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The use of drone-based aerial photogrammetry in population monitoring of Southern Giant Petrels in ASMA 1, King George Island, maritime Antarctica

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ABSTRACT

Southern Giant Petrels (SGPs) are surface nesting birds with a circumpolar Southern Hemisphere breeding distribution. The species tends to have no natural enemies on land, but is sensitive to human disturbance. The search for new methods is crucial and may minimize or exclude stress and risk of nest disturbance, related to ground-based research activities. The aim of this study was to conduct a population census of the SGP of the Antarctic Specially Managed Area no. 1 (ASMA no. 1), Admiralty Bay, King George Island, using an unoccupied aerial system (UAS) based on aerial photogrammetry and to determine the optimal parameters of the aerial mission for the identification of SGP adults and chicks on orthophotos while simultaneously not causing behavioural changes. To this end, in a preliminary survey in the 2019/20 season, the locations of all breeding areas for SGPs in ASMA no. 1 were determined, and the presence of 3 colonies, Llano Point/Rescuers Hills (LP/RH), Vaureal (V) and Petrel Hill (PH), was confirmed. Terrain models for two of the colonies (LP/RH and V) were established, and the flight parameters for the next season were determined. In 2020/21, a total of 23 (DJI Inspire 2 with a Zenmuse X5S camera) drone missions were performed at various stages of the breeding period over the LP/RH and V colonies. This assessment yielded estimation of the number of active nests and chicks over the entire ASMA no. 1 area, and included 508 active nests and 380 chicks for the 2020/21 season. To determine the minimum flight altitude at which no SGP behavioural response was observed, an experiment was performed that showed the vertical distance between the potential nest of SGP and the drone should be greater than 21 m given that lowering the altitude yielded statistically significant differences in bird behaviour. Image analyses showed the possibility of identifying adults and chicks at a ground sampling distance of 2.15 cm, which corresponded to an altitude of 130 m based on the equipment used and the terrain characteristics. The proposed method requires several missions during the incubation phase to determine a reliable number of active nests without using correction factors. To obtain a nesting success factor, it is recommended to perform at least one raid in the post-brooding phase of chick rearing (when the chick is not covered by an adult and is visible in orthophotos). The proposed method is not able to replace traditional methods in the context of many ongoing surveys, but we believe that it may provide a less bird-invasive, human-intensive and time-consuming option to replace ground-based census surveys.

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1. Introduction

The Southern Giant Petrel *Macronectes giganteus* (SGP) is considered a species of 'least concern' according to the International Union for Conservation of Nature (IUCN) guidelines (BirdLife International, 2021). The SGP is recognized as the dominant scavenging seabird species in maritime Antarctic (Conroy, 1972). Warham (1962) characterized the species as a 'surface nester, too large for natural enemies to attack it when ashore'; however, despite the lack of natural enemies, SGP is a bird that tends to be susceptible to human disturbance (Agreement on the Conservation of Albatrosses and Petrels, 2010). Moreover, eggs and chicks may fall prey to skuas, sheathbills and other giant petrels (Conroy, 1972). The phenology and biology of this species was thoroughly studied decades ago (Warham, 1962; Conroy, 1972; Jabłoński, 1986; Voisin, 1988), however, the authors of those studies emphasised the extremely high environmental cost of such projects.

According to Conroy's (1972) report on the SGP colony from Signy Island, human disturbance caused very high chick mortality (90% in 1967, 62% in 1968, 67% in 1969) and interference was so great that data collected from the intensive study areas were not used in survival analyses. Intensive scientific activity, associated with banding and morphometric measurements, was also responsible for egg losses. Conroy (1972) reported that adult birds released after ringing did not return to the nest immediately, resulting in a high percentage of egg losses caused by skuas. In 1966, 30 of 41 eggs abandoned were hunted by predators. Treatments applied the following year to cover the abandoned eggs with fragments of nesting material reduced the percentage of egg loss. Specifically, of 183 eggs, 81 were hunted by predators (Conroy, 1972). Jabłoński (1986) also admitted that in the 1978 season, successful breeding was observed at only 50 of 102 active nests at the Rescuers Hills/Llano Point colony on King George Island, and they attributed the high failure rate to scientific activities that caused birds to escape from incubated nests. Warham (1962) whose investigations occurred on Macquarie Island in seasons from 1959 to 61, reported that many incubating SGPs deserted eggs after human approach and emphasized the high susceptibility of SGPs to being frightened by humans. Therefore, Warham recommends hiding while observing to obtain behavioural data. Bird species of the order *Procellariiformes*, including SGPs, are capable of producing stomach oils with high energy content in proventriculus (Foster et al., 2020) used by birds as a food source for chicks and an energy reservoir enabling them to exploit marine nutrients sources and survive harsh weather conditions (Warham, 1962). When threatened, stomach contents can be ejected by birds, including both adults and chicks, as a defensive measure, resulting in a significant loss to the birds as they lose a source of energy (Warham, 1977). Some works have examined the effects of human disturbances on heart rate and the associated metabolism in incubating albatrosses and petrels. Weimerskirch et al. (2002) reported that the heart rate of wandering albatrosses doubles when human presence is first detected. de Villiers et al. (2006) used heart rate to measure the response of northern giant petrels to human approach and subsequent nest manipulation. The birds' heart rates increased upon detection of a human at a distance of 40 m and continued to increase with the gradual approach of man.

Significant advances in technology in recent years have brought opportunities to minimize or completely reduce the invasiveness of research methods. For example, automatic ground cameras mounted at SGP colonies have been successfully used to monitor breeding phenology (Otovic et al., 2018). In addition, unoccupied aircraft systems (UASs, also called drones) are increasingly being used to monitor bird populations (Lyons et al., 2018; Edney and Wood, 2021; Gallego and Sarasola, 2021), proving that this method is more effective and has a less negative impact on some bird species than do direct observations (Borrelle and Fletcher, 2017; Valle and Scarton, 2020; Krause et al., 2021); however, there are still no legally regulated standards for drone use (Vas et al., 2015; Duffy et al., 2018; Barnas et al., 2020) or flight parameters, so the discussion on this topic at the scientific level is still open (Rümmler et al., 2016; Hodgson and Koh, 2016; Barr et al., 2020). The use of UASs is also considered an option for SGP monitoring (Mustafa et al., 2018; Weimerskirch et al., 2018; Dunn et al., 2021). However, as observed by Weimerskirch et al. (2018), northern giant petrels showed the strongest behavioural response to the presence of the drone. Although the SGPs react less nervously than northern giant petrels, imperial cormorant or brown skua, SGPs were still identified as one of the species most susceptible to stress among the eleven sub-Antarctic seabirds tested in the study. It should be noted, however, that Weimerskirch at al. (2018) approached birds at vertical distances of 3, 10, and 25 m which are short distances. Despite the close distance, sooty albatross showed minimal behavioural responses even when the drone was at the distance of 3 m. Similar experiments with close (4 m) ranges did not seem to disturb birds, such as wild flamingos and greenshanks, as reported by Vas et al. (2015). These researchers did not observe visibly modified behaviour due to the presence of drones and suggested that when used with care, drones can be employed in ornithology for a wide range of observations.

It is extremely challenging to investigate a species as sensitive to human presence as SGPs are, and therefore, there are still gaps in knowledge about the at-sea distribution and survival rates of chicks and adults (Agreement on the Conservation of Albatrosses and Petrels, 2010). Due to the factors complicating the performance of censuses (e.g., high sensitivity of the species or logistical difficulties resulting from conducting surveys under Antarctic or sub-Antarctic conditions), the census procedure has not been standardized (Patterson et al., 2008; Agreement on the Conservation of Albatrosses and Petrels, 2010). The global population size of SGPs has been estimated (based on data from 2005 to 2007) by Poncet et al. (2020) as 50,819 pairs, and BirdLife International (2021) reported the population size of SGPs to be 95,600–108,000 mature individuals. According to Patterson et al. (2008), the South Shetland population is 5409 breeding pairs. For Admiralty Bay, the most recent data were reported by Petry et al. (2016). However, these researchers did not include the areas of the Petrel Hill, Rescuers Hills and Llano Point colonies in the censuses they conducted, and only report data for Vaureal colony, which included 60 breeding pairs in the 2011/2012 season based on their observations. The most recent complete data for Admiralty Bay on the SGP breeding population size is from 1996 (Sierakowski et al., 2017). The number of nests reported for the area of Admiralty Bay varied from 243 to 456 between 1979 and 1996 (Sierakowski et al., 2017), but the current status of the population is unknown.

The main objective of this research was to propose a procedure for monitoring the SGP population using UASs. To establish the optimal timing for performing censuses using this method, a series of photogrammetric missions were performed over the colony area at different stages of bird breeding. The proposed method was used to improve our knowledge about the size and distribution of the breeding population of SGPs in Admiralty Bay. An additional aim of the study was to perform an experiment to investigate the effect of drone presence on SGP responses and to determine the flight altitudes for the drone. In this context, the drones did not disturb animals but still allowed for the easy identification of adults and SGP chicks from orthophoto imagery. In addition, the height from which we could easily identify bird behaviour was determined.

2. Materials and methods

2.1. Study sites

The study area included the entire ice-free shoreline of Admiralty Bay (62°10′S 58°25′W), the largest bay within King George Island, part of the South Shetland archipelago in maritime Antarctica (Fig. 1). Due to its unique environmental, historical, scientific and aesthetic value, the entirety of Admiralty Bay has been established as Antarctic Specially Managed Area no. 1 (ASMA no. 1). The revised total area of both terrestrial and marine areas of ASMA no. 1 is 360 km^2 (Management Plan for Antarctic Specially Managed Area No.1, 2014). Additionally, the region includes (wholly terrestrial) Antarctic Specially Protected Area "Western Shore of Admiralty Bay" (ASPA no. 128) (Management Plan for Antarctic Specially Protected Area No. 128, 2019) and two Important Bird Areas (IBAs no. 045 and 046) (Harris et al., 2015; Fig. 1).

2.2. Field work

The field work was divided into two seasons: 2019/2020 and 2020/2021.

First, during the 2019/2020 season, the locations of SGP breeding colonies on ASMA no. 1 were verified. All potential (both known from the literature and those showing potential in terms of site conditions) localities of SGP colonies were inspected during the pre-laying period by an observer with ground searching methods and from the sea surface with the use of boat and optical equipment. During the 2019/2020 breeding season, SGP breeding colonies were found at three major locations in ASMA no. 1: Rescuers Hills and Llano Point (treated as a single colony, Fig. 1), Cape Vaureal, and Petrel Hill (Fig. 1). Previous literature sources (Jabłoński, 1986; Sierakowski, 1991; Sierakowski et al., 2017) also listed three locations that overlapped with those found in the current study (Fig. 2). The nomenclature that is based on colloquial place names can be confusing to the uninitiated reader; therefore, the colony located at Petrel Hill refers to the part of the previous larger colony located at Point Thomas oasis, which extends from Ecology Glacier to Thomas Point located south of the entrance to Ezcurra Inlet in Admiralty Bay (Fig. 1). The whole Point Thomas colony, which in Trivelpiece et al. (1980) was called Point Thomas West colony in 1977/1978, had 40 nesting pairs (Trivelpiece et al., 1980), including 19 on Petrel Hill (Jabłoński, 1986); however, in 1988, there were only 18 nesting pairs in the whole area, including 17 on Petrel Hill, of which only

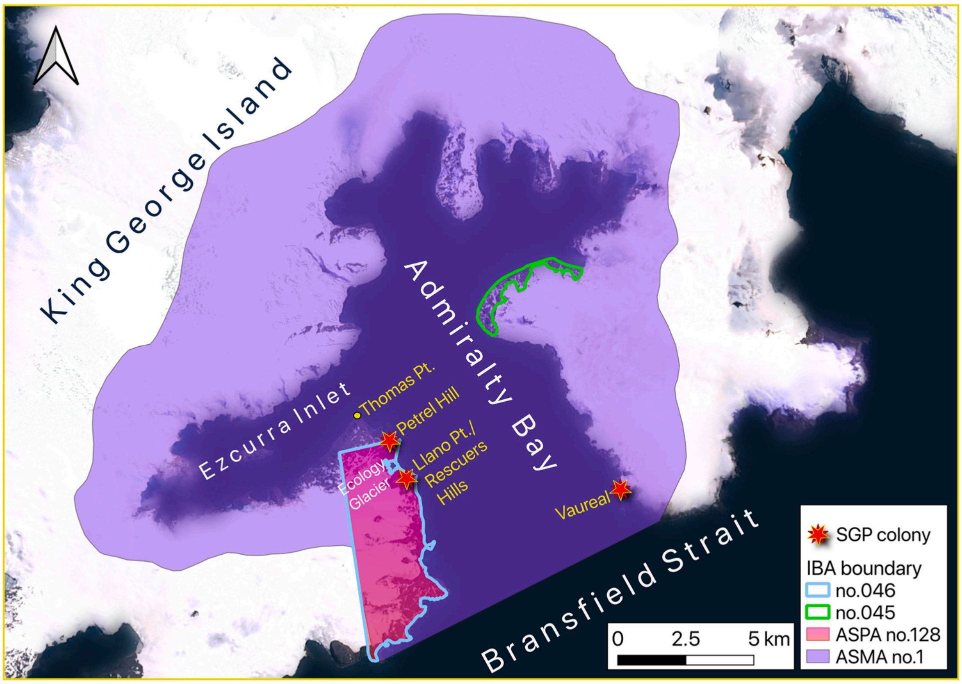

Fig. 1. Study site.

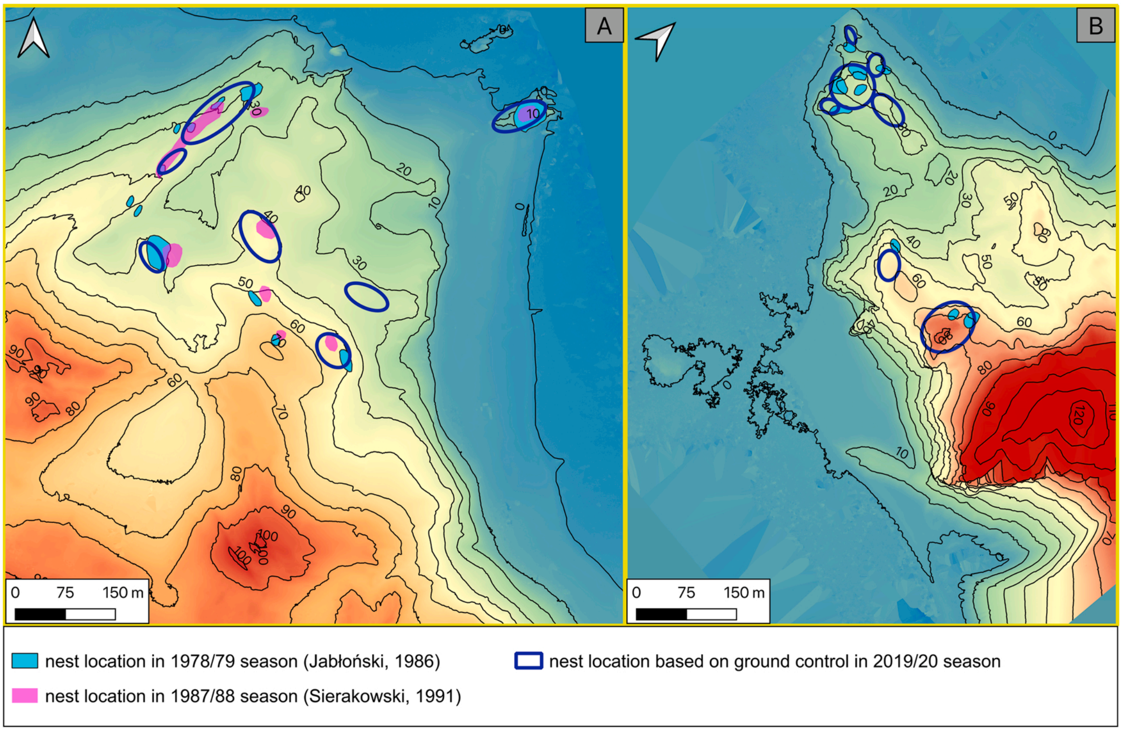

Fig. 2. Hypsometric maps (based on 3D drone missions) of Rescuers Hills/Llano Point colony (A) and Cape Vaureal colony (B) with historical data on the locations of SGP breeding groups.

6 pairs bred successfully (Sierakowski, 1991). In subsequent years, breeding attempts within the Point Thomas colony were made only on Petrel Hill, with no breeding success observed at this colony in the 2018/2019 and 2019/2020 seasons.

At the other two identified locations (Vaureal and Llano Point/Rescuers Hills), in the 2019/2020 season, 3D UAS missions were conducted from a height of 200 m (which was identified by Harris et al., 2019 as the minimal flight distance with no proven disturbance by UAS to SGP) to investigate site conditions and determine the optimal photogrammetry mission heights for the next season. The analysed area was characterized by a variety of elevations represented by glacial moraines and rock formations (Fig. 2). To determine the safe height of the 3D flight while also considering the terrain, the 1:100 000 topographic map of King George Island (Braun et al., 2004) was used. Breeding groups within a single colony were located at varying heights (altitude of the nests above sea level), including from 23 m to 52 m for Rescuers Hills (Fig. 2A), from 9 m to 18 m for Llano Point (Fig. 2A) and from 10 m to 85 m for Cape Vaureal, with two nesting groups clearly identifiable for the situated colony: the first (located N-W, Fig. 2B) with nests at heights from 10 m to 35 m and the second (located S-E, Fig. 2B) with nests at heights from 52 m to 85 m. This difference made it necessary to determine the optimum height at which to carry out the raids while considering the diversity of the terrain, animal safety and optimum ground sampling distance (GSD) resolution.

In the 2020/2021 season, 23 photogrammetric missions were performed over two colonies (19 for Llano Point/Rescuers Hills and 4 for Cape Vaureal), and the flights in all colonies covered the entire breeding cycle of SGPs: pre-laying, incubating, brooding, guarding and post-guarding. According to Otovic et al. (2018), the pre-laying period is the period of pair formation, the incubating period is the period from egg laying to hatching; the brooding period is the period from hatching to the moment when the chick attains homeothermy; the guarding period is the period when at least one parent is visible next to the chick at all times; the post-guarding period is the period when the parent returns to the chick only to feed it. Sierakowski et al. (2017) reported that for the SGP colonies located in Admiralty Bay, the first egg laid was noted 31 October and 10 November, and the first chicks hatched from 31 December to 13 January based on the data from the late 1980s and early 1990s

Moreover, the UAS mission heights were adjusted to the nesting heights, which were verified by 3D missions performed in the previous season, maintaining at least a vertical distance of 50 m between the potential nest of any breeding birds in these areas and the drone (except for raids performed as part of an experiment). The operator responsible for supervising the take-off and landing of the UAS was located in a place not visible to the animals at a horizontal distance of at least 100 m from the breeding group, as suggested by Vas et al. (2015) and Weimerskirch et al. (2018). The operator started and ended the UAS flights at the same point, which was designated separately for the Llano Point/Rescuers Hills and Vaureal colonies. In our planned study, the UAS launch and landing sites were always out of sight of the SGPs.

All UAS missions were conducted using a DJI Inspire 2 drone quadcopter (black/grey body and 4 kg weight) with a Zenmuse X5S 20.8 MP camera (DJI MFT 15 mm/1.7 ASPH lens with a 30-mm-equivalent focal length; DJI, Shenzhen, Guangdong, China). The mission paths (Fig. 3) were programmed in Pix4D Capture (Pix4D S.A., Prilly, Switzerland). The drone automatically started from, returned to and landed at its home position (Fig. 3 - DRONE LAUNCH). After take-off, the drone flew at a vertical speed of 4 m/s to the flight altitude (Table 1) and then flew at a fixed altitude after take-off to the mission start point (Fig. 3 - MISSION START). The overlap of the images (Fig. 3, Table 1) was adjusted to match the length of the mission with the length of the weather window, so the number of photos taken varied (Table 1). The operator maintained eye contact with the drone at all times and took control of the drone if there was a need to land manually by changing flight modes, which also affected the number of photos taken. Of note, although the same mission was repeated many times, the area of the mission itself changed (Table 1), due to the different mission overlaps as well as other factors, such as seawater tidal height. Thus, the number of common points on the land in the images varied. This process allowed the images to be calibrated, thus, fewer images were rejected (Table 1). Although different types of UASs have been used for environmental monitoring in Antarctica, quadcopters are known to be the “least risky” to birds compared to fixed-wing devices (Egan et al., 2020). Moreover, we decided to use the DJI Inspire 2 equipped with Zenmuse X5S Gimbal Camera with 15-mm lens. The significant advantage of this model is that it allows the creation of orthophotos with higher accuracy compared with the other UASs that have already been used in Antarctica. Orthophoto accuracy and detail depend mainly on the field pixel size and resolution, which is called the ground sampling distance (GSD, Table 1). A GSD on the order of 1 cm/px is characteristic of the most accurate orthophotos, allowing for recognition of SGPs at the level of 100% (Mustafa et al., 2019). For comparison, the GSDs for images taken from a 100 m height using different DJI quadcopters with standard cameras were as follows: 4.38 cm (Phantom 3), 2.73 cm (Phantom 4 Pro), 2.34 cm (Mavic 2 Pro), and 2.21 cm (Inspire 2). The dates and technical details of the missions are shown in Table 1.

In the 2020/2021 season, we strictly followed the drone protocol proposed by Barnas et al. (2020). The UAS operators were trained before the start of the study and obtained a UAS operator qualification certificate (UAVO) issued by the Civil Aviation Authority of Poland. The operators were qualified to fly drones weighing up to 25 kg up to 2 km, which is beyond the visual line of sight (BVLOS). All experiments were approved by the Polish Antarctic Programme and performed under permit nos. 2/2019 and 2/2020 given for the period from 25 August 2019–26 February 2022.

2.3. *Experiment of behavioural response to UAS presence*

An experiment was planned for the 2020/2021 breeding season, when the chicks had already reached homeothermia (Otovic et al., 2018) and were in the guarding stage, when at least one parent was still present, usually next to the nest (Otovic et al., 2018), to demonstrate the impact of drone presence at different altitudes above adults and chicks. The experiment was performed on 20 February 2021. The five missions were performed in order of decreasing altitude above the breeding formation starting from 130 m to 30 m over a selected breeding group located on the Llano Point rock formation (Table 1). The duration of all raids was 75 min (the first photo was taken at 12:38, and the last photo was taken at 13:53), taking into account the time required for landing for battery replacement. Each mission started and ended at the same point. The determination of the height of the area occupied for nesting and the height of the planned launch site was based on the previously mentioned 3D terrain model from the previous season. The ground observer, located on a hill adjacent to the study site (with a distance of approximately 250 m from the Llano Point sub-colony), used optical equipment to observe the exchange of individuals, i.e., birds flying away and arrivals of new individuals from the area of the rock, as well as the reaction of birds in the field of view of the telescope.

2.4. *Data processing procedure*

Based on a series of images from the photogrammetric mission, orthophotos were created in Pix4Dmapper (Pix4D S.A., Prilly, Switzerland). The resulting orthophotos were georeferenced (QGIS 3.16.5 ’Hannover’) based on terrain feature points to facilitate comparison of the nests visible on the different maps (Turner et al., 2013). The QGIS Georeferencer plugin was used to perform the transformation, and the Helmert transform was applied to perform simple scaling and rotation transformations. A grid (as a vector layer) delineating transects of 15 m × 15 m was created to facilitate the work of inspecting the site for the presence of nests and the control of nests at subsequent dates.

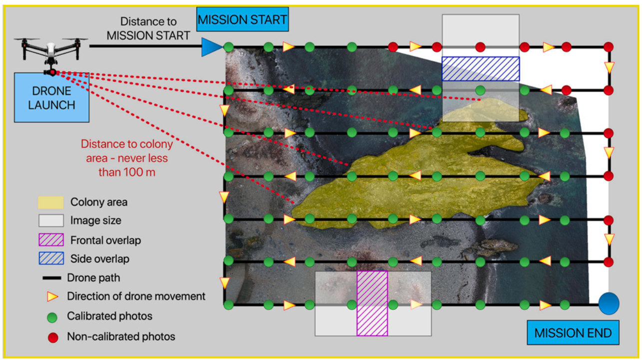

Fig. 3. Conceptual drawing of the drone mission over Llano Point colony.

Table 1
Unoccupied aircraft system (UAS) flight specifications.

Mission Date	Area Coverage	Number of Images Taken (Calibrated)	Flight Altitude	Image Overlap	Ground Sampling Distance (GSD)—Pixel Resolution
Llano Point/Rescuers Hills					
22 Nov 2019 – 3D	1.042 km^2	628 (625)	200 m	75–75%	3.75 cm
14 Oct 2020	0.553 km2	585 (539)	130 m	80–75%	2.13 cm
16 Nov 2020	0.476 km^2	485 (472)	130 m	80–75%	2.24 cm
04 Dec 2020	0.544 km^2	538 (535)	130 m	70–75%	2.28 cm
23 Dec 2020	0.565 km^2	430 (424)	130 m	80–70%	2.30 cm
17 Jan 2021	0.560 km^2	616 (609)	130 m	80–75%	2.23 cm
08 Feb 2021	0.555 km^2	493 (493)	130 m	80–70%	2.39 cm
[a]20 Feb 2021	0.563 km^2	491 (487)	130 m	80–70%	2.15 cm
15 Mar 2021	0.524 km^2	494 (491)	130 m	80–70%	2.30 cm
07 Apr 2021	0.586 km^2	524 (524)	130 m	80–70%	2.41 cm
Llano Point					
14 Oct 2020	0.032 km^2	80 (76)	70 m	78–70%	1.43 cm
16 Nov 2020	0.022 km^2	65 (59)	70 m	78–70%	1.47 cm
04 Dec 2020	0.030 km^2	64 (64)	70 m	78–70%	1.49 cm
23 Dec 2020	0.023 km^2	57 (57)	70 m	78–70%	1.51 cm
17 Jan 2021	0.024 km^2	66 (66)	70 m	78–70%	1.43 cm
08 Feb 2021	0.031 km^2	84 (84)	70 m	78–70%	1.59 cm
[a]20 Feb 2021	0.021 km^2	71 (69)	70 m	78–70%	1.43 cm
Llano Point (experiment)					
20 Feb 2021	0.011 km^2	311 (234)	30 m	80–70%	0.63 cm
20 Feb 2021	0.009 km^2	104 (79)	50 m	80–70%	1.04 cm
20 Feb 2021	0.014 km^2	40 (31)	100 m	80–70%	2.09 cm
Vaureal					
26 Oct 2019 – 3D	1.745 km^2	1553 (1108)	200 m	80–80%	5.56 cm
[b]26 Dec 2020	0.168 km^2	240 (239)	100 m	80–70%	1.98 cm
28 Jan 2021	0.624 km^2	471 (276)	200 m	80–70%	3.96 cm
04 Feb 2021	0.842 km^2	476 (315)	200 m	80–70%	4.08 cm
[b]21 Feb 2021	0.174 km^2	258 (254)	100 m	80–70%	1.98 cm

[a] Data used for the experiment;
[b] Mission done only for the N-W colony.

With an image overlap of 75–80% (Table 1), it is possible to obtain an orthophoto, with no perspective distortion, and the analysed objects (in our case, SGPs) are orthogonally projected onto the base. SGP adults and chicks (from the moment they were no longer covered by an adult) were marked (identified) on each map. This step was performed by both authors twice for each map to minimize the risk of missed bird identifications. The imposed search procedure included searching the image in the order of transects to exclude the possibility of confusion and omission of a given part of the area from the search. In the next step, sites occupied by adult birds at particular time intervals (in more than one chronologically related ortophoto) were selected, thus eliminating one-time findings of an adult at a given location and ruling out the likelihood of a nest there.

2.5. Data processing of bird response analyses at different photogrammetric raid heights

The 100 m altitude map was excluded from the analyses due to its insufficient quality resulting from the brief snowfall that occurred during the 100 m altitude raid. Due to the presence of visible precipitation in the images, we were unable to determine the birds' responses.

The following points describe our methodology:

1. At the beginning, the remaining maps (130, 70, 50, 30 m) were georeferenced (analogous to the maps of the whole area);
2. Analyses were conducted by two people independently;
3. In the order of the missions: from the highest to the lowest altitude and again from the lowest to the highest altitude to double check the data;
4. On each map, the location of adults and nestlings was marked, and the type of reaction of the animal between two consecutive images was distinguished according to the following criteria:
   a) Neutral responses were listed as follows:
      - in both images the animal remained in the "relaxation position" with the head resting on the trunk, position indicating sleep or rest (Fig. 4A (chick) and 4B (adult));
      - in both images, the animal remained in the sitting position with neck straight (Fig. 4C (chick) and 4D (adult)) but did not change its location (slight rotation of body position was acceptable);
      - in the first image, the animal was sitting, and on the second image, it showed a position typical for the "relaxation position".
   b) Potentially indicative responses were listed as follows:

Fig. 4. Examples of positions of adult birds and chicks recognized in the pictures: relaxation position -head resting on the trunk (A-chick; B-adult); sitting position- neck straight (C-chick; D-adult).

- in the first image, the animal stayed in the "relaxation position", and in the second image, it was sitting;
- the animal had moved:
  (i) the animal had joined the colony in relation to the previous image;
  (ii) the animal flew away in relation to the previous image;
- the animal was looking up showing interest in the drone.

2.6. Statistical analysis of data and control data

The observation data were divided into two groups: (1) a change in the location of an individual according to a change in drone flight altitude and (2) five different behavioural responses of individuals to a change in drone flight altitude. In both cases, we assigned ranks to a given bird behaviour. In case (1), a score of 0 meant that the individual did not change position, while a score of 1 meant that the individual changed position. In contrast, in case (2): a score of 0 meant that no change in the behaviour of the individual was noticed or the individual started to rest between two missions at two different altitudes; a score of 1 meant that the individual interrupted rest; a score of 2 meant that the individual flew (jointed) to the colony; and a score of 3 meant that the bird left the colony. This is a modified rank classification proposed by Rümmler et al. (2016) and was subsequently used by Weimerskirch et al. (2018) and Krause et al. (2021). In addition, prior to the experiment, we made 10 continuous observations of the colony, with a length equal to 15 min corresponding to the average duration of a single mission. Observations were made using optical equipment (an ornithological telescope) from a distance of 250 m so that the presence of the observer did not affect the behaviour of the animals. Observations ranged from 14 to 18 birds, giving a total of 160 observations.

Because our data in both case one (change in location) and case two (5 different behaviours) did not have a normal distribution, were ordinal and independent of the control observations and were not equal between groups, we used the Mann-Whitney-Wilcoxon nonparametric test. It is important that this test can be used when the variable is measured on a dichotomous scale (i.e., 0–1) because this is the case for a nominal variable that is also an ordinal variable. The null hypothesis was that there were no differences between the mean ranks. All calculations were performed in MATLAB Version: R2020a, with Statistics and Machine Learning Toolbox Version 11.7.

3. Results

3.1. Number of chicks and adult individuals and estimated number of occupied nests

Comparative analyses of nest site data for Llano Point/Rescuers Hills from different dates indicated the presence of 206 (Table 2) adult-occupied locations on at least two temporally contiguous maps. The listed temporal range and number of sites considered as potential nests which are highlighted in Table 2 provides a summary of the number of adults, the number of chicks, and an estimate of the number of active nests (made from spatiotemporal analyses of apparently occupied nests visible on orthophotos), divided into colonies and sub-colonies. A graphical representation of nest distribution within colonies and sub-colonies is shown in Fig. 5. At Petrel Hill, the establishment of 2 nests, of which breeding success was observed for 1, was indicated.

3.2. Effect of drone presence

Fig. 6 shows a comparison of the selected Llano Point colony area from different raid heights. The different height maps allowed for the identification of individuals, and the number of individuals in independent counts by two observers was identical (results are presented in Figs. 7 and 8), with differences in interpretation between observers only in determining the behaviour of individuals (see Figs. 7 and 8).

Throughout the experiment, we observed the following number of adults at each height: 64 (130 m), 66 (70 m), 69 (50 m), 68 (30 m), of which 58 were present in all images and 21 of which did not change their position or show any other variable behaviour. The distances between one nest and the others were described by the following statistics: mean: 22.42 m ± 14.20 m; median: 19.34 m; minimum: 1.14 m; maximum: 66.53 m. The exchange of individuals (emergence and departure from the colony site) was recorded by a

Table 2
Number of adults, stage, number of active nests and chicks by date in each sub-colony.

Date	Number of adults present at investigated area	Stage	Number of active nests/Number of chicks			
Llano Point/Rescuers Hills						
Rescuers Hills						
14 Oct 2020	10	Pre-laying				
16 Nov 2020	156	Incubating	Active nests		127	
04 Dec 2020	161	Incubating			143	
23 Dec 2020	141	Incubating/brooding			133	
17 Jan 2021	148	Brooding			111	
08 Feb 2021	119	Brooding/guarding	Chicks		66	
20 Feb 2021	161	Guarding			66	
15 Mar 2021	28	Post-guarding			65	
07 Apr 2021	13	Post-guarding			63	
Llano Point						
14 Oct 2020	17	Pre-laying				
16 Nov 2020	76	Incubating	Active nests		61	
04 Dec 2020	75	Incubating			63	
23 Dec 2020	57	Incubating/brooding			53	
17 Jan 2021	65	Brooding			44	
08 Feb 2021	48	Brooding/guarding	Chicks		39	
20 Feb 2021	66	Guarding			39	
15 Mar 2021	9	Post-guarding			39	
07 Apr 2021	4	Post-guarding			39	
Vaureal						
North-West						
26 Dec 2020	364	Incubating/brooding	Active nests		> 235	
28 Jan 2021	267	Brooding/guarding	Active nests	Chicks	235	142
04 Feb 2021	168	Brooding/guarding	Active nests	Chicks	219	205
21 Feb 2021	282	Guarding	Chicks		209	
South-East						
28 Jan 2021	93	Brooding	Active nests	Chicks	> 65	44
04 Feb 2021	66	Brooding/guarding	Chicks		65	
Petrel Hill- based on ground observations						
16 Nov 2020	10	Incubating	Active nests		2	
04 Dec 2020	5	Incubating	Active nests		2	
23 Dec 2020	3	Incubating/brooding	Active nests		2	
17 Jan 2021	6	Brooding	Chicks		1	
08 Feb 2021	3	Guarding	Chicks		1	
20 Feb 2021	3	Guarding	Chicks		1	

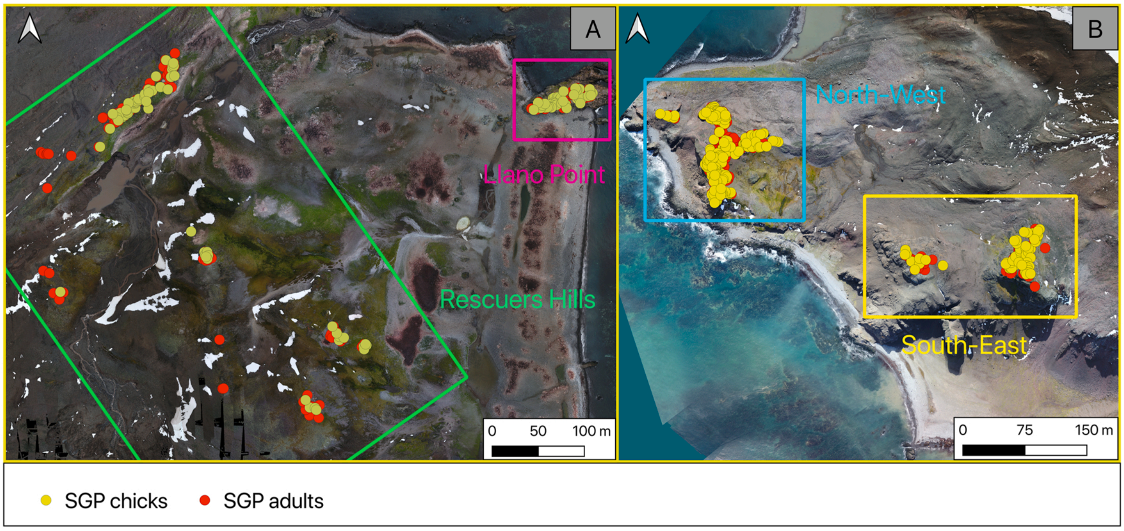

Fig. 5. Distribution of the SGP nests for the Rescuers Hills/Llano Point colony on 08 Feb 2021 (A) and for the Vaureal colony on 04 Feb 2021 (B).

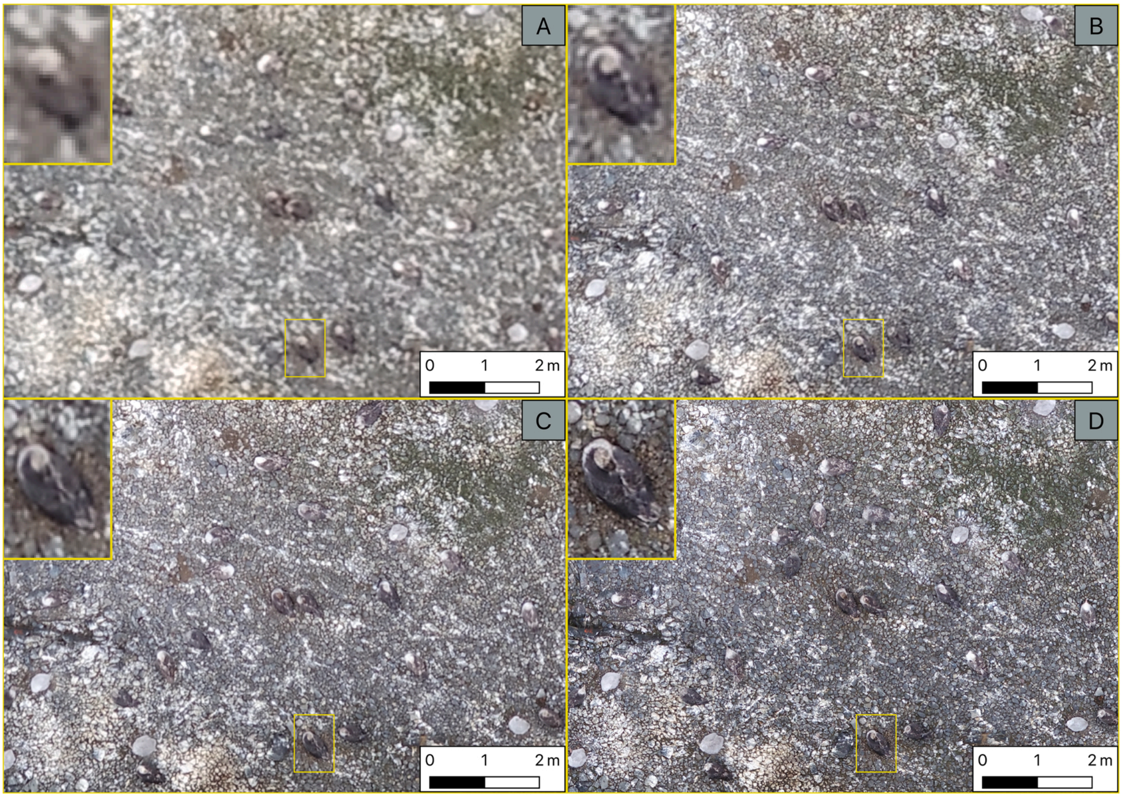

Fig. 6. Comparison of the part of the Llano Point colony area from different raid heights and corresponding GSD: (A) 130 m (2.15); (B) 70 m (1.43 cm); (C) 50 m (1.04 cm); (D) 30 m (0.63 cm).

ground-based observer and confirmed the variable number of individuals recognized at different altitudes. The number of birds that flew away from the colony immediately before the drone launch was 2 individuals, and this value did not statistically differ from that observed during the experiment (two-tailed p-value >> 0.01). It should be emphasized that in the case of the 130-m mission, it was not possible to determine the behaviour of the individual for 18 animals; rather, only their position could be determined. Of the responses listed in the Methods section, "the animal was looking up showing interest in the drone" was not noted either from the photo or by the observer on the ground. Among the remainder, a total of 60 responses were recorded when a lower altitude was used, of which 30

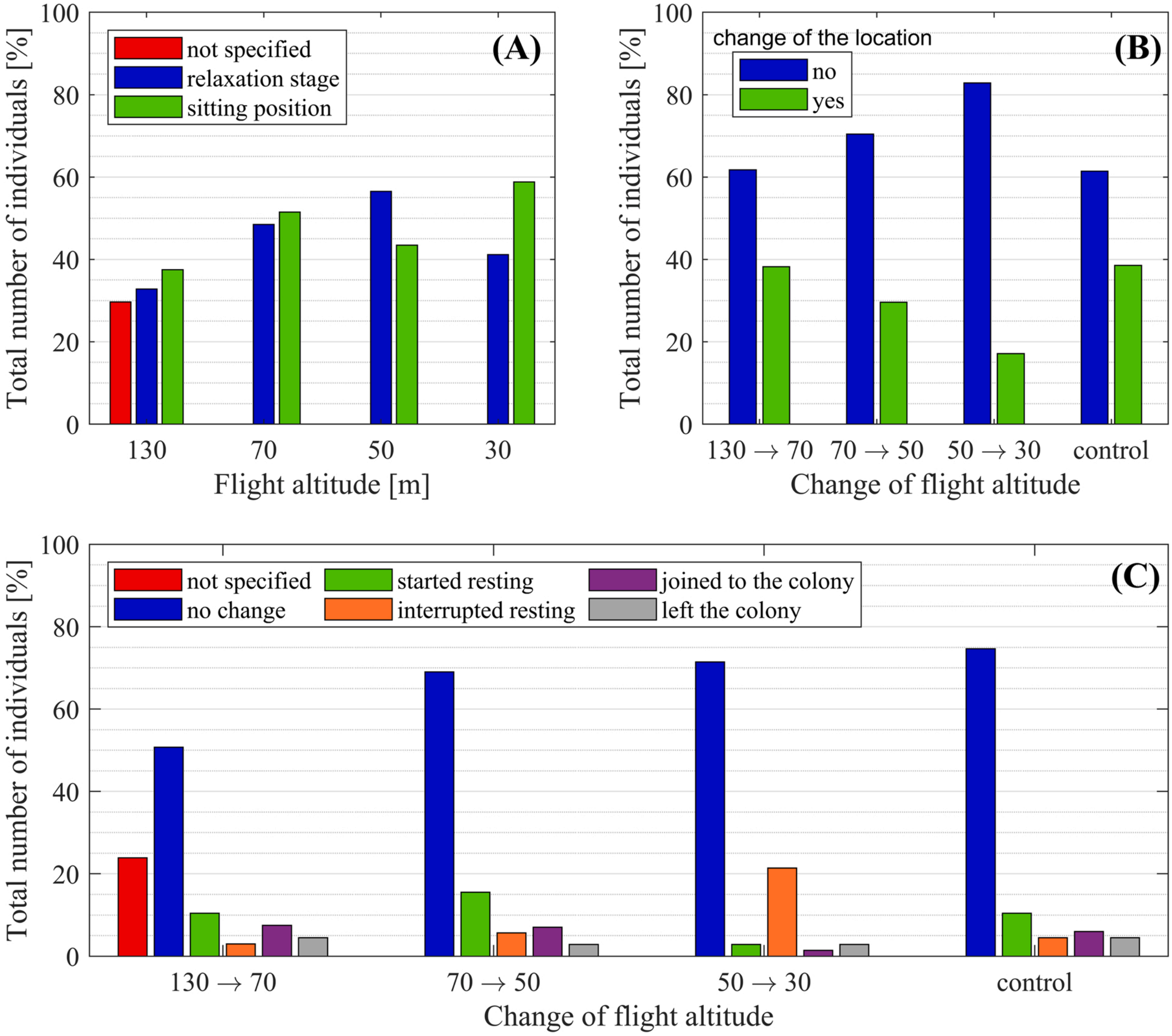

Fig. 7. Total number of adult individuals in maps for each altitude (A); change in position of adult individuals between successive altitudes (B); change in behaviour of adult individuals between successive altitudes (C).

qualified as neutral responses and 30 qualified as potentially negative. For the 39 chicks present in all images (Fig. 8), 16 showed no behaviour change throughout the entire experiment. For the rest, 25 behaviours were recorded, of which 16 were potentially negative and 9 were potentially neutral. Unfortunately, however, it must be stressed that it was not possible to assess the behaviour of 8 individuals during the 130 m mission; additionally, in the 70 m mission, it was not possible to determine the behaviour of 2 individuals. Details of the analysis are presented in Fig. 7 for adults and in Fig. 8 for chicks.

The behavioural responses of adult birds and chicks to all height changes did not differ statistically from the control results (two-tailed p-value $>> 0.01$). Thus, the null hypothesis of similarity of origin between groups could not be rejected. Clearly, in the case of a change in raid height from 50 m to 30 m, an increase in interrupted rest ('1') was noticeable, but for all results, 'no change' or 'start resting' ('0′) was the most frequent result. Furthermore, in the case of a change in position with a change in raid height, for adult individuals, a significant difference (two-tailed p-value $<< 0.001$) occurred for a change in raid height from 50 to 30 m, and we could reject the null hypothesis of equal mean ranks.

To easily identify SGP adults and chicks in the orthophotos, our suggested GSD using a DJI Inspire 2 equipped with a Zenmuse X5S Gimbal Camera and a 15-mm lens was 2.15 cm, which corresponds to a raid height of 112 – 121 m above the birds. Moreover, we could easily identify bird behaviour for a GSD of 1.43 cm, which corresponds to a height ranging from 52 to 61 m above the bird. However, as previously mentioned, for other widely available commercial drones with standard cameras, such identification would require a significant lowering of the vertical distance between the potential nest of SGP and the drone, which, as our experiment showed should be greater than 21 m in order to not disturb animals.

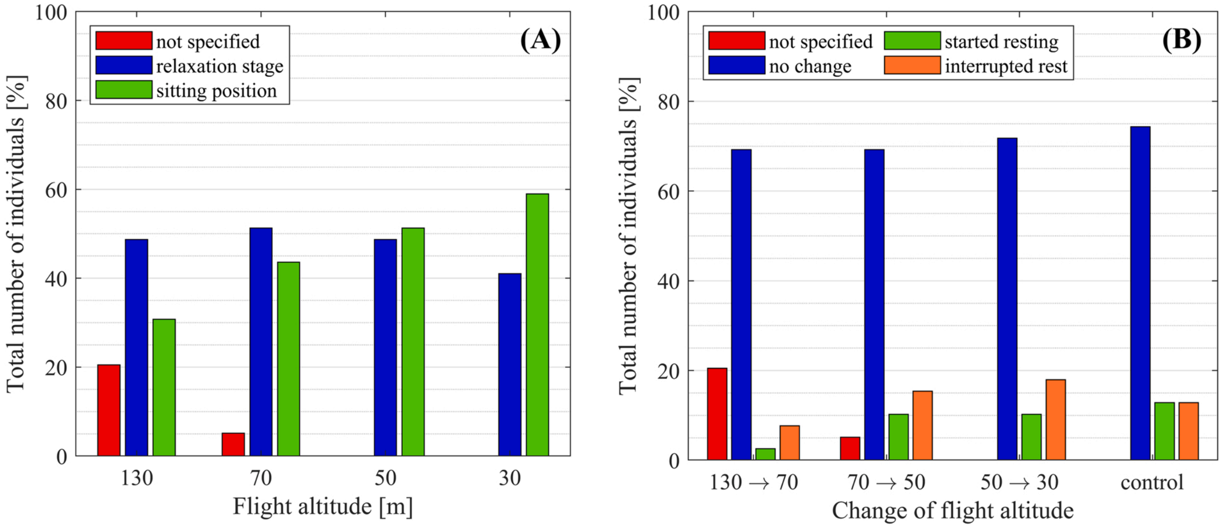

Fig. 8. Total number of chick individuals in maps for each altitude (A); change in behaviour of chick individuals between successive altitudes (B).

4. Discussion and conclusions

Ground counts of adult individuals, chicks, and/or active nests were conducted by different scientific teams at various times during the breeding season, which makes it difficult to identify trends in the breeding population size (Patterson et al., 2008). As Poncet et al. (2020) highlighted, maintaining consistency in research methodology is a major challenge. For giant petrels, factors interfering with this consistency include differences in survey design, area coverage, and timing, lack of corrections for past nesting failures; and poor documentation of historical survey methods. In this context, the method we propose could ensure complete repeatability of the research data in subsequent seasons. The area of the designed mission is stored in a digital record and can be reconstructed and the dates of the missions are noted. Photogrammetric missions facilitate counts of present adult birds and chicks in the composed mosaic of the area and also provide indisputable documentation for future comparative analyses. Obtaining photographic records ensures that the data can be archived and reanalysed years later, perhaps using more modern methods that will be available due to advances in technology. In addition, taking orthophotos can provide documentation of the variability of the environmental background, which, again in a long-term context, can be analysed to determine its effect on the size of the population under study.

An obstacle in the use of orthophoto analyses in the context of identifying active nests is that approximately 15–40% of the adult population capable of breeding may not attend their breeding formation in any one year (Voisin, 1988). Adult birds identified in the mosaic may not necessarily be involved in breeding. However, using visual clues that can be discerned from images (visible nest construction or guano around the nest), the number of apparently occupied nests can be estimated, ignoring one-time sightings of a bird at a given non-nest location. As known from past observations (Creuwels et al., 2005), both non- and failed breeders occupy a certain number of "apparently occupied nests", so a census based on their counts may give an overestimate of the actual number of breeding efforts. To minimize the risk of overestimation, with the use of several photogrammetric missions during one season, an attempt can be made to estimate the number of "active nests", that is, nests containing eggs or chicks, in the colony on the basis of spatial analyses. This procedure does not exclude errors but brings us closer to determining the number of adult birds engaged in breeding. The number of nests occupied in consecutive chronological orthophotos provides an estimate of the number of active nests per season. Given that this method is based on several controls, rather than just one, we can identify nests without successful breeding (a measure of success would be a chick present in the orthophoto image in the period of detection); these nests were detected only in a given interval of the period associated with the egg-laying stage and would not have been recorded without comparative analyses of multiple orthophotos. Noting the number of chicks present in successive orthophotos at the guarding stage (when the chicks were no longer covered by their parents as they emerged from the brooding stage) can aid in the determination of nesting success relative to the number of active nests. In our case, the highest number of simultaneously recorded adults was 236 on 4 December 2020 in the Llano Point/Rescuers Hills colony area and 364 on 26 December 2020 in Vaureal North-West sub-colony. Spatiotemporal analyses based on nine orthophotos from different breeding-season dates allowed us to report the maximum number of active nests, which was 206 for the Llano Point/Rescuers Hills colony on 4 December 2020 and at least 300 (only one orthophoto from the incubation, so the number may be underestimated) on 28 January 2021 for Vaureal. Poncet et.al (2020) indicated the validity of using correction factors to account for differences between the number of pairs that attempted to breed and the number counted or estimated on a given survey date. In the case of the Vaureal colony, due to the insufficient number of orthophotos, we can only determine the minimum number of nests without taking into account early incubation and broods that were lost before 26 December for the North-West subcolony and 26 January for the South-East subcolony. In the study by Poncet et al. (2020), correction factor values were based on observations of 141–185 SGPs nests from 4 seasons of intensively monitored study areas on Bird Island, where all nests were marked and monitored daily during the egg-laying period and weekly thereafter to record failures or hatchings. Because we did not have reference data from previous years, we were unable to apply correction factors for areas where we failed to make an adequate number of raids. We did not want to compare the Llano Point/Rescuers Hills colony, for which we had more data from the study season, to the Vaureal colony because we felt that the two colonies had too many differences (site specifics, location relative to the penguin colony, and the substantially different number of skuas nests observed during the initial check (in the season prior to conducting raids)). Therefore, for the Vaureal colony (Table 2) we provide the minimum (>) number of active nests.

An important point to consider that is specific to the genre, is that SGPs have no obvious enemies that perform aerial attacks (Conroy, 1972), which may be a key factor in how they respond to the presence of UASs. According to Brisson-Curadeau et al. (2017), the presence of aerial predators can result in significant behavioural disturbance and hinder the use of UASs, as in cases where the drone may be perceived as an aerial predator. Vas et al. (2015) observed that the drone's angle of descent above the bird species studied was crucial to their behavioural response. Drone approach angles close to a right angle can be associated by birds as a predator attack. However, the question arises as to whether a drone can be compared to a predator or if its presence has a completely different impact on animals. Mulero-Pázmány et al. (2017) noted that UASs are a potential new source of anthropogenic disturbance and can affect wildlife responses in a negative manner. Small UAS with electric motors have short term impacts, and these impacts are comparable to that caused by natural predators. On the other hand, the commercially available drones studied by Egan et al. (2020) elicited lower disturbance compared to that of the predator model. Ditmer et al. (2019) demonstrated the ability of American black bears to habituate and remain habituated to novel anthropogenic stimuli, such as drones, in 3–4 weeks. These researchers indicated that although cardiovascular effects were reduced (Ditmer et al., 2019), and infrequent behavioural changes in animals were observed (Ditmer et al., 2015), frequent disturbances caused by UASs may have other chronic physiological effects (Ditmer et al., 2019). In our case, we did not observe significant behavioural changes, such as changes in bird location, when the flight altitude was lowered. However, it should be emphasized that physiological stress was not measured, and more critical investigations are needed. It is important to consider additional physiological stressors on animals, especially on seabirds, due to UAS flights when developing regulations or new protocols for UAS use based on new experiments. However, with birds as sensitive to human presence as SGPs are, taking this information into consideration seems more difficult than as required for American black bears (Ditmer et al., 2015, 2019) or for chicks of King Penguins (Weimerskirch et al., 2018).

Another factor necessary to consider when estimating the risk of disturbing animals when using a drone appears to be the level of noise generated by the drone in comparison to naturally occurring ambient sound levels (Goebel et al., 2015; Palomino-González et al., 2021), which was a penguin colony with several thousand individuals in the case of the Rescuers Hills/Llano Point colony (Gentoo and Adelie) and a colony of approximately two thousand individuals in the case of the Cape Vaureal (Chinstrap penguins). Additionally, both colonies were affected by waves naturally crashing on rock formations and wind. Although the level of noise was not measured in the current study, according to Goebel et al. (2015), the hexacopter APH-22 emitting a noise of approximately 54 dB at 30 m altitude was completely masked by the noise from a Chinstrap penguin colony of approximately 600 chicks, whose noise was 84.5 dB in close vicinity to the measurements. The DJI Inspire 2 drone used in the study emits between 69 and 50 dB with the vertical distance of 10–100 m, respectively (Palomino-González et al., 2021; Thirtyacre et al., 2021). Additionally, as the horizontal distance increases, the intensity of the sound decreases regardless of the flight height. For horizontal distances above 100 m, the noise generated by the drone does not exceed 50 dB (Palomino-González et al., 2021). For our missions, this was especially important because the raid was performed continuously over a wide area, which meant that the intensity of the sound varied and decreased as the drone moved horizontally away from a particular nest. For example, for the mission at Rescuers Hills/Llano Point, the drone spent approximately 85% of the mission time at a horizontal distance from the nest exceeding 100 m (calculated as a mean time for the individual nest).

Vas et al. (2015) also highlighted potential differences in bird response to raids in relation to reproductive stage. The experiment presented in our paper was performed during the guarding stage, and the response of birds during the incubation stage may differ significantly from the results presented. As an example, in the experiment of Weimerskirch et al. (2018), conducted during a different phase of the reproductive cycle at the Crozet Islands (12 November - 7 December—a term indicating the incubation phase), SGPs were identified as one of the species most susceptible to stress, among the 11 included in the experiment, caused by the presence of the drone. The different breeding phases may explain the differences in stress reactivity shown between the individuals in the Weimerskirch et al. (2018) experiment and those in our experiment. The authors of the publication noted that some of the SGP individuals involved in the experiment exhibited a state of vigilance even before the drone took off. In their study examining the nesting status of the endangered Chaco Eagle and the degree of disturbance of drone flights to individuals, Gallego and Sarasola (2021) observed that the adults exhibited different behaviours in different breeding periods. For example, birds flew away during the nest building stage, even before drone took off, while they remained on the nest despite the presence of the drone during the incubation period. On the other hand, when they had chicks, all types of responses were observed, including alarm calls and vocalization and a single event of escape behaviour, birds only once flew away as a response to the drone. According to Montgomerie and Weatherhead (1988), these differences may be related to the fact that adults made decisions to avoid unnecessary risks (flew away before drone took-off) or not react (behaviourally) based on the presence of drone during the incubation period due to the possibility of losing a chick, which may have a huge reproductive cost. In our case, the experiment was conducted during the guarding stage and we only observed two birds that flew away before the drone took off, which may have been due to natural behaviour as only one adult was at the nest during this period. This change was not statistically significantly different from the observations obtained before the experiment, as well as during the experiment itself. Another factor that may explain these differences in our experiment and that performed by Weimerskirch et al. (2018) is the location of the colonies we analysed in the vicinity of penguin colonies whose noise drowned out the drone, which was discussed above.

Since the animals we observed during the photogrammetry missions did not show any obvious behavioural signs of disturbance, which is unavoidable during ground-based censuses by an observer, we dare to conclude that the use of a drone, although not fully studied in terms of potential harm, seems to be less obviously harmful than close human presence in the colony area. One of the most important advantages is the possibility to obtain observations over a much larger area, which is not achievable even by a group of observers or in locations that are difficult to reach by people. Moreover, another advantage is that these observations are made in a rapid manner. The acquired photogrammetric documentation, which was 9224 images in our study, will be available in later years when technological developments may allow the extraction of information from the images that we cannot even anticipate today.

CRediT authorship contribution statement

KF and RJB conceived the ideas, designed the methodology, and collected and analysed the data; both authors led the writing of the manuscript, contributed critically to the drafts and gave final approval for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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