Incomplete search effort: a potential source of bias in estimates of Adélie penguin breeding populations in the Australian Antarctic Territory

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ABSTRACT. Potential Adélie penguin *Pygoscelis adeliae* breeding habitat in the Australian Antarctic Territory (AAT: 45°E–136°E, 142°E–160°E) was mapped using a geographic information system (GIS), and the literature reviewed for evidence of the mapped habitat being searched for presence or absence of breeding Adélie penguins. It is concluded that incomplete search effort is a possible source of substantial negative bias of Adélie penguin breeding abundance derived from published count data in some regions of the AAT. The extent of search effort in other regions of Antarctica could be determined using the same approach applied here, because GIS data required for mapping potential habitat are available for the entire continent. We would expect that regions with more scientific and tourist activity, such as the Antarctic Peninsula, are likely to have greater search effort than the AAT.

Contents

Introduction 375
Methods 375
Results and discussion 377
Acknowledgements 379
References 379

Introduction

Much attention is currently being focussed on the development of ecosystem models as tools to predict and manage the impacts of human induced perturbations on Southern Ocean ecosystems. These models require estimates of numerous input parameters for major taxonomic or functional groups (Hill and others 2007). In order for the models to be used wisely, it is necessary to understand any likely biases and uncertainties in estimates of these input parameters.

One of the most fundamental input parameters for these ecosystem models is broad scale population or species abundance. For penguins, an important group of predators in the Southern Ocean, broad scale estimation of abundance is in principle possible from counts of penguins breeding on land (using, for example, direct counts or aerial photography) or foraging at sea. In practice however, estimation efforts have to date used on land count data to estimate breeding populations. Extending estimation to the total population then requires use of demographic data.

Undertaking truly broad scale, synoptic surveys of penguin breeding populations in Antarctica is extremely difficult due to the logistic and practical constraints on survey efforts imposed by remoteness, weather and cost. These constraints have understandably restricted most survey efforts to relatively small areas. Consequently, at present deriving estimates of abundance at bioregional- and circumpolar scales from existing on land count data can only be achieved by bringing together the results from numerous separately planned and implemented survey efforts (for example the compendia of Croxall and Kirkwood 1979; Wilson 1983; Horne 1983; Woehler 1993; Woehler and Croxall 1997). Because these survey efforts have been undertaken in the absence an overarching framework, there has been no planning or design mechanism to ensure that all or most of the occupied breeding habitat in a region has been searched. Consequently, broad scale estimates derived from these compendia may be negatively biased to some degree as a result of incomplete search effort, and hence should be considered as minimum estimates (Woehler 1993; Barbraud and others 1999).

For the purposes of modelling the Southern Ocean ecosystem, it is important to understand the magnitude of any potential bias in penguin population estimates. Until recently, the lack of technologies such as high resolution satellite imagery and geographic information systems (GIS) for mapping habitats over broad scales has limited our ability to quantify potential bias due to incomplete search effort. Here this issue is addressed by firstly quantifying the distribution and extent of potential Adélie penguin *Pygoscelis adeliae* breeding habitat in the Australian Antarctic Territory (AAT: 45°E–136°E, 142°E–160°E, which covers 27% of the Antarctic coastline) using recently compiled digital maps of the coastline and exposed rock across the AAT, and secondly by quantifying the published search effort for Adélie penguin breeding sites within that potential habitat, to determine the extent to which incomplete search effort is a potential source of bias for AAT wide abundance estimates derived from published count data.

Methods

Mapping potential breeding habitat and quantifying the area of potential breeding habitat

At a coarse spatial scale, Adélie penguins are known to breed around Antarctica on ice free islands and outcrops of

ice free continental land close to the ocean (Ainley 2002). At a finer resolution, characteristics of suitable breeding habitat include factors such as slope, drainage, snow accumulation, availability of stones for building nests, and presence of pack ice in winter and spring (Ainley 2002; Bricher and others 2008). Calculating the area of actual breeding habitat for a species requires knowledge of important fine scale habitat characteristics and maps showing the distribution of those characteristics across the entire region of interest. For regions as large and remote as those considered here however, such maps generally exist for only the very coarse scale features.

Recognising this constraint, the authors developed a coarse scale, qualitative model for potential Adélie penguin breeding habitat based on a small number of physical features captured within existing GIS data covering the AAT. Potential breeding habitat was broadly defined as ice free land (either islands or outcrops of continental rock) of minimum size (very small sites were assumed to be unsuitable because they would not provide adequate protection from weather, swell or higher predators such as leopard seals) and within a specified distance of the ocean (proximity to the ocean would minimise the effort required in accessing foraging grounds). Two sets of size and distance criteria were applied in order to explore the sensitivity of results. Values for the least conservative criteria (4000 m^2 area and 500 m distance) were taken as the minimum observed area of all known occupied sites and the maximum distance from the ocean of mapped penguin colonies in three regions of the AAT (Holme Bay, Vestfold Hills and Windmill Islands). Under these criteria, we expected that potential breeding habitat was likely to include the great majority of actual breeding habitat within the longitudinal range of interest. More conservative values (1000 m^2 area and 1000 m distance) were arbitrarily selected as very likely to include all actual breeding habitat.

Physical data (coastline and polygons representing islands and continental exposed rock) for mapping potential breeding habitat in the AAT were assembled within a GIS. Coastline and island polygons were sourced from the AAT Coastline 2003 dataset produced by Geoscience Australia and the Australian Antarctic Division. Exposed rock polygons were sourced from the Antarctic Digital Database version 4.0 produced for the Scientific Committee on Antarctic Research. Any parts of rock polygons extending beyond the coastline from the AAT Coastline 2003 dataset were erased, avoiding any overlap with island polygons.

The GIS was firstly used to identify all islands within 100 km of the continental coastline and outcrops of continental rock adjoining the ocean, regardless of their size. The digital data were insufficient to determine whether islands were completely ice covered or had areas of ice free land. We therefore conservatively considered all islands as having ice free land and therefore potential breeding habitat, except for the three largest islands (Drygalski (65°46'S, 92°27'E), White (66°45'S, 48°32'E) and Dixson (68°7'S, 146°58'E)), for which satellite imagery was available (RAMP AMM-1 SAR Image Mosaic of Antarctica, National Snow and Ice Data Center, 2002) and clearly showed these islands to be ice covered. Two buffers anchored along the interface of the island/rock polygons and the ocean, and extending 500 m and 1000 m inland, were then created. New polygons were derived from the intersection of the buffer polygons and the island/rock polygons, and the area of these polygons was measured. An Albers map projection was used for the buffer creation and intersection and the area calculations. Polygons with minimum areas (either >4000 m^2 or >1000 m^2) were taken to represent sites of potential breeding habitat (hereafter referred to as 'sites') under the two criteria. The polygons were each given a unique identification number and maps covering approximately 5–70 km of coastline were produced for comparison where necessary with published maps.

Quantifying search effort

Publications containing count data or population estimates for Adélie penguins in the AAT (Table 1) were examined to find evidence of any particular site having been searched. The specificity of evidence for search effort in the literature varied, and in response to this evidence was classified as direct or indirect. Direct evidence included cases where counts (either positive indicating presence, or zero indicating absence) of breeding Adélie penguins were reported for specifically named and/or mapped sites, and cases in which an explicit statement was made that all areas within certain boundaries on an accompanying map had been searched. Indirect evidence arose in cases where a map encompassing multiple sites was provided and sites on the map with non zero counts were specifically named, but no sites with zero counts were reported and no explicit statement was made that all sites on the map had been searched. In these cases it was considered that there was direct evidence for search effort at the reported sites, and indirect evidence for search effort in all the unreported sites within the specified boundaries. In cases in which a number of sites in a region with positive counts had been reported but there was neither an accompanying map nor a statement about the extent or completeness of the search effort, the authors considered that there was direct evidence of search effort for the reported sites and no evidence for search effort for any unreported, nearby sites.

A database was established with two tables, one table containing information on sites, and a second table containing information on search effort. The site table had a record for each site, with each record having the identification number, the area of the polygon, and the latitude and longitude of the centre of the polygon. The search table had a record describing each search event for an individual site, with each record having the identification number for the site, the year of the search, and whether the evidence for searching was classified as direct or indirect. The database was then interrogated to summarise direct and indirect evidence for search effort

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Table 1. References used to determine search effort in the Australian Antarctic Territory.

Reference	Region
Kato and Ichikawa (1999), Takahashi and others (2000)	Amundsen Bay, Enderby Land
Bassett and others (1990)	Mt Biscoe, Enderby Land
Ditrich (1979)	Vechernyaya Mountain, Enderby Land
Cooper (1985)	Between Cape Batterbee and the Aargaard Islands, Enderby Land
Robertson (1991)	Kidson Island, Mac.Robertson Land
Woehler and others (1989a)	Mawson and Rookery Islands, Mac.Robertson Land
Low and others (2007)	Robinson Islands, Mac.Robertson Land
Alonso and others (1987)	Scullin and Murray Monoliths, Mac.Robertson Land
Woehler and others (1989b), Whitehead and Johnstone (1990)	Northern Vestfold Hills to the Publications Ice Shelf, Princess Elizabeth Land
Korotkevich (1964)* , Pryor (1964, 1968), Kamenev (1971), Stark (1980)	Haswell Islands, Wilhelm II Land
Melick and others (1993)	Davis Islands, Wilkes Land
Orton (1963), Murray and Luders (1990), Woehler and others (1991)	Windmill Islands, Wilkes Land
Law (1958, 1962)	Lewis, Hudson, Henry and Chick Islands, Wilkes Land
Barbraud and others (1999)	Cape Hunter, Cape Pigeon Rocks and Garnet Point, George V Land
Ensor and Bassett (1987)	Between Commonwealth Bay and Buchanan Bay, George V Land
Horne (1983)	Various sites in the Australian Antarctic Territory

* Horne (1983) and Woehler (1993) cite Korotkevich (1964) as indicating presence of, and therefore search effort for, Adélie penguins at Gaussberg in Wilhelm II Land. However, the only reference to Adélie penguin counts in the text of Korotkevich (1964) is for Haswell Island near Mirnyy Station, and in our reading of Fig. 1 there is no indication of Adélie penguins occurring at Gaussberg. The authors therefore concluded there was no evidence for search effort at Gaussberg.

within 1° longitude sectors across the AAT in relation to the number of sites searched, and the areas of sites searched.

Results and discussion

A total of 4392 island and continental rock polygons was identified along the AAT coastline using the GIS, of which 2492 were >4000 m^2 in area and 3198 were >1000 m^2 in area. The total area of polygons >4000 m^2 in area and within 500 m of the ocean was 637 km^2, and the total area of polygons >1000 m^2 in area and within 1000 m of the ocean was 897 km^2. This potential habitat is distributed discontinuously along the coastline due to the presence of several large ice shelves (Fig. 1). Based on the results of this study, there is substantially more potential habitat in the western half of the AAT than in the eastern half (Fig. 1).

Using the least conservative habitat criteria, we found evidence (direct or indirect) of search effort for 1577 of the 2492 (63%) polygons and for 44% of the total polygon area. When only direct evidence was considered, these percentages were reduced to 53% and 41% for number and area of polygons respectively. Search effort was very similar under the more conservative habitat criteria (66% of polygons and 42% of area using direct or indirect evidence; 54% of polygons and 39% of area using only direct evidence). Fig. 1 indicates that major gaps in search effort occur along the Enderby, Kemp, George V and Oates Land coastlines, and not surprisingly, those areas with lowest search effort are the farthest from stations. Woehler (1993) identified information gaps for most of these areas in an earlier review, and the fact that these gaps have not been addressed in the intervening time no doubt reflects their remoteness and inaccessibility.

This brief analysis shows that the published search effort of potential Adélie penguin breeding habitat in the AAT is substantially incomplete in terms of both the number and area of sites. It does not necessarily follow that the search effort of occupied habitat, nor abundance estimates derived from the published search effort, are negatively biased to the same degree because there may have been search effort that has not been documented or published because only absences were found, or because our very simple model of potential habitat may include large areas that are actually unsuitable for breeding. Nevertheless, the analysis does show that the potential for negative bias from incomplete searching in the AAT is substantial and clearly indicates gaps that might form priority foci for future survey work. The extent of search effort in other regions of Antarctica could be determined using the same approach applied here, because Antarctic Digital Database coastline and exposed rock data are available for the entire continent. We would expect that regions with more scientific and tourist activity, such as the Antarctic Peninsula, are likely to have greater search effort than in the AAT.

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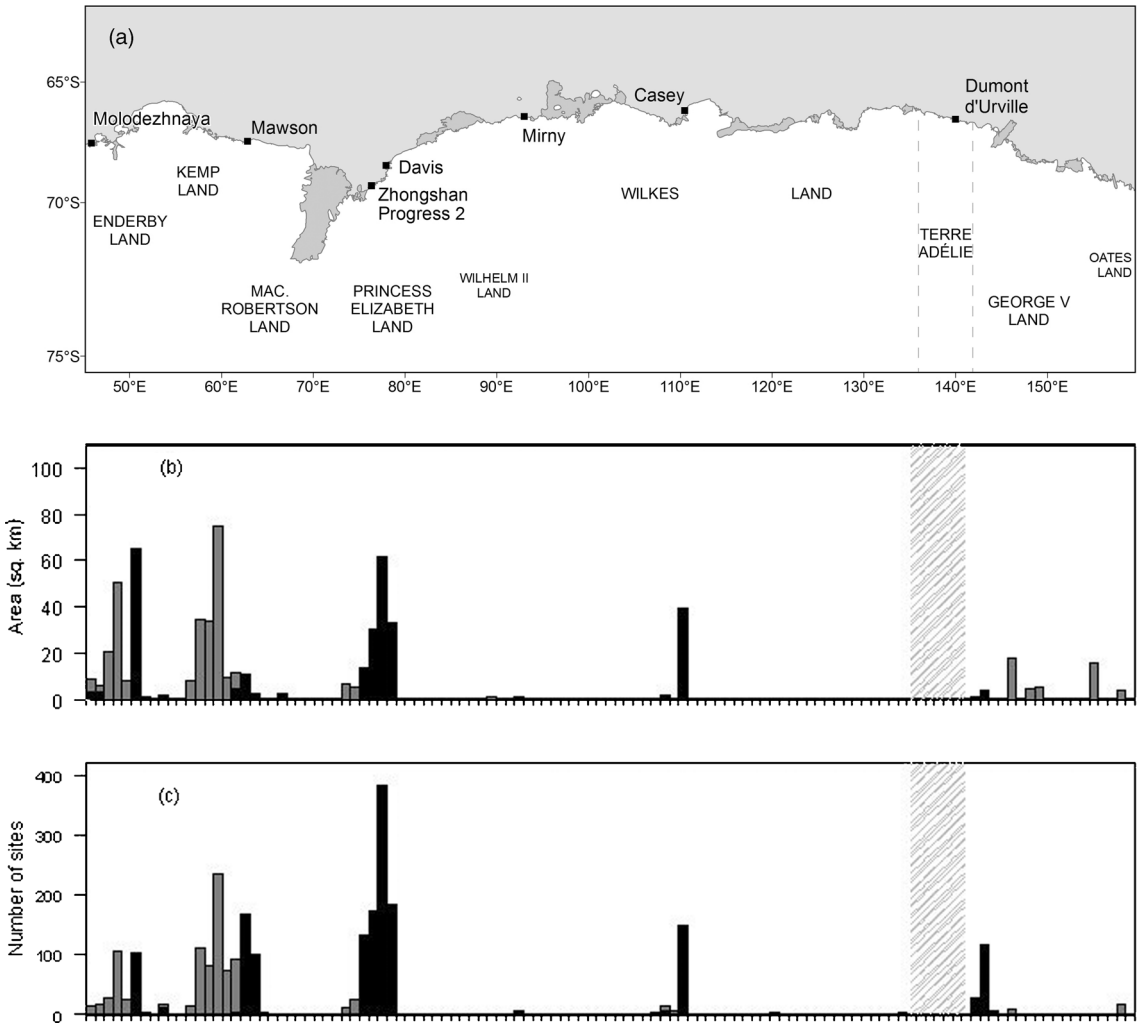

Fig. 1. The distribution of potential Adélie penguin breeding habitat, defined using least conservative criteria (ice-free land >4000 m^2 in area and <500 m from the coast), and evidence of search effort within 1° longitude sectors along the coast of (a) the AAT by (b) area and (c) number of sites. Black bars indicate potential habitat with direct or indirect evidence of search effort; grey bars indicate potential habitat with no evidence of search effort. Also shown are the locations of stations (note that Molodezhnaya has not been occupied since 1989). The sections of (b) and (c) that are cross-hatched in grey are not within the AAT.

One possible approach to accounting for bias in abundance estimates due to incomplete search effort is to extrapolate the measured density of penguins in known sites to unsearched sites. The authors caution against this approach however, for at least two reasons. The first of these is because density in searched sites may not be representative of density at all sites because, for example, sites with high density are more likely to be reported than sites with low density, and the second is that variability in density at searched sites is likely to be large, and this would lead to large uncertainty in estimates of abundance for all sites.

Satellite technology may be the only cost effective means of undertaking a synoptic survey of Adélie penguin breeding locations over the broad scale considered in this study. Past evaluations of the utility of satellite imagery for detecting Adèlie penguin breeding colonies (Bhikharidas and others 1992; Bhikharidas and Peterson 1993; Schwaller and others 1984, 1986, 1989) have demonstrated the great potential of this technology, but also caution, or allude to the need for further evaluation, in regard to problems such as inadequate differentiation of guano from some types of surrounding bedrock, variability in spectral response of guano due to environmental features such as slope and aspect, and mismatch in the spatial resolution of satellite imagery and penguin colonies. While developments in satellite technology since the time of these studies should have addressed the latter problem, further evaluation in relation to the former two issues may be needed before satellite imagery can be confidently used for detecting penguin breeding sites at broad scales.

The authors have not quantified here the issue of incomplete search effort within sites. For example, Ensor and Bassett (1987), in their yacht based survey of islands in the George V Land region, report that many sites with

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Adélie penguins present were incompletely (approximately 50%) searched. We found little acknowledgement of incomplete search effort within sites in the literature, so at face value it would appear to be only a minor additional source of potential negative bias, but it is possible that incomplete search effort at this level could be under reported to some extent. Indeed, Barbraud and others (1999) considered that most surveys previous to theirs along the Terre Adélie and George V Land coastlines, including the survey by Ensor and Bassett (1987), would have probably largely under estimated population sizes.

In reviewing the literature it was found that the evidence available to distinguish a lack of search effort from true absence was sometimes indirect or ambiguous. In many early published accounts describing search effort exactly or even approximately was limited by the availability of navigational equipment and detailed maps of the Antarctic coastline. Given recent technological advances in these areas, researchers are encouraged to include succinct but direct and unambiguous statements or information on search effort and true absences in future reports of penguin count data. While absence or zero count data do not contribute to one off estimates of abundance nor may appear to be inherently interesting, they are as important as presence data for understanding the factors determining distribution (for example Brotons and others 2004) and may be important in documenting or estimating future changes in distribution and abundance (Yoccoz and others 2001).

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