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Mapping Antarctic Seabird Breeding Occupancy From a Century of Observations to Inform Environmental Management and Conservation

Colin Southwell[1] | Louise Emmerson[1] | Nat Kelly[1] | Dale Maschette[1,2] | John Arnould[3] | Christophe Barbraud[4] | Jeroen Creuwels[5] | Robyn Delaney[6] | Karine Delord[4] | John Gibson[1] | Ken Green[1] | Mark Hindell[7] | Harold Heatwole[8] | Peter Hodum[9] | Cindy L. Hull[10] | Akiko Kato[11] | Nobuo Kokubun[11] | Anna Lashko[1] | Gary Miller[12] | Ian Norman[3] | Frederique Olivier[7] | Anant Pande[13,14] | Graham Robertson[1] | Marcus Salton[1] | Akinori Takahashi[11] | Jan van Franeker[15] | Simon Ward[3,6] | Barbara Wienecke[1] | Eric J. Woehler[1]

[1]Department of Climate Change, Energy, the Environment and Water, Australian Antarctic Division, Kingston, Tasmania, Australia | [2]Fisheries and Aquaculture Centre, Institute for Marine and Antarctic Studies (IMAS), University of Tasmania, Hobart, Tasmania, Australia | [3]Department of Botany and Zoology, Monash University, Clayton, Victoria, Australia | [4]Centre d'Etudes Biologiques de Chizé, UMR7372 CNRS/La Rochelle University, Villiers en Bois, France | [5]Department of Marine Biology, University of Groningen, Haren, the Netherlands | [6]Department of Zoology, University of Melbourne, Parkville, Victoria, Australia | [7]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia | [8]Department of Zoology, University of New England, Armidale, New South Wales, Australia | [9]Biology Department, University of Puget Sound, Tacoma, Washington, USA | [10]Zoology Department, University of Tasmania, Hobart, Tasmania, Australia | [11]National Institute of Polar Research, Tachikawa, Japan | [12]Department of Biology, University of New Mexico, Albuquerque, New Mexico, USA | [13]Marine Programme, Wildlife Conservation Society – India, Bengaluru, India | [14]Wildlife Institute of India, Ministry of Environment, Forest and Climate Change, Government of India, Dehradun, India | [15]Wageningen Marine Research, Den Helder, the Netherlands

Correspondence: Colin Southwell (colin.southwell@aad.gov.au)

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ABSTRACT

Aim: To map presence, absence and ignorance of Antarctic seabird breeding occupancy at the spatial resolution of ice-free habitat sites to identify knowledge gaps and inform management and conservation.

Location: East Antarctica between longitudes 30° E and 150° E.

Methods: We develop a unifying spatial and inferential framework to compile and interpret observations of Antarctic seabird breeding occupancy. The spatial framework allowed consistent geo-referencing of observations at the spatial resolution of habitat sites. The compilation included published papers and datasets, unpublished reports, research station logs and unpublished field notes. Where possible, observations and inferences were validated by the 'experts' who originally collected data. The inferential framework categorised levels of uncertainty for inferring occupancy and distinguished knowledge of occupancy from ignorance.

Results: After a century of observations, there are still knowledge gaps in seabird breeding occupancy along large sections of the East Antarctic coastline and across most of continental East Antarctica where breeding habitat is available. The spatial extent of knowledge and ignorance is strongly dependent on the level of certainty used to infer absence. Observations are clustered close to permanently occupied research stations, most of which are located on the coast, and biased in favour of species that are most emblematic

of Antarctica or those with a less secure conservation status. The spatial and temporal coverage of observations in recent decades would be insufficient to effectively detect change in most species' breeding occupancy distributions across their range into the future. **Main Conclusions:** Our compilation and mapping of occupancy data contributes to practical conservation measures to mitigate impacts of human activities including aviation and fisheries on seabirds in Antarctica, and serves as a foundation to strategically improve future environmental management and conservation. We urge future occupancy monitoring to explicitly report the location of search effort and potential absence in addition to presence and to aim to close spatial knowledge gaps.

1 | Introduction

Occupancy or presence-absence data are foundational for studies of populations, communities and biodiversity, and for informing conservation management decisions and actions (Hortal et al. 2015). Such data are crucial for numerous purposes, including detecting changes in species' range, designing field studies of populations and communities, building explanatory and predictive species distribution models, prioritising sites for protection and managing disturbance to wildlife.

Antarctica and the Southern Ocean are amongst the Earth's least known regions with regard to species' occupancy and biodiversity distribution due to their remoteness, difficulty of access and extreme physical environments. While anthropogenic impact has been relatively low in these polar regions in the past compared with elsewhere, human activities and their resultant impacts are increasing rapidly; the corresponding need to manage these environmental impacts is becoming increasingly important.

Seabirds are an iconic Antarctic taxonomic group, are one of the most threatened groups of birds globally (Dias et al. 2019), and are widely considered to be important bio-indicator species for monitoring marine ecosystems (Montevecchi 1993). In Antarctica and the Southern Ocean, seabirds are vulnerable to fishing operations while foraging at sea, to disturbance from human activities while breeding on land, and to the impact of climate change on both marine and terrestrial ecosystems (Croxall et al. 2002; Trathan et al. 2015). In recognition of the threat of fisheries to seabirds and marine ecosystems of the Southern Ocean, three of the seabird species included in this study have been selected as indicator species for the Ecosystem Monitoring Program developed under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) to detect effects of krill fishing on krill-dependent species and the krill-based ecosystem (Agnew 1997). In addition, one of the study species is widely considered a bellwether of climate change in these regions (Ainley 2002).

The degree to which these threats to Antarctic-breeding seabirds can be effectively assessed and mitigated depends on the quantity and quality of occupancy and biodiversity data used to make management decisions. Past studies have identified several gaps and shortfalls of occupancy data that are common to many taxa. One critical shortfall is that knowledge of occupancy is usually spatially incomplete, with survey effort often biased toward locations with convenient access, infrastructure and logistics (Etard et al. 2020; Johnston et al. 2020, 2023; Oliver et al. 2021). Another shortfall is that some taxa receive more survey effort than others (Etard et al. 2020; Hortal et al. 2015), with iconic, larger, more detectable and widely distributed species often recorded earlier and more extensively (Devarajan et al. 2020; Gaston and Blackburn 1994). Survey effort can also have temporal shifts in spatial coverage that can result in spurious conclusions on change in occupancy distribution over time (Bowler et al. 2022; Lobo et al. 2007; Hortal et al. 2008) or on patterns of local extinction (Tessarolo et al. 2017). A well-recognised problem with absence data is that it is impossible to be totally confident that a recorded absence is not an undetected presence (Gu and Swihart 2004; MacKenzie and Royle 2005) when species are highly cryptic or surveyors are inexperienced. Finally, but not exhaustively, errors or imprecision in the geo-referencing of occupancy data can lead to incorrect interpretations and predictions of species distributions (Maldonado et al. 2015). These gaps and shortfalls have led to warnings that the biased and unrepresentative nature of available knowledge of species occupancy distributions may compromise our capacity to make correct decisions for environmental and conservation management (Hortal et al. 2015). In response to these warnings, there is an increasing focus on carefully recognising and quantifying not only knowledge but also uncertainty and ignorance when compiling occupancy data (Rocchini et al. 2011; Ladle and Hortal 2013; Ruete 2015; Stropp et al. 2016).

Here we investigate the state of knowledge and ignorance of seabird breeding occupancy in Antarctica from observations made over the last century. We distinguish knowledge from ignorance by considering whether there is evidence a habitat site has been visited and observed for seabird occupancy (if yes, there is knowledge, if no, there is ignorance), and qualify the certainty of absence by considering attributes of occupancy reporting, search effort and species' detectability. After compiling observational data on seabird breeding occupancy from the published literature, grey literature and expert knowledge of past and currently active researchers working in East Antarctica, we investigated: (1) Where, when and how frequently have we searched available seabird breeding habitat across East Antarctica over the last 100 years, and over what spatial extent of the region do we have knowledge of, or remain ignorant of, seabird breeding occupancy?; (2) What is the extent of spatial, temporal and taxonomic bias in occupancy data?; and (3) Given new understandings gained from answering these questions, what are the implications for some current environmental management and conservation issues in the region and how might decision-making be improved?

2 | Methods

2.1 | Study Region

This study focuses on the region of East Antarctica spanning ~5000 km of coastline from 30° E to 150° E and extending over 2000 km inland to the South Geographic Pole (Figure 1). The 'coastline' is defined as the seaward edge of continental land,

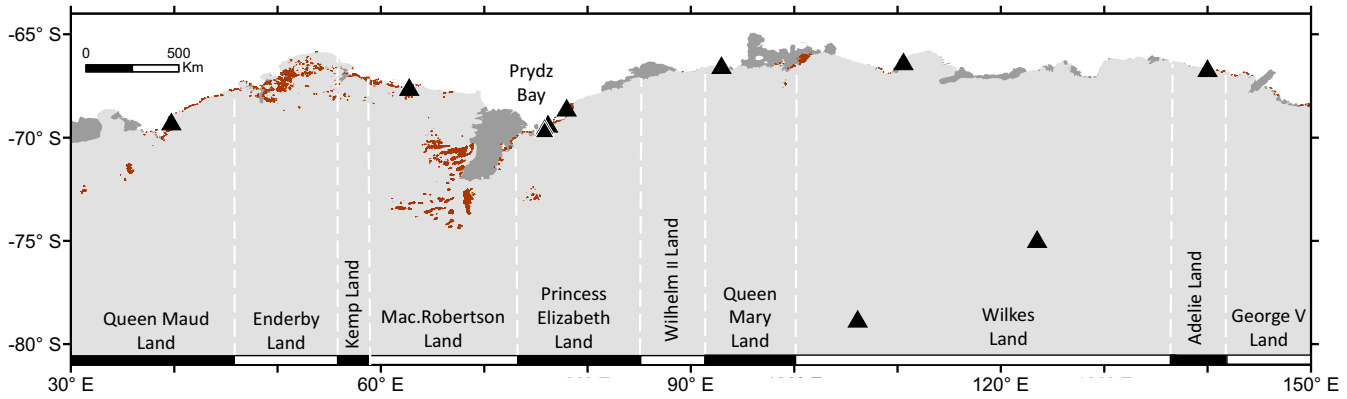

FIGURE 1 | Map of the study region (Equidistant Cylindrical projection) showing the distribution of coastal and continental ice-free areas indicating available seabird breeding habitat in East Antarctica. Brown shading is ice-free land; light grey shading is continental ice; dark grey shading is ice shelf; white is ocean; black and white horizontal bars at the bottom and white dashed vertical lines indicate the extents of named coastal geographic sectors in the text. Black triangles show locations of permanently occupied research stations.

floating glacier tongues or semi-permanent floating ice shelves. This region is characterised by a largely east–west aligned coastline, a continental ice cap rising from sea level to 2800 m above sea level at the South Geographic Pole, extensive sea ice offshore from the coast, and importantly for the study species group, disjunct patches of ice-free land offshore from the coast (islands) and protruding through the continental ice cap (nunataks). These patches of land have been free of permanent ice cover over at least the last 100 years of the study period and are generally only temporarily and partially covered in snow for days to weeks. We hereafter refer to any patch of ice-free land as a 'site', to islands as 'coastal sites', and to nunataks as 'continental sites'. Sites adjoining the marine environment but separated from the open ocean by floating glaciers or ice shelves (e.g., the Bunger Hills) were considered to be continental sites. Defined in this way, the 'site' forms the fundamental spatial unit and resolution of this study.

The coastline of the study region straddles two large offshore management areas (Divisions 58.4.1 and 58.4.2) used by CCAMLR for managing fisheries in the Southern Ocean, and two large spatial areas (Central Indian and East Indian) used for the Marine Ecosystem Assessment of the Southern Ocean (Bestley et al. 2020).

2.2 | Species Group

We focussed on eight seabird species that breed on ice-free land in East Antarctica and more broadly around Antarctica: the Adélie penguin *Pygoscelis adeliae*, Antarctic petrel *Thalassoica antarctica*, Cape petrel *Daption capense*, southern fulmar *Fulmarus glacialoides*, southern giant petrel *Macronectes giganteus*, south polar skua *Stercorarius maccormicki*, snow petrel *Pagodroma nivea* and Wilson's storm petrel (*Oceanites oceanicus*). A small number of brown skuas (*Stercorarius antarcticus*) have recently been observed cross-breeding with south polar skuas at Haswell Island in East Antarctica (Golubev 2022), but this species was not included in the compilation because of the rarity of this event. The Emperor penguin (*Aptenodytes forsteri*) was not included as a study species because it breeds almost entirely on fast ice which is highly variable in extent within and between breeding seasons, making precise geo-referencing of available breeding habitat difficult.

The eight species vary substantially in body size (20 to 100 cm body length), coloniality (dispersed to highly aggregated), abundance at breeding sites (10s to 10s of 1000s), plumage colouration and marking (contrasted to camouflaged against background) and breeding substrate (above-surface to sub-surface) (Appendix S1 in Supporting Information). We reason these differences are likely to affect species' detectabilities and hence the relative certainty with which occupancy can be determined (see section on certainty below). All species breed during the Austral summer that spans consecutive calendar years, which we refer to as split calendar years (e.g., 2020/21 for the breeding season starting in late 2020). The occurrence of Adélie penguin breeding populations across East Antarctica has been collated and geo-referenced previously (Southwell et al. 2016). Here we extend this work to the seven flying seabird species to assess breeding occupancy for all eight land-breeding species across the study region.

2.3 | Geo-Referencing Available Breeding Habitat Sites and Occupancy Observations

For this study, we considered any coastal site, regardless of geological form, type or structure, as available breeding habitat for all eight study species, and any continental site further than 1 km from the ocean as available breeding habitat for the seven flying species, acknowledging the inability of Adélie penguins to access land further inland because they cannot fly. The full extent of available coastal and continental seabird breeding habitat sites has been comprehensively geo-referenced, geo-labelled and mapped in recently developed spatial reference systems for coastal and continental East Antarctica (Southwell et al. 2021 and this study, respectively). We used these systems to consistently geo-reference observations of breeding occupancy at available habitat sites. Habitat sites are represented as polygons in the geographic information systems (GIS) and associated databases that form the spatial reference systems. Each site is identified by a Unique Feature Identifier and the latitude/longitude of the site's centroid, both of which were automatically generated in

the geographic information systems (ArcGIS 9.2). The centroids allow occupancy data to be mapped at the spatial resolution of sites. In addition to these fundamental features in GIS and database form, the spatial reference systems also include the names of sites (where available) from the SCAR Composite Gazetteer (Secretariat SCAR 1992, updated 2014) and the area of sites. The coastal reference system also includes a series of hierarchically-structured maps showing the boundaries of all sites, their relative configurations to each other in space, and their Unique Feature Identifier labels (Southwell et al. 2021). The partitioning of space into maps was done heuristically to (1) attain scales that are practical to use, (2) ensure sites are visually recognisable in the field and could be matched with figures in publications, (3) limit the number of features in each map to ensure readability and (4) ensure boundaries between maps were located within natural gaps in the distribution of sites. The maps covered areas of up to 10 km in east–west and north–south dimensions.

The coastal spatial reference system has 5208 coastal sites that are located on the coast or up to 40 km offshore from the coast. The great majority (99%) of coastal sites are $\leq 10\,km^2$ in area (average area $0.5\,km^2$) and the largest (Vestfold Hills) is $365\,km^2$. The combined area of all coastal sites is $2240\,km^2$. The continental reference system (Appendix S2) has 2577 continental sites totalling $5893\,km^2$ in area (average area $2.3\,km^2$) that extend from 1 to 730 km inland from the coast.

2.4 | Compiling Occupancy Observations

There have been several previous Antarctic-wide compilations of known seabird breeding presence that cover our study species and region (Antarctic petrel: van Franeker et al. (1999); southern fulmar: Creuwels et al. (2007); southern giant petrel: Patterson et al. (2008); Wienecke et al. (2009); snow petrel: Croxall et al. (1995); Francis et al. (2025); Adélie penguin: Woehler (1993); Lynch and LaRue (2014); Che-Castaldo et al. (2023); all species: Woehler and Johnstone (1991); Harris et al. (2015)). Our work aimed to extend, refine and update these compilations in East Antarctica by: (1) most importantly, including information that could be used to infer absence and its certainty in addition to presence; (2) explicitly identifying areas of ignorance; (3) using a common, standardised spatial reference system; and (4) including new observations up to 2020.

We compiled breeding occupancy observations for the seven flying seabird species from various sources, including published papers and datasets, unpublished reports, biology logs from research stations and researchers' unpublished field notes. We hereafter refer to the collective of all these sources as 'source material' and to individual sources as 'source references' (Appendix S3). Each database record described a 'search event' for a particular species at a unique coastal or continental site in a specific breeding season. This compilation was combined with a database of Adélie penguin occupancy in East Antarctica (Southwell et al. 2016) to provide comparable data for all eight species. The database does not include recent observations of Adélie penguin or flying seabird breeding occupancy from satellite imagery (e.g., Lynch and LaRue 2014; Schwaller et al. 2018) because the spatial resolution of locations in those studies is not compatible with the spatial reference systems used here and because satellite imagery is currently unable to distinguish between species of flying seabirds.

The source references ($n = 149$) ranged from observational, ecological and behavioural studies of single species at single sites to multiple species across many sites. Consequently, a single source reference could contain one to multiple search events according to the number of species, sites and seasons studied. The process for compiling search event records is outlined below and summarised in the flowchart in Figure 2.

We first identified whether the source reference explicitly and unambiguously focussed on a specific set of species referenced in the title and/or results; and if so, confined our interpretations to those focal species only. If there was no specific statement about focal species in the title or text of a source reference and the text addressed multiple species, we assumed all eight species were a focus in the study.

We then identified the sites that had potentially been searched for the selected focal species. This was done by matching site names in the text of the source reference or matching a visual representation of sites or the survey region in a figure or map in the source reference to sites in the tables and maps of the spatial reference systems, and using the sites' Unique Feature Identifiers to unambiguously record the site at which each

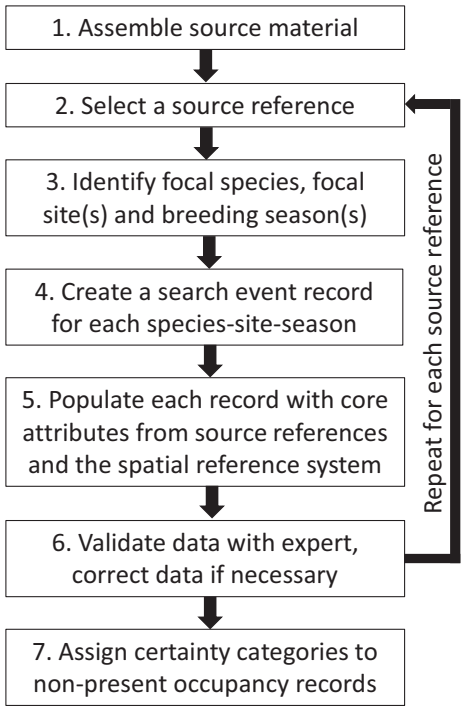

FIGURE 2 | Flowchart showing the steps used to compile the database of search event records. In step 2, source references that contain observations of seabird occupancy included published papers and datasets, unpublished reports, biology logs from research stations, and researchers' unpublished field notes. In step 5, core attributes from source references were species, season, vantage point and occupancy (the latter as present, absent or not reported), and core attributes from the spatial reference system were site identifier, site centroid and site area. In step 7, assignment of certainty to non-present records was conditional on species, vantage point and site area.

search event occurred in the database. If the description of a spatial location could not be matched with a unique site, it was not included in the database.

The combination of each focal species, focal site and breeding season in a source reference defined a search event record. Thus, if *m* focal species and *n* searched sites were identified in a source reference for each of *p* breeding seasons, then *m* x *n* x *p* search event records were created in the database. Each of these *m* x *n* x *p* search event records was then populated with data for a core set of attributes obtained from the source reference, including species, site, season, search vantage point (ground, ship or air) and whether a species was directly reported as present or absent, or if no direct statement about presence-absence at a site was made, recording it as a case of occupancy non-reporting. A direct statement of presence was interpreted either from text in a source reference describing the presence of a breeding species (e.g., birds on nests) or from a table with a non-zero count of a breeding population. A direct statement of absence was interpreted from an explicit statement of absence in the text or an explicit count of zero in the text or a table.

2.5 | Expert Validation

When compiling data, the above process of creating and populating search event records into the database was applied consistently to source references by a small team. Subsequently, the process and compiled data were provided to 'experts' to check that the small team's interpretation was consistent with expert experience and expectation. Experts were chosen on the basis that they had participated in the collection of original source data, and each expert was provided only with a summary of the data they had collected. If the small team's interpretation of an expert's summarised data did not meet that expert's agreement, the compiled data were corrected under the direction of the expert. During validation, experts could also contribute unpublished data that would have otherwise been overlooked.

2.6 | Certainty of Absence Observations

Given the uncertainty associated with correctly attributing absence to wildlife observations, we considered all search event records with absence or not-reported entries for occupancy as cases of potential absence (but for brevity, we hereafter refer to these as 'absence' records) and developed a set of criteria reflecting differing levels of certainty in absence attribution. The highest level of absence certainty was attributed if the source reference contained an explicit statement of absence. Lower certainty levels were attributed if there was no explicit statement or evidence of absence by virtue of a focal species' occupancy not being reported. This lower certainty due to non-reporting was categorised into two certainty levels based on characterisations of species and survey-related detectabilities and the likelihood that a focal site was completely searched. The logic of this categorisation was that if species and survey-related characteristics increase the likelihood of detection if actually present, then conversely, they would also increase the likelihood that non-reporting reflected actual absence. The specific species and survey characterisations used for this categorisation are in Appendix S4. These three absence certainty categories, which we hereafter refer to as higher, medium and lower certainty, were relative in nature and none were intended to imply absolute certainty or uncertainty.

2.7 | Search Effort

We calculated a metric of search effort for each species across sites within specific regions and specific time periods. The metric expressed the area of searched sites as a percentage of the area of all sites, conditional on a minimum absence certainty for a region and time period. Thus, if searched sites based on the presence and only higher certainty (*H*) absence in region *x* and time period *y* had a combined area of S_{Hxy} km^2, and the area of all sites in region *x* was A_x km^2, then the search effort metric E_{Hxy} was

$$E_{Hxy} = 100 \times S_{Hxy} / A_x$$

Considering only higher certainty absences in the search effort metric is a cautious interpretation of search effort and sets a lower bound to the metric. Lowering the minimum certainty of absences allows a more optimistic interpretation of search effort by considering more sites as searched and sets a higher bound to the metric. Thus, if all absences (i.e., higher (*H*), medium (*M*) and lower (*L*) certainty) are considered, the search effort metric is

$$E_{HMLxy} = 100 \times \left(S_{Hxy} + S_{Mxy} + S_{Lxy}\right) / A_x$$

When calculating search effort within a time period, if a site was searched in more than one season, the most certain absence category was used.

2.8 | Analysing Search Effort and Occupancy Data

We first examined the pattern of cumulative knowledge and search effort at the macro-scale of the entire study region over the last century. This was achieved by calculating the cumulative number of known breeding sites and the cumulative search effort for each species at coastal and continental sites across the entire study region within 5-year incrementing time-periods from 1921/22 to 2020/21 (i.e., 1921/22 to 1925/26, 1921/22 to 1930/31, ... 1921/22 to 2020/21). Cumulative search effort was calculated separately for three levels of absence certainty from most cautious to most optimistic (i.e., E_{Hxy}, E_{HMxy} and E_{HMLxy}).

We then assessed how absence certainty influenced interpretation of the distribution of search effort intensity within the study region at a meso-scale of half-degree longitudinal sectors. For this analysis, we calculated cumulative search effort over the full century, for the three levels of search effort certainty, for each species, and for each half-degree sector along the coast. This analysis focussed on coastal sites only because most search effort has occurred there (see results). The distribution of search effort intensity at this spatial scale was represented as 'barcode' maps, with each vertical bar being a half-degree longitudinal sector and the intensity of search effort for each bar represented as four categories of increasing intensity (1: no sites searched; 2: up to 33% of total site area searched; 3: 34%–66% of total site area searched; 4: 67%–100% of total site area searched).

To examine spatial patterns, bias and ignorance, we visually examined maps of the distribution of search effort at both meso- and micro-spatial scales, and used logistic regression to model the relationship between search effort and accessibility, where accessibility was quantified as the distance of a site from the nearest permanently occupied research station. These analyses again focussed on coastal sites only. The meso-scale barcode maps covered the full 5000 km longitudinal extent of the study region and allowed us to visualise the broad pattern of search effort along the coast in half-degree longitudinal sections. The micro-scale maps focussed on sections of the coastline spanning approximately 300 km around research stations, and allowed us to visualise presence, absence certainty and ignorance (not searched) at the spatial scale of individual sites. The logistic analysis was applied to binary search effort data at the micro-scale of sites (sites with evidence of search effort vs. sites with no evidence of search effort). Logistic models were fitted separately for each species and for the three levels of search effort certainty using a generalised linear model with logit link function. Model fits were assessed by comparing them to null models for no accessibility effect using Akaike's Information Criterion (AIC), and also by examining the significance of parameter estimates (p-values). For each model, an AIC value of at least 2 less than the null model's AIC was considered evidence of an accessibility effect. Because of the large number of models across species and certainty levels ($n = 24$), we considered a p-value of < 0.001 to be additional evidence of an accessibility effect.

To assess the utility of the compiled data to monitor change in spatial distribution of breeding sites over time, we determined the frequency at which sites that had been searched over an initial 'baseline' period had subsequently been revisited and searched again over a later 'monitoring' period. The baseline period covered the six decades from 1921/22 to 1980/81, and the monitoring period covered the four decades from 1981/82 to 2020/21. We first calculated the cumulative number of searched sites known from the baseline period and then examined the frequency of repeated observations at each of these sites at the temporal resolution of a decade over the monitoring period. These data were then summarised as the proportion of searched sites that had never been repeatedly searched or had been repeatedly searched in 1, 2, 3 or 4 of the monitoring period decades. This metric was calculated separately for each species and separately for presence and absence sites.

3 | Results

3.1 | Occupancy Database and Expert Validation

The occupancy database comprised 33,297 search event records made over the last century, of which 5014 were records of seabird breeding presence, 11,701 were records of breeding absence, and 16,582 were records where breeding occupancy was not reported and we considered as potential absence records. The experts collectively validated 71% of all records, with more validation of search events occurring after 1980 (97%) than before 1980 (26%). Experts corrected aspects of 61 initially compiled records and provided data on 96 previously unknown search events that would otherwise have not been available.

TABLE 1 | Number of known seabird breeding presence and absence sites, and search effort (percentage of sites with evidence of searching), over the last century in coastal and continental East Antarctica between longitudes 30° E and 150° E.

	Presence sites		Absence sites (most cautious)		Absence sites (most optimistic)		Search effort (most cautious)		Search effort (most optimistic)	
Species	**Coast**	**Continent**	**Coast**	**Continent**	**Coast**	**Continent**	**Coast**	**Continent**	**Coast**	**Continent**
Adélie penguin	248	—	1633	—	3762	—	36.1	—	77.0	—
Antarctic petrel	20	0	1089	7	2764	10	21.3	0.1	53.5	0.2
Cape petrel	60	0	1062	7	2724	10	21.5	0.1	53.5	0.2
Southern fulmar	43	0	1062	7	2724	10	21.2	0.1	53.1	0.2
Southern giant petrel	7	0	1084	7	2376	10	20.9	0.1	45.8	0.2
South polar skua	123	4	65	2	827	5	3.6	0.1	18.2	0.1
Snow petrel	139	14	92	1	771	4	4.4	< 0.1	17.5	< 0.1
Wilson's storm petrel	103	1	86	5	787	8	3.6	< 0.1	17.1	< 0.1

Note: Dash entries for Adélie penguins at continental sites indicate this species cannot access continental habitat. The most cautious absence and search effort values include only higher absence certainty; the most optimistic absence and search effort values include all levels of absence certainty.

3.2 | Presence Observations

To date, the collective search effort has found seabirds breeding at 384 sites (369 coastal; 15 continental). The majority (52%) of known seabird breeding sites have had just a single species reported as present, and only one site has had all eight species reported present (Nelly Island, Wilkes Land) (Appendix S5). At the species level, the number of known breeding sites ranged from 248 for the Adélie penguin to 7 for the southern giant petrel (Table 1). Currently, five species (all of the above-surface nesting species except the south polar skua) are known to breed only at coastal sites. The remaining three species (south polar skua, snow petrel and Wilson's storm petrel) have been observed breeding at a small number of continental sites in addition to coastal sites (Table 1), with one snow petrel breeding site over 400 km inland (Goldsworthy and Thomson 2000) and one site (Bunger Hills) having all three species (Leishman et al. 2020). For coastal sites, the cumulative number of known breeding sites has increased steadily over the last century for some species (Adélie penguin, south polar skua, snow petrel, Wilson's storm petrel; Figure 3), but has remained relatively constant over the past 30 years after an initial increase through the 20th century for other species (Antarctic petrel, Cape petrel, southern fulmar, southern giant petrel; Figure 3).

3.3 | Inferred Absences and Their Certainty

In relation to the features used to assign a certainty level to inferred absence for the 28,283 combined records of absence and non-reporting: (1) Adélie penguins were classed as the most inherently detectable species, above-surface nesting flying species (Antarctic petrel, Cape petrel, southern fulmar, southern giant petrel, south polar skua) as intermediate, and sub-surface nesting species (snow petrel and Wilson's storm petrel) as least detectable (Appendix S4, Table S4.1); (2) the majority of search events were based on observations made from either the ground (63%) or aircraft (36%), with very few from ships (1%); and (3) the majority (98%) of focal sites were small (< 1 km^2) in area.

Assigning absence certainty categories conditional on species inherent detectability and survey-related detectability resulted in varying distributions of absence certainty rankings for the eight species. For the Adélie penguin, 43% of records had a higher certainty, 7% medium certainty and 49% lower certainty. The Antarctic petrel, Cape petrel and southern fulmar all had a more even distribution of certainties (39% higher, 32% medium, 29% lower), whereas most records (88%–89%) for the two sub-surface nesting species (snow petrel and Wilson's storm petrel) were attributed lower certainty. For the south polar skua, 43% and 49% of records had medium and lower certainties, respectively, and few (8%) had higher certainty, while 46% and 37% of southern giant petrel records had higher and medium certainties, respectively, and 17% had lower certainty.

3.4 | Search Effort and Ignorance

Knowledge of search effort provides an important context for presence observations and is critical for identifying ignorance (i.e., no effort). Thus, while the cumulative number of known

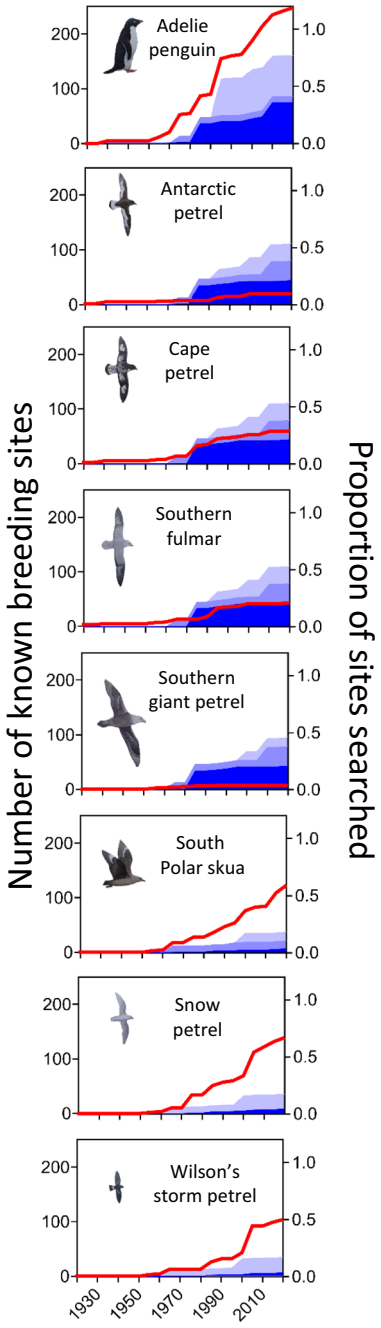

FIGURE 3 | Cumulative number of known breeding sites (red line, left y-axis) and cumulative search effort (blue shading, right y-axis) for East Antarctic land-breeding seabird species in successive 5-year periods over the last century. Increasing darkness of blue shading indicates increasing levels of certainty in search effort.

breeding sites is relatively constant over the last 30 years for Antarctic petrels, Cape petrels, southern fulmars and southern giant petrels (Figure 3), which in isolation could be interpreted as evidence of complete or near-complete knowledge of breeding distribution, the most optimistic estimates of search effort for these species (53%, Table 1) are far from complete and the most cautious estimates (21%) are considerably lower. The number of known breeding sites for sub-surface nesting species has increased steadily over the last century and particularly in the last two decades (Figure 3), but despite this, estimates of cumulative search effort are low (most cautious 4%; most optimistic 17%,

Table 1) suggesting that many breeding sites are yet to be discovered and documented. In contrast, the most optimistic estimate of search effort for Adélie penguins is considerably higher (77%; Figure 3, Table 1). Search effort at continental sites is at trace levels for all species (Table 1).

3.5 | Mapping Search Effort and Breeding Occupancy

At the meso-scale of the barcode maps (Figure 4: Adélie penguin and Appendix S6: all species), the spatial distribution of search effort at coastal sites was similar across the levels of search effort certainty. However, using a more cautious interpretation of search effort (only higher absence certainty) results in fewer sites being interpreted as searched within many sectors.

The barcode maps based on the most optimistic interpretation of search effort (Figure 5) show a strong difference in coastal search effort between the Adélie penguin and the other seven species, and highlight the spatial locations of knowledge gaps for each species. Although we have extensive knowledge of breeding distribution for Adélie penguins across much of coastal East Antarctica, we still lack direct observations in parts of Queen Maud Land, Enderby Land, Kemp Land and George V Land. A recent satellite study suggests there are no large Adélie penguin breeding populations in these areas (Lynch and LaRue 2014), but some small breeding populations could exist that are under the detection threshold of satellite technology (Southwell et al. 2017). Compared with Adélie penguins, we remain ignorant of the breeding distributions of the flying species across large sections of the coastline. These species show strikingly similar patterns of knowledge and ignorance. Of particular note is the lack of knowledge of their breeding distributions in Queen Maud Land, Enderby Land, Kemp Land, in the west of Mac.Robertson Land, along the coast of Princess Elizabeth Land in the south of Prydz Bay, and in the east of George V Land. A striking feature of these extensive areas of ignorance is that they correspond with the most extensive and continuous areas of available seabird breeding habitat in coastal East Antarctica (Figure 5, top barcode for habitat area). All species except the southern giant petrel are known to breed in most half-degree sectors where search effort is most intense (Figure 5). However, a lack of known breeding populations in these most intensely searched sectors could still be due to incomplete search effort because these sectors were estimated to have search efforts of 66–100% rather than just 100%.

The strong difference in search effort between Adélie penguins and all other species is also evident at the micro-scale of individual sites (Figure 6: Mac.Robertson Land coastline around Mawson station; Appendix S7: coastlines around all stations). Visual inspection of these finer spatial resolution maps also reveals a further difference between above-surface nesting colonial species (Antarctic petrel, Cape petrel and southern fulmar) and sub-surface nesting species (snow petrel and Wilson's storm petrel) such that ignorance of sub-surface nesting species is more spatially widespread and records of absence are fewer. Our maps show a strong clustering of presence-absence observations for all species close to stations, with sub-surface nesting species showing the most constrained clustering and Adélie penguins the least constrained clustering. Logistic regression analyses confirmed that search effort decreases with distance from research stations for most (21 of 24) combinations of species and search effort certainty (Figure 7, Appendix S8). The three exceptions from this general finding were for lower certainty search effort for south polar skuas, snow petrels and Wilson's storm petrels.

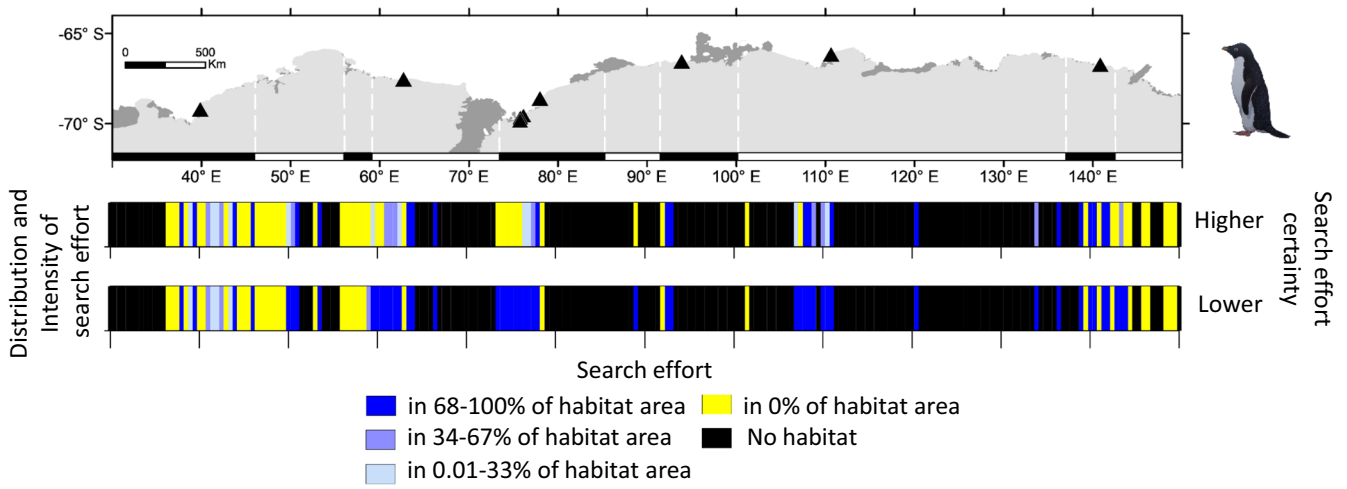

FIGURE 4 | Distribution and intensity of search effort across coastal East Antarctica in relation to the certainty of search effort for the Adélie penguin from observations over the last century, summarised as 'barcode' maps with half-degree longitudinal sections. The map of the East Antarctic coastline (Equidistant Cylindrical projection) shows the location of permanently occupied research stations as black triangles. Black and white bars at the bottom of the map and white vertical dashed lines are the locations of named coastal geographical sectors in Figure 1. The barcode maps show the distribution and intensity of search effort for two categories of decreasing search effort certainty. Barcode maps for all eight species and three levels of search effort certainty are in Appendix S6 in the Supporting Information.

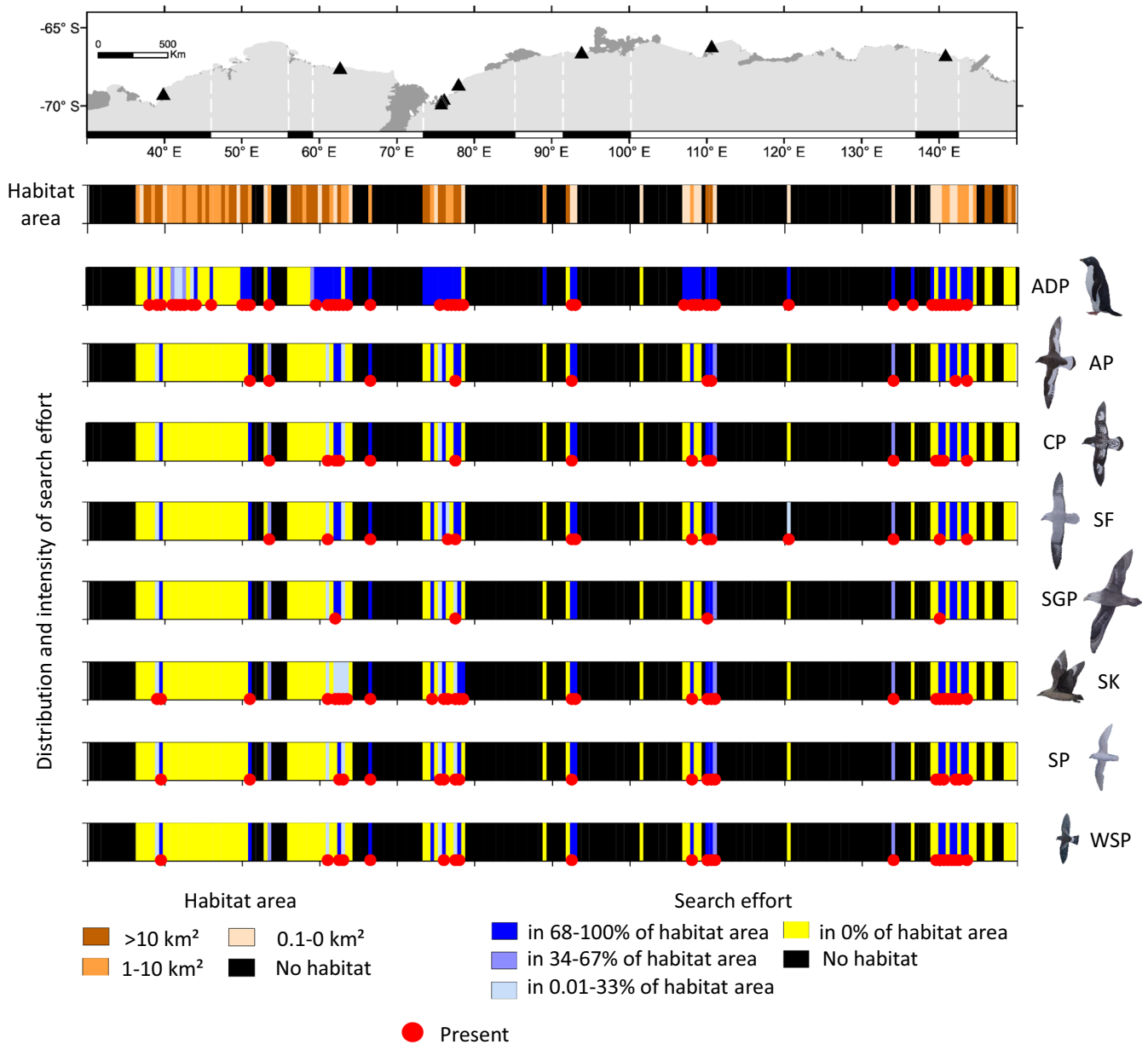

FIGURE 5 | Distribution and intensity of search effort and known breeding distribution from observations over the last century for eight Antarctic land-breeding seabird species across coastal East Antarctica, summarised as 'barcode' maps with half-degree longitudinal sections. The top barcode map shows the distribution of coastal habitat area. The lower eight barcode maps show the distribution of search effort and known presence of breeding populations for each species. Search effort is based on the most optimistic interpretation of absence (i.e., includes all absences from higher to lower certainty). Species abbreviations are ADP: Adélie penguin; AP: Antarctic petrel; CP: Cape petrel; SF: Southern fulmar; SGP: Southern giant petrel; SK: South polar skua; SP: Snow petrel; WSP: Wilson's storm petrel.

3.6 | Occupancy Monitoring

Of the 89 Adélie penguin breeding sites known in 1980/81, all were searched in at least one of the subsequent four decades to 2020/21, and 72% were searched in at least three of the four decades (Figure 8). Southern giant petrel breeding sites were monitored with similar intensity, with all six breeding sites known in 1980/81 searched in at least two subsequent decades and four sites searched in at least three decades. Monitoring intensity for the presence of all other species was lower, with 47% of the known breeding sites of other species combined searched in at least one subsequent decade and 18% searched in more than one decade. In contrast, but with the exception of the Adélie penguin, very few sites (1%) deemed as having an absence of seabird breeding populations up to 1980/81 were searched in the subsequent four decades. For the Adélie penguin, all sites deemed as not having breeding penguins (i.e., absent) in 1980/81 have been searched in one of the subsequent four decades (Figure 8).

4 | Discussion

In this study, we employ a spatial and inferential framework to compile, standardise and unify observations of Antarctic breeding seabirds made over the last century and investigate

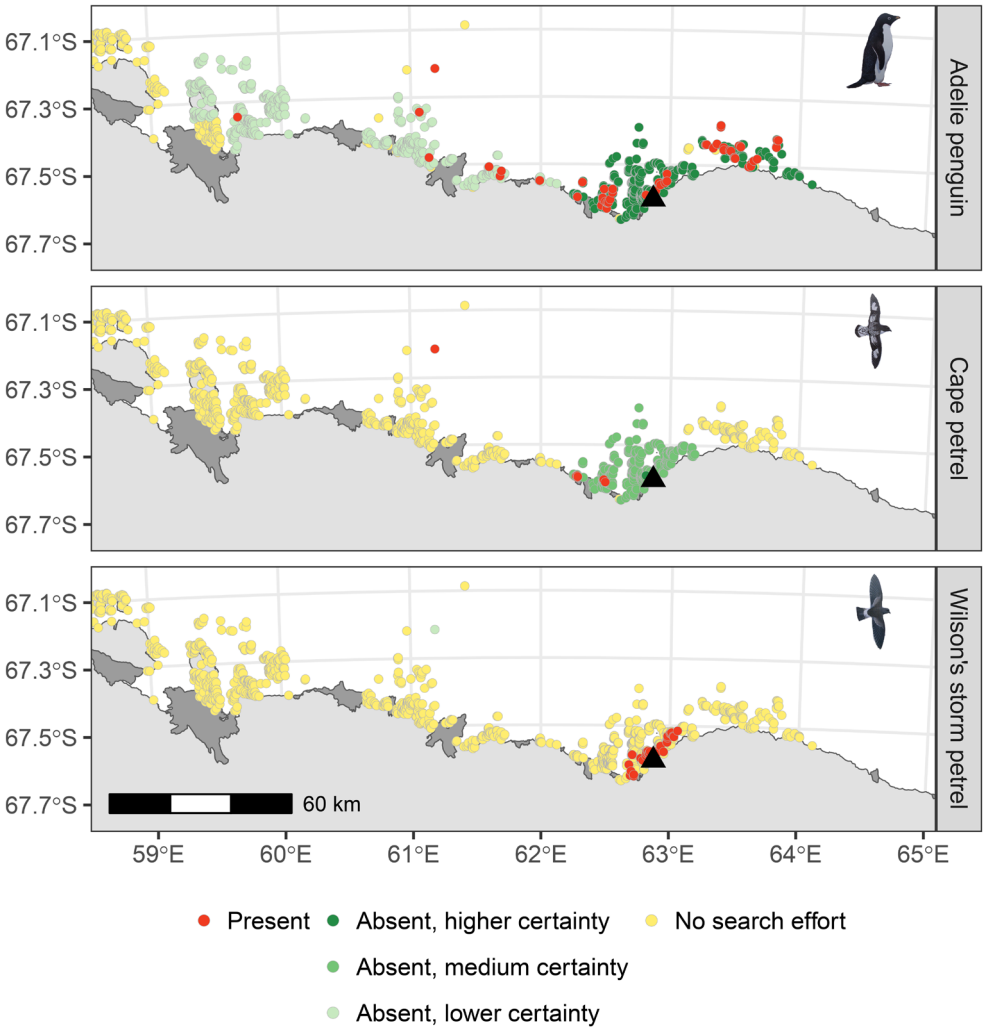

FIGURE 6 | Maps (Lambert azimuthal equal-area projection) of known presence, inferred absence and ignorance at the spatial resolution of islands of available breeding habitat along the coast in the Mac.Roberston Land sub-region for each of three land-breeding seabird species in East Antarctica. The three species cover the full range of inherent detectabilities. The black triangle is the location of Mawson research station, light grey shading is continental ice, dark grey shading is ice shelf, and white shading is ocean. Maps for all eight species and six sub-regions around occupied research stations are in Appendix S7 of Supporting Information with additional explanatory information.

questions of pattern, bias and certainty in seabird breeding occupancy data. A particular advance from this study was to use the framework to address the difficult issue of absence attribution and its certainty, and to infer ignorance and absence. The big picture that emerged from this process is that although seabird occupancy is better known than other Antarctic taxa (Wauchope et al. 2019), there are strong spatial, temporal and taxonomic biases in knowledge and large spatial areas of ignorance that have implications for both pure biogeographic studies and applied environmental management, conservation and monitoring activities.

This compilation brought together data collected under independently operating national research programmes, over several generations of researchers, and under evolving logistic capabilities and research priorities of the times. The emergent insights and limitations reflect these multiple and changing priorities, but the overriding key constraint to observations has been and remains the difficulty of accessing sites of available seabird breeding habitat across this vast and remote region. It is not surprising then that observations are clustered close to permanently occupied research stations, most of which are located on the coast. Because certain environmental features may have been preferred when establishing stations (Riddle and Goldsworthy 2002), seabird observations may also have an inherent environmental bias related to the location of stations. A secondary access-related constraint is that different national research programmes vary in their logistic capabilities, and that these too have changed over time. Recent development in satellite technology may offer new logistic options for surveys, and already such technology has facilitated a spatial and temporal expansion of observation for some environmental features and the most detectable seabird species (emperor and Adélie penguins: Fretwell and Trathan 2009; Lynch et al. 2012). However, a priority for future work is to determine the limits and limitations of satellite-based observations for these and other less detectable species.

In addition to a spatial bias in search effort toward research stations, there are also taxonomic biases in search effort and

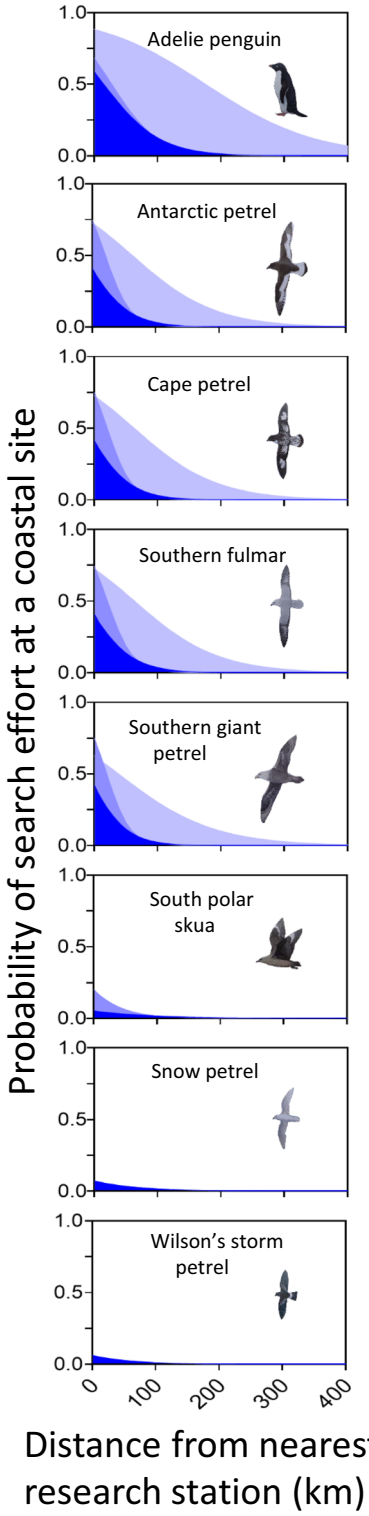

FIGURE 7 | Predicted probability of available breeding sites of land-breeding seabird species having been searched in relation to distance from research stations over the last century of observations in coastal East Antarctica. Predictions were derived using logistic regression on search effort data for each of the eight species. Darker blue shading indicates higher levels of search effort certainty (more cautious).

differing intensities at which species' occupancy has been monitored across East Antarctica. Adélie penguins have long been considered emblematic of Antarctica and a sentinel species reflecting the impacts of fisheries and climate change in the marine environment (Trivelpiece et al. 1990; Ainley 2002). A greater focus on search effort and occupancy monitoring for this species than for other species across much of East Antarctica reflects this sentinel status. In contrast, the relatively high monitoring intensity of southern giant petrel occupancy is probably related to the small number of known breeding populations and the species' conservation status of 'Near Threatened' before 2009 (BirdLife International 2009). The relatively poor knowledge of occupancy for other species, especially the Wilson's storm petrel, is likely due to their lower detectability and tendency to occupy less accessible locations.

In contrast to many occupancy and biodiversity databases that focus only on presence data, a centrepiece of our study was to infer absence and its certainty in addition to presence, and to distinguish inferred absence from ignorance. This involved developing a framework of absence-inference decision rules and scrutinising data sources to find supporting evidence for inferring absence and its certainty. Given the challenge of accurately and consistently interpreting diverse data sources produced over multiple decades and researchers, we consulted with the data experts (original data collectors) wherever possible to minimise errors in translation and discover data that would have otherwise be known only to the expert (unknown knowns; Hortal et al. 2015). One important outcome from this focus on absence certainty is the ability to better assess risk when considering occupancy in environmental management decisions. Our study contributes to the mitigation and management of human impacts on Antarctic seabirds in several ways.

Aviation is increasingly being used to support both national scientific research programs and tourism operations in Antarctica. However, aviation can disturb Antarctic wildlife if not managed carefully, and breeding seabirds are particularly vulnerable to such disturbance during the austral summer at the peak of human activities (Rounsevell and Binns 1991). Consequently, guidelines on recommended separation distances between aircraft and wildlife or recommended flight paths have been developed and adopted by the Antarctic Treaty Consultative Parties (ATCPs 2004; Australian Antarctic Division 2020). Specifying flight paths is most effective with accurate knowledge of the spatial distribution of seabird breeding sites in areas where aviation operations occur. Based on this work, we can now produce refined and comprehensive maps of known seabird breeding sites and highlight sites where we have no or uncertain knowledge to develop minimally disturbing flight paths for aviation operations. Mapping where we have no knowledge or are least certain of absence in a spatial sense is important from a disturbance risk perspective, because without this information, breeding populations could be mistakenly assumed to be absent when they are actually present, leading to an increased chance of inadvertent disturbance.

As consumers of marine prey such as krill and fish, Antarctic seabirds can be impacted by fishery operations in the Southern Ocean. The management framework adopted by CCAMLR for the krill fishery incorporates information on the distribution and abundance of krill and krill predators to minimise the risk of fisheries operations by spatially and temporally distributing catch limits (Kelly et al. 2018; Warwick-Evans et al. 2022). Under

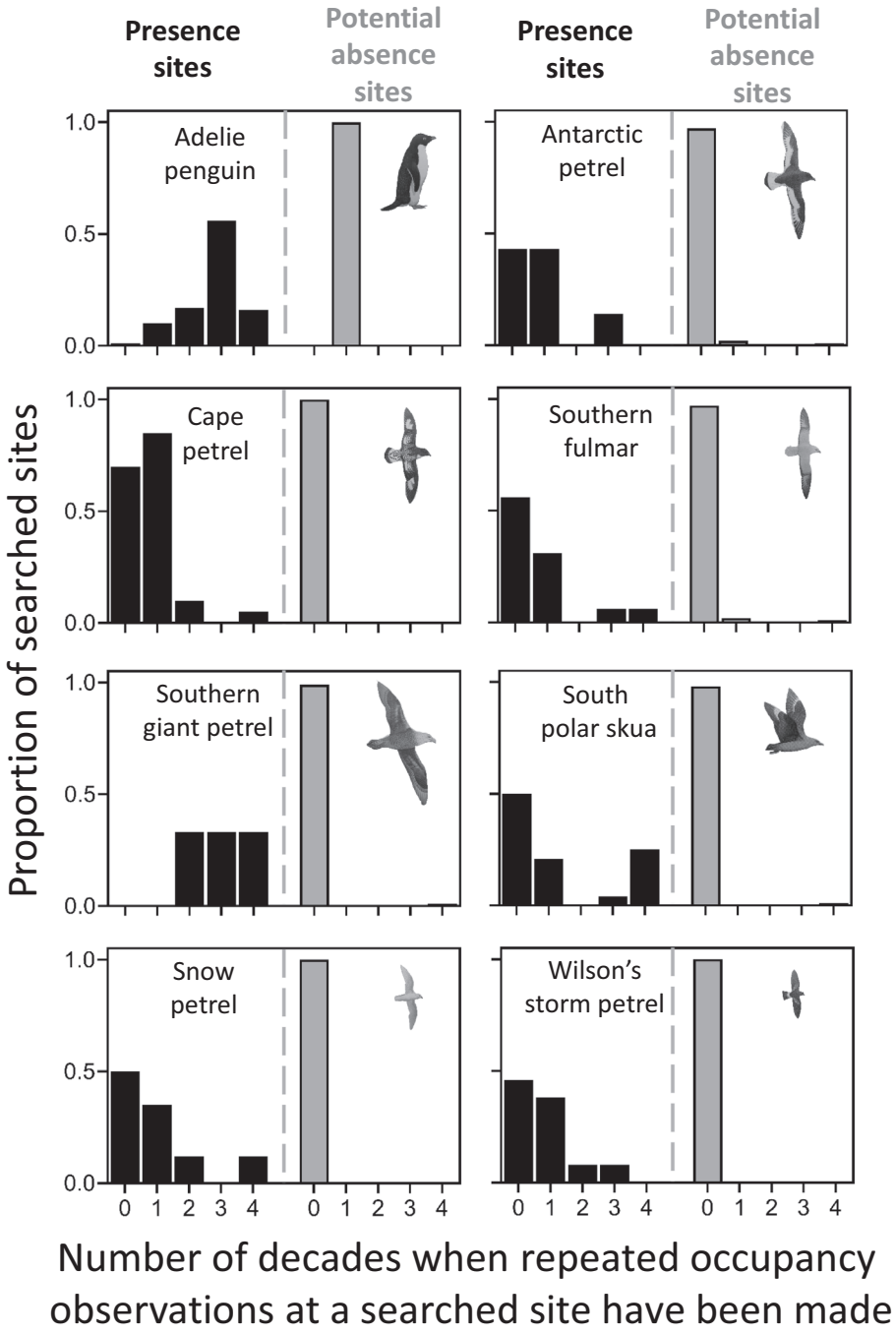

FIGURE 8 | Frequency of presence-absence monitoring for land-breeding seabirds over the last four decades from 1981/82 to 2020/21 at sites searched before 1981/82 in coastal East Antarctica. Frequencies are shown separately for sites where breeding populations were present and absent before 1981/82.

the Convention, CCAMLR is required to use the best available scientific evidence to develop catch limits. We show that information on seabird breeding occupancy along the coast of East Antarctica is currently incomplete due to either no search effort or low certainty of absence. Hence, existing population counts at known breeding sites are likely to underestimate the total populations in the CCAMLR Management Areas. By identifying the extent, magnitude, location and certainty of gaps in knowledge of seabird breeding populations, this information could be used to scale up abundance estimates derived from counts of known but incompletely characterised breeding populations, or focus new surveys where count data are missing or least certain, to better represent seabird populations in the krill risk management framework.

Finally, with species distributions and populations changing globally in response to a changing climate (Lenoir et al. 2020), a comprehensive baseline of occupancy data is urgently needed for comparison with future observations. Our study indicates that current knowledge provides an incomplete baseline of seabird occupancy in East Antarctica, and that the spatial and temporal coverage of observations in recent decades would not be sufficient

to confidently detect future changes in breeding occupancy for most seabird species at most sites. The study species generally show strong fidelity to their breeding sites, and comparison of recent occupancy observations of three species (Adélie penguin, Cape petrel and south polar skua) with observations made at the same sites over the last 4–5 decades indicates that only minor changes in occupancy of small populations have occurred in that time (Southwell and Emmerson 2013; Kliska et al. 2022; Golubev and Golubev 2024, respectively). However, detecting colonisations at currently unoccupied sites as a species distribution expands or changes will be particularly difficult. By revealing the gaps in knowledge that exist, this work provides a foundation to plan how to expeditiously and strategically improve both the current state of knowledge and future monitoring.

4.1 | Future Work

While an important issue in our study and for occupancy studies in general is the attribution of absence and its certainty, further development of this issue would be worthwhile. Remote regions such as Antarctica are usually data-poor, forcing knowledge to often be based on data collected over multiple decades. A useful general extension to our approach of attributing certainty to absence data, especially if the data are to be used for current conservation management actions, could be to incorporate the concept of data recency or 'freshness' (Tessarolo et al. 2017; Murray et al. 2021) by also weighting certainty according to how recent data are. Alternately, our compilation and results could be used to strategically identify sites where more frequent and certain observations of breeding occupancy are required to inform future conservation management decisions. The application of new observational platforms such as satellites offers the prospect of expanding the spatial scope of future occupancy observations but has specific detection biases and uncertainties that will need to be considered. We urge that future occupancy monitoring explicitly report the location and date of search effort and absence in addition to presence to reduce uncertainty in identifying local colonisations and extinctions when species distributions change.

Author Contributions

C.S. and L.E. contributed to conceptual development, literature search and data compilation. J.A., C.B., J.C., R.D., K.D., J.G., K.G., M.H., H.H., P.H., C.L.H., A.K., N.K., A.L., G.M., I.N., F.O., A.P., G.R., M.S., A.T., J.F., S.W., B.W. and E.J.W. provided expert validation of data. C.S., L.E., N.K. and D.M. contributed to analysis and interpretation. C.S. led manuscript writing and all authors reviewed and edited the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting this study are available from the Australian Antarctic Data Centre at Southwell and Emmerson (2025).

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ddi.70066.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix S1:** Summary of species characteristics of relevance to the study. **Appendix S2:** Continental spatial reference and identification system. **Appendix S3:** Source material used to assess presence, absence and ignorance of eight land-breeding seabird species at sites of available breeding habitat in East Antarctica. **Appendix S4:** Assigning certainty levels for absence from characterisations of species and survey-related detectabilities. **Appendix S5:** Distribution of known species richness at breeding sites. **Appendix S6:** Distribution and intensity of search effort across coastal East Antarctica in relation to search effort certainty, summarised as 'barcode' maps at the spatial resolution of half-degree longitudinal sections, for eight land-breeding seabird species. **Appendix S7:** Maps of known presence, inferred absence and ignorance at the spatial resolution of geographic sites along the coastlines around research stations for each of eight land-breeding seabird species in East Antarctica. **Appendix S8:** Model fitting results for logistic generalized linear models of search effort in relation to distance from the nearest research station. **Appendix S9:** Further acknowledgements.