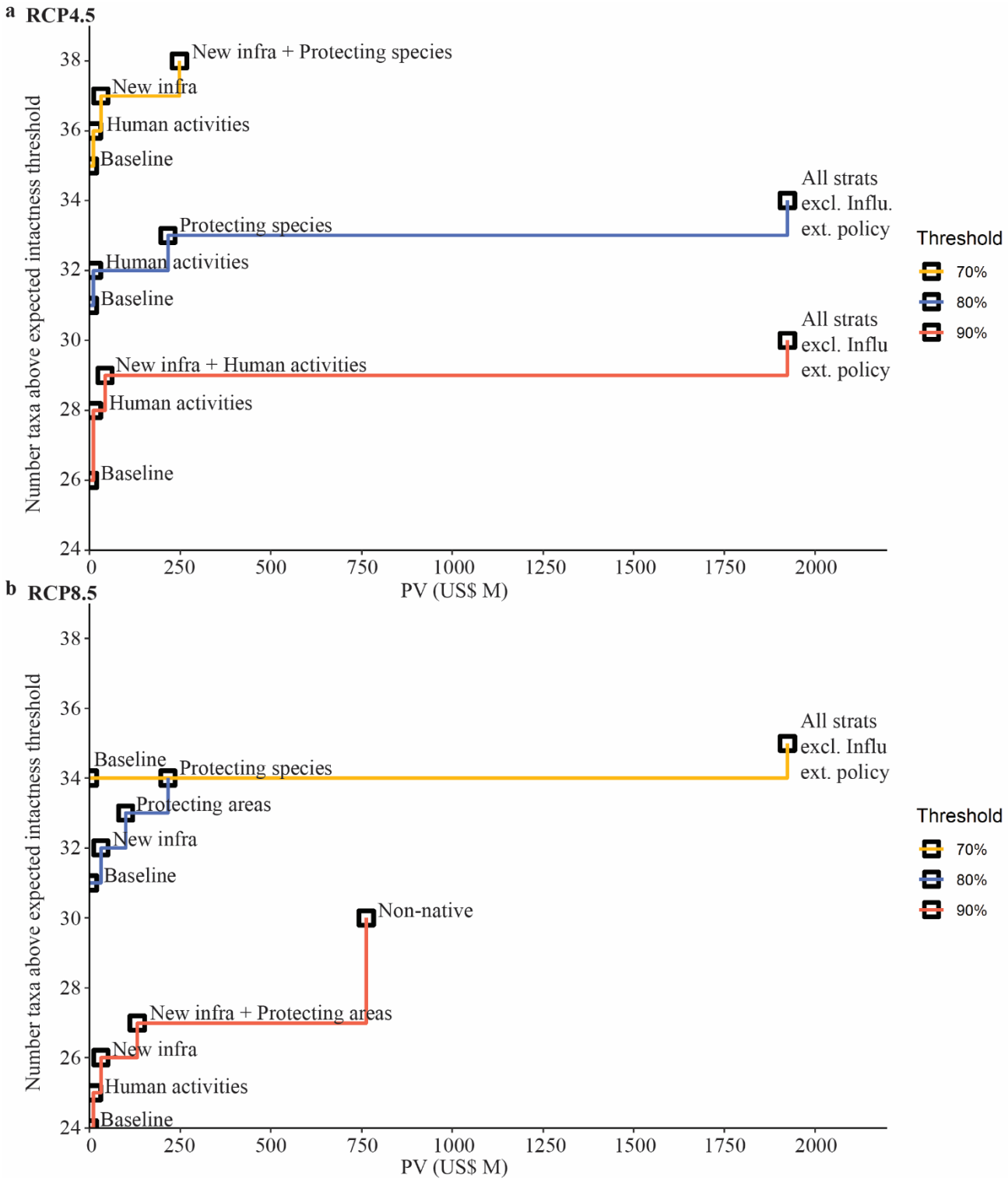


Fig. 3. Complementary solutions for conserving Antarctic terrestrial biodiversity for any given budget under three intactness thresholds and where there is no possibility of reducing climate

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

Implementation of threat management strategies

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

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

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

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

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

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

Uncertainty

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

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

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

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

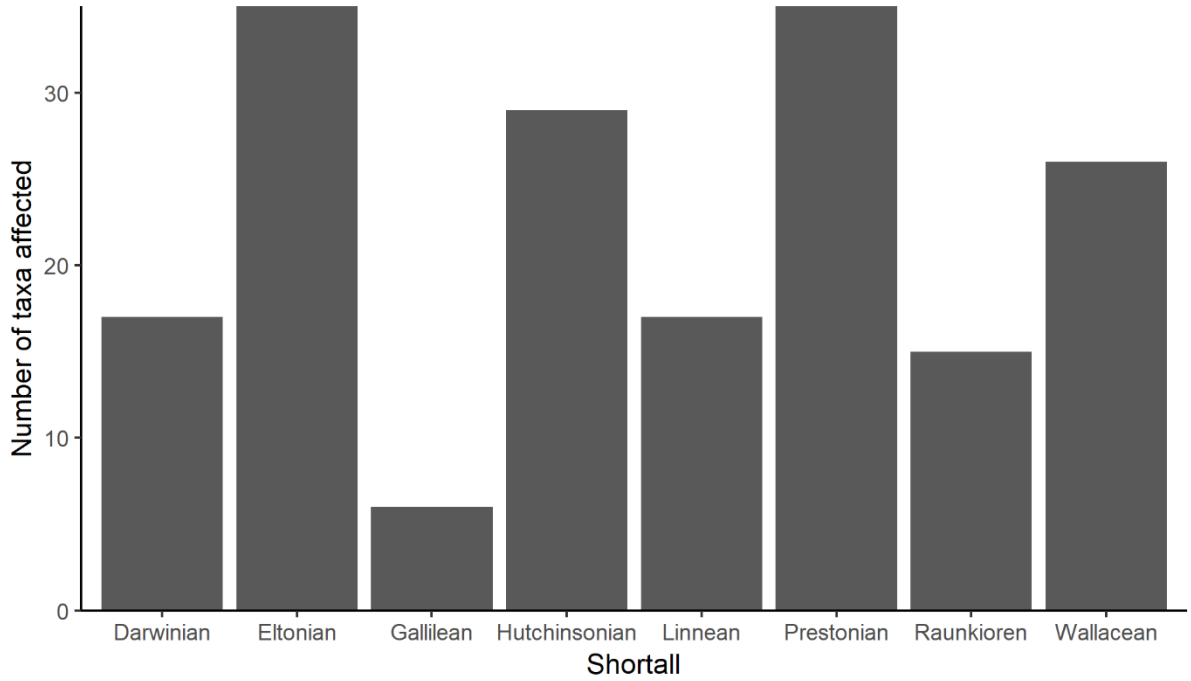


Fig. 4. Number of taxa for which each of eight knowledge shortfalls were identified that limit understanding and assessment of Antarctic terrestrial biodiversity. See S1 Table for a definition of each of the eight shortfalls and S2 Table that lists the shortfalls identified for each biodiversity taxon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

Conclusions

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

Materials and methods

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

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

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

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

Region, timeframe, and climate scenarios

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

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

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

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

Expert participants and elicitation

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

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

Selection of taxonomic groups

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

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

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

Threats

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

Management strategies

Experts agreed on a total of 13 strategies for managing and conserving Antarctic terrestrial biodiversity to 2100 (Table 1; S1 Data). A quantifiable aim was determined for each strategy (Table 1). Whilst differing aims may result in a different prioritisation, a large amount of time 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

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

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

Feasibility and cost

Feasibility consisted of two aspects: 'likelihood of uptake' and 'likelihood of success', which were estimated by the experts using a scale of 0 – 100%, where: 0 = *Impossible*, 15 = *Improbable*, 25 = *Unlikely*, 50 = *Fifty-fifty*, 75 = *Likely*, 85 = *Probable*, 100 = *Certain*. Likelihood of uptake was estimated for each action and represents the likelihood that policymakers will agree to implement this action considering social and political factors, assuming that cost is not a barrier. The likelihood of uptake estimates were averaged for all actions in the strategy to obtain an overall estimate per strategy, which will be lower overall for strategies that include one or more actions that are more socio-politically challenging. Likelihood of success was estimated per strategy and represents the likelihood that the strategy will meet its objectives in reducing impacts of threats, assuming that all actions have been implemented. Overall feasibility per strategy was calculated as a product of the two likelihoods and is provided as a probability (S3 Fig.; S1 Data).

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

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

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

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

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

Benefit assessments

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

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

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

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

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

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

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

Expert's values of predicted future baseline intactness allowed us to identify which taxa are likely to be vulnerable to future changes in the region. Some taxa that are predicted to have future intactness values similar to current (100%) levels are classified as vulnerable in Analysis 1, but as benefiting in Analysis 2. This occurs when the averaged expert intactness value is below 100% when the values are capped, but where the average might be above 100% when uncapped (see S14 Table, and raw values on the Australian Antarctic Data Centre; 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

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

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

Benefits were summarised at different scales, including potential benefits per taxon, per region and per climate scenario, and then summed to give regional and overall potential benefits for all biodiversity taxa combined. We assume that benefits accrue over time at a similar rate up to the maximum improvement estimated for each action. Hence for ease of interpretation, we 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 $$P_{ij} = \bar{P}_{baseline j} + F_i \bar{B}_{ij},$$
988
989 with $\bar{P}_{baseline j}$ 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

	$\underset{y_i}{\text{minimize}} \sum_{i \in S} y_i C_i$	
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)

Solving this ILP requires finding the values of two sets of binary decision variables. The first set of decision variables y_i determines if a strategy $i \in S$ is selected ($y_i = 1$) or not ($y_i = 0$). If strategy *i* is selected, the taxon *j* with values of T_{ij}=1 is assumed secured. The second set of auxiliary decision variables x_{ij} identifies the taxon *j* secured by strategy i – these decision variables ensure we reach the target of a given number of taxa to secure (identified by Target). We sought to minimise the cost of implementing strategies while respecting four constraints:

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

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

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

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

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

Sensitivity analyses

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

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

Additional information: Antarctic priority threat management database containing intactness values, benefits and uncertainties for each biodiversity taxon has been made available through the Australian Antarctic Data Centre (AADC; https://doi.org/10.26179/5da8f8e7a2256).

Acknowledgements:

We thank the organisers of the SCAR Biology 2017 Symposium at Katholieke Universiteit Leuven in Belgium, especially Anton Van de Putte and Bruno Danis, for organising workshop rooms and schedules. We thank Patricia Ortúzar for her input and participation in the 2017 workshop, Craig Salt who helped to facilitate the workshop and Jenny Baeseman who provided administrative support. We thank A. Lynnes, A. Hobday and H. Murphy for valuable feedback on earlier drafts. This research is a contribution to the Integrated Science to Inform Antarctic and Southern Ocean Conservation (Ant-ICON) Scientific Research Programme of the Scientific Committee on Antarctic Research (SCAR).

Author contributions: J.L. oversaw the development of the methodology, data collection, formal analysis, interpretation and writing – original draft, and undertook data curation and visualisation. I.C. conceptualised the study and undertook the complementarity analysis. A.T. undertook workshop funding acquisition. I.C., A.T., J.C., J.S., R.F., and H.P. contributed to developing the methodology, formal analysis, and interpretation. I.C., A.T., J.C., J.S., R.F., H.P, S.C., P.C., K.H., E.M., and H.L. contributed to writing – original draft. M.L. developed and maintained the software. All authors contributed to the data collection, and writing – review & editing.

References

Adams BJ, Wall DH, Gozel U, Dillman AR, Chaston JM, Hogg ID. The southernmost worm, *Scottnema lindsayae* (Nematoda): diversity, dispersal and ecological stability. Polar Biology. 2007; 30(7):809-15.

Amesbury MJ, Roland TP, Royles J, Hodgson DA, Convey P, Griffiths H, et al. Widespread biological response to rapid warming on the Antarctic Peninsula. Current Biology. 2017; 27(11):1616-22.e2.

Andriuzzi WS, Adams BJ, Barrett JE, Virginia RA, Wall DH. Observed trends of soil fauna in the Antarctic Dry Valleys: early signs of shifts predicted under climate change. Ecology. 2018; 99(2):312-21.

ATCM. ATCM interests in international climate change discussions – options for enhanced engagement. WP032 submitted by Australia; 2012.

ATCM. Resolution 4 (2017); Green Expedition in the Antarctic. Antarctic Treaty Secretariat; 2017.

ATCM. New IAATO procedures for operating in the vicinity of whales. IP097 submitted by the International Association of Antarctica Tour Operators; 2019.

ATCM. Resolution D (2021); Antarctica in a Changing Climate. Antarctic Treaty Secretariat; 2021.

ATCM. Paris Declaration on the occasion of the Sixtieth anniversary of the entry into force of the Antarctic Treaty and on the Thirtieth anniversary of the signing of the 1991 Madrid Protocol on Environmental Protection to the Antarctic Treaty. Paris, France: Antarctic Treaty Secretariat; 2021.

Auerbach NA, Tulloch AIT, Possingham HP. Informed actions: where to cost effectively manage multiple threats to species to maximize return on investment. Ecological Applications. 2014; 24(6):1357-73.

Balmford A, Gaston KJ, Ana SLR, James A. Integrating costs of conservation into international priority setting. Conservation Biology. 2000; 14(3):597-605.

Bartlett JC, Convey P, Pertierra LR, Hayward SAL. An insect invasion of Antarctica: the past, present and future distribution of *Eretmoptera murphyi* (Diptera, Chironomidae) on Signy Island. Insect Conservation and Diversity. 2020; 13(1):77-90.

Bedford R, Cooke RM. Mathematical tools for probabilistic risk analysis. Cambridge: Cambridge University Press; 2001.

Bender NA, Crosbie K, Lynch HJ. Patterns of tourism in the Antarctic Peninsula region: a 20-year analysis. Antarctic Science. 2016; 28(3):194-203.

Bennett JR, Maxwell SL, Martin AE, Chadès I, Fahrig L, Gilbert B. When to monitor and when to act: Value of information theory for multiple management units and limited budgets. Journal of Applied Ecology. 2018; 55(5):2102-13.

Bennett JR, Shaw JD, Terauds A, Smol JP, Aerts R, Bergstrom DM, et al. Polar lessons learned: long-term management based on shared threats in Arctic and Antarctic environments. Frontiers in Ecology and the Environment. 2015; 13(6):316-24.

Bergstrom DM, Robinson S, Alexander S. Record-smashing heatwaves are hitting Antarctica and the Arctic simultaneously. Here's what's driving them, and how they'll impact wildlife. The Conversation. 2022 Mar 22 [Cited 28 March 2022]. Available from: https://theconversation.com/record-smashing-heatwaves-are-hitting-antarctica-and-the-arctic-simultaneously-heres-whats-driving-them-and-how-theyll-impact-wildlife-179659

Bokhorst S, Huiskes A, Convey P, van Bodegom PM, Aerts R. Climate change effects on soil arthropod communities from the Falkland Islands and the Maritime Antarctic. Soil Biology and Biochemistry. 2008; 40(7):1547-56.

Bottrill MC, Joseph LN, Carwardine J, Bode M, Cook C, Game ET, et al. Is conservation triage just smart decision making? Trends in Ecology & Evolution. 2008; 23(12):649-54.

Brooks ST, Jabour J, van den Hoff J, Bergstrom DM. Our footprint on Antarctica competes with nature for rare ice-free land. Nature Sustainability. 2019; 2:185-90.

Brucker, P. NP-Complete operations research problems and approximation algorithms. Zeitschrift für Operations-Research. 1979; 23:73-94.

Burgman M. Expert frailties in conservation risk assessment and listing decisions. In: Hutchings P, Lunney D, Dickman C, editors. Threatened species legislation: Is it just an act? New South Wales: Royal Zoological Society of New South Wales; 2004. pp. 20-29.

Câmara PEAS, Convey P, Rangel SB, Konrath M, Barreto CC, Pinto OHB, et al. The largest moss carpet transplant in Antarctica and its bryosphere cryptic biodiversity. Extremophiles. 2021; 25(4):369-84.

Cannone N, Guglielmin M, Convey P, Worland MR, Favero Longo SE. Vascular plant changes in extreme environments: effects of multiple drivers. Climatic Change. 2016; 134(4):651-65.

Cannone N, Malfasi F, Favero-Longo SE, Convey P, Guglielmin M. Acceleration of climate warming and plant dynamics in Antarctica. Current Biology. 2022; 32:1-8.

Carwardine J, Martin TG, Firn J, Reyes RP, Nicol S, Reeson A, et al. Priority Threat Management for biodiversity conservation: A handbook. Journal of Applied Ecology. 2019; 56(2):481-90.

Carwardine J, O'Connor T, Legge S, Mackey B, Possingham HP, Martin TG. Prioritizing threat management for biodiversity conservation. Conservation Letters. 2012; 5(3):196-204.

CEP. Annex 8 to the CEP VIII Final report; Guidelines for CEP consideration of Proposals for New and Revised Designations of Antarctic Specially Protected Species under Annex II of the Protocol. Committee for Environmental Protection; 2005.

CEP. Final Report of the Twenty-third Meeting of the Committee for Environmental Protection (CEP XXIII). Antarctic Treaty Secretariat; 2021.

Chadés I, Nicol S, van Leeuwen S, Walters B, Firn J, Reeson A, et al. Benefits of integrating complementarity into priority threat management. Conservation Biology. 2015; 29(2):525-36.

Chown SL, Brooks CM, Terauds A, Le Bohec C, van Klaveren-Impagliazzo C, Whittington JD, et al. Antarctica and the strategic plan for biodiversity. PLoS Biology. 2017; 15(3):e2001656.

Chown SL, Clarke A, Fraser CI, Cary SC, Moon KL, McGeoch MA. The changing form of Antarctic biodiversity. Nature. 2015; 522(7557):431-8.

Chown SL, Convey P. Spatial and temporal variability across life's hierarchies in the terrestrial Antarctic. Philosophical Transactions of the Royal Society B. 2007; 362:2307–31.

Chown SL, Huiskes AHL, Gremmen NJM, Lee JE, Terauds A, Crosbie K, et al. Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. Proceedings of the National Academy of Sciences. 2012; 109(13):4938-43.

Chown SL, Leihy RI, Naish TR, Brooks CM, Convey P, Henley BJ, et al. (Eds.). Antarctic Climate Change and the Environment: A Decadal Synopsis and Recommendations for Action. Scientific Committee on Antarctic Research, Cambridge, United Kingdom: 2022.

Coetzee BWT, Chown SL. A meta-analysis of human disturbance impacts on Antarctic wildlife. Biological Reviews. 2016; 91(3):578-96.

Council of Managers of National Antarctic Program. Application to COMNAP AGM for the creation and funding of a 2019/20 task force. 2020 [cited 2020 Sep 8]. Available from: https://www.comnap.aq/projects/efficiency-taskforce-peninsula-2019-2020/

Convey P. The influence of environmental characteristics on life history attributes of Antarctic terrestrial biota. Biological Reviews. 1996; 71(2):191-225.

Convey P. Antarctic terrestrial biodiversity in a changing world. Polar Biology. 2011; 34(11):1629-41.

Convey P. Antarctic Ecosystems. In: Levin SA, editor. Encyclopedia of Biodiversity. 1: Elsevier; 2017. p. 179-88.

Convey P, Peck LS. Antarctic environmental change and biological responses. Science Advances. 2019; 5(11):eaaz0888.

Cordero RR, Sepúlveda E, Feron S, Damiani A, Fernandoy F, Neshyba S, et al. Black carbon footprint of human presence in Antarctica. Nature Communications. 2022; 13(1):984.

Duffy GA, Coetzee BWT, Latombe G, Akerman AH, McGeoch MA, Chown SL. Barriers to globally invasive species are weakening across the Antarctic. Diversity and Distributions. 2017; 23(9):982-96.

Duffy GA, Lee JR. Ice-free area expansion compounds the non-native species threat to Antarctic terrestrial biodiversity. Biological Conservation. 2019; 232:253-7.

Firn J, Maggini R, Chadès I, Nicol S, Walters B, Reeson A, et al. Priority threat management of invasive animals to protect biodiversity under climate change. Global Change Biology. 2015; 21(11):3917-30.

Frame B, Hemmings AD. Coronavirus at the end of the world: Antarctica matters. Social Sciences & Humanities Open. 2020; 2(1):100054.

Game ET, Kareiva P, Possingham HP. Six common mistakes in conservation priority setting. Conservation Biology. 2013; 27(3):480-5.

Gasser T, Guivarch C, Tachiiri K, Jones CD, Ciais P. Negative emissions physically needed to keep global warming below 2 °C. Nat Commun. 2015; 6:7958.

Graf HF, Shirsat SV, Oppenheimer C, Jarvis MJ, Podzun R, Jacob D. Continental scale Antarctic deposition of sulphur and black carbon from anthropogenic and volcanic sources. Atmospheric Chemistry & Physics. 2010; 10(5):2457-65.

Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. Proceedings of the National Academy of Sciences. 2017; 114(44):11645-50.

Hausfather Z, Peters GP. Emissions - the 'business as usual' story is misleading. Nature. 2020; 577:618-20.

Hemming V, Armstrong N, Burgman MA, Hanea AM. Improving expert forecasts in reliability: Application and evidence for structured elicitation protocols. Quality and Reliability Engineering International. 2020; 36(2):623-41.

Hemming V, Burgman MA, Hanea AM, McBride MF, Wintle BC. A practical guide to structured expert elicitation using the IDEA protocol. Methods in Ecology and Evolution. 2018; 9(1):169-80.

Hill PW, Farrar J, Roberts P, Farrell M, Grant H, Newsham KK, et al. Vascular plant success in a warming Antarctic may be due to efficient nitrogen acquisition. Nature Climate Change. 2011; 1(1):50-3.

Höhne N, Elzen Md, Rogelj J, Metz B, Fransen T, Kuramochi T, et al. Emissions: world has four times the work or one-third of the time. Nature. 2020; 579:25-8.

Hortal J, Bello Fd, Diniz-Filho JAF, Lewinsohn TM, Lobo JM, Ladle RJ. Seven shortfalls that beset large-scale knowledge of biodiversity. Annual Review of Ecology, Evolution, and Systematics. 2015; 46(1):523-49.

Hughes K, Pertierra L, Molina-Montenegro M, Convey P. Biological invasions in terrestrial Antarctica: what is the current status and can we respond? Biodiversity and Conservation. 2015; 24(5):1031-55.

Hughes KA, Convey P. Implications of the COVID-19 pandemic for Antarctica. Antarctic Science. 2020; 32(6):426-39.

Hughes KA, Convey P, Pertierra LR, Vega GC, Aragón P, Olalla-Tárraga MÁ. Human-mediated dispersal of terrestrial species between Antarctic biogeographic regions: A preliminary risk assessment. Journal of Environmental Management. 2019; 232:73-89.

Hughes KA, Convey P, Turner J. Developing resilience to climate change impacts in Antarctica: An evaluation of Antarctic Treaty System protected area policy. Environmental Science & Policy. 2021; 124:12-22.

Hughes KA, Ott S, Bölter M, Convey P. Colonisation processes. In: Bergstrom DM, Convey P, Huiskes AHL, editors. Trends in Antarctic terrestrial and limnetic ecosystems. Netherlands: Springer; 2006. pp. 35-54.

Hughes KA, Pertierra LR, Walton DWH. Area protection in Antarctica: How can conservation and scientific research goals be managed compatibly? Environmental Science & Policy. 2013; 31:120-32.

Hughes KA, Pescott OL, Peyton J, Adriaens T, Cottier-Cook EJ, Key G, et al. Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. Global Change Biology. 2020; 26(4):2702-16.

International Association of Antarctica Tour Operators. IAATO Antarctic visitor figures 2019-2020. 2020 [cited 2020 Sep 8]. Available from: https://iaato.org/wp-content/uploads/2020/06/IAATO-on-Antarctic-visitor-figures-2019-20-FINAL.pdf

IPCC. Climate Change 2013: The Physical Science Basis. Cambridge, United Kingdom and New York, NY, USA: 2013.

IPCC. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva: World Meteorological Organisation; 2018.

IPCC. Summary for Policymakers. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2022.

Jenouvrier S, Che-Castaldo J, Wolf S, Holland M, Labrousse S, LaRue M, et al. The call of the emperor penguin: Legal responses to species threatened by climate change. Global Change Biology. 2021; 27:5008-5029.

Jenouvrier S, Holland M, Iles D, Labrousse S, Landrum L, Garnier J, et al. The Paris Agreement objectives will likely halt future declines of emperor penguins. Global Change Biology. 2020; 26(3):1170-84.

Lee JR, Maggini R, Taylor MFJ, Fuller RA. Mapping the drivers of climate change vulnerability for Australia's threatened species. PLoS ONE. 2015; 10(5):e0124766.

Lee JR, Raymond B, Bracegirdle TJ, Chadès I, Fuller RA, Shaw JD, et al. Climate change drives expansion of Antarctic ice-free habitat. Nature. 2017; 547:49-54.

Leihy RI, Coetzee BWT, Morgan F, Raymond B, Shaw JD, Terauds A, et al. Antarctica's wilderness fails to capture continent's biodiversity. Nature. 2020; 583:567-71.

Lv Y, Sun S, Liu J. Biodiesel production catalyzed by a methanol-tolerant lipase A from *Candida antarctica* in the presence of excess water. ACS Omega. 2019; 4(22):20064-71.

Lynch HJ, Naveen R, Trathan PN, Fagan WF. Spatially integrated assessment reveals widespread changes in penguin populations on the Antarctic Peninsula. Ecology. 2012; 93(6):1367-77.

Martin TG, Burgman MA, Fidler F, Kuhnert PM, Low-Choy S, McBride M, et al. Eliciting expert knowledge in conservation science. Conservation Biology. 2012a; 26(1):29-38.

Martin TG, Kehoe L, Mantyka-Pringle C, Chades I, Wilson S, Bloom RG, et al. Prioritizing recovery funding to maximize conservation of endangered species. Conservation Letters. 2018; 11(6):e12604.

Martin TG, Nally S, Burbidge AA, Arnall S, Garnett ST, Hayward MW, et al. Acting fast helps avoid extinction. Conservation Letters. 2012b; 5(4):274-80.

Maxwell SL, Fuller RA, Brooks TM, Watson JEM. Biodiversity: The ravages of guns, nets and bulldozers. Nature. 2016; 536(7651): 143-5.

Maxwell SL, Rhodes JR, Runge MC, Possingham HP, Ng CF, McDonald-Madden E. How much is new information worth? Evaluating the financial benefit of resolving management uncertainty. Journal of Applied Ecology. 2015; 52(1):12-20.

McBride MF, Garnett ST, Szabo JK, Burbidge AH, Butchart SHM, Christidis L, et al. Structured elicitation of expert judgments for threatened species assessment: a case study on a continental scale using email. Methods in Ecology and Evolution. 2012; 3(5):906-20.

Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, et al. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change. 2011; 109(1):213.

Moilanen A, Wilson K, Possingham H. Spatial conservation prioritization: quantitative methods and computational tools: Oxford University Press; 2009.

Molina-Montenegro MA, Carrasco-Urra F, Rodrigo C, Convey P, Valladares F, Gianoli E. Occurrence of the non-native annual bluegrass on the Antarctic mainland and its negative effects on native plants. Conservation Biology. 2012; 26(4):717-23.

Molina-Montenegro MA, Bergstrom DM, Chwedorzewska KJ, Convey P, Chown SL. Increasing impacts by Antarctica's most widespread invasive plant species as result of direct competition with native vascular plants. NeoBiota. 2019; 51:19-40.

Muñoz PA, Márquez SL, González-Nilo FD, Márquez-Miranda V, Blamey JM. Structure and application of antifreeze proteins from Antarctic bacteria. Microbial Cell Factories. 2017; 16(1):138

Murdoch W, Polasky S, Wilson KA, Possingham HP, Kareiva P, Shaw R. Maximizing return on investment in conservation. Biological Conservation. 2007; 139(3):375-388.

Murdoch W, Ranganathan J, Polasky S, Regetz J. Using return on investment to maximize conservation effectiveness in Argentine grasslands. Proceedings of the National Academy of Sciences. 2010; 107(49):20855-62.

Nicol S, Brazill-Boast J, Gorrod E, McSorley A, Peyrard N, Chadès I. Quantifying the impact of uncertainty on threat management for biodiversity. Nature Communications. 2019; 10(1):3570.

Ponce Reyes R, Firn J, Nicol S, Chadès I, Stratford DS, Martin TG, et al. Priority threat management for imperilled species of the Queensland Brigalow Belt. Brisbane: CSIRO, 2016.

Raftery AE, Zimmer A, Frierson DMW, Startz R, Liu P. Less than 2 °C warming by 2100 unlikely. Nature Climate Change. 2017; 7:637.

Raymond TC, Snape I. Using triage for environmental remediation in Antarctica. Restoration Ecology. 2017; 25(1):129-34.

Rintoul SR, Chown SL, DeConto RM, England MH, Fricker HA, Masson-Delmotte V, et al. Choosing the future of Antarctica. Nature. 2018; 558(7709):233-41.

Robinson SA, Klekociuk AR, King DH, Pizarro Rojas M, Zúñiga GE, Bergstrom DM. The 2019/2020 summer of Antarctic heatwaves. Global Change Biology. 2020; 26: 3178-80.

Schrimpf MB, Che-Castaldo C, Lynch HJ. Regional breeding bird assessment of the Antarctic Peninsula. Polar Biology. 2020; 43:111-122.

Secretariat of the Antarctic Treaty. Protocol on Environmental Protection to the Antarctic Treaty. 1991 [cited 2020 Sep 8]. Available from: https://www.ats.aq/e/protocol.html

Secretariat of the Antarctic Treaty. The Antarctic Treaty. 1959 [cited 2020 Sep 8]. Available from: https://www.ats.aq/e/antarctictreaty.html

Shaw JD, Terauds A, Riddle MJ, Possingham HP, Chown SL. Antarctica's protected areas are inadequate, unrepresentative, and at risk. PLoS Biology. 2014; 12(6):e1001888.

Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, et al. Biophysical and economic limits to negative CO2 emissions. Nature Climate Change. 2016; 6(1):42-50.

Smith P, Price J, Molotoks A, Warren R, Malhi Y. Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2018; 376(2119):20160456.

Speirs-Bridge A, Fidler F, McBride M, Flander L, Cumming G, Burgman M. Reducing overconfidence in the interval judgments of experts. Risk Analysis. 2010; 30(3):512-23.

Strassburg BBN, Beyer HL, Crouzeilles R, Iribarrem A, Barros F, de Siqueira MF, et al. Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. Nature Ecology & Evolution. 2019; 3(1):62-70.

Terauds A, Lee JR. Antarctic biogeography revisited: updating the Antarctic Conservation Biogeographic Regions. Diversity and Distributions. 2016; 22:836-40.

Trathan PN, Wienecke B, Barbraud C, Jenouvrier S, Kooyman G, Le Bohec C, et al. The emperor penguin - Vulnerable to projected rates of warming and sea ice loss. Biological Conservation. 2020; 241:108216.

Trusel LD, Frey KE, Das SB, Karnauskas KB, Kuipers Munneke P, van Meijgaard E, et al. Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. Nature Geoscience. 2015; 8(12):927-32.

Tulloch AIT, Chadès I, Dujardin Y, Westgate MJ, Lane PW, Lindenmayer D. Dynamic species co-occurrence networks require dynamic biodiversity surrogates. Ecography. 2016; 39(12):1185-96.

Tulloch AIT, Chadès I, Possingham HP. Accounting for complementarity to maximize monitoring power for species management. Conservation Biology. 2013; 27(5):988-99.

Tulloch VJD, Tulloch AIT, Visconti P, Halpern BS, Watson JEM, Evans MC, et al. Why do we map threats? Linking threat mapping with actions to make better conservation decisions. Frontiers in Ecology and the Environment. 2015; 13(2):91-9.

Turner J, Bindschadler R, Convey P, Prisco Gd, Fahrbach E, Gutt J, et al., editors. Antarctic climate change and the environment: Scientific Committee on Antarctic Research; 2009.

Turner J, Lu H, White I, King JC, Phillips T, Hosking JS, et al. Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. Nature. 2016; 535(7612):411-5.

UNFCCC. Adoption of the Paris Agreement. Paris: United Nations Framework Convention on Climate Change, 2015.

Utami NWF, Wirawan IGP, Firn J, Kepakisan ANK, Kusdyana IPGA, Nicol S, et al. Prioritizing management strategies to achieve multiple outcomes in a globally significant Indonesian protected area. Conservation Science and Practice. 2020; 2(6):e157.

Wauchope HS, Shaw JD, Terauds A. A snapshot of biodiversity protection in Antarctica. Nature Communications. 2019; 10(1):946.

Williams HP. Model building in mathematical programming. 5 ed. West Sussex PO19 8SQ, England: John Wiley & Sons; 2013. 432 p.

Williams SE, Shoo LP, Isaac JL, Hoffmann AA, Langham G. Towards an integrated framework for assessing the vulnerability of species to climate change. PloS Biology. 2008; 6(12):2621-6.

Wintle BA, Cadenhead NCR, Morgain RA, Legge SM, Bekessy SA, Cantele M, et al. Spending to save: What will it cost to halt Australia's extinction crisis? Conservation Letters. 2019; 12(6):e12682.

World Bank. Global economic prospects, June 2020. World Bank. 2020 [cited 2020 Sep 8]. Available from: https://openknowledge.worldbank.org/bitstream/handle/10986/33748/9781464815539.pdf

World Bank. Gross domestic product 2019. World development indicators database, July 2020. World Bank. 2020 [cited 2020 July 7]. Available from: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

Supporting information

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

S2 Data. Workbook containing the numerical values underlying the Figures in the Main text and Supporting information. The values for each Figure are provided in separate worksheets. These values were calculated from the raw values using the methods described in the 'Materials and methods' section of the Main text. The cost and feasibility values are available

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

S8 Table. The three most cost-effective conservation management strategies for Antarctic taxa under climate forcing scenario RCP8.5; identified in order of significance as 1, 2, 3. Benefits of strategies are calculated using best estimates of improved intactness provided by experts and include benefits to taxa expected to expand beyond current (100%) intactness (An2). The cost-effectiveness values were calculated using a discount rate of 2% for the present value.

S9 Table. The three most cost-effective conservation management strategies for Antarctic taxa under climate forcing scenario RCP4.5; identified in order of significance as 1, 2, 3. Benefits of strategies are calculated using best estimates of improved intactness provided by experts and include benefits to taxa expected to expand beyond current (100%) intactness (An2). The cost-effectiveness values were calculated using a discount rate of 2% for the present value.

S10 Table. Methodological terms relating to priority threat management.

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

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

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

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