Polar Biol (2000) 23: 545–549

ORIGINAL PAPER

Simon Chamaillé-Jammes · Christophe Guinet
Frédéric Nicoleau · Marie Argentier

A method to assess population changes in king penguins: the use of a Geographical Information System to estimate area-population relationships

Accepted: 7 February 2000

Abstract During the last decades, king penguin (*Aptenodytes patagonicus*) populations have been reported to increase throughout most of their breeding range. In this study, we compared the results obtained from direct counts of incubating king penguins with the results yielded by the estimation of the change in area occupied by breeding birds at the Ratmanoff king penguin colony at the Kerguelen Islands. The area of the colony was determined using a Geographical Information System with a georeferencing extension on aerial pictures taken in 1963, 1985 and 1998. Individual king penguin were counted on the same pictures or pictures taken on the same day. The overall population increase between 1963 and 1998 was 733% while the colony area increased by 677%. This study indicates that monitoring change in colony size is a good indicator for detecting and monitoring large population changes in king penguins, in particular for remote colonies. The discrepancy between the two results may be from two different kinds of bias. Firstly, there could be a possible error in the estimation of the area occupied by the colony resulting from the georeferencing of oblique pictures, and secondly, the density of king penguins may also change with population number. This method, which only requires high-altitude pictures, also reduces the possible disturbance to breeding made by low- to medium-altitude flights.

S. Chamaillé-Jammes · C. Guinet (✉)
Centre d'Etudes Biologiques de Chizé,
CEBC-CNRS,
79360 Villiers en Bois, France
e-mail: guinet@cebc.cnrs.fr
Fax: +33-5-49096526

F. Nicoleau · M. Argentier
Institut atlantique d'aménagement des territoires,
Téléport 4 Antares, Avenue du Téléport-BP 70 130,
86961 Futuroscope Chasseneuil Cedex, France

F. Nicoleau
UFR Sciences fondamentales et appliquées,
Université de Poitiers, France

M. Argentier
Société SPOT Image, Toulouse,
16 bis avenue Edouard Belin, BP 4359,
31 030 Toulouse Cedex, France

Introduction

Increases in populations of king penguins (*Aptenodytes patagonicus*) have been reported at all breeding localities where long-term census data were available (see Woehler and Croxall 1997 for review): the Kerguelen Islands (Weimerskirch et al. 1989), South Georgia (Lewis Smith and Tallowin 1979), Macquarie Island (Rounsevell and Copson 1982), Heard Island (Gales and Pemberton 1988), and the Crozet Islands (Barrat 1976; Weimerskirch et al. 1992; Guinet et al. 1995).

At the Kerguelen Islands (49°S, 70°E), the total breeding population of king penguins was estimated to be about 173,000 incubating pairs in January 1985 (Weimerskirch et al. 1989). This demonstrates a considerable increase from the previous studies. Derenne et al. (1974) estimated that in the early 1970s less than 30,000 pairs of king penguins were breeding at Kerguelen Island. In mid-January 1963, Bauer (1967), from an aerial picture, counted 12,800 king penguins breeding on the Ratmanoff colony. In mid-January 1985, 52,414 king penguins were counted at the Ratmanoff colony from aerial pictures (Weimerskirch et al. 1989).

In most penguin studies, population numbers have been determined from direct counts of individuals on sites or on photographs (Croxall et al. 1988; Weimerskirch et al. 1989, 1992; Woehler and Riddle 1998). However this method has some disadvantages, such as the time needed to count several tens of thousands of king penguins, and the stressful conditions imposed on incubating penguins by low- to medium-altitude flights, which are required to allow a sufficient photographic resolution for the individual counts. Some authors applied, more recently, an alternative remote sensing method based on assumptions of a constant area-population relationship, i.e. density, using aerial photography or satellite pictures (Schwaller et al. 1986, 1989; Bhikharidas et al. 1992; Guinet et al. 1995). Some penguin species breeding in large colonies with individuals regularly spaced appear suitable for the use of this method.

We conducted a recent direct census at one site, the Ratmanoff king penguin colony (Kerguelen Island), to assess population changes over the last four decades. Furthermore, we tested the reliability of the remote sensing method in that species by comparing population changes assessed by direct counts with changes in colony surface area estimated from aerial photography using a Geographical Information System (GIS).

Materials and methods

The direct censuses were conducted by making individual counts of all breeding birds on aerial images taken in early January 1963 (i.e. breeding cycle 1962/1963) by the IGN (Institut Geographique National, Paris), in mid-January 1985 (i.e. breeding cycle 1984/1985) by H. Weimerskirch and mid-December 1998 (i.e. breeding cycle 1998/1999) by T. Micol. The IGN photograph was taken vertically from approximately 1000 m flight altitude. The flight altitude in 1985 and 1998 was approximately 500 m but these two photographs were oblique, particularly the 1998 one.

Colony surface areas were obtained from the same photographs used for direct counts (1985) or from photographs taken on the same day from a higher altitude flight (1963 and 1998). Photographs were integrated into a Geographical Information System, ArcViewGIS (ESRI). Photographs taken in 1963 and 1985 were georeferenced, i.e. latitude/longitude co-ordinates were attributed to each pixel of the image, using the ERDAS Imagine 8.3.1 and a SPOT Image satellite image already georeferenced. The satellite images (P and XS) were taken in mid-January 1995. We made a "P + XS" image and with this map reference georeferenced the IGN aerial photograph taken in 1963. The GIS can be used to georeference a picture when at least four points are given geographical co-ordinates. Georeferencing was done by extracting geographical co-ordinates of a pixel in a georeferenced picture and attributing the same co-ordinates to a pixel in a non-georeferenced picture. The 1963 and 1985 images show large areas around the colony of king penguins, i.e. on the west side, ground, rocks, and lakes, and on the east side, ocean, beach, and coast. These natural permanent geographical elements were used to find exactly the same points from the 1995 georeferenced Spot image, allowing the 1963 and 1985 images to be georeferenced in X and Y. Once georeferenced, the 1963 picture was then used to georeference the 1998 aerial pictures, by using natural permanent ground marks to find exactly the same point on the two necessary photographs. Photographs taken in 1998 were georeferenced using ArcViewGIS with the Géoref-Image (Data-Image) extension.

The georeferencing allows the rectification of pictures that are not taken vertically and from unknown altitude. The boundaries of the colony are easily identified as there is a clear limit between the breeding colony and the surroundings and incubating birds are generally spatially segregated from the non-breeding birds. Furthermore, the regular spacing of the incubating birds makes them clearly identifiable. This change of feature can be distinguished with a ground resolution of approximately 0.5 m, which is achievable with a 50-mm lens at a flight altitude of about 1000 m. Once the pictures were georeferenced, the boundaries of the colony were then hand-drawn and the surface area of the colony was calculated by the GIS. This procedure was repeated four times for each photograph taken in 1963, 1985 and 1998. A small portion of the northern part of the colony was lacking on the photograph taken in 1998, so we drew this part of the map using ground marks from an oblique photograph taken the same day.

The intrinsic annual exponential rates of increase were calculated using the formula $N_{tn} = N_{t0}e^{rt}$, where N_{t0} is the number of individuals or the surface area occupied by the colony at the first count, N_{tn} the number of penguins or surface area of the colony at the second count, t the number of years elapsed between $t0$ and tn and r the intrinsic annual rate of increase, which was converted to an annual percentage change by:

$$r(\%) = [(\text{Log}\,N_{tn} - \text{Log}\,N_{t0})/(t)] \times 100$$

Results are given as the mean ± standard deviation and the coefficient of variation.

Results

The surface area of the colony and the number of birds counted in 1963, 1985 and 1998 on the Ratmanoff colony are given in Table 1. Assuming no errors in the number of penguins counted, we calculated penguin density for each year by dividing the number of breeders obtained from the direct census by the area calculated with the GIS (Table 1). Over the whole study period the estimated density was found to range between 1.66 and 1.91 birds/m^2 with a mean of 1.72 ± 0.07 ($n = 12$).

Once georeferenced, boundaries of the colony in different years could be perfectly superimposed (Fig. 1). For each year, the boundary of the colony with the closest value from the mean value was drawn (Fig. 1). The spatial extent and shape of the colony varied during the period of the study (Fig. 1). In 1963 the colony was present only at the north of the overflow. Between 1963

Table 1 Number of king penguin pairs counted for each study year, estimated surface areas of the colony and the calculated density for the Ratmanoff colony

Breeding cycle	1962/1963		1984/1985		1998/1999	
Counted birds	12,800		52,414		106,583	
	Area (m^2)	Density (birds/m^2)	Area (m^2)	Density (birds/m^2)	Area (m^2)	Density (birds/m^2)
Area 1	7695	1.66	31,629	1.66	63,442	1.68
Area 2	7600	1.68	31,157	1.68	57,738	1.85
Area 3	7565	1.69	30,436	1.72	55,688	1.91
Area 4	7536	1.70	30,950	1.69	59,308	1.80
Mean	7599	1.69	31,043	1.69	59,044	1.81
SD	69	0.02	494	0.03	3285	0.10
CV (%)	0.9	0.9	1.6	1.6	5.6	5.4

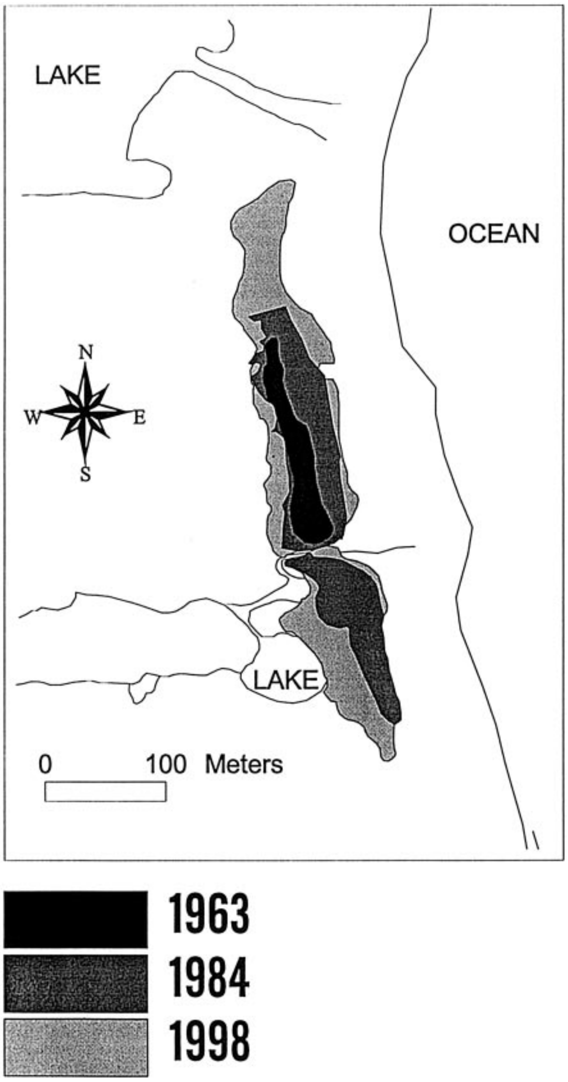

Fig. 1 Change in the surface area occupied by the Ratmanoff king penguin colony from 1963 to 1998

and 1985 the colony had extended 30 m to the east (towards the sea) and about 280 m to the south, and in 1985 nearly half of the colony was located south of the overflow. Between 1985 and 1998 the colony boundaries extended 195 m to the north, slightly to the west and south but not towards the sea (east).

The direct censuses indicate that the overall increase in breeding king penguin numbers was 733% between 1963 and 1998 (Table 1). Between 1963 and 1985, the colony increased by 310%, and by only 103% between 1985 and 1998. This corresponds to a decrease of the annual intrinsic rate of increase (*r*) from 6.4% between 1963 and 1985 to 5.1% between 1985 and 1998.

The surface area occupied by the colony increased by 677% between 1963 and 1998 (Table 1). This rise was 309% between 1963 and 1985, and 90% between 1985 and 1998. This corresponds to a decrease of the annual rate of increase from 6.4% between 1963 and 1985 to 4.6% between 1985 and 1998.

Discussion

Assessing the colony surface area using a GIS to monitor changes in population size

Estimating the surface area occupied by the colony from aerial pictures using a GIS procedure is a fast and easy technique in theory. However, georeferencing is the key step of this method. Photographic sources of co-ordinates for georeferencing must have at least four notable permanent points that can be precisely situated on the picture to georeference. We found that oblique photographs taken in 1985 and 1998 were more difficult to georeference correctly, as indicated by the higher coefficient of variations of the surface area estimate found between the different trials for the oblique 1985 picture and the even more oblique 1998 picture compared to the 1963 vertical IGN picture. The best way to improve this method is to place on the ground around the colony several fixed marks whose geographical co-ordinates are known, using a differential GPS for instance, and to use photographs that were taken as vertically as possible.

The detection of population changes using this technique is dependent on assumptions of area-population relationships, i.e. on the variability in space and/or time of density. Very few studies have reported densities of breeding penguins. Bauer (1967) used estimated densities of macaroni penguins (*Eudyptes chrysolophus*) and king penguins (respectively, 1.8 ± 0.2 and 1.6 ± 0.2 birds/m^2) to assess population sizes at different localities, assuming a constant density in space. King penguins breed in flat open areas and do not build nests. Therefore the only spatial constraint within a colony is the distance between neighbours, as king penguins express aggressive territorial behaviour during incubation, fighting with theirs beaks and flippers without moving. We estimated the theoretical density, assuming that the territory of each individual is a perfect circle with a radius (0.42 m) equal to an average flipper length (0.32 m, Weimerskirch et al. 1989) plus half of the body width (assuming that value to be 0.10 m) and that territories are contiguous. We thus determined the distribution of exclusive territories, allowing the highest density of incubating king penguins. Thus, at the highest theoretical density, three contiguous penguins should be on each of the summits of a 0.84-m-sided isosceles triangle. We thus calculated the area of the smallest triangle containing three territories, which allowed us to obtain this theoretical density. The calculated theoretical density is 1.67 birds/m^2, a value that is consistent with the range of densities found at the Ratmanoff colony in our study.

Our study shows that values of the intrinsic rate of increase (*r*) estimated by direct censuses or by surface-area calculation are similar and we conclude that breeding population size and surface area occupied by the breeders are strongly related. This result is consistent with that found in Adélie penguins (*Pygoscelis adeliae*) where change in colony size explained 96.4% of the variance in colony populations but pair density was found to rise with population size (Woehler and Riddle 1998). This change in density with population number may be the reason for the discrepancy we found between the rate of population change calculated from the number of king penguins counted and that calculated from the surface area of the colony between 1985 and 1998. In our study, the variation in density could result from two different causes. The first may result from a real change of the density in relation to population number, while the second may be related to an error in the estimation of the surface area resulting from the difficulty of georeferencing oblique pictures, as indicated by the increase of the coefficient of variation observed for the 1985 and 1998 oblique pictures compared to the 1963 vertical picture.

Future studies should investigate, not only if density of king penguins changes with population numbers, but also density for a given year within the colony (i.e. periphery vs within the colony) and between colonies, as found in Adélie penguins (Woehler and Riddle 1998).

Pictures were taken in December or early January, when the surface area occupied by incubating penguins is at maximum. Nevertheless, Weimerskirch et al. (1992) showed that, at this time, the number of breeding king penguin at Possession Island can vary significantly from one year to another, sometimes nearly 20%, although these changes are not part of any long-term trends. The lack of breeding individuals in a particular year can result from a lower number of birds having reached breeding condition, probably because of reduced food availability during the winter and early spring (Weimerskirch et al. 1992).

However, monitoring of colony surface area using aerial photographs integrated in a GIS, an easy and time-saving method, appears to be an efficient way of determining large interannual changes, as well as medium- to large-scale changes in population sizes of king penguins. Ground surface area of the colony can be determined from the use of high-altitude photographs where colony boundaries are visible but individual penguins are indistinguishable from each other. This reduces the disturbance to breeders induced by low- to medium-altitude flights.

The surface area of the colony can be assessed by using tools other than aerial pictures. The use of a theodolite allows the precise drawing of the colony boundary (C. Guinet, S. Chamaillé-Jammes, E. Hervé). This technique allows us to take into account the relief of the colony and thus its real surface, and not only its projection on a plane as we did by using aerial pictures. In our study this was not a problem as the Ratmanoff colony is located on a flat area. Another very promising technique is the use of a differential GPS to define the contour of the colony. This technique allows a very precise georeferencing (centimetres) of the colony in three dimensions (latitude, longitude and altitude).

These methods are likely to be used for other species of penguins breeding in large colonies, such as Adélie penguins, chinstrap (*P. antarctica*) and also macaroni (*E. chrysolophus*) and royal (*E. schlegeli*) penguins. However, it is crucial to assess how density may change with population number, colony soil (bare rocks, blocks, boulder, sand) and relief.

These new approaches allow us to address some additional issues that are not studied here, such as the spatial dynamics of the colonies and the impact of penguins on vegetation when populations are either increasing or decreasing.

Patterns and causes of long-term trends in population changes of king penguins

During the last decades, king penguin populations have increased through most of their breeding range, and we show in this study a rise from 12,800 breeders in 1962/1963 to 106,583 in 1998/1999 at the Ratmanoff colony, which is the greatest long-term increase reported in all breeding localities where censuses have been carried out. This colony is the largest of the Kerguelen archipelago. Similar trends were observed for the Cap Digby colony, with an overall increase of 981% from 1962/1963 to 1998/1999 (Table 2). Similar to the Ratmanoff colony, the annual intrinsic rate of increase was higher between 1962/1963 and 1984/1985 breeding cycles (7.2%) than between 1984/1985 and 1998/1999 breeding cycles (4.9%). The total number of breeding pairs of king penguins at Kerguelen Island in 1998/1999 was estimated to be about 342,000 pairs, if we extrapolate the average annual intrinsic rate of increase we found for the Ratmanoff and Cap Digby colonies between 1984 and

Table 2 The sizes of king penguin breeding colonies on the Kerguelen Islands (number of breeding pairs in January). For 1998/1999 the numbers in *bold type* are from the colonies where counts were conducted and the numbers in *square brackets* were estimated from the previous census and using an annual growth rate of 5% for the 1981–1999 period

Locality	1962/1963	1972/1973	1981/1982	1984/1985	1986/1987	1998/1999
Ratmanoff	12,800[a]			52,414[c]		**106,583**
Cap Digby (north)	2800[a]			19,222[c]		**35,530**
Cap Digby (south)	4600[a]			17,175[c]		**37,100**
Baie Larose		3000[b]		21,491[c]		[43,300]
Feu de Joie Beach (north)					30,595[c]	[55,700]
Feu de Joie Beach (beach)					9407[c]	[17,100]
Telluromètre Valley			20,000[c]			[46,800]
Estimated total						342,113

[a] Bauer (1967)
[b] Derenne et al. (1974)
[c] Weimerskirch et al. (1989)

1985 (5%) to the colonies which have not been counted since 1982 (Table 2).

Several reasons were put forward to explain the rapid increase of king penguin populations in all subantarctic islands (see Woehler and Croxall 1997 for review). Conroy and White (1973) and Rounsevell and Copson (1982) suggested that king penguins have been recovering from past exploitation in the nineteenth and early twentieth centuries. Furthermore, myctophids (*Electrona carlsbergi*, *Krefftichtys anderssoni*, *Protomyctophum tenisoni*), which are the main prey of king penguins all over their foraging range (Cherel and Ridoux 1992; Bost et al. 1997; Geoffrey et al. 1998), appear to have stocks enhanced by the large crustacean biomass freed due to the almost complete extermination of large baleen whales in subantarctic waters that took place during the mid-twentieth century. Some authors (Conroy and White 1973; Rounsevell and Copson 1982) suggested that this increase in food supply availability has greatly benefited king penguins, and it probably could explain the observed increase in adult survival and breeding success (Weimerskirch et al. 1992).

Data both from direct censuses and from monitoring the change in the surface area suggest that the intrinsic annual rate of increase calculated between 1985 and 1998 is lower than the annual rate of increase calculated over the 1963–1985 period. The most obvious cause for this reduction is probably food competition between king penguins during the breeding season (Jouventin et al. 1994) but also direct or indirect competition with other top marine predators such as fur seal and baleen whales; the fisheries do not appear to be a direct cause as neither the crustacean preys of the myctophids nor the myctophids themselves have been, or are presently, commercially exploited.

Acknowledgements We are very grateful to SPOT Image, who have allowed us to use images for our methodology research. We thank Henri Weimerskirch and Thierry Micol for taking the pictures and Sylvie Caule, Géraldine Mabille, Murielle Gesthem and Delphin Ruché for counting penguins on the 1998 photograph. This work was supported by the Institut Français pour la Recherche et la Technologie Polaires and by the GDR 1069 CNRS "Ecosystèmes Polaires et Anthropisation". We also thank three anonymous referees for their constructive comments.

References

Barrat A (1976) Biologie et écologie du manchot royal ā Crozet. Comité National Français des Recherches Antarctiques, N° 40

Bauer A (1967) Dénonbrement des manchotières de l'Archipel des Crozet et des Iles Kerguelen à l'aide de photographies aeriennes verticales. Terres Australes et Antarctiques Françaises, 1–15

Bhikharidas AK, Whitehead MD, Peterson JA (1992) Mapping Adélie penguin rookeries in the Vestfold Hills and Raver Islands, East Antarctica, using SPOT HRV data. Internation J Remote Sens 13: 1577–1583

Bost CA, Georges JY, Guinet C, Cherel Y, Pütz K, Charrassin JB, Handrich Y, Zorn T, Lage J, Le Maho Y (1997) Foraging habitat and food intake of satellite-tracked king penguins during the austral summer at Crozet Archipelago. Mar Ecol Prog Ser 150: 21–33

Cherel Y, Ridoux V (1992) Prey species and nutritive value of food fed during summer to king penguin *Aptenodytes patagonica* chicks at Possession Island, Crozet Archipelago. Ibis 134: 118–127

Conroy JWH, White MG (1973) The breeding status of the king penguin *Aptenodytes patagonicus*. Br Antarct Surv Bull 32: 31–40

Croxall JP, McCann TS, Prince PA, Rothery P (1988) Reproductive performance of seabirds and seals at South Georgia and Signy Island, South Orkney Islands 1976–1986: implications for Southern Ocean monitoring studies. In: Sahrage D (ed) Antarctic Ocean and resources variability. Springer, Berlin Heidelberg New York, pp 261–285

Derenne P, Lufbery JX, Tollu B (1974) L'avifaune de l'archipel Kerguelen. CNFRA 33: 57–87

Gales R, Pemberton D (1988) Recovery of the king penguin *Aptenodytes patagonicus* population on Heard Island. Aust Wildl Res 15: 579–585

Geoffrey JM, Robertson G, Wienecke B (1998) Food requirements of breeding king penguins at Heard Island and potential overlap with commercial fisheries. Polar Biol 20: 293–302

Guinet C, Jouventin P, Malacamp J (1995) Satellite remote sensing in monitoring change of seabirds: use of Spot Image in king penguin population increase at Ile aux Cochons, Crozet Archipelago. Polar Biol 15: 511–515

Jouventin P, Capdeville D, Cuenot-Chaillet F, Boiteau C (1994) Exploitation of pelagic resources by a non-flying seabird: satellite tracking of the king penguin throughout the breeding cycle. Mar Ecol Prog Ser 106: 11–19

Lewis Smith RI, Tallowin JRB (1979) The distribution and size of king penguin rookeries on South Georgia. Br Antarct Surv Bull 49: 259–276

Rounsevell DE, Copson GR (1982) Growth rate of a king penguin *Aptenodytes patagonicus* population after exploitation. Aust Wildl Res 9: 519–525

Schwaller MR, Olson CE Jr, Benninghoff WS, Wehnes KM (1986) Preliminary report on satellite remote sensing of adelie penguin rookeries. Antarct J US 21: 205–206

Schwaller MR, Olson CE Jr, Ma Z, Zhu Z, Dahmer P (1989) Remote sensing analysis of adelie penguin rookeries. Remote Sensing Environ 28: 199–206

Weimerskirch H, Zotier R, Jouventin P (1989) The avifauna of the Kerguelen Islands. Emu 89: 15–29

Weimerskirch H, Stahl JCJ, Jouventin P (1992) The breeding biology and population dynamics of king penguins *Aptenodytes patagonicus* on the Crozet Islands. Ibis 134: 107–117

Woehler EJ, Croxall JP (1997) The status and trends of Antarctic and sub-antarctic seabirds. Mar Ornithol 25: 43–66

Woehler EJ, Riddle MJ (1998) Spatial relationships of Adélie penguin colonies: implications for assessing population changes from remote imagery. Antarct Sci 10: 449–454