Mapping seabird nesting habitats in Franz Josef Land, Russian High Arctic, using digital Landsat Thematic Mapper imagery

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Supervised classification of digital Landsat satellite images was used to locate seabird nesting habitats in the Russian High Arctic archipelago of Franz Josef Land, a region where the avifauna is poorly known and ecologically vulnerable. Major seabird nesting colonies are readily identifiable in Landsat Thematic Mapper (TM) imagery of the region due primarily to the distinctive spectral signature of vegetation on ornithogenically altered soils below bird cliffs. Supervised image classification was used to pinpoint areas displaying spectral characteristics typical of documented seabird nesting habitats. A total of 101 seabird nesting colony locations identified in Russian and Western literature from 1898 to 1996 was used as training sites to develop spectral signatures from a summer TM image mosaic for use in a supervised maximum likelihood classification. The classified image was thresholded and compared to a map of documented nesting locations. Of the 101 field-documented nesting sites, 96 were clearly identified in the classified image. An inventory was produced of all undocumented seabird habitats suggested by the classification, totalling over 300 sites. The methodology used may be applicable to other arctic regions and is intended as a first step when planning ecological protection zones in remote and inaccessible arctic regions.

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Introduction

The changed relationship between Western nations and the former Soviet Union since 1989 has led to a steep rise in both scientific and economic activity in the Russian High Arctic islands. Growing concern in recent years over the need to protect the wildlife of the High Arctic region has prompted proposals to create a trans-boundary system of marine and terrestrial protected areas in the northern Barents Sea, covering northern Novaja Zemlja, Svalbard and Franz Josef Land (Theisen 1993). The information currently available on the avifauna of the Russian Arctic is insufficient to design effective local protection policies. This paper aims to demonstrate the potential of remote sensing techniques to identify the location of seabird nesting habitats on little studied arctic islands, using the Franz Josef Land archipelago as an example. Franz Josef Land (Fig. 1) was selected because it represents one of the few remaining extensive wilderness areas in Europe whose ecosystems are self-regulating and not strongly modified by human impact.

The Franz Josef Land archipelago comprises 191 islands located between 79°46′ and 81°52′N and 44°52′ and 64°25′E, stretching 375 km from east to west and 235 km from north to south (Fig. 1). The islands themselves occupy only 20% of the area, with a coastline of over 4425 km in length. Glaciers dominate the archipelago, covering 13,700 km^2 or 85% of the total land area (Dowdeswell et al. 1996; Dowdeswell et al. in press). The archipelago is inaccessible by sea for much of the year owing to sea ice, the summer break-up of sea ice generally not occurring until July. The surface geology of the archipelago is dominated by horizontal and sub-horizontal layers of basalts and dolerites of the "Barents-Kara Platform" (Govorukha 1970). Basalts crop out along the northern, western and southern periphery of the archipelago whilst, on the eastern islands, the basaltic sheets have been largely removed by erosion and the ice-free surfaces are

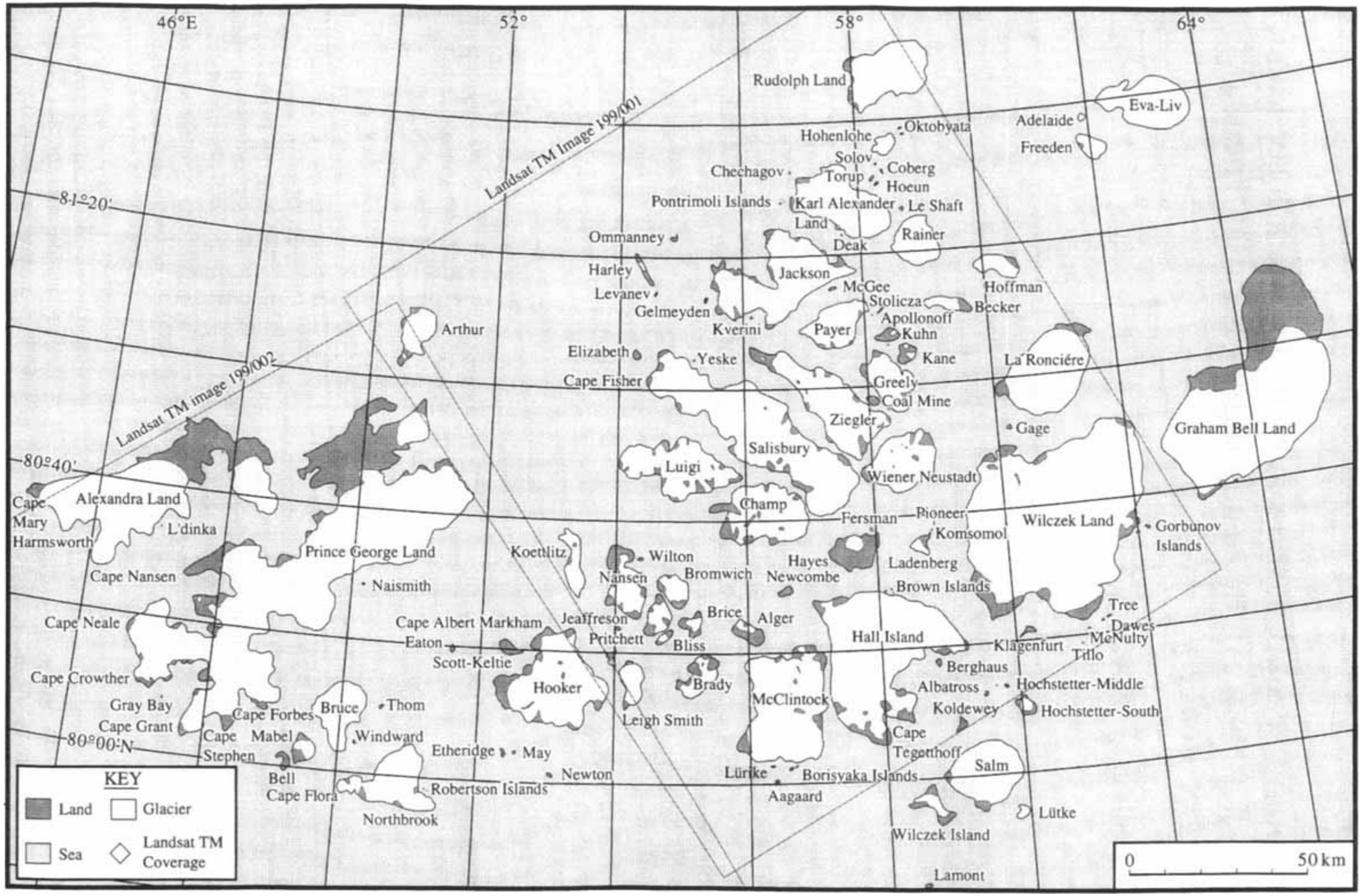

Fig. 1. Location map of Franz Josef Land, showing coverage of Landsat TM imagery used for this study. Bare land is dark shading and glaciers white.

dominated by flat plains of friable Mesozoic sedimentary rocks, pierced by dykes.

Franz Josef Land has been identified as an environmentally sensitive area in which nature reserves would be desirable (Uspenskiy et al. 1987), and the archipelago gained protected area status in April 1994 (Matishov & Drobysheva 1994). The marginal sea-ice zone and tundra areas of the Arctic are particularly sensitive to the impacts of oil and gas development, mining, shipping, military activities and tourism. Seabirds play a vital role in arctic island ecosystems and are highly vulnerable to marine environmental pollution. The potential impacts of oil spills are particularly high because adequate technologies do not exist for effective oil spill clean-up operations in ice-infested waters (Theisen 1993). Seabird distribution is generally patchy (Fauchald & Erikstad 1995), so for assessment of potential oil spill impacts on bird populations it is important to be able to predict the location of seabird aggregations (Fauchald & Erikstad 1995).

The avifauna of Franz Josef Land is little studied due to difficulties of access, severe climatic conditions, and the exclusion of Western visitors from the 1920s until 1989. Literature on the local avifauna gives a generally fragmentary coverage and is often based on data collected prior to 1935. A total of 41 bird species has been recorded on the archipelago (Weslawski & Stempniewicz 1995), of which 14 are known to nest (Tomkovich 1984). The majority of species recorded are seabirds nesting in cliff colonies, with over 60 major colonies (each greater than 1000 nesting pairs) identified in the literature (Uspenskiy & Tomkovich 1987), together with many more minor colonies. Estimates by Uspenskiy & Tomkovich (1987) suggest that, during a typical nesting season, the archipelago is home to roughly 200,000 Brünnich's guillemots (*Uria lomvia*), 500,000 little auks (*Alle alle*), 30,000 black guillemots (*Cepphus grylle*), 20,000 fulmars (*Fulmarus glacialis*) and 20,000 kittiwakes (*Rissa tridactyla*). Some of the largest nesting colonies of the ivory gull (*Pagophila eburnea*) in the former USSR are located within the Franz Josef Land archipelago. The ivory gull is included in the Red data book of the USSR (But'ev 1983), which lists rare and endangered animal and plant species.

Frantzen et al. (1993) expressed concern that only a small number of the birdcliffs on Franz Josef Land were mapped, yet most of the 191 islands would appear to have one or more seabird cliffs. Many of the cliff colonies are in inaccessible locations and therefore remain unstudied. An accurate map of seabird colony locations is likely to become of increasing importance as this region opens up to economic activities, in order to identify those sites most at risk from human impact.

Bird species

Of the 13 bird species listed by Weslawski & Stempniewicz (1995) as common breeders in Franz Josef Land, 10 species were considered in this study. These 10 species, listed in Table 1, represent those seabirds known to nest on cliffs and rocky sites in significant numbers.

Vegetation cover

Vegetation on Franz Josef Land varies considerably owing to differing environmental conditions (Safranova & Glazovskij 1995). On many of the islands vegetation is poorly developed, vascular plants are scarce, and lichens dominate. Only a limited number of plant species are able to survive in this region owing to low temperatures, short summer growing seasons, permafrost, low radiation balance and limited nutrient turnover (Safranova & Glazovskij 1995). Vegetation typically covers no more than 5–10% of the ground surface, the number of plant species and the percentage of ground cover generally decreasing from south-west to north-east owing to increasing climatic severity (Safranova & Glazovskij 1995). The stony slopes below basaltic cliffs are an exception to the general vegetation pattern. These slopes are the most favourable habitat for plants owing to good drainage and, where they are south-facing, warming from the daytime sun. Where cliffs are occupied by bird colonies, fertilisation of the slopes below by guano encourages additional vegetation growth and often results in 100% ground cover by a mat of brightly coloured vegetation. This feature has been noted by several visitors to the region (Demme 1934; Odasz 1993; Rowlands 1994; Safranova & Glazovskij 1995). The most intensively studied bird cliffs in the archipelago are at Rubini Rock on Hooker Island (Figs. 1, 2, 3 4), where a talus slope is present at the base of the cliffs (Stempniewicz 1993),

Table 1. Summary table of typical nesting habitats of all common seabird species known to nest in significant numbers in Franz Josef Land.

Bird Species	Common name	Typical nesting habitat
Fulmarus glacialis	Northern fulmar	Widely distributed on Franz Josef Land, nesting at inaccessible sites on rocky cliffs and basaltic crags (Bruce & Clarke 1899).
Somateria mollissima	Common eider	Widespread on Franz Josef Land. Occupies a variety of habitats, including rocky, sandy, vegetated and bare shores (Bruce & Clarke 1899).
Stercorarius pomarinus	Pomarine skua	Usually found slightly inland on flat areas free from vegetation (Frantzen et al. 1993).
Stercorarius parasiticus	Arctic skua	Usually found slightly inland on flat areas free from vegetation (Frantzen et al. 1993).
Larus hyperboreus	Glaucous gull	Observed throughout Franz Josef Land but not in large numbers. Nesting sites are dispersed, primarily on igneous dykes (Uspenskiy & Tomkovich 1987) and high basaltic cliffs (Jackson 1899).
Rissa tridactyla	Kittiwake	Nests on sheer cliffs, common in the south of the archipelago. Often nests on basaltic cliffs among Uria lomvia, but generally prefers the lower rocks below Uria lomvia colonies (Jackson 1899). Also found nesting on talus slopes (Bruce & Clarke 1899).
Pagophila eburnea	Ivory gull	Observed throughout Franz Josef Land, numerous in places. Occasionally nests on low basaltic cliffs (Bruce & Clarke 1899), but colonies typically located on level rocky, sandy or grassy surfaces (Uspenskiy & Tomkovich 1987) such as found on raised beaches (Bruce & Clarke 1899; Jackson 1899).
Uria lomvia	Brünnich's guillemot	The second most common species on Franz Josef Land, particularly numerous in southern and central parts of the archipelago. Nests on steep cliffs, rock ledges and talus slopes (Uspenskiy & Tomkovich 1987)
Cepphus grylle	Black guillemot	Widely distributed on Franz Josef Land, generally occupying similar habitats to Alle alle (Stempniewicz 1993).
Alle alle	Little auk	The most common species on Franz Josef Land. Nests in large colonies, predominantly on steep cliffs. Nests on rocky basalt cliffs, among loose stones of talus slopes, and in rock fissures (Jackson 1899). Lower sections of talus slopes below cliffs are generally only occupied by sub-colonies at sites where population pressure is high, and the number of safe nesting sites is limited, owing to vulnerability of lower talus slopes to polar bear & arctic fox predation (Stempniewicz 1993; Weslawski & Stempniewicz 1995).

inclined at approximately 45° and covered with dense vegetation. The vegetation cover below the Rubini Rock bird cliffs is made up primarily of *Alopecurus alpinus*, *Poa arctica*, *Ranunculus sulphureus* and *Cochlearia groenlandica* (Gavrilo et al. 1994).

The characteristic vegetation below birdcliffs displays a very distinct spectral signature and can be identified clearly in Landsat TM satellite images of the region (Figs. 2, 3 and 4). The methodology presented here is designed to locate seabird nesting habitats primarily by distinguishing the spectral signature of the vegetation-covered talus slopes below bird cliffs.

Data sources and methods

The satellite imagery used for this study is from the Landsat 5 Thematic Mapper (TM). The images used were in digital form, with a spatial resolution of approximately 30 × 30 metres (120 metres for band 6), recorded in 7 spectral bands (Lillesand & Kiefer 1994), with the following wavelengths: TM Band 1: 0.45–0.52 µm, TM Band 2: 0.52–0.60 µm, TM Band 3: 0.63–0.69 µm, TM Band 4: 0.76–0.90 µm, TM Band 5: 1.55–1.75 µm, TM Band 6: 10.40–12.50 µm, TM Band 7: 2.08–2.35 µm.

Two adjacent Landsat TM satellite images from

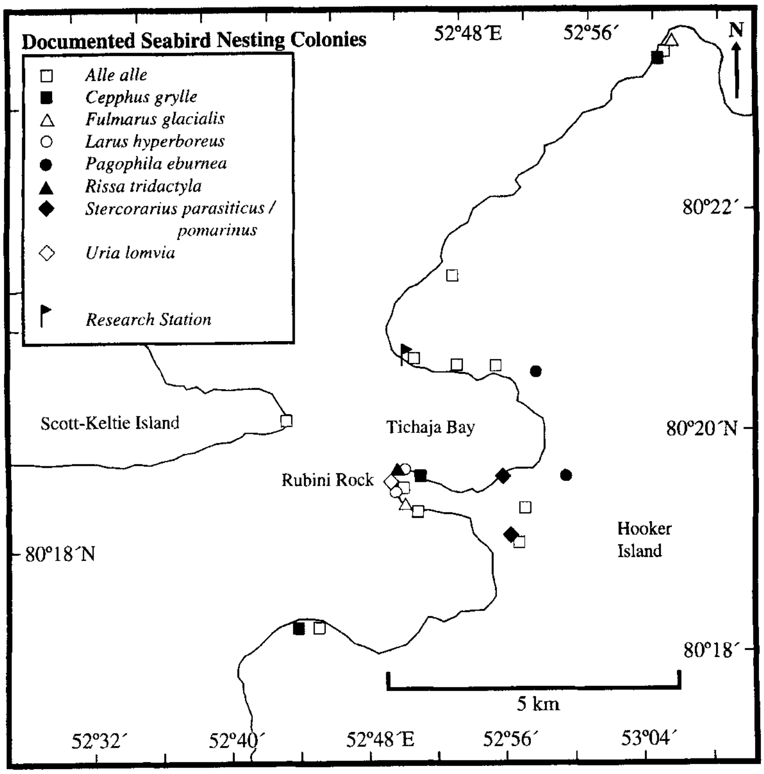

Fig. 2. Map of Tichaja Bay, Hooker Island, showing the approximate locations of seabird nesting colonies documented by Skakuj (1992) and Gavrilo et al. (1994).

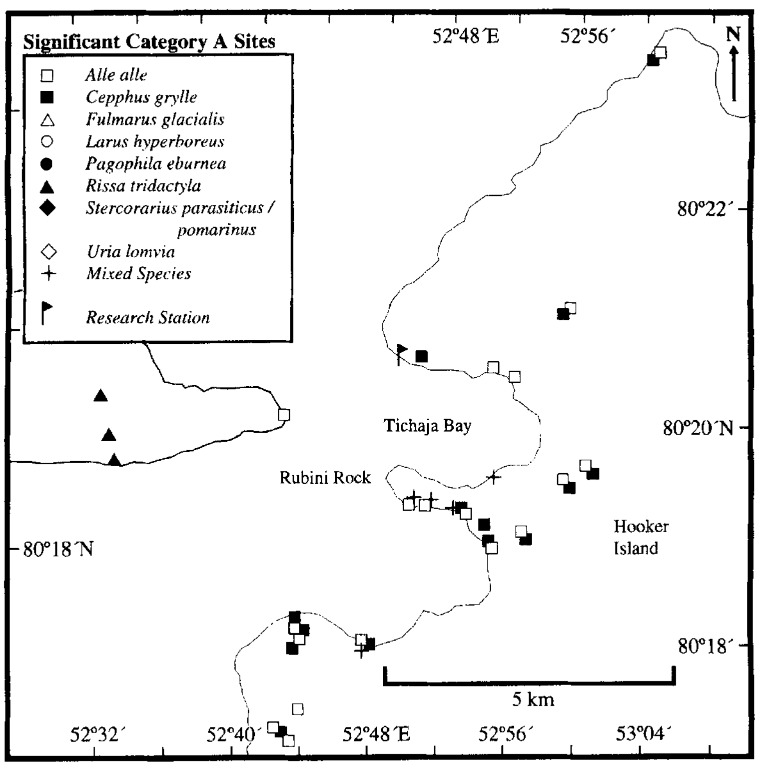

Fig. 3. Map of Tichaja Bay, Hooker Island, showing the approximate locations of significant category A sites (seabird nesting habitats with associated ornithogenic alteration of vegetation) identified by Landsat TM image classification. For a full definition of category A see text.

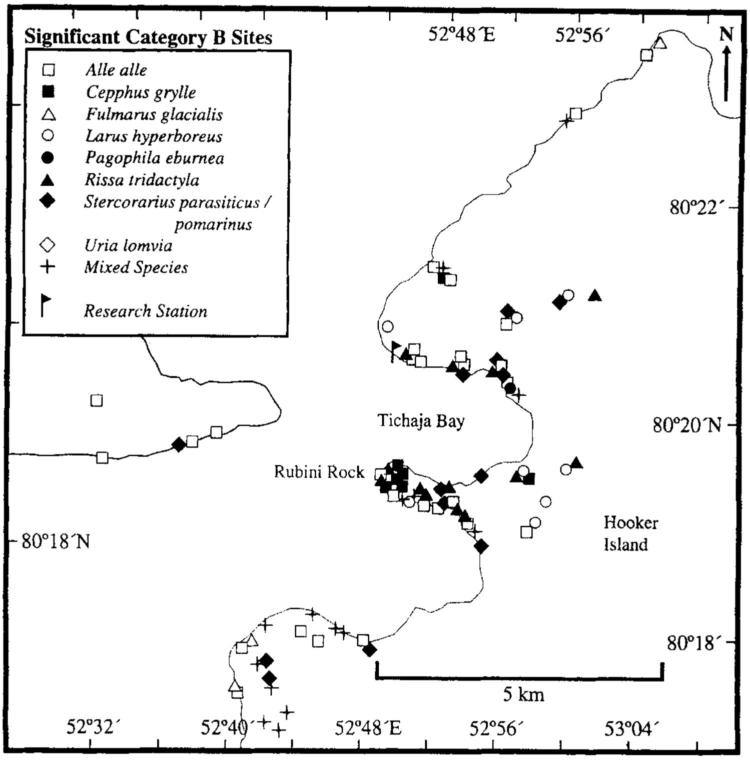

Fig. 4. Map of Tichaja Bay, Hooker Island, showing the approximate locations of significant category B sites (sites with little or no ornithogenic vegetation changes, but with topographical and geological characteristics likely to provide suitable nesting sites for seabird colonies) identified by Landsat TM image classification. For full definition of category B see text.

path 199 and rows 001/002 recorded on 25 July 1986 were used, each covering an area of approximately 185 × 185 km. These provided cloud-free coverage of approximately 90% of the archipelago, with Graham Bell Island the only major island excluded from the coverage (Fig. 1). Mid-summer Landsat imagery was selected to correspond with the peak of the vegetation growing season and in order to minimise the relief shadowing effects caused by low sun elevations. The average sun elevation for the Landsat image mosaic was 29° from the horizontal, with an azimuth of 60° from north. Shadowing in the image mosaic is therefore most severe below cliffs facing to the east and north-east. Shadowing of talus slopes may result in some seabird nesting colonies remaining undetected by spectral classification owing to failure of the classification to detect ornithogenic alteration of talus slope vegetation in these areas of shading. Using simple trigonometry it can be calculated that a talus slope below an ENE facing cliff will be entirely in the shadow of the overlying cliff if its width is less than 1.8 times the height of the cliff.

The satellite imagery was processed on a Unix computer system using ERDAS Imagine 8.2 image processing software. The images were radiometrically corrected to give reflectance values using the standard methodology developed by Markham & Barker (1986). They were then geometrically corrected using Global Positioning Satellite (GPS) data collected in summer 1992 by S. Sink'evich of the Institute of Geography, Russian Academy of Sciences, Moscow. A total of 17 GPS points was used to correct the eastern scene 199/001, giving an overall positional accuracy of 19 metres (RMS error 0.627 pixels) whilst correction of the western scene 199/002 gave an accuracy of 14 metres (RMS error 0.476 pixels) using 11 GPS points. The images were transformed to UTM zone 40 co-ordinates, using a first-order transform, and resampled using a nearest neighbour algorithm to a pixel size of 30 × 30 m, corresponding to the nominal spatial resolution of the Landsat TM sensor. The two images were then mosaiced using a linear edge-feathering technique (Albertz et al. 1987) to form a single georeferenced reflectance image for use in the digital classification.

The first stage of the classification procedure was to identify locations from which supervised spectral signatures could be derived to characterise specific ground cover types using standard satellite image processing methods (Swain & Davis 1978). A search was carried out to pinpoint suitable training locations from the sparse literature on the avifauna of Franz Josef Land. Ornithological observations from both Russian and Western expeditions between 1898 and 1992 were compiled to identify training sites representing field-documented colonies of varying size, density, and species composition.

Russian scientific activity in Franz Josef Land was significant in the 1920s and 1930s but decreased considerably when the Tichaja Bay research station on Hooker Island (Figs. 1, 2, 3 and 4) closed in 1959. Since 1990 there have been several multinational expeditions to the region which have carried out ornithological observations. Gorbunov (1932) summarised early ornithological observations, and later work is discussed by Frantzen et al. (1993) and Weslawski & Stempniewicz (1995). Additional sources used for this study include Bruce & Clarke (1899), de Korte (1991), Demme (1934), Gavrilo et al. (1994), Gorbunov (1932), Jackson (1898), Jackson (1899), Norderhaug et al. (1977), Rowlands (1994), Skakuj (1992), Tomkovich (1984), Uspenskiy & Tomkovich (1987), and Weslawski & Malinga (1993).

The most intensively studied part of the archipelago is the Tichaja Bay area of Hooker Island (Figs. 1, 2, 3 and 4), the site of an international research station since 1990. Detailed observations were carried out of the seabird colonies in the Tichaja Bay area during summer expeditions in 1990, 1991 and 1992 (Skakuj 1992; Stempniewicz 1993; Gavrilo et al. 1994). Following these expeditions, a schematic map was produced by Weslawski & Malinga (1993) of the wildlife of Franz Josef Land, marking bird colonies observed by recent Russian and Western expeditions. This map also utilised data from previous expeditions noted in Gorbunov (1932), Norderhaug et al. (1977) and Uspenskiy & Tomkovich (1987). Bird colonies were distinguished by size (minor colonies <1000 birds, major colonies >1000 birds) and dominant species.

In total, 101 seabird nesting areas were identified from the Weslawski & Malinga (1993) map and other literature sources, corresponding to 242 spatially distinct nesting colonies. These 242 colonies included both mixed species and single species colonies, and a range of population densities. The approximate locations of all documented seabird nesting colonies are shown in Figures 5, 6 and 7. Attempts were made to identify each of the major seabird colonies documented in the literature on the Landsat TM image mosaic, and a supervised spectral signature was obtained from TM bands 1–5 and 7 from all the colonies that could be located unequivocally. A summary of the locations and data sources used is given in Table 2. At a number of locations cited in the literature it was not possible to obtain a clearly defined spectral signature. This was for a number of reasons, including uncertainty over precise location, lack of significant ornithogenic alteration of vegetation, colonies of insufficient size or density to be detected in the Landsat TM imagery, and shadowing of talus slopes by cliffs above. If doubt existed over the validity of a spectral signature at a given site, it was excluded from the classification procedure. A total of 91 training signatures was used to derive the signature set for the final image classification. The statistical distances between signatures were calculated using the Jefferies-Matusita (JM) distance method (Lillesand & Kiefer 1994; Schowengerdt 1983), to determine how distinct the 91 spectral signatures were from one another. This revealed some spectral overlap between signatures. In order to eliminate spectral confusion due to overlapping classes, signatures showing poor spectral separability were merged together to form new spectral classes. Merging of overlapping classes resulted in 72 spectrally separable hybrid signatures (average JM distance of 1399 and a minimum of 1022).

A maximum likelihood classification (Schowengerdt 1983) was applied to the image mosaic using the hybrid spectral classes. This assigned each pixel in the image to a specific spectral class, if it matched one of the class definitions, or left it unclassified if it did not. No prior knowledge existed regarding the proportional areas of the different habitats, so an equal probability weighting was applied to each class in the classification. An interactive threshold was then applied to the classified Landsat image mosaic to eliminate those pixels whose class assignment showed low statistical probability.

The classified Landsat imagery was compared with a list of all the field-observed seabird nesting

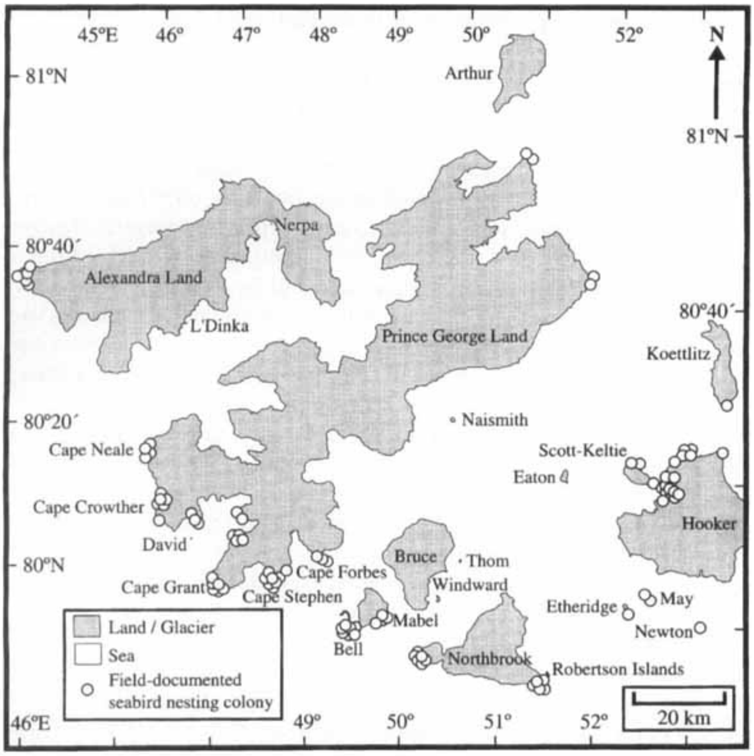

Fig. 5. Map of western Franz Josef Land showing the approximate locations of field-documented seabird nesting colonies identified from previous literature.

Fig. 6. Map of northeast Franz Josef Land showing the approximate locations of field-documented seabird nesting colonies identified from previous literature.

colony locations to derive a qualitative assessment of classification accuracy. Quantitative assessment was not possible with this dataset because literature sources note only the approximate locations of colonies and not the precise co-ordinates, density or spatial extent of individual colonies. The locations of all significant clusters of classified pixels that did not correspond to observed colonies were recorded and listed as sites with possible nesting colonies requiring further investigation in the field. A significant cluster was defined as a cluster of three or more contiguous pixels.

Classification results

Spectral identification of known seabird nesting sites

A qualitative comparison of the classified Landsat imagery with a map of documented nesting locations revealed that all except five of the 101 generalised locations documented in the recent literature were detected successfully. Some of the colony locations noted by early expeditions are considered doubtful or of insignificant size. For example, Bruce & Clarke (1899) note an *Alle alle* colony on Bruce Island which was not detected by later expeditions or in the classified imagery.

Classification accuracy was high for habitats associated with *A. alle*, *Cepphus grylle*, *Uria lomvia* and *Fulmarus glacialis*. This is because these species are generally associated with habitats that are spectrally distinguishable in the satellite imagery due to extreme ornithogenic alteration of soil and vegetation (Table 1). The classification was less successful at identifying habitats associated with seabird species which only induce minor ornithogenic vegetation changes.

The spectral classes representing *Larus hyperboreus* nesting colonies tended to overclassify because the glaucous gull is only found in small numbers, has a low nesting density, and nests in a variety of different habitats (Table 1). It was not possible to obtain a distinct spectral signature for habitats associated with *L. hyperboreus*.

Typical *Stercorarius parasiticus/pomarinus* habitats were difficult to define spectrally as a result of several factors. *S. parasiticus/pomarinus* are typically solitary breeders, usually nesting on flat inland areas free from vegetation (Frantzen et al. 1993). These areas are not spectrally distinct, and may be associated with more common species such as *A. alle*. The spectral classification failed to detect documented *S. parasiticus/pomarinus* nesting habitats on Borisyaka Islands and Newton Island (Figs. 5 and 7).

Somateria mollissima mostly nests on flat ground where vegetation is sparse and ornithogenic alterations are minimal, so it was not possible to obtain a distinct spectral signature for this species, the classification failing to detect a documented colony on Aagaard Island.

A significant limiting factor in the classification was the presence of relief shadows in the satellite imagery due to the relatively low elevation of the sun in the High Arctic. As noted in the previous section, some major seabird colonies on ENE facing cliffs may not have been detected in the imagery due to the vegetated talus slopes below them being in the shadow of the overlying cliffs at the time of image acquisition. Other nesting colonies may be too small or of too low a density to be detected at the spatial resolution of the Landsat TM.

Spectral identification of undocumented seabird nesting habitats

Over 300 undocumented sites displaying the spectral characteristics of known seabird nesting habitats were identified on the archipelago that warrant investigation in the field (Figs. 10, 11 and 12). The seabird habitats identified by the classification fall into two broad categories: Category A, associated with ornithogenic vegetation changes due to seabird colonies, which are easily detected spectrally. Spectral profiles of typical category A signatures are shown in Fig. 8; and Category B, representing sites at which there is no detectable ornithogenic alteration of vegetation but the topographic and geological characteristics are likely to provide suitable nesting sites for seabird colonies. Spectral profiles of typical category B signatures are shown in Fig. 9. This category indicates only the presence of habitats technically capable of supporting seabird nesting colonies and does not necessarily indicate the presence of seabird colonies. Suitability of spectrally identified category B sites for nesting colonies is influenced by a number of factors which cannot be determined from the satellite imagery. These influences include proximity to

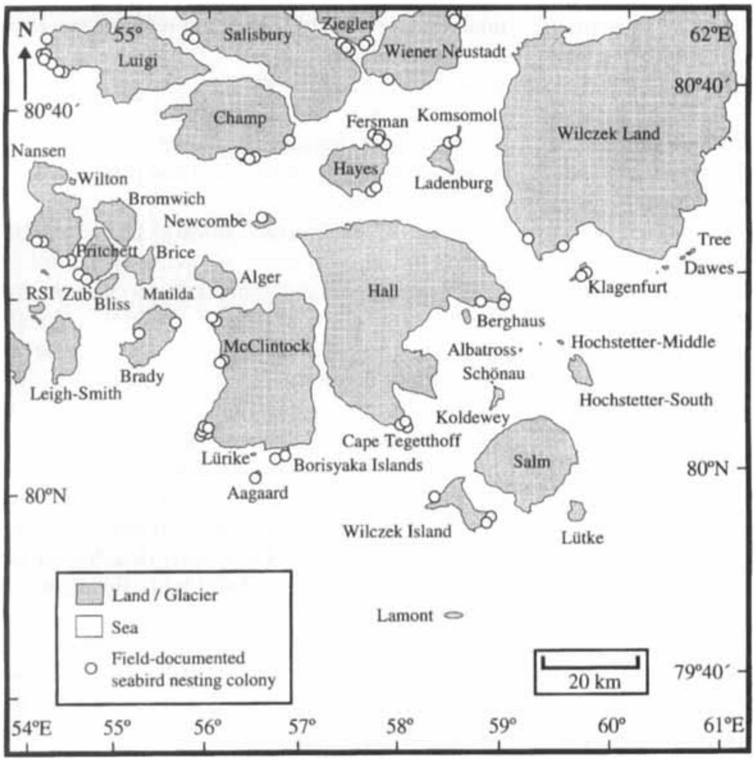

Fig. 7. Map of southeast Franz Josef Land showing the approximate locations of field-documented seabird nesting colonies identified from previous literature. Royal Society Islands are labelled as RSI.

open-water feeding grounds and accessibility of nesting locations to predators such as polar bears (Stempniewicz 1993; de Korte et al. 1995) and arctic foxes (Weslawski & Stempniewicz 1995). Many category B sites may not be occupied in consecutive years due to changing natural conditions and variations in population pressure from year to year.

The approximate locations of all significant seabird nesting habitats identified by satellite image classification (represented by clusters of 3 or more contiguous pixels) are shown in Figs. 10, 11 and 12. Owing to the limitations of map scale, it is not possible to graphically represent the precise geographical location and extent of each of the nesting habitats identified by the image classification on Figs. 10, 11 and 12, or the inferred species composition and nesting density. Summarised details of the major undocumented seabird nesting habitats detected by the classification, listed by island, are presented in Table 3. Subset maps of the Tichaja Bay area are presented as Figs. 2, 3 and 4 to provide an example of the level of detail available from the classification. Fig. 2 shows the documented seabird nesting colonies around Tichaja Bay, whilst Figs. 3 and 4 show the location of significant category A and B habitats, and the dominant seabird species inferred by the image classification. Digital copies of the entire classified image mosaic and further details of the supervised classification scheme used can be obtained from the authors on request.

Seabird habitats identified successfully include basaltic sea cliffs, dykes, isolated basalt crags, and talus slopes with varying amounts of vegetation cover. Spectral classification indicates the presence of over 160 undocumented major sea cliff colonies, detected due to extreme ornithogenic alteration of talus slope vegetation. The most important such sites were located on Alger (western and southwestern coasts), Bliss (southern coast), Brice, Bromwich (southern coast), Champ (western coast), Greely (southern coast), Karl Alexander Land (WSW tip), Mabel (northern tip), Nansen (ENE coast), Salisbury (SW coast), Wilton, and the NW tip of Ziegler (Figs. 10, 11

Table 2. Summary table of existing data on seabird nesting locations in Franz Josef Land, compiled from published literature. All location names are identified on Fig. 1.

Location (Fig. 1)	Field Documented Nesting Species	Documented by‡	Major colonies†
Aagaard Island	SM	E	
Alger Island	SP	E	
Alexander Land	CG, FG, PE, SP, SM	A, E	
*Appollonoff Island	AA, CG	A, F	AA
*Bell Island	AA, CG, FG, LH, PE, RT, SP, UL	F	AA, CG, RT, UL
Borisyaka Islands	SP	E	
*Brosch Island	AA, CG, FG, LH, RT	A, F	RT
Brady Island	AA, CG, LH	A	
Bruce Island	AA	B	
*Cape Albert Markham	AA, CG, FG, LH, RT, UL	E, F	AA, CG
Cape Crowther	FG, LH, RT, SP, UL	B, H	
Cape Flora	AA, FG, LH, PE, RT, SP, UL	B, H, F	RT, UL
Cape Forbes	AA, FG	B	AA
*Cape Grant	AA, CG, FG, LH, RT, SP, UL	B, F, H	AA, RT, UL
Cape Mary Harmsworth	FG, PE, SM	B, H	SM
Cape Neale	LH, RT	H, E	
Cape Stephen	FG, LH, PE, UL	B	UL
*Cape Tegetthoff	AA, CG, FG, LH	F	
Champ Island (southern)	AA, FG, LH, RT	A, E, F	RT
Etheridge Island	PE	E	
Fersman Island	AA, CG, PE	E	
Graham Bell Island	LH, PE, RT, SP	A, E, H	
Gray Bay	AA, RT, SP, UL	B	AA, RT
Prince George Land	AA, CG, FG, LH, PE, RT, SP, UL	A, E	AA, CG, FG, RT
Hall Island	AA, CG, FG, LH, PE	A, E	AA
Hayes Island	AA, CG, PE, SP	A, E	
Hochstetter Islands	AA, CG, LH, SP	A	
Hooker Island	AA, CG, FG, LH, RT, SM, SP, UL	C, D, G, H	AA, CG, FG, RT, UL
Hvidtenland (Eva-Liv)	AA, FG	B	
Jackson Island	AA, CG, LH, PE, RT, SP, UL	A, B, D, G	AA, CG, RT
Kane Island	AA, CG	A, E	
Karl Alexander Land	AA, CG, FG, RT, UL	A, E	AA, FG, RT, UL
*Klagenfurt Island	AA, CG, FG, LH	A, E, F	
Koettlitz Island	LH, SP	E, H	
Komsomol Island	PE, SP	E	
Kuhn Island	AA, CG, RT	E	AA, RT
Luigi Island	AA, CG, UL	A, E	AA, UL
Mabel Island	CG, FG, LH, UL	A, B, E	CG, FG
May Island	AA, CG, PE	E, H	AA, CG
McClintock Island	AA, CG, LH, RT, UL	A, B, E, H	AA
Nansen Island	AA, CG, LH	A, E, H	
Newcombe Island	CG, LH	A	
Newton Island	CG, SM, SP	A, E, H	
Northbrook Island	AA, CG, LH, PE, RT, SP, UL	A, E, H	CG, UL
Payer Island	AA, CG	E	
Pritchett Island	AA, CG	E	AA, CG
Rubini Rock	AA, CG, FG, LH, PE, RT, SM, SP, UL	C, D, E, H	AA, CG, FG, RT, UL
Rudolph Island	AA, CG, FG, LH, PE, RT, SP, UL	A, E, H	CG, FG, UL
Salisbury Island	AA, CG, FG, RT, UL	A, E	AA, CG, RT
Scott-Keltie Island	AA, SM, SP	A, H	
*Stolicza Island	AA, CG, LH, RT	A, F	AA
Tichaja Bay (Hooker Isl.)	AA, CG, FG, LH, PE, RT, SM, SP, UL	C, D, E, F, H	AA, CG, FG, RT, UL
Torup Island	AA, CG, LH	A, B, H	AA
Wiener Neustadt Island	AA, CG, FG, UL	A, E	AA, CG
*SW Wilczek Island	CG	F	
*NE Wilczek Island	LH, RT	F	
Wilczek Island	AA, CG, LH, RT, SP	A, E	
*SSW Wilczek Land	RT	F	RT
*WSW Wilczek Land	AA, CG	F	
Wilczek Land	AA, CG, RT	A, E, F	
Ziegler Island	AA, CG	E	

* Specific sites for which bird counts from 1991/92 are given by Frantzen et al. (1993).
† A major colony is defined as greater than 1000 birds observed on a single date, as noted in references F & G.
‡ References: A = Weslawski & Stempniewicz (1995)
B = Bruce & Clarke (1899)
C = Skakuj (1992)
D = Stempniewicz (1993)
E = Weslawski & Malinga (1993)
F = Frantzen et al. (1993)
G = Uspenskiy & Tomkovich (1987)
H = Jackson (1899)

Species: AA = *Alle alle*
CG = *Cepphus grylle*
FG = *Fulmarus glacialis*
LH = *Larus hyperboreus*
PE = *Pagophila eburnea*
RT = *Rissa tridactyla*
SM = *Somateria mollissima*
SP = *Stercorarius (parasiticus & pomarinus)*
UL = *Uria lomvia*

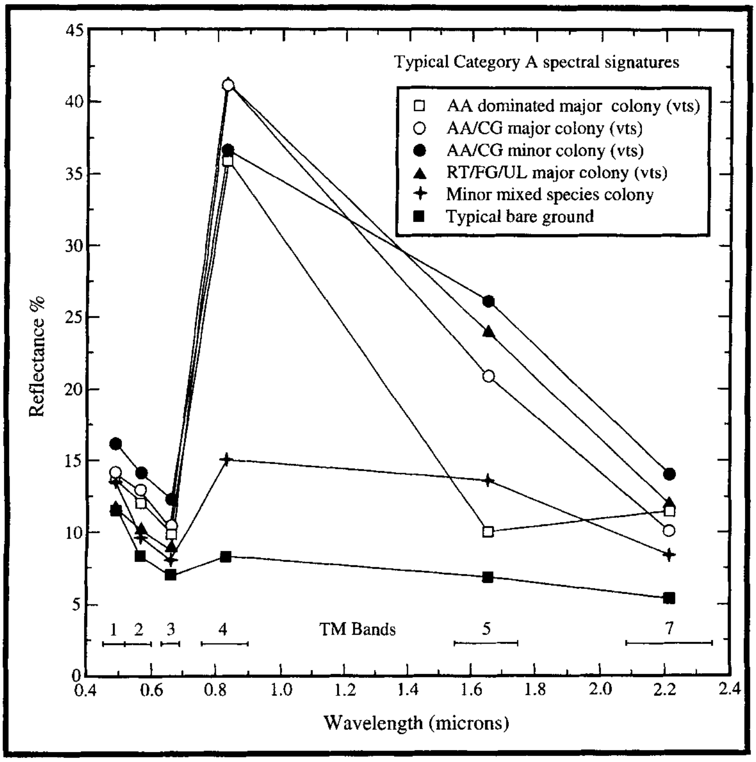

Fig. 8. Spectral profiles of typical category A seabird nesting habitats (vts = vegetated tundra sites). For abbreviations see Table 2, and for category A definition see text.

and 12). Many of the larger undocumented colonies detected, including those on Bliss, Brice, Nansen, and Ziegler Island, were located in regions marked as polar bear denning areas on the ecology map produced by Weslawski & Malinga (1993), which may explain why they remain undocumented by field expeditions.

The satellite classification suggests the presence of several colonies aligned along igneous dykes on the north coast of Salisbury Island, the

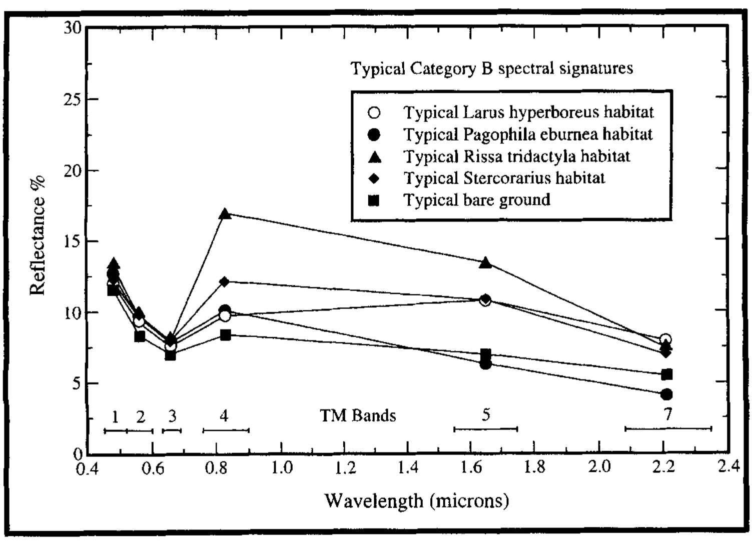

Fig. 9. Spectral profiles of typical category B spectral signatures. For abbreviations see Table 2, and for category B definition see text.

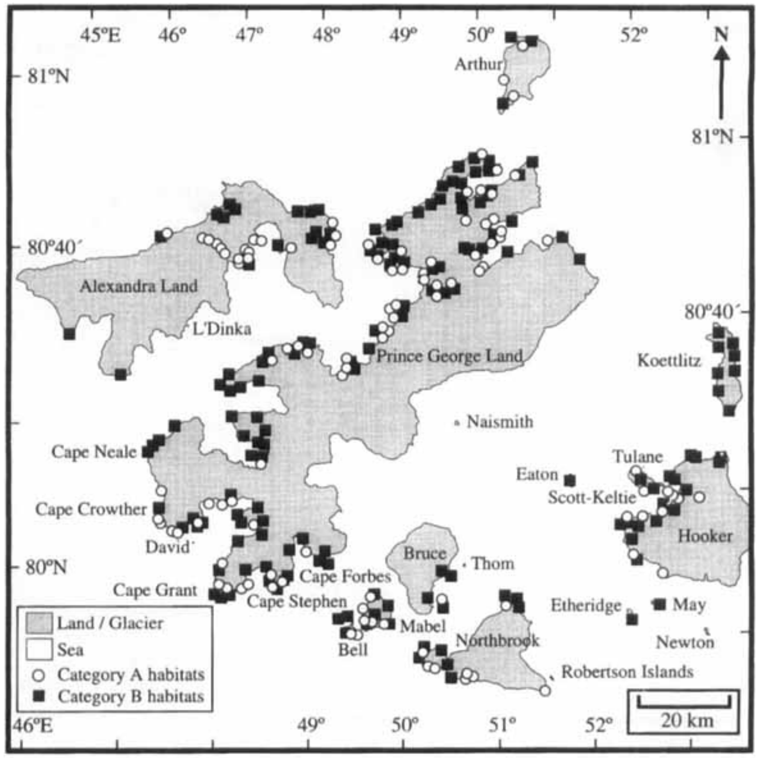

Fig. 10. Map of western Franz Josef Land showing approximate locations of all significant (clusters of greater than 3 pixels) locations classified as category A or B seabird habitats by digital classification of Landsat TM imagery.

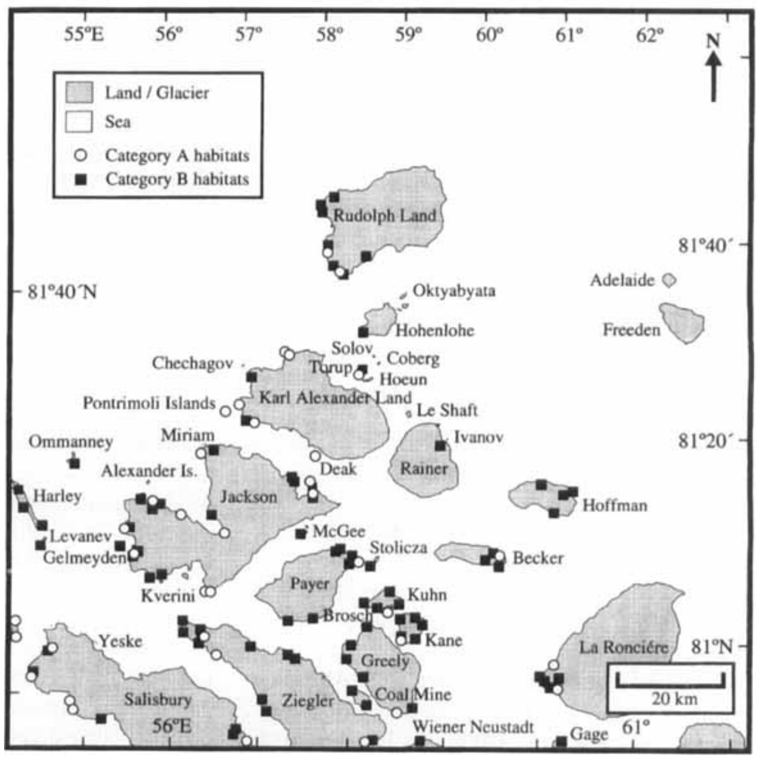

Fig. 11. Map of northeast Franz Josef Land showing approximate locations of all significant (clusters of greater than 3 pixels) locations classified as category A or B seabird habitats by digital classification of Landsat TM imagery.

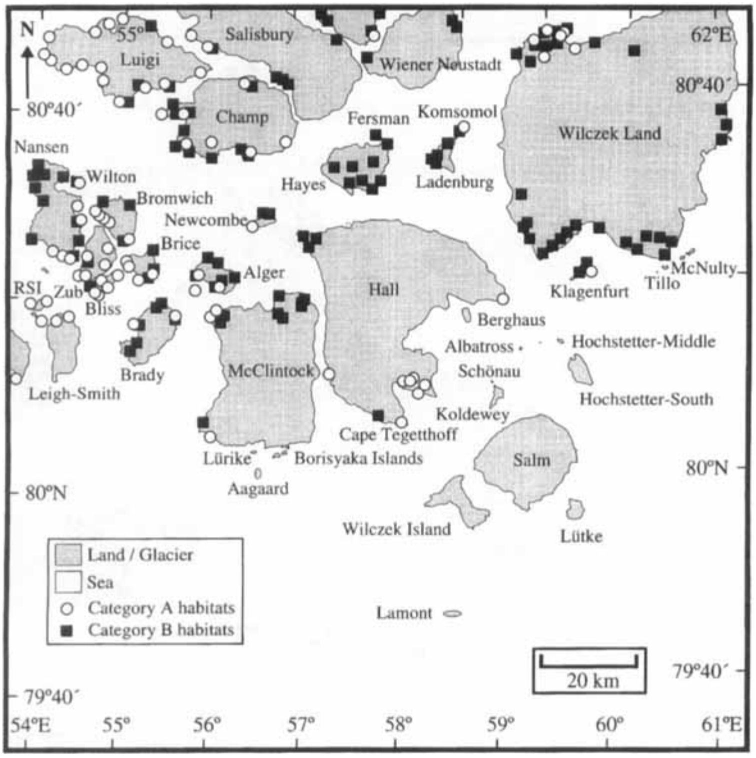

Fig. 12. Map of southeast Franz Josef Land showing approximate locations of all significant (clusters of greater than 3 pixels) locations classified as category A or B seabird habitats by digital classification of Landsat TM imagery. Royal Society Islands are labelled as RSI.

NW tip of Ziegler Island, NE tip of Payer Island, western Hayes Island, and the NE coast of McClintock Island (Figs. 11 and 12).

At many of the larger colonies indicated on the classified image, a distinct spatial stratification is seen. This corresponds to the preferred habitats of different species. Lower talus slopes are predominantly classified as *Alle alle/Rissa tridactyla*, the upper talus slopes and main cliffs above as *A. alle/Cepphus grylle/Fulmarus glacialis*, upper slopes as *Uria lomvia/Cepphus grylle*, and isolated crags further inland as *R. tridactyla/U. lomvia*. Such stratification is clearly observed at colonies on Brice, Bromwich (south coast), Luigi (south coast) and Salisbury (southeast coast).

It was possible to exclude many islands from further investigations because habitats characteristic of bird colonies were not detected. The list of excluded islands comprised Albatross, Alexander Island, Berghaus, Brown Islands, Chechagov, Coberg, Dawes, David, Gorbunov Islands, Hochstetter-Middle, Ivanov, Koldewey, Kverini, L'dinka, Le Shaft, Levanev, Lürike, McNulty, Miriam, Naismith, Nerpa, Oktyabyata, Robertson Islands, Schönau, Solov, Thom, Tillo, Tree, Tulane and Yeske (Fig. 1).

Conclusions

The remote sensing techniques demonstrated here are useful for predicting the probable location of undocumented seabird nesting colonies. Satellite image classification is not capable of demonstrating conclusively the presence of seabirds colonies at any specific location, but it is a useful tool for indicating the presence of associated habitats, and to eliminate areas in which suitable habitats do not exist. Data from satellite classification may be used to target specific locations for field investigation. The methodology used should be applicable to other arctic regions, as a first step when

Table 3. Summary details of undocumented seabird nesting habitats identified by digital classification of Landsat TM imagery. Abbreviations are used for species names – for key to abbreviations see Table 2. For category A & B definitions see text.

Island Name	Undocumented Category A & B Seabird Nesting Habitats Identified by Landsat Image Classification – Summary Details
Alger Island	8 major AA/FG & mixed species category A & B habitats identified on SW & W coast, with vegetated talus slopes. One mixed species category A habitat identified on N coast.
Arthur Island	Scattered small AA/CG & mixed species nesting habitats identified – categories A & B.
Bliss Island	6 large category A sea cliff nesting colonies identified on south coast, documented by Jackson (1899) but not in later literature.
Brady Island	Mixed species category A habitat identified on NE tip, scattered CG dominated category B habitats on west coast.
Brice Island	17 undocumented category A habitats identified on E & W coasts, with distinct zonation of UL/FG/AA spectral classes on upper slopes & AA/CG/mixed species spectral classes on lower slopes.
Bromwich Island	Major category A seabird cliffs identified on SW coast, with AA spectral classes dominating lower slopes, UL on upper slopes. Mixed species category B habitats identified on south & east coasts.
Champ Island	Over a dozen undocumented category A seabird cliffs identified on western headland. Spectral classification suggests presence of all major species, AA dominant. RT dominated category A sites identified on south coast.
Coal Mine Island	A significant category B mixed species habitat identified on NW tip. AA/CG/UL and RT dominated category B habitats identified, scattered over island.
Deak Island	AA/CG category B habitats identified on isolated crags.
Eaton Island	Scattered small AA/CG category B habitats identified.
Elisabeth Island	Scattered category A & B habitats identified, predominantly AA/FG.
Gage Island	Large AA dominated category B AA/CG habitat identified.
Greely Island	8 major category B cliff sites identified on ENE tip, and scattered minor AA/CG/RT dominated category A & B habitats on west & south coasts.
Hall Island	Scattered small AA/CG dominated category B habitats identified on NW tip & south coast. AA/CG category A habitat identified on W coast.
Harley Island	Two major category B cliff sites identified on east & NE coast, FG spectral class dominant.
Hayes Island	Numerous minor mixed species category B habitats detected, along the line of basaltic dykes and inland cliffs.
Hooker Island	Numerous category A & B habitats identified along south coast – all major species indicated by classification.
Jackson Island	AA/CG/FG dominated category A & B habitats identified on north coast.
Kane Island	Major AA/CG category A cliff habitats identified on north coast, and a single AA/CG category A site on the south coast.
Karl Alexander Land	Cliffs with major AA/CG dominated category A habitats identified on WSW tip.
Ladenberg Island	Significant category B habitats identified on basaltic dykes, predominantly RT/CG & mixed species spectral classes.
La Ronciére Island	Scattered AA/CG/RT dominated category A & B habitats identified on SW tip.
Leigh-Smith	Two small AA/CG/RT dominated category A habitats identified on north coast.
Levanev Island	Scattered small CG & RT dominated category B sites identified.
Luigi Island	AA/mixed species category A & B sites identified on north coast. Scattered AA/UL/CG dominated category A cliff habitats identified on south coast. Some sites show distinct zonation with AA/UL/CG on coastal cliff & UL on inland crags.
Mabel Island	8 major uncited category A habitats identified on west and north coasts, spectral classes representing all major species identified.
Matilda Island	Dense AA/mixed species category A site identified.
McClintock Island	Numerous scattered category B mixed species habitats identified on north & NE coasts.
McGee Island	Minor AA/CG category B habitats identified.
Nansen Island	Numerous scattered category B habitats identified on N coast (mostly low density AA & LH classes). Major category A habitat identified on E coast, dominated by dense AA colony spectral class.
Newcombe Island	Minor category B habitats identified on NE coast, dominated by AA spectral class.
Northbrook Island	Major mixed species category B habitats identified on south coast and NE tip.
Ommanney Island	Small category B habitats identified, FG & CG spectral classes dominant.
Payer Island	8 major AA/RT dominated category A & B habitats identified on NE tip, along the line of two basaltic dykes.
Pritchett Island	Major mixed species category A habitats on south & east coasts, and one CG dominated category A habitat location on NE coast.
Pontrimoli Islands	Minor LH/CG/AA dominated category A habitats identified.
Prince George Land	Numerous mixed species category B habitats identified on southern part of island.
Royal Society Islands	AA/mixed species category A habitats identified on south coast of largest island.
Salisbury Island	Scattered AA/CG habitats identified on southern coast. Several major category A sea cliffs detected on SW coast, showing strongly developed stratification (high crags UL/CG dominated, main cliff & talus slope AA dominated spectral classes). Several mixed species category B habitats identified along the line of basaltic dykes on the northern Coast.
Wilczek Land	Scattered minor category B sites identified. CG, FG, AA & LH spectral classes detected, CG dominant. CG dominated category A habitats identified on NW coast.
Wiener Neustadt	Mixed species category B habitat identified on western tip.
Wilton Island	Significant AA/mixed species category B habitats identified, and minor category A habitats.
Windward Island	Major AA/mixed species category A habitat identified.
Ziegler Island	Dense mixed species category A & B habitats identified on NW tip. Several isolated mixed species category B habitats identified on SW coast, along the line of basaltic dykes.
Zub Island	Small AA/mixed species category B habitat identified.

planning ecological protection zones in remote arctic regions where accessibility is restricted.

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