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Using the unique spectral signature of guano to identify unknown seabird colonies

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ABSTRACT

Despite the threats faced by seabirds in both terrestrial and marine habitats, even basic knowledge of the locations of colonies, population sizes and trends is lacking for many remote areas of the world. Recent studies have shown that the guano of Adélie penguins can be identified from Landsat Enhanced Thematic Mapper (ETM) imagery and used to map colonies on coasts around continental Antarctica. Our study highlights a new technique based on the unique spectral signature of guano that can be used to discriminate seabird colonies from background geology and vegetation in a wider range of natural environments, including the vegetated and zoologically-diverse region of the Antarctic Peninsula; moreover, the method was effective for all densely colonial, surface-nesting seabirds. Using Landsat ETM imagery, we correctly identified all known seabird colonies of over 50 pairs in the area of Marguerite Bay. Almost all other areas with a similar spectral signature that were outside known breeding areas were single pixels that were readily distinguishable from genuine colonies. If these were excluded, only 4.1% of pixels appeared to represent unknown breeding or roosting sites, and warrant further investigation. The spatial extent of the guano provided a general guide to the number of individuals present, but further work would be required to determine the accuracy of this method for estimating population size. Spectral profiles of guano collected by satellite and hand-held spectrometers were compared with available data in spectral libraries and did not match with any known geological profile. There may also be potential for discriminating colonies of different species that differ in phenology and show seasonal changes in diet by the carefully-timed acquisition of suitable satellite imagery. We conclude that the remotely-sensed guano signature is a good indicator of the location of seabird breeding or roosting sites, with potentially wide application to other areas of the world.

1. Introduction

According to the Red List index compiled by the World Conservation Union (IUCN), the conservation status of seabirds has deteriorated more rapidly than any other species group since 1988, with 28% of species currently listed as Threatened, of which 5% are considered to be Critically Endangered (Croxall et al., 2012). Well-documented threats include competition and bycatch in commercial fisheries, pollution, and predation and habitat destruction by invasive species at breeding sites (Croxall et al., 2012; Lewison et al., 2012). Impacts of global climate change are increasing, including the problem of rising sea levels and greater frequency of storm events causing inundation of breeding colonies on low-lying islands (IPCC 2007), and changes in oceanography that will have knock-on effects on prey distribution and abundance (Baker, Littnan, & Johnston, 2006; Barbraud et al., 2012). Despite the need for an improved understanding of demography and ecology in order to manage and mitigate these processes, in more remote areas of the world even basic knowledge of breeding site locations, population sizes and trends of many seabird species is sparse (Brooke, 2001). This includes Antarctica where projected changes in sea ice extent and duration are predicted to have major impacts on food webs (Ainley et al., 2010; Barbraud et al., 2011), potentially exacerbated by an increase in fisheries for Antarctic krill *Euphausia superba*, which is a key prey for many seabirds, including penguins and petrels (Watters, Hill, Hinke, Matthews, & Reid, 2013). One example of the paucity of knowledge of Antarctic seabirds is the Antarctic petrel *Thalassoica antarctica*, a bird that forages in the Southern Ocean on crustaceans (including krill), fish and squid, and breeds on remote nunataks, mountain ranges and the steep slopes of coastal Antarctic islands (Arnould & Whitehead, 1991; Lorentsen, Klages, & Rov, 1998). Ship-based estimates of abundance suggest a global population of 10 to 20 million birds, perhaps representing 4–7 million breeding birds and an at least equal number of non-breeders and immatures (Brooke, 2004). However the breeding locations of only around 500,000 pairs (i.e. 1 million breeders) are known (van Franeker, Gavrilo, Mehlum, Veit, & Woehler, 1999), probably under a quarter of the estimated total.

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Recent analysis has shown the utility of satellite remote-sensing for studying seabirds in inaccessible regions. The identification of emperor penguin *Aptenodytes forsteri* breeding sites using freely-available, medium-resolution imagery has demonstrated our ability to search very extensive areas to locate colonies (Fretwell & Trathan, 2009; Schwaller, Southwell, & Emmerson, 2013). Once these sites are known, higher-resolution satellite platforms or aerial photography can be used to estimate the population size of particular species, e.g., emperor, Adélie *Pygoscelis adeliae* and chinstrap penguins *Pygoscelis antarcticus* using Very High Resolution (VHR) satellites (Fretwell et al., 2012; LaRue et al., 2014; Naveen, Lynch, Forrest, Mueller, & Polito, 2012), masked boobies *Sula dactylatra* in satellite imagery from Google Earth (Hughes, Martin, & Reynolds, 2011), and lesser flamingos *Phoeniconaias minor* using aerial photography (Groom, Petersen, Anderson, & Fox, 2011). The most appropriate methodology depends on a number of factors, including breeding habitat. Emperor penguins breed on sea ice, which makes their colonies relatively easy to find; in medium resolution imagery, the guano is clearly identifiable in the visible wavelengths as a reddish brown stain against the homogeneous white background of the sea ice. Nothing else on the sea ice has this chromatic signal and therefore emperor penguin colonies can be identified visually in manual searches, or by automated analysis (Fretwell & Trathan, 2009).

The emperor penguin is the only seabird that breeds on sea ice, and so the identification of breeding or nonbreeding aggregations of other species on rocky substrates in the Antarctic requires a different approach. Early work on the spectral signature of guano of Adélie penguins showed that colonies in the Ross Sea region could be differentiated using bivariate plots from surrounding snow and certain rock types (basalt and tuffs) in medium resolution Landsat Thematic Mapper (TM) imagery (Schwaller, Benninghoff, & Olson, 1984; Schwaller, Olson, Zhenqui, Zhiliang, & Dahmer, 1989). An improved approach using Landsat Enhanced Thematic Mapper (ETM) was used subsequently to assess the breeding distribution of Adélie penguins around the entire Antarctic coastline with the exception of the Antarctic Peninsula region (Schwaller et al., 2013). The analysis involved algorithms that distinguished Adélie penguin guano from bare rock and snow. Using ground-truthing from East Antarctica, this successfully determined the location of Adélie penguins with errors of commission in the order of 1% or less, and errors of omission of around 3–4% (by population). One of the problems noted in that study was the positive bias towards classifying colonies of other seabird species as Adélie penguin. This was one of the factors that deterred the authors from applying the method to the Antarctic Peninsula region, where the ornithological landscape is more diverse than East or West Antarctica. Other reasons were that all the ground truthing was carried out in East Antarctica; colonies of Adélie penguins around the Peninsula tend to be smaller and often include other penguin species; the climatic regime differs, and; the peninsula region is more vegetated than the more southerly coasts of West and East Antarctica.

Our aim was to develop a remote-sensing methodology using easily accessible "off the shelf" image processing software and methods that could be used to map seabird colonies in environments that are more complex and diverse than those in East and West Antarctica. We were particularly interested in finding an approach that could be used to detect colonies of flying seabirds, in which nests are often more dispersed than those of penguins, and which could reliably differentiate guano from vegetation. Our expectation was that an approach that worked in the Antarctic Peninsula region might be transferable to temperate or tropical environments where remoteness or lack of resources similarly limits knowledge of the breeding distributions and abundance of seabirds.

2. Methodology

2.1. Acquiring test spectra

To compare the spectral profiles, we measured the reflectance factors of frozen and thawed Adélie penguin guano samples, collected from Cone Island on the Antarctic Peninsula, under laboratory conditions using an ASD FS3 full wavelength (400 nm to 2500 nm) spectroradiometer. Two frozen pieces of guano were chosen for sampling. Each was measured multiple times; five measurements were taken from different aspects of the guano piece following rotation each time by c. 40°, and this procedure was repeated five times to give an average profile. The frozen guano was then left at room temperature and the procedure was repeated with the thawed sample. These data were subsequently converted to a Landsat-equivalent profile of 6 spectral bands using the satellite optical sensor band filter functions available from the Natural Environment Research Council Field Spectroscopy Facility (NERC FSF) website (http://fsf.nerc.ac.uk/user_group/user_group.shtml >) and processed using the FSF Matlab Toolbox, available from the same source. We compared the raw and Landsat-equivalent profiles to published geological spectral libraries from USGS (Clark et al., 2007), and almost 2000 unpublished archival spectra profiles of Antarctic (mostly rock samples but with some Antarctic vegetation samples) held locally at British Antarctic Survey mostly collected around the test site, and samples from other regions collected by the British Geological survey. The technique for collecting field samples is described in the published literature (Haselwimmer & Fretwell, 2009). Profiles were compared using the ENVI routine Spectral Analyst, which uses Binary Encoding, Spectral Angler Mapper and Spectral Feature Fitting to rank the match of a sample spectrum to an existing spectral library.

2.2. Landsat analysis

A single Landsat scene (ID 220108000105050) of Marguerite Bay (68°30′W, 68°30′S) at the Antarctic Peninsula was used in our initial analysis. Landsat data consist of a number of bands that cover the electromagnetic spectrum from visible wavelengths to thermal infra-red (Landsat 7 Science Data Users Handbook). We used bands 1–5 and band 7 which comprise data between 450 and 2350 nm. The advantages of using Landsat images are that they are freely available, each image covers a large footprint (typical scene width of ~180 km), and there is a comprehensive archive of Landsat TM and Enhanced Thematic Mapper (ETM) images from 1984 and 1993, respectively, to the present that cover all continental land masses. This large archive ensures that there is an available cloud-free scene of most locations at the time of year when the extent of the guano in bird colonies is likely to be high (see Section 4 Discussion).

There is information available on the location and size of Adélie penguin colonies in the area of Marguerite Bay (Harris, Carr, Lorenz, & Jones, 2011, British Antarctic Survey unpublished data). In addition, this area is close to the British Antarctic Survey (BAS) research station at Rothera Point, and the BAS archives hold records of counts of Antarctic shags *Phalacrocorax bransfieldensis,* snow petrels *Pagodroma nivea nivea,* southern giant petrels *Macronectes giganteus,* skuas (south polar skua *Stercorarius maccormicki* and brown skua *Stercorarius antarcticus)* and southern fulmar *Fulmarus glacialoides* (Fig. 1 and Tables 1 and S1). As well as information on bird colonies, the geology of the area is better mapped than many parts of Antarctica (Riley, Flowerdew, & Haselwimmer, 2011).

The Landsat image was changed from raw digital numbers (DN) to reflectance using ERDAS Imagine software. No aerosol model was used as the Antarctic atmosphere is considered cold and clean with minimum aerosol levels (Bindschadler et al., 2008). A number of classification methods were tested for the ability to discriminate areas of guano. Of these, Spectral Angle Mapper in ENVI image processing software (Exelis Visual Information Solutions) provided the best results. Spectral Angle Mapper uses the shape of the spectral profile from a number of training pixels that are manually identified by the user. We used a training sample of 44 and 88 pixels of guano from Adélie penguin colonies at Cone Island (69°09′25″W, 67°40′38″S) and Lagotellier Island (67°22′52″W, 67°53′22″S). Spectral Angle Mapper (SAM target finder with BANDMAX in ENVI software) was then applied to produce a "similarity

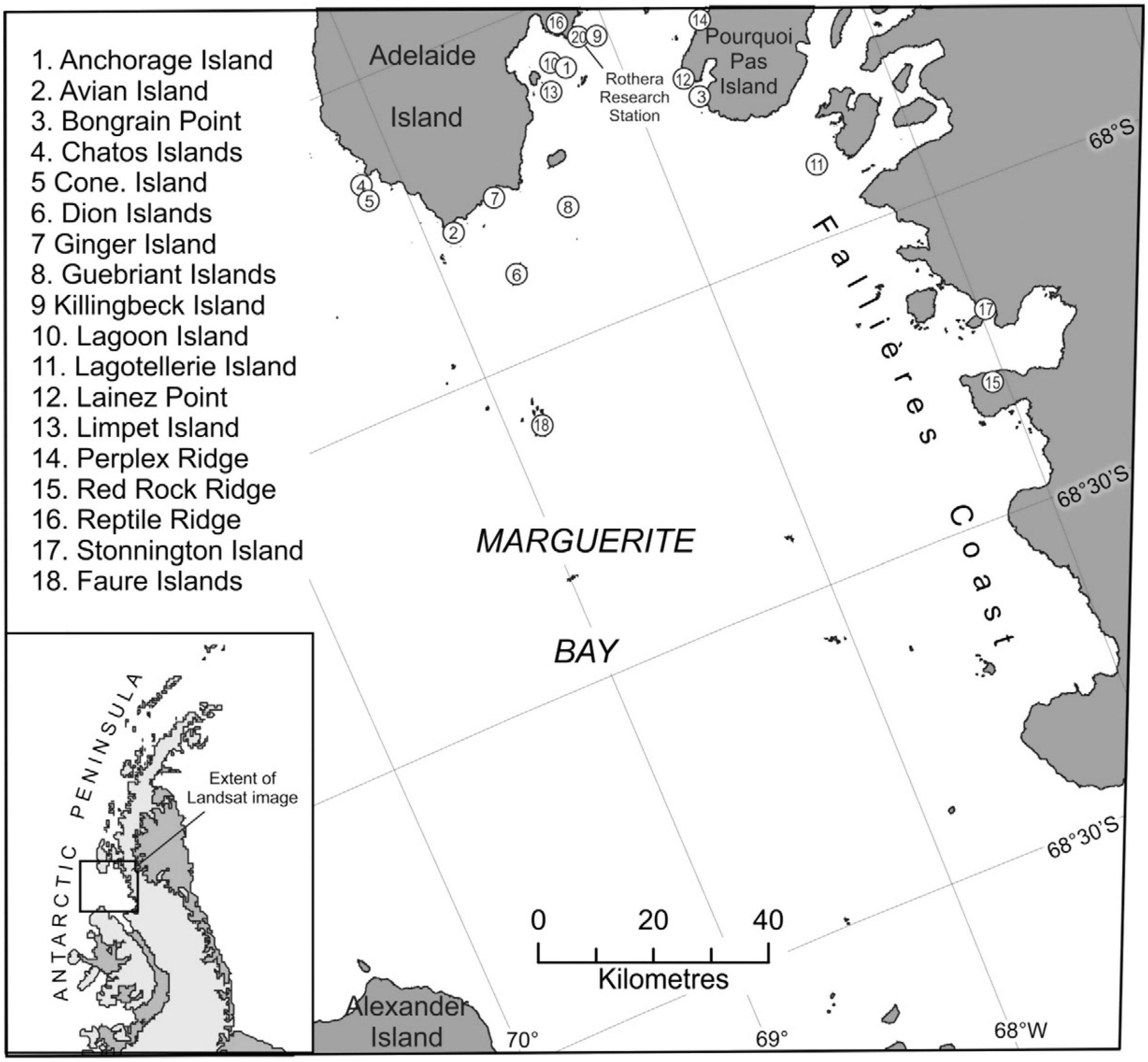


Fig. 1. Known seabird colonies in Marguerite Bay within the coverage of Landsat path 220 row 108 date 19/02/2001. Colony sizes are given in Table 1.

Table 1
Population sizes (number of pairs) in known seabird colonies in the Marguerite Bay area compiled from various sources (see references in main text). + = present, ++ = abundant. Further details are supplied in Supplementary Table S1 (the abbreviation PQP refers to Pourquoi Pas Island).

	Skuas	Dominican gull	Ant. shag	Snow petrel	Adelie penguin	Sthn. fulmar	Sthn. giant petrel
Anchorage	100 s						
Avian Island	200	60	670		77,515		250
Bongrain Pt, PQP					700		
Chatos					100		
Cone Island			55		2790		
Dion Islands	22	2	500		700		
Ginger Island			275		3000		
Guebriant	35		Colony				
Killingbeck		3	30				
Lagoon Island	200		58				
Lagotellerie Island			++		1700		
Lainez Point, PQP							76
Limpet Island	8						
Mikkelsen Island	Present						
Perplex Ridge, PQP						Many 1000s	
Red Rock Ridge					12,400		
Reptile Ridge				200			
Rothera Point	18–25	40					
Stonington Island	+		135				

ratio", which is the ratio of the nearness of the spectral profile of each individual pixel in the Landsat image to these sample pixels. The SAM algorithm requires the user to set a maximum angle which the programme applies to the spectra of each pixel to match the profile in n-dimensional space. The software then rejects pixels which do not conform to the required angle. Using trial and error, the best results for our image were using an angle of 0.05%. The resulting output contained some noise in the marine areas of the image. An initial marine mask was applied, based on the threshold of the near-infra-red (band 4) image of the corresponding Landsat scene, and the coastline from the best available digital data (SCAR ADD 6). (http://http://www.add.scar.org/) As the coastline is often poorly mapped in this area, we applied a buffer of 1 km to ensure that all land pixels were included. The resulting grid can be viewed as a ratio of the similarities of each pixel to the training dataset, and could be further refined to give the best results. Therefore two further analyses were performed. The first eliminated the least similar third of the resulting pixels (analysis 1); the second did likewise, but also eliminated single pixels (analysis 2).

2.3. Vegetation discrimination

One of the possible confounding factors that may limit the ability of satellite imagery to discriminate guano on the Antarctic Peninsula is the presence of vegetation (Schwaller et al., 2013). We used the atmospherically corrected Landsat imagery to test whether the results from the SAM analysis were sensitive to the presence of vegetation. Landsat imagery has been used to detect vegetation on the Antarctic Peninsula by NDVI analysis (Fretwell, Convey, Fleming, Peat, & Hughes, 2011) and we used this methodology to identify vegetation in the test area. We then calculated the number of rock polygons from the Antarctic Digital Database that had vegetation and compared this to the number of polygons that contained guano. The earlier vegetation work classified the NDVI results into three types; probably vegetation, very probably vegetation, and almost certain vegetation, depending upon the NDVI value of each pixel. We assessed the spatial correlation of guano pixels derived from the SAM analysis against these three classes.

Table 2
Estimates of the total number of birds from ground surveys in comparison with guano area estimates from the two Spectral Angler Mapper analyses. Analysis 1 includes single pixels, analysis 2 does not. The Faure Island colony was discovered in this study.

Location	Ground counts (estimated total breeding pairs, all species)	Analysis 1 (m^2)	Analysis 2 (m^2)
Anchorage	100	1800	1800
Avian Island	78,445	130,500	108,000
Bongrain Pt, PQP	700	9900	2700
Chatos	100	900	0
Cone Island	2845	21,600	10,800
Dion Islands	1224	14,400	5400
Ginger Island	3275	2700	2700
Guebriant	35	6300	1800
Killingbeck	30	0	0
Lagoon Island	258	4500	3600
Lagotellerie Island	1700	14,400	10,800
Lainez Point, PQP	80	1800	0
Limpet Island	8	900	0
Perplex Ridge, PQP	4000	28,800	3600
Red Rock Ridge	1200	3600	1800
Rothera Point	64	0	0
Reptile Ridge	200	5400	2700
Stonington Island	135	0	0
Faure Islands	Unknown	22,500	3600
Area of known colonies (m^2)		270,000	159,300
Area of a returns from the analysis		362,700	162,900
% of area accounted for by known colonies		74.4	98.1

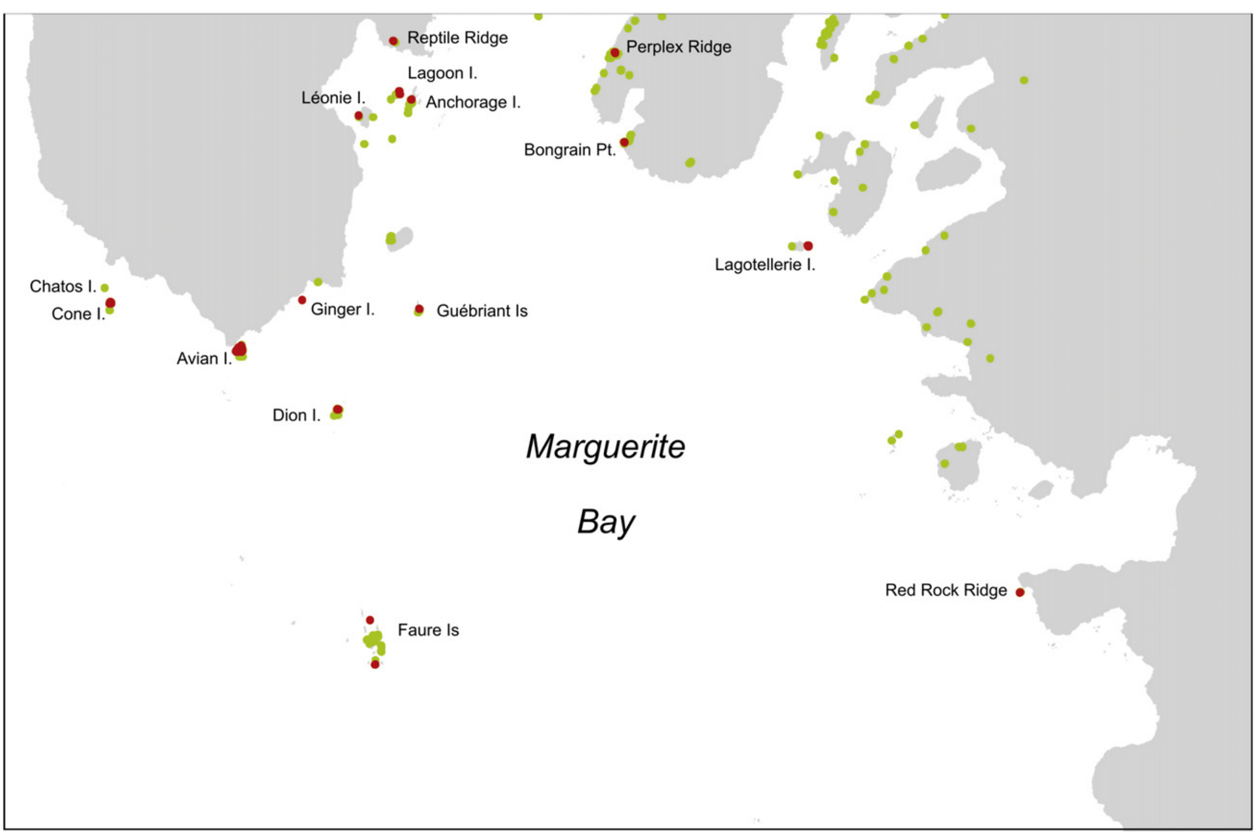


Fig. 2. Results of the Spectral Angle Mapper analysis. Green pixels — results from analysis 1 which included single pixels. Red dots — results from analysis 2 where only multiple pixels were returned.

3. Results

3.1. Comparison of spectral results with archival data

From the original ~42 million pixels (on-the-ground resolution of 30 × 30 m) contained within the Landsat scene, the SAM analysis identified 309 pixels in analysis 1, and 177 pixels in analysis 2 that matched the training data from the Adélie penguin colony at Cone Island. Of these pixels, 74.4% and 98.1%, respectively, were at, or near, known seabird colonies (Fig. 2 and Table 2). Analysis 1, which included single pixels, highlighted almost all known bird colonies with the exception of the three small colonies (<150 birds) at Killingbeck Island and Stonington Island. However, 91 pixels (29.5%), particularly single pixels, were in areas where there are no known bird colonies. It is unknown what proportion of these pixels represent small colonies of breeding birds, or roosting sites. As the majority of the single pixels had a low similarity ratio, it seems likely that most are false positives rather than genuine colony locations. It is important to note that several of the smaller colonies with <100 known breeding pairs were clearly identified in the analyses. Analysis 2, which excluded single pixels, identified 177 pixels that matched the training data; around half the number of analysis 1. This successfully identified all eight known seabird colonies that held >100 pairs in the area of the image, in addition to two locations where the number of birds was either unknown (Faure Islands) or small (Guébriant Island). It is questionable, however, if the pixels on Anchorage and Lagoon islands reflect the location of guano associated with penguin colonies. On Anchorage Island, in the Leonie Island group, there were 18 pixels identified in analysis 1 and four in analysis 2. As these pixels are dispersed and there are no breeding colonies of penguins, they would appear to reflect areas of guano associated with the several hundred skuas that nest on the islands. Although skuas breed at low density, substantial numbers of birds (presumably nonbreeders and failed breeders) congregate around ponds and other sites, some associated with seal wallows on the island (P. Geissler pers. coms.). Three of the four single pixels from analysis 2 on these islands are in such areas where skuas are known to congregate.

3.2. Examination of outliers

Analysis 2 returned only 8 pixels (4.5%) outside known colony locations. These pixels were in four separate groups located in three different areas; Léonie Island, the Faure Islands, and an un-named ridge

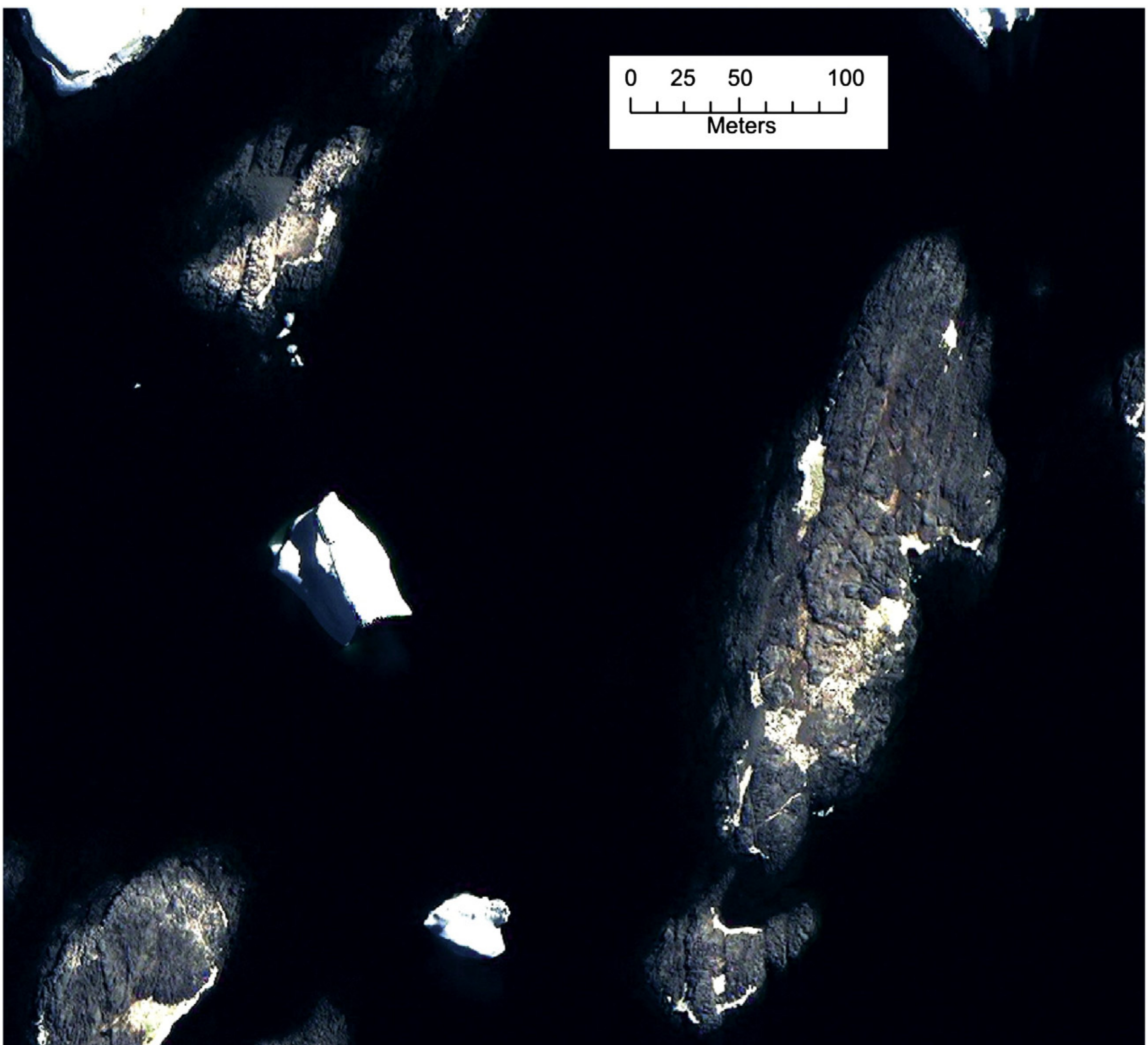


Fig. 3. Quickbird VHR imagery from the 31st of January 2010 of three islands in the Faure archipelago. Pink areas indicate guano stains. Our analysis highlighted that this island group potentially holds major seabird colonies.

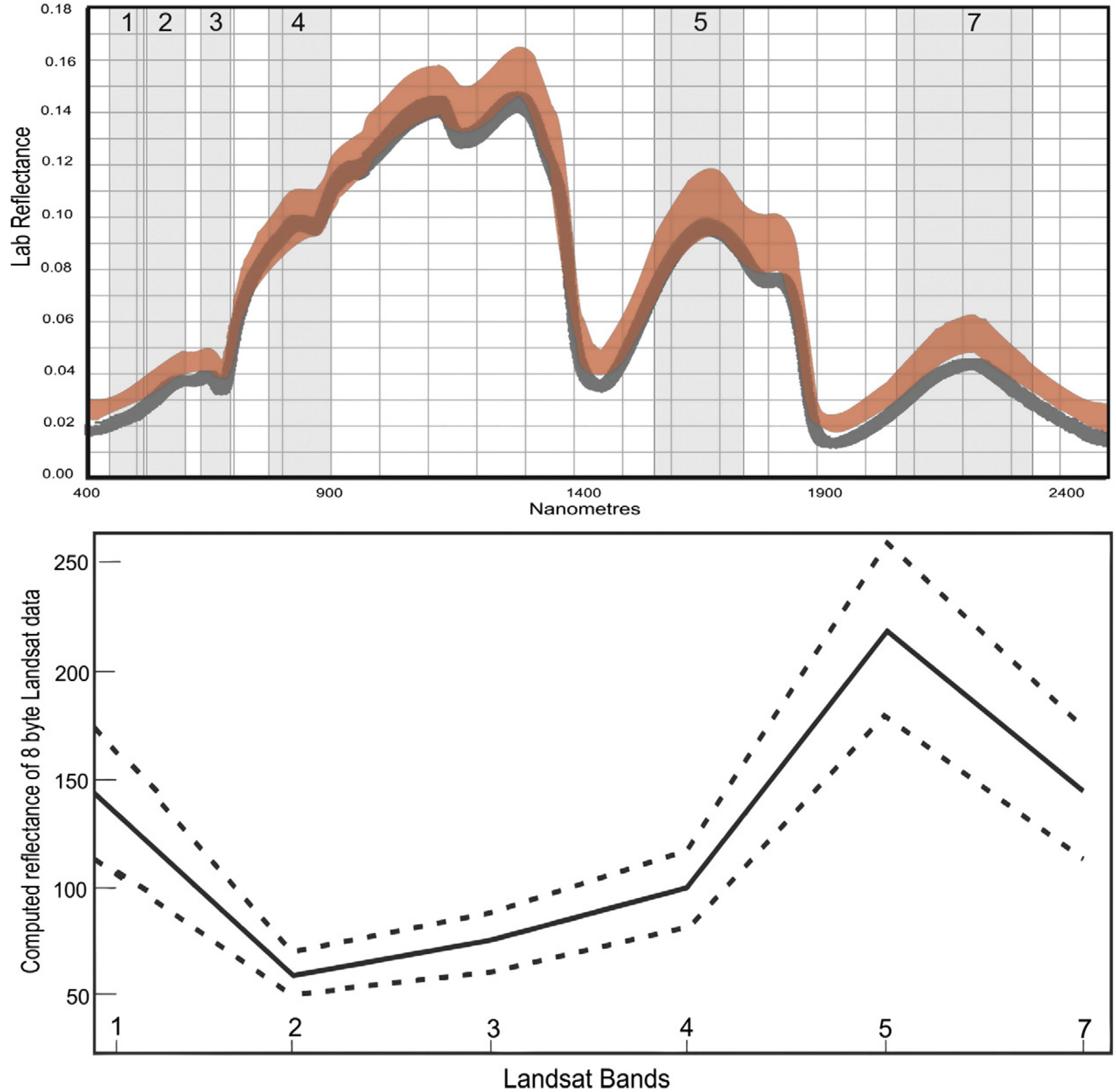
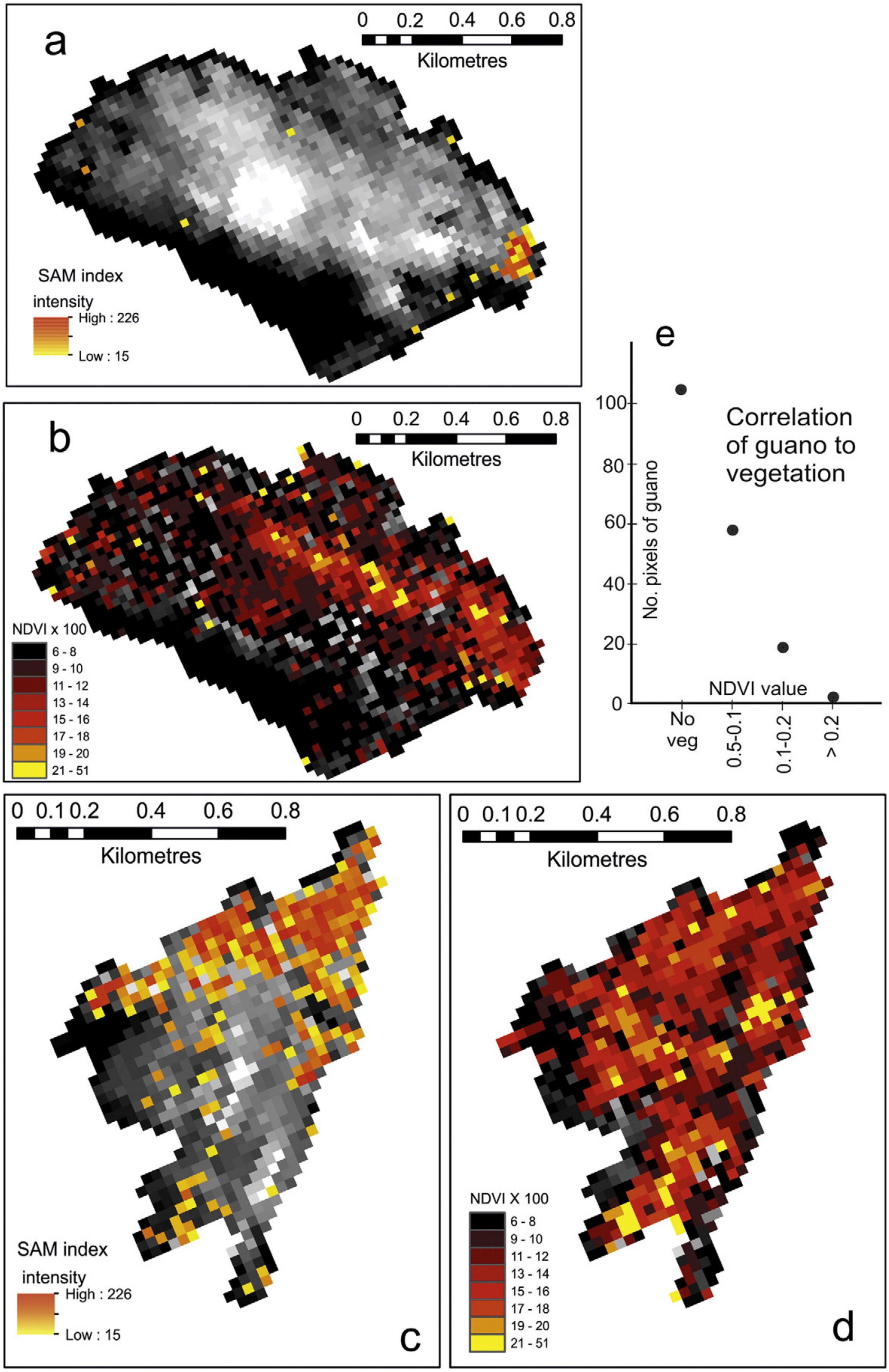


Fig. 4. Above: Laboratory derived spectral profile of Adélie penguin guano. The two lines – pink and grey – denote the two sample pieces. Variation indicated by the line width denotes the range of the 20 scans from various angles of each piece. The light grey vertical lines denote the Landsat band widths for reference. Below: Spectral profile of guano from the training sample at Cone Island convolved to Landsat bandwidths. Black line denotes mean value of 44 pixels across the 6 Landsat bands; dashed lines indicate +/− 1 SD.

south of McMorrin Glacier. On the Faure Islands, analysis 1 returned 25 pixels and analysis 2 returned 4 pixels. With this in mind, a small QuickBird VHR satellite image of the area was obtained from the 31st of January 2010 (QuickBird2 catalogue number 101001000B06C800). This imagery has a resolution of 2.4 m in the multispectral bands and 0.64 m in the panchromatic. Fig. 3 shows an example of part of this image. A faint pink colouration can be identified on three of the islands, which is suggestive of guano. To determine whether this reflected the presence of seabirds, a survey flight was undertaken in early December 2012 (during the incubation period of Adélie penguins). Although there was no sign of any breeding birds in the archipelago on that date, reports from scientists who frequently visit the area suggest that this is a major roosting site for Adélie penguins in winter (Bill Fraser pers. coms.). Including the Faure Islands, the percentage of pixels in our analysis that are explained by known colonies or roosting sites are 76.7 and 98.1% in analysis 1 and 2 respectively. Overall, a linear regression relating the area of guano identified from the satellite image to the number of breeding pairs of seabirds has an r^2 value of 0.9505 if all colonies are included, and 0.5899 without an obvious influential outlier, which was the single large colony on Avian Island. This lower r^2 value may be due partly to the differing nesting densities of each species.

3.3. Comparison with spectral libraries

We tested the spectral profile of the guano pixels used as a training sample (from Cone Island and Lagotellerie) against the profiles of guano sampled in the lab and published spectral libraries (Fig. 4). These profiles show that guano has a high reflectance in band 5 in relation to the other bands, in contrast with most types of geology, vegetation or other substrates. Initial comparison with other profiles in spectral libraries suggests that although a number of geologies have high reflectance in band 5 (e.g. hydrothermally altered clays such as illite and kaolinite), no other known profile of the several thousand spectra from different types of geology and vegetation matched the spectral signature of guano.


a
0 0.2 0.4 0.6 0.8
Kilometres
SAM index
intensity
High : 226
Low : 15
b
0 0.2 0.4 0.6 0.8
Kilometres
NDVI x 100
6 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 51
e
Correlation of guano to vegetation
No. pixels of guano
100
80
60
40
20
0
NDVI value
No veg
0.5-0.1
0.1-0.2
> 0.2
c
0 0.1 0.2 0.4 0.6 0.8
Kilometres
SAM index
intensity
High : 226
Low : 15
d
0 0.1 0.2 0.4 0.6 0.8
Kilometres
NDVI X 100
6 - 8
9 - 10
11 - 12
13 - 14
15 - 16
17 - 18
19 - 20
21 - 51

3.4. Differentiating from vegetation

The identification of pixels from the SAM was independent of the presence of vegetation. The test area contained 169 rock polygons with vegetation from the NDVI analysis, whereas only 35 rock polygons contained guano. All rocky areas that had guano also had vegetation. Of the 177 pixels returned as guano in analysis 2, 57% did not correspond directly with vegetation polygons. Of those that did, 84.8% (36.2% of all guano) were in the lowest vegetation class, with NDVI values of between 0.05 and 0.10, 12.6% pixels (5.4% of all guano) were in the second class, termed "very probably vegetated" with NDVI between 0.10 and 0.20, and only 2.6% (1.1% of all guano) were in the "almost certain vegetation" class, with an NDVI >0.2. Fig. 5 shows examples of the correlation from two of the larger penguin colonies in the area: Fig. 5a shows guano results from the SAM analysis of Lagotellerie Island. The intensity represents spectral match to the guano training data given by the SAM analysis and can be seen as an indication of the amount of guano. Fig. 5b shows the corresponding NDVI results that indicate the presence of vegetation. Fig. 5c and b represents the corresponding analysis of guano and vegetation on Avian Island. In line with the overall results on both islands, the majority of guano pixels tend to be in areas of low or possible vegetation, and not in the areas of highest vegetation.

4. Discussion

4.1. Overview of results

Our results show a close match between the location of known seabird breeding colonies or, in a few cases, probable roosting aggregations, and the pixels highlighted by the SAM analysis. In the more restricted analysis with a higher threshold for inclusion, all colonies with >150 breeding pairs were identified; only a few of the smaller colonies were omitted, and there were very few errors of commission (false positives). The two colonies that were not identified in our analysis were both of Antarctic shags. This species feed predominantly on fish rather than krill and it may be that the different diet affects the spectral profile of the guano. Further work is needed to clarify whether bird with a predominantly fish diet such as Antarctic shags has guano with spectra as unique as those ones used in this study. It is also probable that surface-nesting birds that breed at low densities (e.g. terns), and burrow- or crevice-nesting species (e.g. petrels) are less suited to this type of analysis.

Less than 2% of the identified pixels were unaccounted for by known seabird colonies or roosting sites. This suggests that the spectral signature of guano from our training sample is distinct from both the vegetation and geological substrates in the same areas. The less restricted test (analysis 1) highlighted many single pixels on low unglaciated islands; there is some evidence, especially on the Leonie Island group, that this may reflect the presence of skuas where they congregate in higher densities. However, the availability of ground truthing data even in this relatively well visited region of Antarctica is insufficient to verify if that is indeed the case.

The SAM analysis does not confuse guano with vegetation which, on the whole, is much more widely distributed. This is presumably because although most seabirds are found in, or around, vegetated areas, and several studies show that aerosol and runoff from seabird colonies can fertilize nearby vegetation (Myrcha & Tatur, 1991; Xie, Sun, Wang, & Liu, 2002), extensive areas of vegetation do not persist within dense colonies of nesting seabirds. Our test area in Marguerite Bay has a limited range of geological types, mostly of plutonic or volcanic origin (Riley et al., 2011), which do not reflect the complexity of geology on the Antarctic Peninsula. However, tests of the spectral profile of guano obtained in the laboratory against almost 3000 reference spectra from spectral libraries suggest that its signature is indeed unique and that guano can be discriminated from any type of background geology. The SAM algorithm is a widely-used analytical technique tailored to extract a single end-member from an image. It is not sensitive to albedo and less sensitive to changes in lighting, absolute illumination (sun angle/slope/detector off-nadir angle) or shading than many similar algorithms (Dennison, Halligan, & Roberts, 2004). It is therefore ideal for many areas of the Antarctic where digital elevation models needed to calculate absolute reflectance are inadequate. Also, unlike supervised classifications which require the input of many end-member signatures from of all surfaces in the image, the SAM analysis restricts itself to search for a single end-member, and the number of training pixels used need to reflect just this single surface type. This reduces the user input required to choose pixels, making this both a pragmatic and effective methodology.

4.2. Assessing population sizes

There was a significant correlation between the total breeding population size of all species of seabird at each site, and the area of guano indicated by the spectral analysis, although the correlation was much weaker without the statistical outlier of Avian Island. In analysis 1, the area comparison had an r^2 value of 0.951 when Avian Island was included and of 0.589 without Avian Island. In analysis 2, the respective r^2 values were 0.988 and 0.366. Three of these four regressions were significant at $p < 0.05$, and the other was borderline (0.058). Nevertheless, we would caution against using these relationships to predict the size of unknown seabird breeding colonies for various reasons. The resolution of the Landsat sensor is relatively coarse. In addition, most of the data on colony sizes in the study area were collected in surveys conducted in the 1950s to 1980s, many were rough estimates, and numbers have changed, often substantially, at the few sites that have been revisited; at Avian Island, for example, counts of Adélie penguins range from c. 36,000 pairs to 77,000 pairs (data from 1979 to 2002; ASPA management plan of Avian Island). New colonies may have become established at some sites, and some of the population estimates were from outside the breeding season. In addition, the differing nesting densities among seabird species, and the marked variation in density even within species, such as the Adélie penguin, will reduce substantially the degree of correspondence between colony or guano extent, and breeding numbers (Woehler & Riddle, 1998). Moreover, the 30 m pixel resolution of Landsat does not allow discrimination of the unoccupied areas of ground between nearby colonies (Naveen et al., 2012).

There is also extensive variation among different seabird species, and also to some extent between colonies, in diet, timing of breeding, and body size, which will affect the amount and chemistry of the guano on site, which in turn influences the spectral signature. Nor is the breeding density or nesting location constant during the season; birds fail, non-breeders arrive and depart, and in penguins, the structure changes from discrete nest sites always attended by at least one pair member during the incubation and brooding stages, to large groups of mostly-unattended chicks during crèche. We believe that the size of the guano signature in the satellite imagery, especially from medium resolution sensors, should only be considered as a general guide to the number of breeding pairs, pending further, extensive validation and quantification of the effects of the key variables affecting the relationship.

There are a number of considerations to take into account if the approach described here was to be extended to different regions and species. Atmospheric correction must be applied to Landsat data (Bindschadler et al., 2008), and the coarse resolution will only enable the location of large guano concentrations. These concentrations could

Fig. 5. Four examples of the correlation between the SAM guano analysis and NDVI vegetation analysis from two of the larger penguin colonies in the area. Fig. 5a shows guano results from the SAM analysis of Lagotellerie Island, the intensity represents spectral match to the guano training data given by the SAM analysis and can be seen as an indication of the amount of guano. Fig. 5b shows the corresponding NDVI results that indicate the presence of vegetation. Fig. 5c and d represents the corresponding analysis of guano and vegetation on Avian Island. Fig. 5e shows the strong negative correlation between the areas of guano and the NDVI results over the whole study area.

represent breeding colonies or non-breeding aggregations of a number of species depending on regional biogeography. However, higher resolution information from VHR satellites, aerial photography or ground survey could be used to confirm presence and species identity. If VHR satellite imagery or aerial photography is available, individual colony boundaries may be identified from the distinct patches of guano (Naveen et al., 2012). Careful timing of data acquisition may elucidate the species if there are differences in their timing of breeding based on colour change of guano in the period after chick hatching, but more field work will be required to assess how this affects the spectra. Thus, a combined approach of large-scale Landsat survey to find seabird colonies or roosting sites, and carefully timed higher-resolution imagery to estimate population size should be feasible, especially with the launch of superspectral VHR sensors such as WorldView3 and Sentinel-2, both planned for the next year. With such data, similar techniques could feasibly be expanded to any suitable area of the globe, including deserts and polar regions, and to other species, although further ground-truthing will clearly be required.

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