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Scaling up ocean conservation through recognition of key biodiversity areas in the Southern Ocean from multispecies tracking data

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Article impact statement: Key biodiversity areas, vital for species' persistence, exist across the Southern Ocean and should be considered for marine conservation.

Abstract

Biodiversity is critical for maintaining ecosystem function but is threatened by increasing anthropogenic pressures. In the Southern Ocean, a highly biologically productive region containing many endemic species, proactive management is urgently needed to mitigate increasing pressures from fishing, climate change, and tourism. Site-based conservation is one important tool for managing the negative impacts of human activities on ecosystems. The Key Biodiversity Area (KBA) Standard is a standardized framework used to define sites vital for the persistence of global biodiversity based on criteria and quantitative thresholds. We used tracking data from 14 species of Antarctic and subantarctic seabirds

[Correction added on 19/06/2024, after first online publication: The region was updated for South Georgia/Islas Georgias del Sur and Figure 3 was modified to improve clarity.]

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and pinnipeds from the publicly available Retrospective Analysis of Antarctic Tracking Data (RAATD) data set to define KBAs for a diverse suite of marine predators. We used track2kba, an *R* package that supports identification of KBAs from telemetry data through identification of highly used habitat areas and estimates of local abundance within sites. We compared abundance estimates at each site with thresholds for KBA criteria A1, B1, and D1 (related to globally threatened species, individual geographically restricted species, and demographic aggregations, respectively). We identified 30 potential KBAs for 13 species distributed throughout the Southern Ocean that were vital for each individual species, population, and life-history stage for which they were determined. These areas were identified as highly used by these populations based on observational data and complement the ongoing habitat modeling and bioregionalization work that has been used to prioritize conservation areas in this region. Although further work is needed to identify potential KBAs based on additional current and future data sets, we highlight the benefits of utilizing KBAs as part of a holistic approach to marine conservation, given their significant value as a global conservation tool.

KEYWORDS
key biodiversity areas, marine predators, site-based conservation, Southern Ocean, tracking data

INTRODUCTION

Biodiversity plays a critical role in supporting ecosystem services and is of high cultural and intrinsic value to humanity worldwide. Increased biodiversity can bolster ecosystem resilience to environmental change through increased adaptive capacity from genetic diversity (Ehlers et al., 2008; Liu et al., 2022) and increased redundancy within functional groups (Isbell et al., 2015; Oliver et al., 2015; Peterson et al., 1998). Yet, the world is in the midst of a biodiversity crisis; global ecosystems are deteriorating as a result of anthropogenic pressures, all of which are exacerbated by climate change (IPBES, 2019; Richardson et al., 2023). As knowledge of the importance of biodiversity expands and threats proliferate, there are increasing global, national, and local initiatives to identify and conserve biodiversity (e.g., Convention on Biological Diversity, 2022), as well as numerous research efforts to guide these management actions (Stevenson et al., 2021).

The Southern Ocean is one of the most productive and wild marine regions on the planet and has been identified as an important area for conservation (Chown & Brooks, 2019; Jones et al., 2018). Despite relatively high ecological integrity (e.g., Halpern et al., 2015; Jones et al., 2018), the Southern Ocean was historically heavily exploited. Harvesting of Antarctic species began in the 1770s; extensive take of seals was followed by large-scale whaling (Hofman, 2017). Finfish, squid, crab, and krill have all been fished to some degree since the 1960s (Caccavo et al., 2021; Hofman, 2017). Currently, Antarctic krill (*Euphausia superba*)—a key prey species in the Southern Ocean food web—and toothfishes (*Dissostichus* spp.)—the top fish predators—are the primary fisheries in the Southern Ocean (CCAMLR, 2021). Although current fishing rates are low relative to other parts of the world, there is increasing pressure to expand these fisheries (Brooks et al., 2018; Nicol & Foster, 2016; Trathan, 2023a).

Meanwhile, physical changes in the Southern Ocean due to climate change, as well as other anthropogenic threats, are already underway and are expected to accelerate in coming years (Chown & Brooks, 2019; Chown et al., 2022; Siegert et al., 2023). Climate change is causing seawater to freshen, warm, and acidify (Chown et al., 2022), and sea ice has shown a steady decline since 2016. In 2022 and 2023, sea ice levels were catastrophically low (NSIDC, 2023; Siegert et al., 2023). Sea ice decline reduces krill habitat and opens up previously unfished areas, potentially exacerbating overexploitation (Cavan et al., 2019; Meyer et al., 2020; Sylvester et al., 2021). A rapidly expanding tourism industry poses additional pressures (Tejedo et al., 2022); more than 117,000 tourists were predicted to visit Antarctica in the 2023–2024 season (IAATO, 2023). Avian influenza has been confirmed in multiple bird species in the subantarctic (South Georgia/Islas Georgias del Sur) and the Antarctic Peninsula region (SCAR, 2024). Pollution, in the form of mercury, plastic, and persistent organic pollutants, is also a threat, as is potential land-based disturbance from invasive species (Bestley et al., 2020).

In response to conservation concerns, especially regarding potential ecosystem changes driven by the large krill harvest in the 1970s, Antarctic Treaty Consultative Parties established the Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention). The Convention, which came into force in 1982, sets guidelines for conserving Southern Ocean ecosystems, including sustainable fisheries management, and is implemented through the multinational Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Spatial management, including through a representative network of marine protected areas (MPAs), is a core tool supporting CCAMLR's work for achieving conservation objectives (Brooks et al., 2020; CCAMLR, 1980), alongside precautionary catch limits (Constable et al., 2000). Site-based conservation can help achieve conservation goals by protecting vulnerable habitats (Pennino et al., 2018), foraging grounds, nursery grounds, or migratory stopover sites for highly mobile species (Gilmour et al., 2022; Hindell et al., 2020; Lascelles et al., 2014).

A primary conservation concern in the Southern Ocean is the overlap of fisheries with important predator foraging grounds and migration pathways, especially as sea ice retreats and previously inaccessible areas become fishable (Bestley et al., 2020; Dahood et al., 2020). Increased fisheries overlap elevates risk of mortality of nontarget species through incidental catch and exacerbates competition between fisheries and predator species. Research on trophic dynamics and historical productivity of the Southern Ocean indicates that current reference points deemed sustainable may be underestimating fisheries impact (Pinkerton & Bradford-Grieve, 2014; Savoca et al., 2021). Additionally, as climate change effects increase, it is likely that current fisheries impacts will be compounded by other stressors, possibly irrevocably straining ecosystem dynamics and species populations (Dahood et al., 2020; Watters et al., 2020).

Telemetry (tracking) data are a valuable tool for delineating specific areas of ecological importance for highly mobile predator species (Hays et al., 2019). Moreover, identifying these areas can also illuminate underlying properties of marine ecosystems. The location of foraging sites at the individual and community scale can indicate highly productive regions of the ocean. Indeed, many highly mobile marine predator species have been shown to be sentinels of climate change impacts and ecosystem dynamics through diet and stable isotope analyses and distribution of high-use areas or prey hotspots throughout the seascape (Cherel & Weimerskirch, 1995; Gagne et al., 2018; Hazen et al., 2019; Hindell et al., 2020; Walters et al., 2020). Tagging and monitoring of air-breathing predators, such as seabirds and marine mammals, is a substantial undertaking but provides broad-scale data that complement direct measurements of oceanographic properties and species distributions obtained from ship-based and other surveys.

One way of identifying important sites for specific animal populations, and biodiversity more broadly, has been through the use of standardized criteria against which data can be assessed. Different criteria have been established for ecosystems and regions (ecologically and biologically significant areas [EBSAs]) and various taxa, such as birds (important bird and biodiversity areas [IBAs]), marine mammals (important marine mammal areas [IMMAs]), sharks and rays (important shark and ray areas), and sea turtles (important marine turtle areas) (Bandimere et al., 2021; di Sciara & Hoyt, 2020; Donald et al., 2019; Hoyt & Di Sciara, 2021; Johnson et al., 2018; Kyne et al., 2023; Lascelles et al., 2016; Tetley et al., 2022). Key biodiversity areas (KBAs) provide a unifying set of criteria that can be used across taxonomic and geographic scales in marine, freshwater, and terrestrial systems. These areas contribute significantly to the global persistence of biodiversity (IUCN, 2016). A standardized process (*A Global Standard for the Identification of Key Biodiversity Areas*) was formally adopted by the IUCN Council and launched alongside the KBA Partnership at the World Conservation Congress in 2016 (IUCN, 2016) with the support of 13 of the world's leading nature conservation organizations.

We used publicly available data from the Retrospective Analysis of Antarctic Tracking Data (RAATD) project (Ropert-Coudert et al., 2020) to identify potential KBAs for 10 seabirds and 4 pinniped species in the Southern Ocean. Recent work has demonstrated the importance of the RAATD data set in improving knowledge of predator movements and habitat use in this region. Results of 2 recent studies have defined multispecies areas of ecological significance (AESs) and predator-derived ecoregions based on models derived from these data (Hindell et al., 2020; Reisinger et al., 2022).

Our approach complements previous RAATD work by focusing on individual species rather than merging species into multispecies data sets. Although sites utilized by multispecies complexes play an important role in conservation strategies, it is also essential to ensure species persistence by identifying sites critical for each unique species and life-history stage. Such knowledge allows management plans to take into account the specific needs of each studied population and improves understanding of the expected outcomes of conservation actions. Our work builds on the extensive habitat modeling and population monitoring work that has informed the development of robust MPA network proposals and fisheries regulations in the Southern Ocean by providing information on sites of importance for these individual populations in regions with available data. We are the first to apply KBA criteria across a wide range of species at this large of a geographic scale in international waters. As such, our work can provide insights into tools and challenges for applying these criteria at scale.

METHODS

Data set

Our data set is a subset of the RAATD data set (Ropert-Coudert et al., 2020), a Scientific Committee on Antarctic Research (SCAR) project led jointly by its expert groups on birds and marine mammals and Antarctic biodiversity informatics. The publicly available data set includes tracking data from 17 predator species, 4002 individual animals, and more than 2.8 million observed locations in the Southern Ocean (circumpolar waters south of 40°S). The 17 species included 12 birds: Adélie penguin (*Pygoscelis adeliae*), emperor penguin (*Aptenodytes forsteri*), king penguin (*Aptenodytes patagonicus*), macaroni penguin (*Eudyptes chrysolophus*), royal penguin (*Eudyptes schlegeli*), Antarctic petrel (*Thalassoica antarctica*), white-chinned petrel (*Procellaria aequinoctialis*), wandering albatross (*Diomedea exulans*), black-browed albatross (*Thalassarche melanophris*), grey-headed albatross (*Thalassarche chrysostoma*), sooty albatross (*Phoebetria fusca*), and light-mantled albatross (*Phoebetria palpebrata*). The 5 mammals were Antarctic fur seal (*Arctocephalus gazella*), crabeater seal (*Lobodon carcinophaga*), southern elephant seal (*Mirounga leonina*), Weddell seal (*Leptonychotes weddellii*), and humpback whale (*Megaptera novaeangliae*). This data set was derived by compiling data shared by many different contributors collected through a wide range of studies. The study by Ropert-Coudert et al. (2020) includes details on the data, including the filtering workflow, associated tools, and data products and hosting platforms.

Data filtering and processing

We used the portion of the RAATD data that included PTT (platform transmitter terminal) and GPS (global positioning system) tag data, but we excluded GLS (global location sensor) tags due to potentially large location uncertainty not suitable for use with our methods. We excluded humpback whale data because the temporal and spatial coverage of the tracks was not adequate for determining high-use areas on the scale required. This data set had been checked for quality and filtered to remove spurious data, such as detections on land, prior to our use (Ropert-Coudert et al., 2020). Rather than raw locations, we used state-space model outputs generated by Hindell et al. (2020), which provided regular, temporally interpolated tracks from the raw data.

Prior to analyses, we partitioned the PTT and GPS data into distinct data groups—species, tagging location or colony, and seasonal stages appropriate to species—as determined by Hindell et al. (2020). Stages included incubation, chick rearing (early and late, where data allowed), and postbreeding for seabirds and breeding, postbreeding, postmolt, and no stage for pinnipeds. We retained data groups with over 10 individual animals for analyses as recommended by Bealet al. (2021).

Life-history and population estimates

High-use area identification required life-history, movement, and population size estimates as input values. These included local and global population size estimates and the estimated distance and duration of local foraging trips for central-place foragers. We drew our population data from similar assessments conducted by Hindell et al. (2020). We supplemented and updated these estimates with information from relevant databases, literature, and expert opinion (solicited via email correspondence) when estimates from the literature were unavailable. We then converted all population estimates to numbers of mature individuals following KBA guidelines and conservative conversion factors (specific conversions for each data group are listed in Appendix S2). In addition, we convened a workshop in August 2022 affiliated with the SCAR Open Science Conference (Brooks et al., 2022) to validate our estimates with data collectors and other species experts. We presented methodology and preliminary results at the workshop and subsequently incorporated recommendations from participants.

We identified population size estimates at the spatial scale of each data group (i.e., dataGroup, as per track2KBA) wherever possible. Because more relevant and accurate population size estimates were available for some species and locations than others, we also assigned a confidence value to each estimate (hereafter called "population score"): 1, estimates were available for the specific tagging location; 2, estimates available for a slightly broader- region; 3, estimates approximated from a larger area; and 4, local or regional estimates not available and data were downscaled from the global estimates.

Identification of high-use foraging sites

All analyses were conducted in R 4.1.1 (R Core Team, 2021). The track2kba R package, described in Beal et al. (2021), is designed for using tracking data to identify potential sites that can be assessed against KBA criteria. This tool generates kernel density estimates (KDEs) (Worton, 1989) to estimate core use areas for each animal. We defined individual core use areas as the area within the 50% KDE contour (Ford & Krumme, 1979; Soanes et al., 2013). For all central place foragers, we divided tracks into foraging trips. These trips have a minimum distance from the colony of 1 km, which retains at-sea locations while removing colony locations. Using only at-sea locations enhances accurate scaling of smoothing parameters by not biasing the estimate with terrestrial location data. We also included an outer buffer to define trip completeness by setting a cutoff point that a return trip must have reached to be considered complete and included in the analyses. We tested a range of outer buffers to determine cutoff points (10th, 50th, 75th, 90th, and 100th percentages of the mean foraging trip distance) and selected the value that retained the greatest amount of data for each group. Dividing these tracks into individual trips starting at a minimum of 1 km from the colony and ending no farther from the colony than the outer buffer allowed us to retain the data that represented complete or nearly complete foraging trips and then identify high-density areas along the foraging movement path. For individuals with multiple trips, all trips were pooled together to identify individual animal high-use areas.

We then estimated high-use areas for each data group by quantifying the proportion of individual core use areas in each grid cell to assess spatial overlap between individual core use areas. Additionally, the representativeness of individual tracks to the site population was assessed by using iterative resampling to randomly select a subset of tracks, identify an in-sample utilization distribution and core use area, and calculate the percentage of out-of-sample locations predicted by the core area (Beal et al., 2021). To estimate the number of mature individuals using each site, we multiplyied these representativeness scores by the overlap and local population size values(see Beal et al. [2021] for details).

KBA Standard and criteria

The final step of KBA site identification was to compare the number of mature individuals estimated for each high-use area to the appropriate KBA criteria, as indicated by the KBA Standard (IUCN, 2016). For this project, we focused on species-level criteria under A, B, and D—specifically criteria A1, B1, and D1 (Table 1). Criterion A1 is relevant for globally threatened species, B1 for individual geographically restricted species, and D1 for demographic aggregations. We tested the A1 thresholds against species classified as vulnerable, endangered, or critically endangered on the IUCN Red List of Threatened Species (IUCN, 2022), including white-chinned petrels, wandering albatross, and macaroni penguins for vulnerable species

TABLE 1 Key biodiversity area (KBA) species-level criteria definitions and guidelines for criteria used in our analyses of sites of conservation importance for populations of 10 seabird and 4 pinniped species in the Southern Ocean.

Criterion	Subcriterion	Threshold guidelines
A. Threatened biodiversity	A1. Threatened species: Sites qualifying as KBAs under criterion A1 hold a significant proportion of the global population size[b] of a species facing a high risk of extinction and so contribute to the global persistence of biodiversity at genetic and species levels.	Sites regularly hold one or more of the following: a. ≥0.5% of the global population size AND ≥5 reproductive units[a] of a CR or EN species b. ≥1% of the global population size AND ≥10 reproductive units[a] of a VU species c. ≥0.1% of the global population size AND ≥5 reproductive units[a] of a species assessed as CR or EN due only to population size reduction in the past or present[c] d. ≥0.2% of the global population size AND ≥10 reproductive units[a] of a species assessed as VU due only to population size reduction in the past or present[c] e. effectively the entire global population size of a CR or EN species.
B. Geographically restricted biodiversity	B1. Individual geographically restricted species: Sites qualifying as KBAs under criterion B1 hold a significant proportion of the global population size[b] of a geographically restricted species and so contribute significantly to the global persistence of biodiversity at the genetic and species level.	Site regularly holds ≥10% of the global population AND ≥10 reproductive units[a] of a species.
D. Biological processes	D1. Demographic aggregations[d]: Sites qualifying as KBAs under criterion D1 hold a significant proportion of the global population size[b] of a species during one or more life-history stages or processes and so contribute significantly to the global persistence of biodiversity at the species level.	Site predictably holds one or more of the following: a. an aggregation[d] representing ≥1% of the global population size of a species, over a season, and during one or more key stages of its life cycle b. a number of mature individuals that ranks the site among the largest 10 aggregations[d] known for the species.

Note: Language in table and footnotes a–d drawn verbatim from the KBA Global Standard, where more detail on applying these and other KBA criteria is located (*A Global Standard for the Identification of Key Biodiversity Areas*).

Abbreviations: CR, globally critically endangered; EN, globally endangered; VU, globally vulnerable (IUCN, 2022).

[a]Reproductive units: minimum number and combination of mature individuals necessary to trigger a successful reproductive event at a site (Eisenberg, 1977). Examples of 5 reproductive units include 5 pairs, 5 reproducing females in one harem, and 5 reproductive individuals of a plant species.

[b]Proportion of the global population size can be observed or inferred through any of the following: number of mature individuals, area of occupancy, extent of suitable, habitat, range, number of localities, and distinct genetic diversity.

[c]Restricted to those species qualifying only under criterion A of the IUCN (International Union for Conservation of Nature) Red List Categories and Criteria, in any of subcriteria A1, A2, or A4. Species qualifying only under criterion A3 of the IUCN Red List are expected to experience future rapid decline in population size but currently may still be quite abundant, and so these species are subject to the higher thresholds of KBA subcriteria A1a and A1b. There is no reproductive unit requirement for subcriterion A1e because sites holding all remaining mature individuals of CR or EN species make a highly significant contribution to their persistence.

[d]Aggregations typically occur for breeding, for feeding, or during migration and are indicated by highly localized relative abundance 2 or more orders of magnitude larger than the species' average recorded numbers or densities at other stages during its life cycle.

and grey-headed albatross and sooty albatross for endangered species. No species in our data set had a designation of critically endangered. We assessed criterion B1 for royal penguins, which nest only on Macquarie Island, and criterion D1 for all species in our data set because all sites represented important foraging aggregations (a full list of species and data groups assessed under each criterion is in Appendix S1).

Uncertainty in population sizes estimates

Although we used best population estimates to determine whether a site passed the KBA criteria, we also tested robustness to population size uncertainty for some sites. Where our literature review revealed a range of site population size estimates, we used minimum, maximum, and best estimates to generate a range of possible sites and numbers of mature individuals to test against KBA criteria. In addition, we generated a range (minimum, maximum, and best) of KBA thresholds when multiple global population size estimates were identified in the literature. For the 36 data groups for which multiple population size estimates were identified, we tested all combinations of sites against all global thresholds. We used population accuracy ranks (see "Life-history and population estimates" section) in combination with these robustness tests to assign a qualitative overall confidence score to each site. We assigned qualitative robustness ranks ranging from 1 to 5 to indicate which KBA thresholds (minimum, maximum, or best population estimates) were met under which local site population sizes (also minimum, maximum, or best estimates); the higher the score, the greater the robustness. We then weighted these scores according to how much data were available by multiplying fully tested sites by 1, partially tested sites by 0.5, and sites with not enough data to generate a range of population scores by 0.1. We then divided this by the population accuracy scores (of 1–4). A low score indicated greater accuracy, resulting in full confidence scores ranging from 0 to 5 (5, high robustness and large population size estimate accuracy; 0–4, greater sensitivity to population values or less accurate population size estimate).

TABLE 2 Number of data groups (data subsets based on species, populations, and seasonal stage) remaining per seabird and pinniped species after data filtering to select only data groups with at least 10 individuals tracked with GPS or PTT tags, number of high-use areas identified, number of potential key biodiversity areas identified, best global population estimates, International Union for Conservation of Nature (IUCN) Red List threat status, and global population trends.

Common name	No. data groups	No. high-use areas	No. potential KBAs	Population	Status	Population trend
Adélie penguin	7	6	1	10,000,000	LC	Increasing
Emperor penguin	2	2	2	512,000	NT	Decreasing
King penguin	3	3	2	2,200,000	LC	Increasing
Macaroni penguin	6	5	2	12,600,000	VU	Decreasing
Royal penguin	1	1	1	1,500,000	LC	Unknown
Antarctic petrel	2	2	1	6,500,000	LC	Stable
White-chinned petrel	2	2	2	3,000,000	VU	Decreasing
Black-browed albatross	1	1	NA	1,400,000	LC	Increasing
Grey-headed albatross	4	4	4	375,000	EN	Decreasing
Sooty albatross	2	2	2	24,945	EN	Decreasing
Antarctic fur seal	6	6	3	850,000	LC	Decreasing
Crabeater seal	3	1	1	4,000,000	LC	Unknown
Southern elephant seal	13	10	4	325,000	LC	Stable
Weddell seal	5	5	5	300,000	LC	Unknown

Abbreviations: EN, endangered; GPD, global positioning system; LC, least concern; NT, near threatened; PTT, platform transmitter terminal; VU, vulnerable.

RESULTS

Final data set and population estimates

After data filtering, 57 data groups, comprising 14 species, 1640 animals, and 1,617,598 locations, remained for analyses (Table 2; Figure 1). Wandering albatross and light-mantled albatross were removed due to insufficient sample sizes after data were subdivided into data groups. Best estimates of population size at the global level are shown in Table 2, and site-level population estimates are shown in Appendix S1. Although there was limited information or uncertainty for some sites, these estimates represented an in-depth review of the available literature and expert opinion.

KBA site identification

Of the 57 data groups analyzed, 51 high-use areas were identified. Of these, 30 sites met at least one criterion and could be considered potential KBAs (Figures 2 & 3; Tables 1 & 2; and Appendix S1). Comparisons with criterion A1 resulted in potential KBAs for 9 of the 13 data groups eligible for assessment against this criterion, which requires that species be listed as vulnerable, endangered, or critically endangered on the IUCN Red List. Criterion B1 triggered a potential KBA for the one data group assessed against it: incubating royal penguins. All data groups with a representative high-use area (51 of the 57 groups analyzed) were assessed against criterion D1; 28 data groups met this criterion. Several data groups met KBA thresholds under multiple criteria (Table 3; Appendix S1).

These sites are distributed throughout Antarctic and subantarctic waters, with greatest coverage in the East Antarctic and the Southern Indian Ocean. Several sites were in the Ross and Weddell Seas and nearby subantarctic islands, including South Georgia/Islas Georgias del Sur, Marion, Macquarie, and Heard and McDonald Islands. There was less coverage in some of the Pacific sectors of the Southern Ocean, such as the Bellinghausen and Amundsen Seas (Figure 2).

Species that triggered potential KBAs included Adélie penguin, emperor penguin, king penguin, macaroni penguin, royal penguin, Antarctic petrel, white-chinned petrel, grey-headed albatross, sooty albatross, Antarctic fur seal, crabeater seal, southern elephant seal, and Weddell seal (i.e., 13 of the total 14 species for which representative high-use areas were identified) (Figure 2; Table 3). Though a high-use area was identified for black-browed albatross, this site did not meet the conditions of any of the relevant KBA criteria. Appendix S1 provides details on which data groups resulted in high-use areas and which of these areas triggered potential KBAs, and Table 2 provides a summary of the number of data groups assessed for each species, how many of these resulted in high-use areas to assess against KBA criteria, and how many of these sites resulted in potential KBAs. Criterion D1 triggered the vast majority of potential KBAs (28 of 30), and criterion A1 triggered 10, 8 of which were also triggered by D1 (Table 1). Criterion B1 triggered a potential KBA for the one data group (royal penguins) that it was assessed against. Potential KBAs had a wide range of sizes, from 817 km^2 (i.e., Weddell seals at Dumont d'Urville, Terre Adélie) to 2,055,150 km^2 (i.e., postbreeding sooty albatross at Marion Island) (Table 3). Most fell somewhere in between these 2 extremes; the average size was

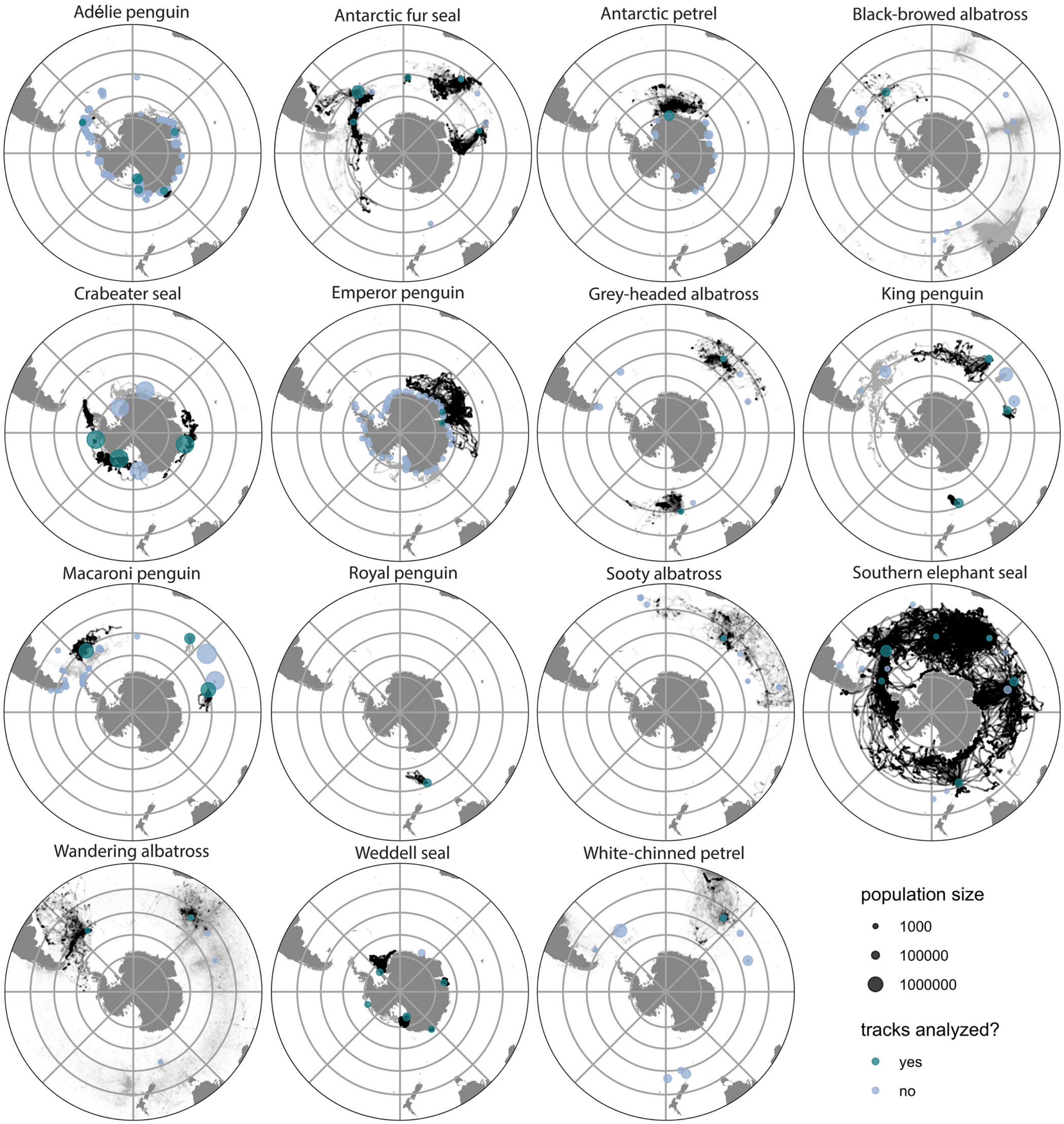

FIGURE 1 Colony locations and population estimates compiled by Hindell et al. 2020 per colony (seabirds) or region in which tagging site was located (pinnipeds) for all known populations of the species analyzed (green indicates locations for which we analyzed tracks; light blue indicates locations with no analyzed tracking data; analyzed tracks are shown in gray).

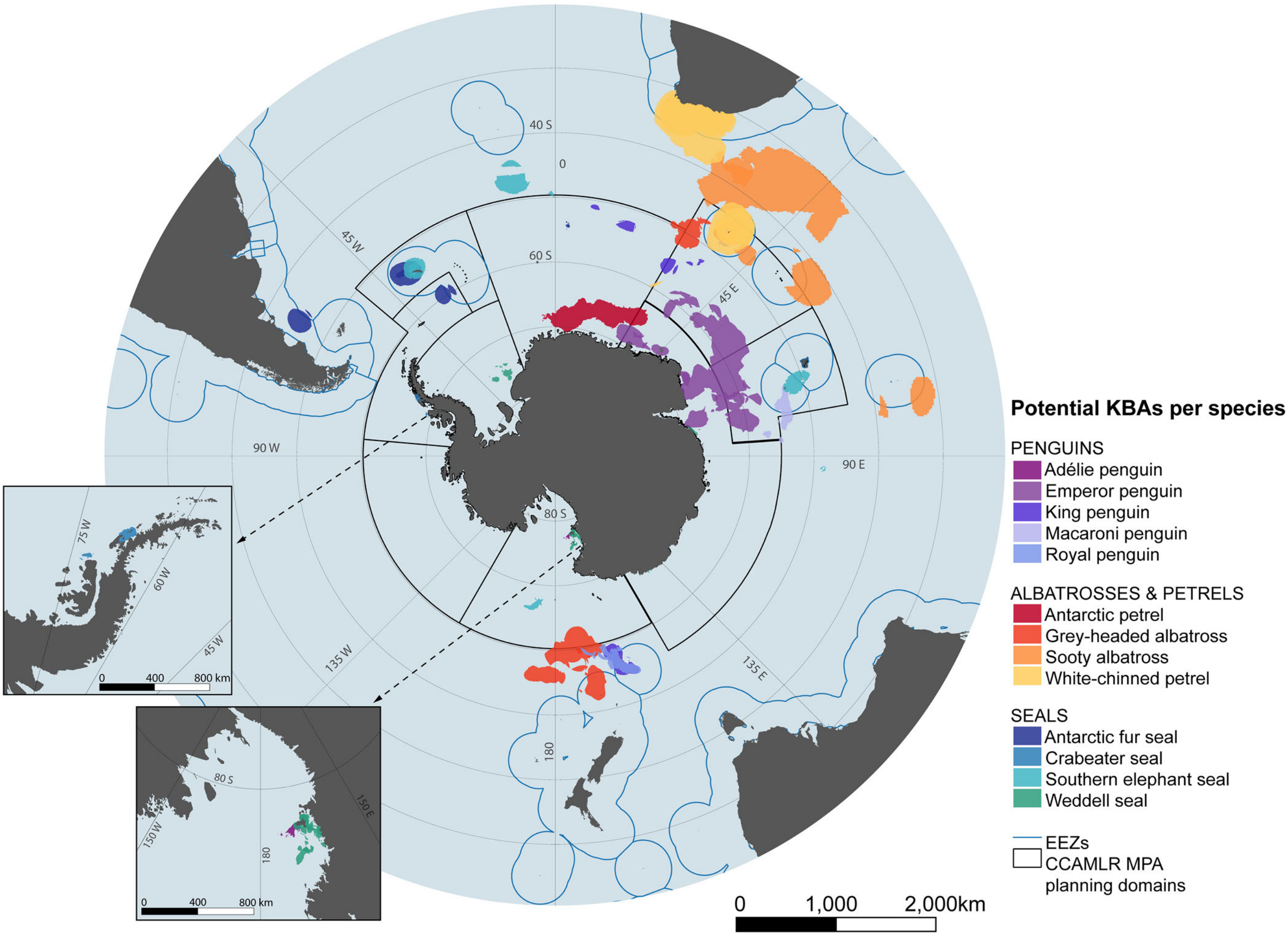

FIGURE 2 Potential key biodiversity area (KBA) sites representing high-use areas for seabird and pinniped species. These sites passed at least 1 of the 3 species-scale KBA criteria (A1, B1, and D1) defined by the KBA Global Standard, which sets out guidelines for determining thresholds to measure importance of a site to the persistence of global biodiversity—in this case for the persistence of these individual species (EEZs, national exclusive economic zones; CCAMLR, Commission for the Conservation of Antarctic Marine Living Resources Marine Protected Area Planning Domains).

301,801 km^2. In total, the area covered by these 30 potential KBAs was 9,021,421 km^2.

Uncertainty in life-history and population estimates

Confidence scores ranged from 0.5 (highly sensitive to observed population variation) to 5 (highly robust to observed population variation) (mean [SD] = 1.9 [1.51] across all 57 assessed groups) (Appendix S1). Potential KBAs had a mean (SD) score of 2.25 (1.44) (Table 3; Appendix S1). The majority of the 36 data groups for which we conducted uncertainty testing showed relatively high sensitivity to population estimates or low confidence in accuracy of population estimates (17 with low scores of 0.5 or 1), whereas 12 showed moderate sensitivity or confidence (scores of 1.25–2.5). Seven data groups had higher scores of 3–5, and 4 groups showed high robustness with a score of 5 (Table 3).

DISCUSSION

Our results confirmed the global significance of many sites of conservation interest in the Southern Ocean and identified several areas not currently marked by other existing conservation designations as important to specific predator populations. For predators, such as seabirds and pinnipeds, that use terrestrial sites for breeding, rearing young, resting, and molting, identifying the location of marine high-use areas and movement corridors between them can ensure conservation plans adequately cover areas important for different seasonal and life-history stages and maintain connectivity between them (Lascelles et al., 2012). In addition to the 30 potential KBAs, the high-use sites and the life-history literature review are valuable summaries for future research and also identify important areas where improvements of population size data are needed.

This approach complements habitat modeling and bioregionalization work in the Antarctic by focusing on sites that are directly observed to be important for specific populations and

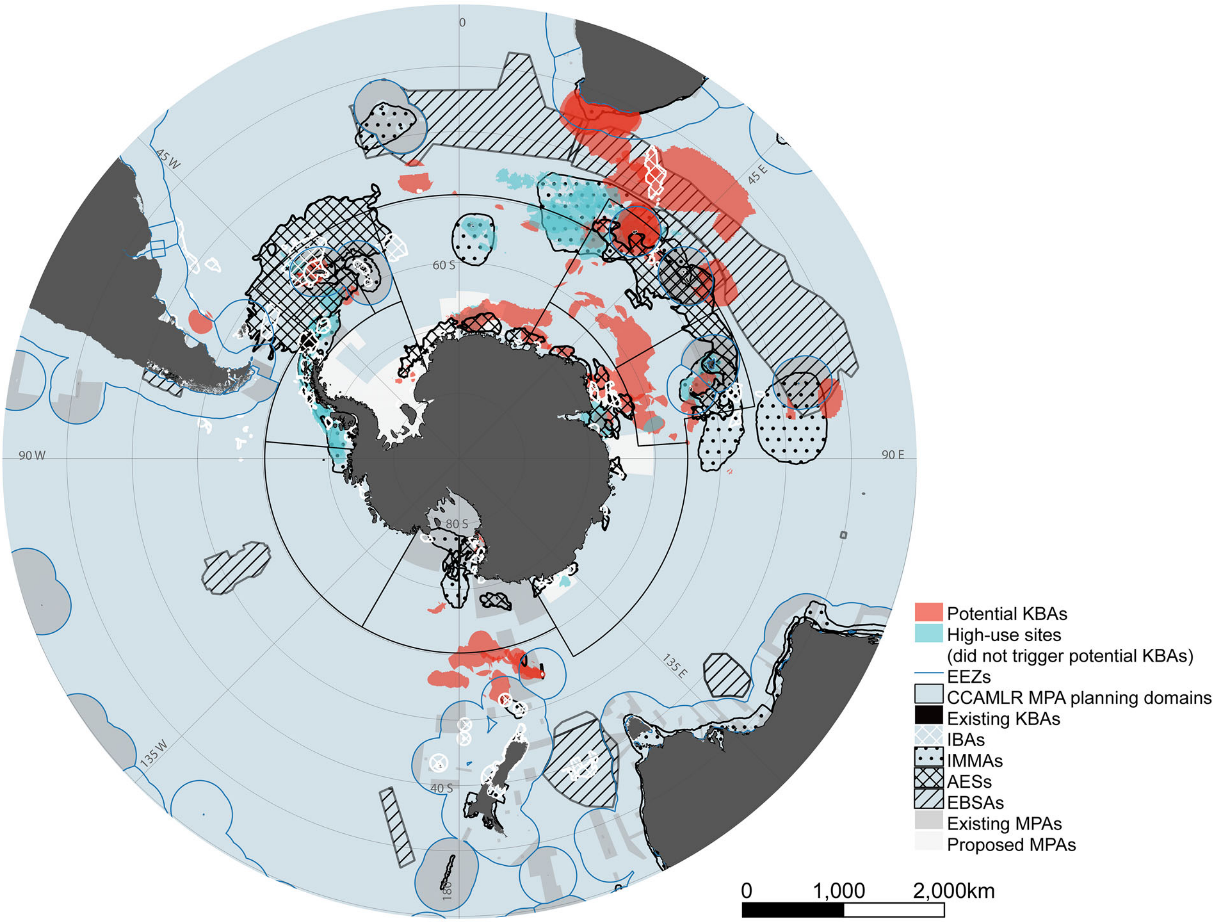

FIGURE 3 Potential key biodiversity area (KBA) sites, high-use sites that did not trigger KBAs, and other spatial designations of conservation significance, such as ecologically and biologically significant areas (EBSAs), important bird areas (IBAs), important marine mammal areas (IMMAs), existing KBAs, and areas of ecological significance (AESs). Management areas, MPAs and proposed MPAs (as of 2023), Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Marine Protected Area Planning Domains, and national exclusive economic zones (EEZs) are also shown.

seasons. The location of potential KBAs can also provide information on prey-base and biomass distribution patterns (Rajpar et al., 2018). Indeed, seabirds and marine mammals have often been used as proxies for biodiversity or productivity and as sentinels for the underlying processes of marine ecosystems and impacts of anthropogenic pressures such as fishing (Brisson-Curadeau et al., 2017; Hazen et al., 2019; Stevenson et al., 2021). This can be especially useful in the Southern Ocean, which is remote and difficult to study. This work is the first attempt to identify potential KBAs over a very large geographic region (i.e., the entire Southern Ocean) and relied entirely on publicly available data sets and open-source tools.

Geographic distribution of potential KBAs

Potential KBAs spanned a range of pelagic and benthic regions (Douglass et al., 2014; Raymond, 2017; Reisinger et al., 2022). Their distribution reflected the scope of the RAATD data set, which had a broad geographic span but did not include tracks from all populations (Figure 1). Many of the potential KBAs identified, such as the Antarctic fur seal site on the Patagonian shelf or the Weddell seal and Adélie penguin sites in the Ross Sea, are of known high productivity and importance to marine predators and their prey (e.g., Ballard et al., 2012; Boyd et al., 2002; Croxall & Wood, 2002; Lynch & Larue, 2014). Several sites along the Antarctic Peninsula appeared in areas of known high krill biomass (Siegel & Watkins, 2016), and a high concentration of sites around South Georgia/Islas Georgias del Sur reinforced the known importance of this area for seabirds and pinnipeds (BirdLife International, 2023).

Many regions where we identified potential KBAs for multiple species (e.g., the waters surrounding South Georgia/Islas Georgias del Sur, Marion, Kerguelen, and Heard and McDonald Islands) are also sites that are important for other species or have been identified based on other criteria or methods, such as IBAs, IMMAs, EBSAs, or AESs (Handley et al., 2020; Hindell et al., 2020) (Figure 2). In these instances, our results provide additional evidence for the importance of these locations. In contrast, several other potential KBAs for individual species highlighted areas vital for specific populations not previously recognized. For example, the grey-headed albatross potential

TABLE 3 Summary of potential key biodiversity areas (KBAs) identified from our analyses of sites of conservation importance for populations of 10 seabird and 4 pinniped species in the Southern Ocean, KBA criteria thresholds they passed, confidence scores for each site, and size of each site.

Common name	Deployment site	Stage	Criterion	Confidence score	Area (km^2)
Adélie penguin	Cape Crozier, Ross Sea	Chick rearing	D1	5.00	5,426
Antarctic fur seal	Bird Island, South Georgia	Breeding	D1	0.50	19,459
Antarctic fur seal	Bird Island, South Georgia	Postmolt	D1	0.50	342,370
Antarctic fur seal	Nyrøysa, Bouvet Island	Breeding	D1	4.00	3,429
Antarctic petrel	Svarthamaren, Queen Maud Land	Incubation	D1	2.00	547,006
Crabeater seal	Western Antarctic peninsula	No stage	D1	1.25	11,826
Emperor penguin	Amanda Bay, Prydz Bay	Postbreeding	D1	NA	562,479
Emperor penguin	Auster Rookery, Mawson Coast	Postbreeding	D1	NA	1,143,969
Grey-headed albatross	Campbell Island	Early chick rearing	A1ab A1cd D1	5.00	522,313
Grey-headed albatross	Campbell Island	Incubation	A1ab A1cd D1	5.00	162,848
Grey-headed albatross	Grey-headed Ridge, Marion Island	Early chick rearing	A1ab A1cd D1	2.50	269,299
Grey-headed albatross	Grey-headed Ridge, Marion Island	Incubation	A1ab A1cd	2.25	3,344
King penguin	Marion Island	Chick rearing	D1	1.00	157,600
King penguin	Sandy Bay, Macquarie Island	Incubation	D1	2.50	145,205
Macaroni penguin	Capsize Beach, Heard Island	Late chick rearing	A1cd	NA	123,792
Macaroni penguin	Funk Beach, Marion Island	Early chick rearing	A1ab A1cd D1	NA	1,184
Royal penguin	Sandy Bay, Macquarie Island	Incubation	B1 D1	2.50	151,180
Sooty albatross	Marion Island	Incubation	A1ab A1cd D1	1.00	303,554
Sooty albatross	Marion Island	Postbreeding	A1ab A1cd D1	1.00	2,055,150
Southern elephant seal	Isthmus area, Macquarie Island	Postmolt	D1	0.50	26,692
Southern elephant seal	Kerguelen Island	Postmolt	D1	NA	101,094
Southern elephant seal	South Georgia	Postbreeding	D1	1.00	25,643
Southern elephant seal	South Georgia	Postmolt	D1	1.00	245,096
Weddell seal	Dumont d'Urville	No stage	D1	2.00	817
Weddell seal	McMurdo Sound	No stage	D1	NA	15,631
Weddell seal	Pack ice, Amundsen Sea	No stage	D1	3.00	22,073
Weddell seal	Pack ice, Weddell Sea	No stage	D1	4.00	33,215
Weddell seal	Vestfold Hills	No stage	D1	2.00	5,864
White-chinned petrel	Marion Island	Early chick rearing	A1ab A1cd D1	NA	925,509
White-chinned petrel	Marion Island	Incubation	A1ab A1cd D1	NA	1,099,354

Note: Measure of confidence that the site results would persist despite observed uncertainty in population parameters (NA, question not assessable). Confidence score range: 0.5 (sensitivity to observed variation in population estimates) to 5 (highly robust to population uncertainty).

KBA near Campbell Island highlighted an important marine area during 2 phases of the breeding period for this endangered species. Another example is the Antarctic petrel potential KBA off Queen Maud Land (adjacent to the Weddell Sea), which highlighted a region identified for increased protection in the Weddell Sea Phase 2 MPA proposal (CCAMLR, 2023c, 2023d). Emperor penguin postbreeding potential KBAs highlighted high-use areas for this species that had not been flagged previously as conservation priorities (Trathan et al., 2024). These areas warrant additional consideration in species conservation plans and justify research to examine underlying drivers of high use by these species.

Areas with fewer potential KBAs identified, such as in the Amundsen and Bellinghausen Seas, have inherently fewer colonies due to the relative absence of islands for nesting or haul-out sites. They are also data poor compared with other regions in the Southern Ocean (e.g., Griffiths, 2010), and therefore, there was less information available on existing colonies. Nevertheless, future efforts to apply KBA criteria to other predator tracking data sets and to fill data gaps in these regions could continue to provide vital information on the location of important marine predator high-use areas in these regions.

Sizes of potential KBAs varied greatly. Small sites could represent a small individual core-use area (e.g., breeding female Antarctic fur seals around Nyrøysa, Bouvet Island [Appendix S1]) or a small area of high-density use by highly mobile species displaying more variable individual movements. Southern elephant seals are one such example. They are highly mobile, but low overlap in their movements led to potential KBAs that were small relative to the extent of their tracks, such as postmolt movements around Macquarie Island that represented a 26,692-km^2 potential KBA, despite wide-ranging tracks spanning an area many times this size. Large sites, in contrast, indicated highly mobile species with high overlap in movements. Emperor penguins, for example, showed high mobility and high overlap, triggering large potential KBAs (562,479 and 1,143,969 km^2, respectively) (Appendix S1).

Ecological role of potential KBAs

Highly used marine sites often indicate foraging areas or movement corridors (Boyd et al., 2014; Meier et al., 2015; Thaxter et al., 2012), and although additional analyses are needed to determine the specific behaviors and details of habitat use of these potential KBAs, these sites likely play an important role for these populations' access to foraging sites. The continued ability of species to utilize foraging areas and movement corridors has wide ranging implications for individual fitness and population trajectories of these species. For breeding seabirds, foraging areas accessible from nesting colonies are vitally important for both survival and breeding success (Dugger et al., 2010; Michelot et al., 2021; Weimerskirch, 2002, 2018). Potential KBAs for nonbreeding seabirds and sites for molting and breeding for seals could indicate the location of highly productive foraging sites and migration pathways. Nonbreeding periods for seabirds are very important for rebuilding body condition, as are the foraging periods following fasting during molting and breeding for seals (Atkinson, 1997; Stearns, 1989). Postbreeding or molting migrations to distant but highly productive foraging areas, where adults can rebuild depleted body condition, are common for seabirds and seals (Desprez et al., 2018; Phillips et al., 2017; Stearns, 1989).

Caveats and future work

Next steps for the KBA identification process include determining final site boundaries through delineation decisions, such as whether to refine raw polygons into smoothed borders, subdivide sites by jurisdiction, and combine overlapping sites into multispecies KBAs (Handley et al., 2020). These decisions can vary depending on what is most conducive to management needs (Donald et al., 2019). Preliminary considerations for determining boundaries in the Southern Ocean KBAs was discussed at length at a 2022 workshop and will form the starting point for future decisions (see Brooks et al., 2022). Once formal boundaries are finalized, we will propose sites to the KBA Secretariat for inclusion in the World Database of KBAs (https://wdkba.keybiodiversityareas.org).

To address potential future shifts in site location or eligibility, the KBA Standard stipulates identifying sites based on the current observed distribution of assessed species but requires that sites undergo periodic reassessment every 8–12 years. These reassessments must use updated population estimates to maintain the best possible accuracy. Assessing changes over time in location, size, and shape of high-use areas is important for tracking shifts driven by changing environmental conditions and trophic dynamics under climate change. Although all potential KBA sites require reassessments, those that were more sensitive to population uncertainty warrant particular focus in reassessments. It may also be valuable to revisit high-use areas (Figure 3; Appendix S1) that did not qualify as potential KBAs under this round of assessment if new data become available.

Sensitivity of KBAs to population estimates highlights the importance of continuing to use the best available population data in future assessments and for prioritizing where investment in gathering additional data might be most beneficial. The confidence scores we calculated for these potential KBAs represented a broad estimate of confidence based on a combination of site sensitivity to observed variation in population sizes and confidence in population estimates. High sensitivity to population estimates does not negate the value of these sites because a high-use area on its own indicates that these sites are of ecological importance to a population. It does, however, show that recognition as a potential global KBA is sensitive to these parameters.

Changes to threat status should also be taken into account in reassessments. This is especially important for species, such as emperor penguins, that are not currently listed as threatened by the IUCN but are starting to be negatively affected by climate change (Fretwell et al., 2023; Trathan et al., 2024) and are anticipated to become severely threatened in the near future (Jenouvrier et al., 2021; Trathan et al., 2020). This was illustrated by the recent breeding failures of colonies in the Bellingshausen Sea (Fretwell et al., 2023), indicating that emperor penguins are already showing signs of circumpolar broad-scale decline (LaRue et al., 2024), and the recent listing of emperor penguins under the United States Endangered Species Act (Jenouvrier et al., 2021; US Fish & Wildlife Service, 2023). Recovery of previously threatened species must also be considered in reassessments.

There are many colonies and populations, as well as life-history and breeding stages, of species for which data were not available (Figure 1). The potential KBAs we identified are therefore best interpreted as the presence of an important site for data groups represented within the RAATD data. Their identification does not imply that other unassessed areas or populations are not of conservation importance. Although assessing additional data sets would reveal additional KBAs, this would not undermine the validity of the sites already identified. Additionally, although more efficient than some alternatives, tracking data are nevertheless expensive, time consuming, and resource intensive to collect. Utilizing existing data sets rather than relying on bespoke deployments for each new research question is highly efficient for time, resources, and cost to the study species. Although our specific methods are not appropriate for GLS tags, using only PTT and GPS data can exclude small, far-ranging, or postbreeding stages that require lighter GLS tags. It is important for the research community to develop methods to incorporate GLS data into KBA assessments, particularly during the nonbreeding period, which are underrepresented in the RAATD data set.

The use of quantitative thresholds in the KBA criteria means that KBAs can be identified independently, without comprehensive data on all colonies as long as there is a reasonable global population size estimate. Thus, sites we identified as potential KBAs are globally significant and will remain so when data from additional sites become available, as long as there is not a sudden increase in global population size estimate (e.g., a new major colony is discovered). This differs from sites identified as important though complementarity-based decision tools, such as Marxan, because introducing new data in these types of analyses can lead to a significant shift in complementarity patterns (Ball et al., 2009). It also differs from approaches that use a percentage of habitat for a species because this metric is also sensitive to new data (Guisan & Zimmermann, 2000; Jones-Farrand et al., 2011). Although collecting data from all colonies is not realistic for most species, this points to the high value of prioritizing the collection of tracking data from less studied colonies that are likely globally important in terms of size.

Future research should include incorporating additional data in future assessments from more recent tag deployments in our target groups and from new populations and species. This will continue to build a more complete picture of the complex mosaic of important foraging areas for Southern Ocean predator species. Filling geographic data gaps in tracking data and identifying high-use areas from these additional tracks could help supplement and validate habitat-model-based identification of important ecological areas. Similarly, building more robust data sets that have large enough sample sizes to be further subdivided by sex or life-history stage could provide more nuanced information about which population subsets are using these sites. Further, assessing overlap between different spatial designations of conservation importance and the potential ecological value they identify could be useful to inform spatial management and conservation planning in the Antarctic region.

Management implications

Identifying sites of conservation importance is useful for site-based (e.g., MPAs) and activity-based (e.g., fisheries) management. Knowing where important sites for different species occur, and during which seasons, can help managers prioritize fisheries regulations such as seasonal restrictions or modified catch limits. The potential KBAs we identified combined with future KBA work and consideration of other spatial designations of conservation importance could continue to inform new and updated MPAs and spatial fishing regulations in the Southern Ocean and thus support ongoing efforts.

Overall, KBAs, both current and future, can provide a strong basis for data-driven protection of our ocean (Davies et al., 2021). In other regions, data-group-specific information from KBAs and associated information have helped inform area-based management decisions, including the re-zoning of the subantarctic South Georgia/Islas Georgias del Sur and South Sandwich Islands MPA and associated management plans (Handley et al., 2020) and identification of special protected areas under the European Birds Directive (Waliczky et al., 2019). In the high seas, multispecies tracking data have also been used to identify areas suitable for protection, including the North Atlantic Current and Evlanov Seabasin MPA designated by the OSPAR Commission in 2021 (Davies et al., 2021).

This study is among the first to apply KBA criteria in international waters, where the recent High Seas Treaty may, for the first time, create pathways toward robust conservation action, including MPAs (UNGA, 2023). This important agreement increases the need for research that helps identify important areas for biodiversity in the high seas, and KBAs could be a tool to help inform this broad-scale conservation planning. Many of our sites cross several jurisdictions, including national exclusive economic zones (EEZs), international waters where some fisheries are managed by Regional Fisheries Management Organizations (RFMOs), and the CCAMLR area. Although working across jurisdictions is inherently challenging, it will be necessary for future biodiversity conservation (e.g., Maina et al., 2020), including in managing potential KBAs we identified. Notably, CCAMLR already manages across jurisdictions to some degree. For example, fisheries in the waters around Heard Island and McDonald Islands, which fall under Australia's EEZ, are governed in collaboration with CCAMLR, including according to CCAMLR's decision rules (Brooks et al., 2019). CCAMLR further communicates with adjacent RFMOs on species and topics of interest, including on issues related to fisheries sustainability and conservation (CCAMLR, 2023a). Potential KBAs we identified for sooty and grey-headed albatross occurring in international waters, for example, may indicate a need for increased engagement among national governments, CCAMLR, and adjacent RFMOs to enforce the use of bycatch mitigation measures (Bealet al., 2021).

Incorporating species-level high-use areas into management decisions and planning is especially important amidst the expansion of fisheries and tourism in the Southern Ocean. Site-based conservation, to which KBAs can provide guidance, will be a key step in regulating where and how both of these industries can continue to operate. Meanwhile, as climate change accelerates, the importance of reducing these compounding threats increases. Due to the changes in the Southern Ocean environment, seabird and mammal populations are changing with range shifts and alterations in life histories (Bestley et al., 2020). Most notably, loss of sea ice is having devastating impacts on emperor penguin colonies, where the 2022 record low sea ice was linked directly to widespread breeding failure (Fretwell et al., 2023). In addition, the large postbreeding potential KBAs identified for emperor penguins overlap with areas fished for krill and with exploratory toothfish fisheries (CCAMLR, 2023b, 2023e) and may be especially important to monitor to minimize fisheries impact on predator access to prey. Indeed, the first recorded loss of an emperor penguin colony was on the Antarctic Peninsula (Trathan et al., 2011), an area that is warming rapidly and that is also a major focus for the krill fishery (Trathan, 2023b). Although spatial management, whether through MPAs or targeted fisheries regulations, cannot stop climate change impacts, management actions to reduce other stressors, such as competition with fisheries for prey, can bolster resiliency (Jacquemont et al., 2022; Roberts et al., 2017).

The promise of these and future KBA results to contribute to conservation planning lies in the value of applying standardized and ecologically relevant criteria to diverse data sets. Worldwide application of a standardized process will ensure that a comparable overview on the state of global biodiversity is documented. The persistence of high-quality foraging habitat within reasonable traveling distance to terrestrial breeding and haul-out sites is vital for successful conservation of seabird and pinniped species. Supplementing the ongoing work to design a protected area network and implement ecosystem-based fisheries management in the Southern Ocean with evidence of important sites for specific species, populations, and life-history stages—where data are available—helps build a more complete picture of the complex and interlocking habitat needs of marine predators in this region. As sites are delineated and reassessed in future stages of this work, we will be able to track whether and how sites critical for the persistence of species are shifting in use or location with climate change. Although we prioritized working with existing data, as more data are shared or made publicly available, geographic gaps in our results can be progressively filled, allowing decision makers to consider specific species and populations more holistically in management decisions. We utilized an approach to identify potential KBAs in a large geographic region that spans both national and international waters. Given the newly adopted High Seas Treaty, which will allow for area-based management tools like MPAs in international waters, along with the new Global Biodiversity Framework, which includes commitments to protect 30% of the ocean by 2030, KBAs will have an important role to play in identifying key areas for marine conservation across the world's oceans. When used in conjunction with complementary tools such as habitat modeling and bioregionalization, KBAs are a valuable tool to highlight specific needs for species of conservation concern and to guide spatial conservation efforts.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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