Advances and shortfalls in knowledge of Antarctic terrestrial and freshwater biodiversity

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Abstract

Antarctica harbors many distinctive features of life, yet much about the diversity and functioning of Antarctica's life remains unknown. Evolutionary histories and functional ecology are well understood only for vertebrates, whereas research on invertebrates is largely limited to species descriptions and some studies on environmental tolerances. Knowledge on Antarctic vegetation cover showcases the challenges of characterizing population trends for most groups. Recent community-level microbial studies have provided insights into the functioning of life at its limits. Overall, biotic interactions remain largely unknown across all groups, restricted to basic information on trophic level placement. Insufficient knowledge of *many groups limits the understanding of ecological processes on the continent. Remedies for the current situation rely on identifying the caveats of each ecological discipline and finding targeted solutions. Such precise delimitation of knowledge gaps will enable a more aware, representative, and strategic systematic conservation planning of Antarctica.*

Antarctica, one of Earth's last great wildernesses, harbors singular and underappreciated biodiversity (*1*). In just two centuries of exploration, research on Antarctic ecosystems has generated critical insights into the evolution and functioning of biodiversity at the cold, nutrient-deficient, and dry limits to life on Earth (*2*, *3*). Antarctic ecosystems provide vital services (*4*), including modulating global oceanic and atmospheric systems, and the continent is a bellwether of the planet's climate state, given its rapid transformation and its global connections and impacts (*5*).

Antarctic terrestrial biodiversity faces considerable threats from global environmental change and human pressures, including wildlife disturbance and invasive alien species (*6*, *7*). Its isolation, extreme conditions, and comparatively low disturbance levels (*1*) make Antarctica a key sentinel for global change (*4*). In recent decades, extensive international research cooperation has led to breakthroughs in understanding of Antarctic biodiversity, overturning previous paradigms of evolutionary patterns and processes across biological scales (*8*, *9*). The coexistence of several national biological research programs studying the relatively low diversity of the continent make the inventory of Antarctic organisms more complete than in many other regions (Fig. 1). Despite such considerable funding, scientific progress has been uneven, with research biased toward mainstream fields of study, focusing on the most accessible or charismatic species (*10*). Substantial knowledge gaps remain, particularly with regard to complex functions and remote and cryptic ecosystems and species (*11*). Early syntheses of available knowledge of Antarctic biodiversity have, however, largely overlooked the substantial biases resulting from shortcomings in understanding the continent's ecological dynamics (*12*), critically limiting the development of effective conservation efforts (*13*). This underscores the need for a more informed account of recent advances, gaps, and biases in biodiversity knowledge to guide future research and conservation investments (*14*). In this analytical review, we provide a comprehensive assessment of the state of knowledge of all terrestrial biodiversity in Antarctica [see materials and methods (*15*) and supporting data files (*16*)]. We compiled all records on Antarctic species identities into TerrANTALife, a database covering all terrestrial and freshwater eukaryotic species and amplicon sequence variants of prokaryotes (*9*, *17*) of the continent. Data coverage was evaluated through discovery rates and spatial distribution of survey completeness for spatiotemporal occurrence data and using major global repositories (*18*–*22*) for mapping out coverage of other aspects of biodiversity (Fig. 2). We classify knowledge limitations (hereafter, "shortfalls") into basic areas of ecological and evolutionary research (*14*): (i) species inventory; (ii) evolution of Antarctic life; species' (iii) spatial and (iv) temporal dynamics; trait-based (v) environmental tolerances and (vi) ecosystem functions; and (vii) biotic interactions. We assess the severity of these knowledge shortfalls relative to the scientific and conservation value of the missing information. Policies that account for uncertainty and knowledge gaps are better suited to advance scientific research and conservation practice under the Antarctic Treaty System (*13*, *23*). Lastly, the current state of ecological knowledge was assessed by a panel of Antarctic biodiversity experts through an IDEA (investigate, discuss, estimate, and aggregate) elicitation process (*24*) (Fig. 3).

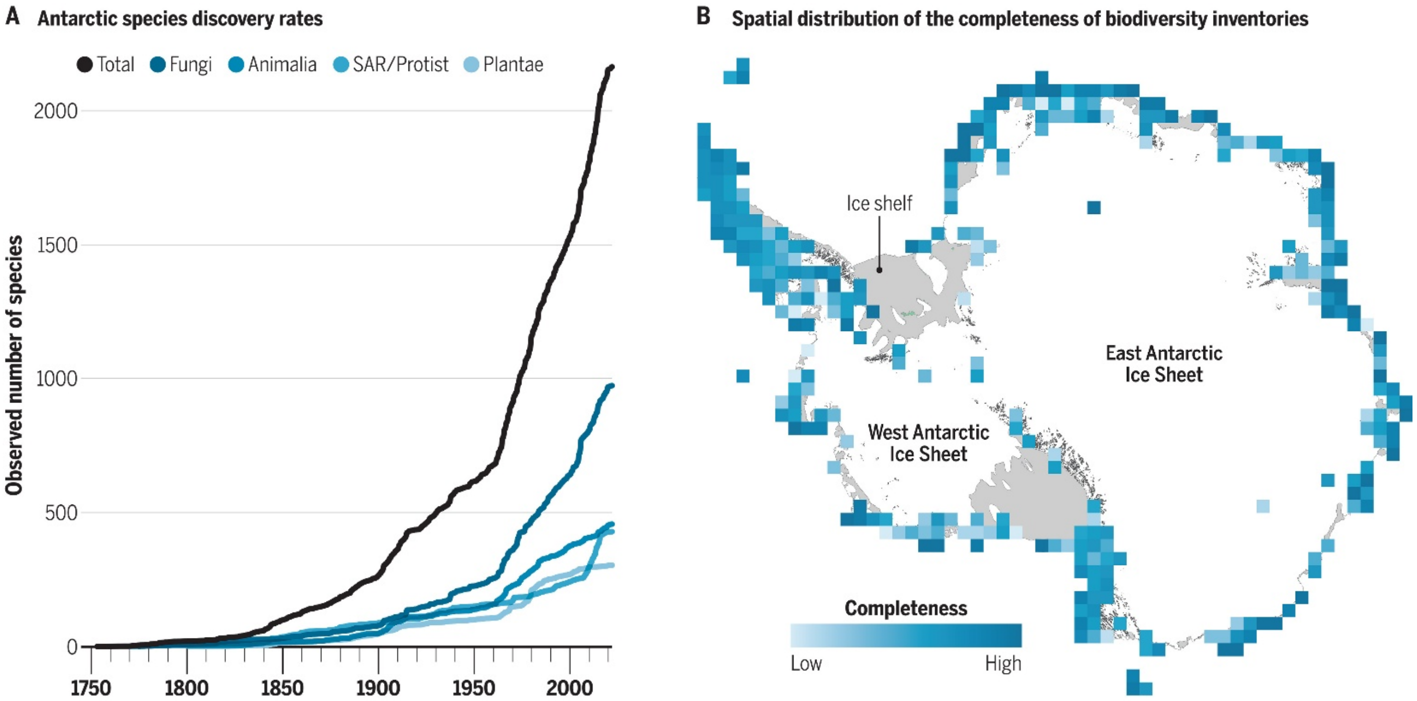

Fig. 1. Spatial and temporal process of inventory of the terrestrial Antarctic biota.
(**A**) Historical discovery rates of species that are present in terrestrial and freshwater ecosystems of Antarctica. Curves indicate the total number of species inventoried through time for the four eukaryotic kingdoms (sensu lato): Animalia, Fungi, Plantae, and SAR/protist (including stramenopiles, alveolates, rizarians, and other unrelated unicellulars such amoaebas). The curated list of 2193 known eukaryotic species analyzed here (*15*, *16*) was compiled in (*17*). For all these species, the year of first discovery and description in Antarctica, together with the first description worldwide (for species present on other continents), were taken from global metarepositories (*18*, *26*). (**B**) Survey completeness indicates how well the local species composition is characterized by the available occurrence data [supporting files 3 and 4 (*16*)]. It is calculated as the slope of the relationship between survey effort—measured as number of occurrence records—and the number of new species added to the local inventory. High completeness indicates slope values close to 0 (i.e., no new species are recorded with extra surveys), whereas progressively lower completeness values indicate progressively higher current rates of addition of new species to the local inventory with new surveys. Completeness was calculated with *KnowBR* (*53*) for local inventories at a grid size of 50 km by 50 km, randomizing the order of entrance of new records in each cell to account for temporal unevenness in survey effort. Occurrence records for all the Antarctic eukaryotic terrestrial species were retrieved first from the GBIF repository. This dataset was complemented with Wauchope *et al.*'s (*26*) compilation of additional records from scientific literature and technical reports such as protected area management plans, which is available at the Australian Antarctic Data Centre (*121*).
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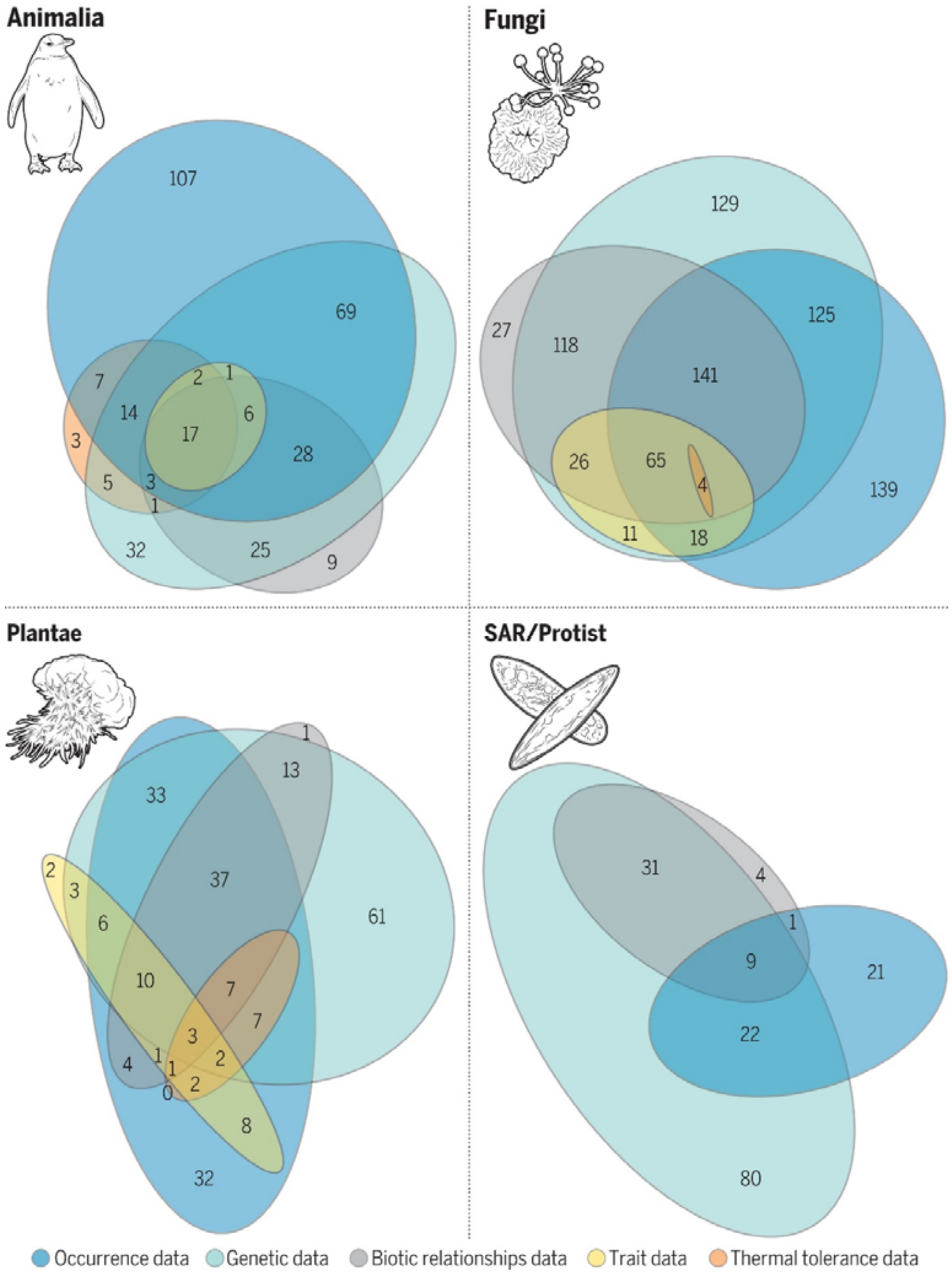

Fig. 2. Cross-availability of data on different ecological and evolutionary aspects per species for all Antarctic eukaryotes.

Venn diagrams depicting cross-availability of ecological and evolutionary data for all Antarctic species within each of the four eukaryote kingdoms, measured as counts of species with data entries in centralized metarepositories representative of five disciplines (*15*, *16*). The disciplines represented and their indicators are: (i) geographic distribution knowledge, georeferenced GBIF occurrence records (*18*); (ii) evolutionary knowledge, genome sequences deposited in GenBank (*19*); (iii) functional traits knowledge, measured trait info availability in either EltonTraits (*122*) for fauna or Plant Traits Database (TRY) (*21*) for flora; (iv) abiotic tolerance knowledge, profiling of thermal limits gathered in the Globtherm dataset (*22*), expanded with Antarctic literature; and (v) biotic relationships knowledge, between-species interactions listed in the Global Biotic Interactions (GloBI) database (*20*).

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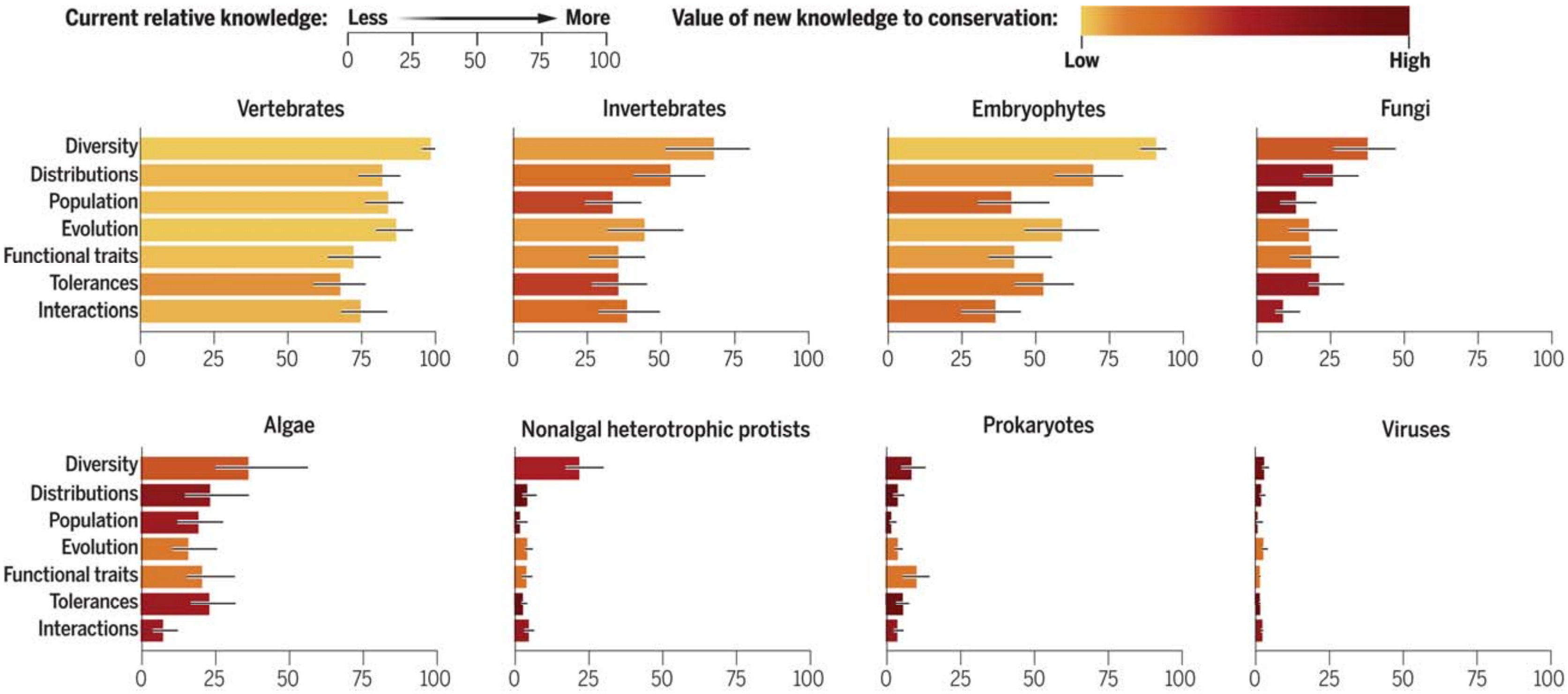

Fig. 3. Assessment of biodiversity knowledge gaps and implications for applied conservation practice through an expert elicitation.
The 29 participant experts were consulted to evaluate Antarctic science progression around the seven main biodiversity knowledge shortfalls: species diversity ("Diversity"), geographic distributions ("Distributions"), population dynamics ("Population"), evolutionary relationships ("Evolution"), functional traits ("Functional traits"), abiotic tolerances ("Tolerances"), and biotic relationships ("Interactions") (*14*). Scores indicate the joint knowledge progression perceived by the experts toward having a baseline knowledge in each discipline about eight eukaryotic and prokaryotic groups present in the terrestrial Antarctic (*15*, *16*). The *x* axes indicate the scoring provided by the experts. Scores close to 0 indicate large knowledge gaps, and scores close to 100 indicate extensive coverage. The "best estimate" (i.e., the prevailing view) is shown together with uncertainty levels (constructed from minimum and maximum perceived estimates and confidence levels) using the IDEA elicitation formula (*24*). Note that "algae" includes both cyanophyta, green algae, and diatoms, as they are typically studied together. Bars are colored by the shortfall filling importance for conservation identified by experts. This importance was calculated as the integration of the depth of the knowledge gap set by Antarctic biodiversity experts and the joint general value for conservation practices (set as climate change action, biosecurity, pollution control, living resources management, and area protection) set by five experts in biodiversity knowledge shortfalls science. Red indicates high filling importance, and yellow indicates comparatively low importance.
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Advances in describing Antarctic biodiversity and evolution

About 2100 terrestrial eukaryotic species have been identified from Antarctica, including nearly 1000 fungi (half of them lichen-forming), >400 animals, 300 plants, and >400 SAR/protists (such as stramenopiles, alveolates, rizarians, and other unrelated unicellular organisms including amoebae) (*17*). For most groups, more than half of the known Antarctic species have been discovered in the past 50 years (Fig. 1), partly driven by the growth in Antarctic research after the International Geophysical Year (1957–1958) and the International Polar Year (2007–2008) scientific campaigns. Many endemic species, especially prokaryotes, remain undiscovered (*25*). Limited species descriptions for all major groups and underexplored regions reveal considerable potential for further discoveries (Fig. 1). Comprehensive inventories are essential for effective area protection and threat assessment (*13*, *26*) and, indirectly, for safeguarding future bioprospecting potential.

Knowledge of animal diversity varies widely (*27*), from comprehensive vertebrate inventories to moderately complete checklists for invertebrates such as microarthropods, other soil and freshwater microinvertebrates, and ecto- and endoparasites (Fig. 1). Knowledge of ancestry and phylogenetic relationships is, however, limited to a few species, mostly of megafauna (Figs. 2 and 3). Expanding molecular studies to microarthropods and other microinvertebrates has revealed previously unknown species and inferred species-level divergences in mites (*28*), springtails (*29*), tardigrades (*30*), nematodes (*31*), and rotifers (*32*), although species counts remain uncertain for parasites, gastrotrichs, and flatworms. With a limited fossil record, diversification patterns can be alternatively infererred from population genetics and time-calibrated phylogenies on the basis of non-Antarctic lineages (*33*, *34*). Although marine vertebrates breeding on land are relatively well studied, there are major gaps in knowledge about their speciation (*35*) and hybridization (*36*) processes.

Knowledge of floral diversity is generally adequate for the two native vascular plant species (Antarctic hair grass, *Deschampsia antarctica*, and Antarctic pearlwort, *Colobanthus quitensis*) and the greater diversity of bryophytes and lichen-forming fungi (Fig. 2 and fig. S1). In contrast, knowledge of free-living microalgal and fungal groups is poorer, with further taxonomic progress expected from molecular analyses. Molecular and phylogeographic tools have clarified relationships among plant populations and some dispersal dynamics. Although the phylogeography of some Antarctic plants has been assessed phylogenetically in depth (*37*), most Antarctic flora has yet to be studied with molecular methods. Similarly, comprehensive phylogenetic and phylogeographic studies are limited to a few lichen genera [e.g., (*38*, *39*)].

Antarctic microorganisms are, in general, poorly known across all groups, from algae and other protists to fungi to bacteria, archaea, and viruses (Fig. 3). Nevertheless, increased surveys coupled with molecular techniques have uncovered a rich cryptic diversity often hiding in plain sight (*40*). Knowledge of the molecular diversity of snow algae (*41*) and freshwater algae is limited, although a diatom compendium is now available (*42*). Comprehensive surveys of autotrophic microorganisms are restricted to a few regions of terrestrial Antarctica, such as the McMurdo Dry Valleys, with estimates suggesting that more than half of the species remain undescribed [e.g., Cyanophyta (*43*)]. In contrast, heterotrophic protists are better known, although total species numbers are uncertain (*44*). Considerable information gaps remain for other unicellular Eukaryota, such as yeasts (*45*). Broad characterizations of microbial metacommunities in regions such as Victoria Land (*46*) have identified >80,000 bacterial amplicon sequence variants for the continent (*17*). Although inventorying microbial diversity in subglacial and endoglacial environments and the atmosphere entails specific technological challenges, there have been many notable discoveries of life surviving at extreme habitats in recent years (*47*–*49*). Finally, knowledge of virus diversity remains extremely poor, albeit a few highly localized surveys in freshwater and soil systems have identified at least 10,000 genotypes across virus families [e.g., (*50*, *51*)]. Thus, viruses represent the last frontier of Antarctic diversity.

Advances in mapping the spatiotemporal dynamics of Antarctic biota

Surveys of terrestrial biodiversity in Antarctica have been uneven in both space and time (*52*). Inference methods accounting for survey effort (*53*) show that biodiversity inventories remain poor for many areas (Fig. 1B). Georeferenced species occurrence records on the Global Biodiversity Information Facility (GBIF) metarepository vary widely between taxonomic groups (Fig. 2 and fig. S2). Nonetheless, GBIF mobilizes occurrence records for many species that are little known in most other respects (*18*). Relatedly, species distributions modeling has been widely used to assess the risk of invasive species expansion [e.g., (*54*)] but has seldom been applied to native species distributions, in contrast to the Southern Ocean marine biota.

Repeated surveys and monitoring programs are absent for most groups and regions. Long-term fauna and vegetation trend data exist for very few locations (Argentine Islands, Signy Island, Bailey Peninsula, and Cape Hallett), where surveys have been sporadically repeated over the course of 30 to 60 years without any planned program [e.g., (*55*, *56*)]. Experts identified substantial gaps in knowledge of population trends across almost all major Antarctic biodiversity groups (Fig. 3). However, decade-long multitaxa monitoring stations recently set up in areas such as the Victoria Land Dry Valleys are starting to offer insights into local ecosystem dynamics (*57*). Expanding this approach is promising but faces the critical challenge of a lack of long-term funding for maintaining such monitoring stations.

Large vertebrates illustrate the value of long-term research. Dynamic population trend studies across species ranges have been consolidated for many breeding vertebrates, such as in the Mapping Application for Penguin Populations and Projected Dynamics series (*58*). These data reveal increasing abundance of some penguin species (e.g., *Pygoscelis papua*) and declines in others (*P. antarctica*). Satellite imagery and repeated surveys of breeding colonies enable comprehensive mapping of seabird or seal species [e.g., (*59*)]. For several seals, penguins, and other seabirds, robust data exist on population ecology aspects such as predator-prey dynamics (*60*) or breeding phenology (*61*).

In contrast, knowledge of spatiotemporal patterns of Antarctic invertebrates ranges from moderate to poor (Fig. 3). Biogeographic studies remain scarce but with some notorious exceptions establishing regional population ancestry and paleobiogeographic inferences in groups such as Collembola (*62*) with even some species-specific, large-scale studies (*29*). Nematodes lack even preliminary species inventories for the continent, hampering phylogeographic analyses [but see (*31*)]. Studies of invertebrate population dynamics are largely restricted to describing life cycles and biodemographic rates [e.g., in tardigrades (*63*) and nematodes (*64*)]. Interannual abundance and population trends of native soil microarthropods remain poorly studied, with very few studies on temporal population dynamics (*56*).

Data mobilization is high for the Antarctic flora (Fig. 2), albeit knowledge about spatiotemporal patterns of plants and fungi is moderate (Fig. 3). Detailed ground surveys have enabled assessment of population trends for vascular plants and some mosses in maritime Antarctica, including the rapid expansion of vascular plants in Signy Island during the past decade, linked to regional warming (*65*). The non-native grass *Poa annua*, introduced to Thomas Point, King George Island, in the 1980s, has spread widely and with increasing speed since, with a resilient soil seedbank that has hampered eradication (*66*). Remote systems such as drones and satellite imagery are advancing vegetation mapping on the continent (*67*). Rapid shifts in moss and lichen populations have been detected but are generally monitored, with notable exceptions, only for a few groups and locations, such as East Antarctica (*68*). Albeit restricted, studies of lichen community dynamics show that this group may be particularly sensitive to climate change (*69*), and surveys in remote regions such as Shackleton Glacier (~87°S) offer future opportunities for range-shift monitoring (*70*, *71*).

Knowledge on microbiome spatiotemporal patterns lags behind that of flora and fauna (Fig. 3). Nonetheless, remote sensing mapping of the total extent of green snow algae in the Antarctic Peninsula offers a promising way forward (*72*). Moreover, biogeographic regionalizations of diatoms and cyanobacteria indicate high endemism and well-defined bioregions within Antarctica (*42*, *73*). Some local-scale studies of biological soil crusts provide estimates of algal growth, which may serve as proxies for the terrestrial Cyanophyta biomass (*74*). Techniques such as environmental DNA metabarcoding are rapidly advancing the understandig of soil microbial diversity spatiotemporal variations, offering novel insights on the structure and temporal trends of microorganism comunities across environmental gradients (*75*).

Advances in characterizing functional traits and abiotic tolerances

All Antarctic taxa face severe knowledge gaps with regard to functional traits, their variability, and, above all, their ecological significance in extreme environments (Figs. 2 and 3 and fig. S3). Basic knowledge about the functional strategies and trait-function relationships of Antarctic primary producers is still required to understand their adaptations, and the lack of systematic trait inventories prevents comparison with organisms from other regions. The apparently high number of Antarctic species with substantial functional trait data is misleading, as it is limited to certain characteristics of a few plant and animal groups (Fig. 3). Most studies of environmental tolerances have focused on responses to low temperatures, regional climate change, and ozone layer depletion (*7*). Without accurate information on species across space and time, which is lacking for many groups (Fig. 3), it is impossible to understand how traits such as temperature tolerance vary within communities among seasons and geographic locations. These knowledge gaps hinder conservation, as traits can predict species' responses to environmental change, and inform bioprospecting, for example, by identifying previously unknown molecules of pharmacological importance.

The most detailed functional trait information available is for breeding vertebrates, particularly about the physiology, reproduction, and foraging strategies of penguins and seals (*76*, *77*). However, ethical constraints make characterizing abiotic stress tolerances in vertebrates challenging, thus requiring researchers to rely on correlative niche modeling and adaptive genomic studies to infer their responses to environmental change (*78*).

Virtually no trait information is available for many invertebrate groups, with the notable exceptions of cold and desiccation tolerance strategies studied for a handful of model arthropods such as the mite *Alaskozetes antarcticus*, the springtail *Cryptopygus antarcticus*, and the dipterans *Belgica antarctica* and *Parochlus steinenii* (*79*, *80*). In nonarthropod microinvertebrates, functional studies also focus on abiotic stress tolerance, including cold and desiccation tolerance, as well as other edaphic factors such as salinity [e.g., nematodes (*81*), tardigrades (*82*), and rotifers (*83*)]. Although functional ecology studies are limited to a small fraction of the microinvertebrate species living in species-rich regions such as the Antarctic Peninsula, they cover a high proportion of those residing in species-poor areas such as the Dry Valleys. Thus, advancing functional knowledge requires prioritizing underrepresented guilds in species-rich regions.

Various studies have examined the responses to extreme conditions of the two native vascular plants of the maritime Antarctic, including photoprotection, photosynthetic activity, desiccation, cold tolerance, and fitness [e.g., (*84*, *85*)], although adaptations to low temperature, desiccation, and radiation stress remain poorly understood. For the more diverse bryophytes, trait coverage is generally poorer than for other aspects of biodiversity (Fig. 3). Case studies in the maritime Antarctic are limited to a few bryophyte species and locations, focusing on climate warming responses [e.g., (*86*)]. In contrast, the few bryophyte species present in continental Antarctica have been studied relatively extensively [e.g., (*87*)].

The assessment of functional knowledge by experts was higher for lichens than other groups (Fig. 3), with many studies focusing on growth (*69*) and metabolic activity (*88*). Research in maritime and continental Antarctica has addressed the influence of abiotic factors including temperature, light, and water availability on lichen photosynthesis and growth (*89*, *90*). Strong links between lichen diversity, annual growth, average temperature, and precipitation have also been demonstrated across the continent (*91*).

Studies on microorganisms have been mostly limited to snow algal growth and tolerances and baseline knowledge on freezing and radiation resistance [e.g. (*92*)]. Genomic, metagenomic, and proteomic research on Antarctic prokaryotes is already yielding insights into functional traits at the community level (*93*), although in situ functional assay data are scarce. For instance, recent soil habitability studies have identified the functional attributes of microbial communities driven by abiotic gradients (*75*, *94*), but metatranscriptomic studies documenting gene expression at the community level are severely hampered by the low mRNA extraction yields resulting from the low biomass and low transcription rates in many Antarctic habitats, particularly soils. Some community-level functional data exist on carbon fixation, respiration rates, nitrogen cycling, and trace gas (CO_2, H_2O) assimilation (*93*–*95*), yet microbial community responses to abiotic conditions remain poorly understood. Recent in situ and ex situ studies have explored the effects of radiation, temperature, nutrient supplementation, and/or soil wetting [e.g., (*96*)], but largely focusing on microbial community composition rather than on its functionality. Although the abiotic and, to a lesser extent, biotic drivers behind the response of microbial community structure to environmental gradients are beginning to be disentangled (*97*, *98*), their influence on ecosystem functioning over space and time is still unresolved.

Advances in understanding species interactions and ecological networks

The role of biotic interactions in structuring Antarctic terrestrial ecosystems remains largely unexplored. Competitive interactions have been classically considered to play a minor role in Antarctica compared with other regions owing to the reduced biodiversity and extreme abiotic pressures (*99*). Growing evidence of such interactions, albeit still limited, is now emerging at all levels (*11*, *100*). Although there is a basic understanding of which are the primary producers, grazers, predators, parasites, and detritivores in terrestrial food webs (*101*), interactions are seldom quantified, and the original expectations of progress (*102*) have only materialized for a few systems (*103*). Indeed, databases hold virtually no records of ecological interactions even for goups with data about other aspects of biodiversity (Figs. 2 and 3 and fig. S4), despite the critical importance of this knowledge for biosecurity and living resources management, which requires understanding the resilience of ecological networks to disturbances.

Complex hypotheses about interactions have only been assessed in the best-studied animal groups, such as coastal macrofauna (seals and seabirds) (*104*). Trophic interactions between different elements of the terrestrial food web can, however, be informed by stable isotope studies [e.g., (*105*)], although few such studies are yet available [but see (*106*)]. Lists of ectoparasites, epibionts, and endoparasites of Antarctic vertebrates have recently been published (*107*), and a recent study describes forms of neutral commensalism of tardigrades associated with seabird nests (*108*).

Several studies have assessed potential competition and facilitation among native and non-native vascular plants (*109*), but little attention has been given to bryophytes and lichens, which are the primary components of Antarctic vegetation. Although competition for space would appear to be the most important biotic interaction affecting these groups, its impact on the composition and structure of their communities in Antarctica has not been studied in depth. Symbiotic relationships, such as between lichen photobionts and mycobionts, have been more widely explored [e.g., (*110*)], and the symbiont forms of rhizobacteria, fungal endophytes of plants, have received increasing attention (*111*). Plant competition and succession under climate change is also emerging as a growing field that requires long-term in situ monitoring and/or ex situ experimentation (*109*).

The analysis of interspecific microbial interactions remains a more complex challenge, but the study of carbon pathways (*11*) and the use of quorum-sensing techniques (*112*) offer additional insights into the characterization of trophic connectivities in polar ecosystems. Nonetheless, interactions between primary producers (phototrophic and chemoautotrophic taxa), heterotrophic prokaryotes, and microscopic eukaryotes are very poorly understood [but see (*113*)], perhaps with the exception of the recently characterized soil food webs of the McMurdo Dry Valleys (*114*). Virus and bacteriophage activity remains largely unexplored, although metabarcoding and metagenomics are starting to clarify their influence on Antarctic host species and communities (*51*, *115*). Knowledge of species interactions is entirely lacking for SAR/protist species (Fig. 3).

Future directions for Antarctic biodiversity science and identifiable priority gains of knowledge for conservation practice

Systematic knowledge acquisition in Antarctica that maximizes the value of information for understanding and preserving its biodiversity requires four consecutive steps: (i) completing biodiversity inventories; (ii) obtaining robust spatial and temporal data coverage; (iii) collecting the information required to address the remaining knowledge shortfalls; and (iv) managing and mobilizing data into centralized information repositories that allow biodiversity trends to be assessed.

Representative biodiversity inventories

Many species remain to be discovered or (re)described, including differentiating cryptic taxa. The increasing application of molecular biology approaches is enhancing the identification of species and cryptic speciation events, leading to rapid increases in knowledge of microbial diversity. The main challenges remaining in the description of Antarctic terrestrial and freshwater diversity arise primarily from survey limitations and the paucity of experienced taxonomists. Two main steps are required to overcome these challenges: training of specialists and increasing application of evolutionary and environmental omics approaches [such as recent work on soil biodiversity detection (*116*)]. Environmental DNA surveying requires not only systematic implementation but also the availability of both voucher specimens with precise taxonomic identifications and more comprehensive and quality-controlled sequence databases and biological sample repositories (*9*).

Increasing spatiotemporal coverage

Biodiversity science relies on the availability of representative collections. A systematic monitoring favors a better understanding of global change dynamics and conservation practice. Many ice-free locations and inland waters in Antarctica have not been surveyed or resurveyed since the early 20th century or the initiation of substantive scientific research activities in the 1950s (*25*). Thus, virtually no recent spatial data are available to fill knowledge gaps in areas including environmental tolerance breadth, patterns of functional traits, and forms of biological interactions for most of the continent. Improved characterization of species' distributions requires spatially targeted broad field surveys to reduce spatial biases in remote areas such as the Prince Charles Mountains or the Queen Maud Mountains (*71*, *116*) together with development of remote sensing imagery and analyses (*25*).

Data upscaling and standarization

Environmental vulnerability studies have informed policy-making discussions about the protection of, for example, the emperor penguin as an Antarctic Specially Protected Species (*117*) but are still lacking for terrestrial biota. Overall, current gaps in knowledge about species interactions make it very difficult to understand the cascading effects of global change beyond the impacts on each species considered in isolation (*7*). Interdisciplinary studies that evaluate relationships between groups through, for instance, genomic, fatty acid, and/or isotope-based analyses of food webs, are required. Disentangling biotic interactions will also require promotion of interdisciplinary integrative research that examines functional relationships between groups, such as the diversity and influence of viruses in Antarctic host species and communities (*115*). Baseline descriptions of species co-occurrence should be augmented by manipulative field experiments or, alternatively, growth chamber experiments that realistically mimic Antarctic field conditions [e.g., (*118*)]. Because of microorganisms' complexity and plasticity, standardized collection remains both a challenge and a necessary step in the characterization of functional aspects. Standardized protocols are required to ensure that future studies of the responses of different groups to global change are comparable.

Data mobilization, centralization, and reanalysis

A critical component of knowledge acquisition is data mobilization and centralization, that is, data retrieval from bibliographic sources, institutional repositories, and/or private databases and harmonization into open repositories with transparent data audit and consolidation (*18*). Data mobilization, centralization, and reanalysis ultimately make important contributions to providing policy-makers with the critical summaries of biodiversity and ecosystem functioning trends required for supporting their strategic conservation planning efforts. Notably, recent calls have raised the need to integrate existing Antarctic biological data from decentralized sources (*119*). The complementary adoption and expansion of monitoring "model bio-sentinel" organisms and "priority areas" can help identify rapid changes (*120*), alleviating current knowledge gaps. In this work, we have identified species and groups of organisms that have data across multiple aspects of biodiversity (Fig. 3). Further assessment of the representativeness of these organisms would eludicate how well they provide baseline systems of reference and would contribute to priorizing additional target groups or species. In this context, combining (i) works increasing data completeness for particular species with (ii) in-depth case studies would provide basic, yet representative, understanding of their responses to global change, helping to maximize conservation gains under limited funding. An assessment of priority knowledge gains, as conducted here, can set the basis for developing strategic programs to fill critical knowledge gaps. However, the full "value of information" that balances the scientific, economic, and societal costs and gains of priorizing research to improve completeness across key aspects of biodiversity remains to be ascertained for Antarctica (*12*).

Conclusions

Recent scientific advances have shed new light on the functioning of Antarctic ecosystems. Major gaps in knowledge of Antarctic biodiversity still hamper our understanding of the functioning of its ecosystems, limiting the effectiveness of conservation policies and actions. This continent-wide review of biodiversity knowledge shortfalls provides a basis for future integrative analyses of research needs and ways to inform conservation requirements in a changing environment, not only for Antarctica but also as a model approach for scaling up shortfall assessments from a single taxonomic group to whole biomes that can be applied to other regions. To address the here-described shortfalls, future research planning should establish targeted international collaborative programs focused on addressing these key questions. Despite more than a century of Antarctic research and exploration under an umbrella of international scientific cooperation, there is still much to learn about the ecology and biogeography of this enigmatic continent. Moreover, the pervasive impacts of contemporary human-induced environmental change urgently require these knowledge gaps to be filled to better safeguard the continent's singular biodiversity and the ecosystem services it provides.

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Competing interests:

S.L.C. was president of the Scientific Committee on Antarctic Research (SCAR) from 2016 to 2021 and immediate past president until 2022. He is now a lifetime honorary member of SCAR. The authors declare that they have no other competing interests.

Data and materials availability:

Materials and methods and supplementary figures are available in the supplementary materials. All supporting data and code needed to evaluate the conclusions in the paper have been deposited in Zenodo (*16*). The Antarctic biodiversity checklists generated for this work are available in (*17*).

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