Population surveys of burrow-nesting seabirds on the St Kilda archipelago: results and insights from the 2019 Seabirds Count census

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Supplementary Material

1 Surveys and analyses

1.1 Puffin survey

1.1.1 Boreray

The distribution of Atlantic Puffin *Fratercula arctica* quadrats on Boreray is shown in Figure A1. No surveys were carried out in zones BOR9 or BOR12 because of difficulties of access, though small numbers of Puffins were observed using these areas. Zone BOR7 was a smooth, grassy slope that was easy to access but was almost completely devoid of Puffin AOB except around the lip of the cliffs on its northern side. Survey of BOR7 was therefore discontinued after five exploratory transects at the northwestern end. Access to Sunadal (BOR11) was difficult, and time constraints permitted only four transects in this zone. Visual assessment suggested that it should be divided into a lower, high-density zone (BOR11a) and an upper, low-density zone (BOR11b). No access was possible to the northern end of the island, which is extremely steep, though there are a number of grassy gullies which are used by Puffins.

1.1.2 Soay

Due to limited time on Soay, transects were only surveyed in zones SOY3, SOY6, SOY7, SOY9, SOY10 and SOY12 (Figure A2). Visual inspection suggested that Zones 8 and 9 should be divided into a lower, high-density zone (SOY8a and SOY9a) and an upper, low-density zone (SOY8b and SOY9b). Zone SOY7 is a large boulder field (Tigh Dugan) in which it is difficult to count individual burrows but clearly many Puffins occupy it. Nevertheless, an attempt was made to estimate AOB by searching for signs of occupation (Puffin footprints/tracks, faeces, etc.) below and between boulders. This is likely to produce an underestimate of the true AOB as large boulders may conceal multiple entrances.

1.1.3 Dùn

The Puffin colony on Dùn was surveyed in 2018 (Luxmoore *et al.* 2019) and so it was not necessary to resurvey it entirely. To do so would have caused excessive disturbance to the Northern Fulmar *Fulmarus glacialis* colony and reduced the time available to survey the other species. Instead, five transects were sampled in the high-density zones (B and F) at the southern end of the island (Figure A3) to enable comparison with the 2018 survey.

1.1.4 Hirta

The main Puffin colony on Hirta is on the western slopes around Carn Mòr. This was not adequately surveyed in 2018 and so additional surveys were carried out in 2019. The grassy slopes to the south of Carn Mòr (zones 19 and 20, Figure A4) cannot be accessed safely on foot, so three transects were laid out and surveyed using rope-access techniques.

The Carn Mòr boulder field was assessed with a transect of ten square quadrats. Although the length of each side of a quadrat was measured with a 10 m rope, the uneven ground meant that the rope was draped over rocks and the actual length of each side was less than 10 m. The horizontal distance between the first and the last quadrat was measured as 70.3 m, with an altitude change of 48.1 m, based on the GPS locations. This implies that the ten quadrats covered 85.2 m, measured parallel to the slope; an effective length of 9.47 m for each side, when corrected for the unevenness of the terrain. The area of each quadrat can therefore be estimated as 89.7 m^2 (9.47 m x 9.47 m).

1.2 Playback surveys for European Storm-petrel and Manx Shearwater

The European Storm-petrel *Hydrobates pelagicus* playback recording was made on Mousa, Shetland Islands, and consisted of a male purr song of 10 s duration, followed by a 20 s gap to listen for responses. The Manx Shearwater *Puffinus puffinus* playback recording was made on Ramsey Island, Pembrokeshire, and consisted of a duetting male and female of 25 s duration, followed by a 25 s gap to listen for responses. Both recordings are provided as Supplementary Material. We performed the playback by holding a portable speaker (EasyAcc model LX-839) facing towards the ground, approximately 1 m above the survey point, and playing the recording at maximum volume (c. 75 dB). All playbacks were conducted between 07:30 and 18:30 local time (BST).

A hierarchical distance sampling method was used, described in detail in Deakin *et al.* (2021). Briefly, hierarchical distance sampling models enable availability for detection (i.e. response rate), detection function (decline in detection with increasing distance from the observer), and abundance to be modelled simultaneously and in relation to covariates (Kéry & Royle 2016, Sillett *et al.* 2012). To estimate the detection function, the distance to all detected responses at each playback point was measured in 0.5 m increments from 0 to 4 m. To enable the response rate to be estimated, some sites were surveyed on multiple occasions.

Figure A1 gives an overview of the sites at which playback was conducted on Boreray, with the addition of 40 cleitean ('cleit' – a small, ruined dry-stone storage building; plural 'cleitean') in zones BOR1–BOR6 (Deakin *et al.* 2021). Figure A2 shows the playback sites on Soay. The northwest end of Dùn was subject to intensive survey (322 sites, see Deakin *et al*. 2021) and additional transects were surveyed at the southeastern end (shown in Figure A3).

On Hirta, playback was conducted on the transects in zones 19 and 20 and the transects in Carn Mòr shown in Figure A4. An additional survey of Gleann Mòr and the two large gullies to the west of Glen Bay was carried out on 30 June, whereby playback was conducted at likely sites (boulder piles, cleitean and visible burrows; Figure A6). However, this survey was not exhaustive and represents a sample of the total areas. In Village Bay, playback was performed approximately every 2 m around the walls of the cleitean and enclosures above the head dyke, and in the old village. For the Gleann Mòr and Village Bay surveys, observers simply recorded the number of responses detected, rather than using distance sampling. As part of routine monitoring, the NTS Seabird Ranger surveyed European Storm-petrels within the head dyke of Village Bay between 14 and 23 July 2019, with a calibration plot just outside the head dyke (see Lawrence 2019 for details).

1.2.1 European Storm-petrel analysis

For European Storm-petrels, too few responses were detected to enable analysis using a hierarchical distance sampling method. To obtain rough estimates of Apparently Occupied Sites (AOS) for the species, a two-stage correction of the survey data was performed: first for distance and then for response rate. Since only one response was detected in the distance sampling survey outside of the cleitean and boulder fields, we included only data from the cleitean (Boreray), Carn Mòr (Hirta) and the Tigh Dugan boulder field (Soay) in the distance sampling model and estimated abundance only within these areas.

The 'distsamp' function of the 'unmarked' package (version 1.0.1, Fiske & Chandler 2011) in R was used to model the detection function and estimate the density of responding European Storm-petrels across the surveyed areas. Model selection was in two steps, with the model with the lowest AIC selected to progress to the next step. First, models were fitted with half-normal, hazard rate, exponential and uniform detection functions. Next, the best fitting model was tested with and without 'Island' as a covariate of abundance, and finally, the better of these models was evaluated for goodness of fit by parametric bootstrapping (Sillett et al. 2012). We used the 'parboot' function of the 'unmarked' package in R to simulate 1,000 new datasets from the model, refitted the model to each data set and calculated the Freeman–Tukey fit statistic for each iteration. The distance sampling model with a half-normal detection function and 'Island' as a covariate of abundance best fitted the data, based on AIC. This model had a Freeman–Tukey P value of 0.469, suggesting an adequate fit to the data.

A response rate correction factor was then applied to the distance-corrected estimates of response density to produce estimates of AOS density for each zone. Since the limited time in the field and the low number of responses did not enable response rates to be estimated during the survey period, an estimated response rate (0.441, 95% CL: 0.319–0.562) from a separate survey of European Storm-petrels in Village Bay was used (Lawrence 2019). Playback for this response rate estimation was conducted later in the season (16–23 July 2019), when daytime nest occupancy and hence estimated

response rate was likely higher than during the Seabirds Count survey. This makes the population estimates in our study conservative. Following correction for distance and response rate, the estimated AOS densities were multiplied by the total area of each zone to produce population estimates.

1.2.2 Manx Shearwater analysis

For the main Manx Shearwater survey, hierarchical distance sampling models were fitted in R using the 'gdistsamp' function of the 'unmarked' package (Fiske & Chandler 2011), as in Deakin *et al*. (2021). Altitude (linear and quadratic), slope (linear and quadratic), island and zone were included in the model set as abundance covariates. Time (linear and quadratic), date (linear and categorical) and wind speed were included as availability covariates. Wind speed and observer were included as detection covariates.

The survey of Manx Shearwaters in Gleann Mòr and the gullies to the west of Glen Bay was conducted by recording all birds responding to a 30 s call, whether or not they were within 4 m of the observer, and without recording distance from the observer. The correction factor of 1.919 (95% CL: 1.786–2.070) from the response rate calibration conducted by the NTS St Kilda Seabird Ranger on 8–25 June 2018 (Hatsell 2018) was applied to the results from this survey to give a minimum estimate for the number of Manx Shearwater AOSs in the area.

The data from the 2022 survey of zone H20a on Hirta were analysed using the two-stage correction method described above for European Storm-petrel. A correction factor of 1.795 was used, based on the average response rate elicited from a calibration plot (plot A in sector H20a; Figure A4) by the NTS Seabird Ranger on 21, 22 and 25 June 2022 (Nisbet 2022).

2 Comparison with previous surveys

2.1 Atlantic Puffin

2.1.1 Boreray

Previous attempts to survey the Puffin population of Boreray (Brooke 1972, Duncan *et al.* 1982, Tasker *et al.* 1988, Mitchell *et al.* 2000) produced estimates ranging from 50,999 to 80,000 AOB. The most complete of these surveys was Mitchell *et al.* (2000) Their total estimate, though higher than ours, was within our 95% confidence limits and was the lowest estimate of the previous surveys. Our estimates for the southwestern slopes, where most of the colony is, are very similar to Mitchell *et al.* (2000) but their total for the eastern slopes (Sunadal) was higher. It is not possible to calculate confidence limits for Sunadal as Mitchell *et al.* (2000) carried out a full colony count for this zone instead of using sample quadrats. We conclude that there is no evidence of a change in the Puffin population of Boreray since 2000.

All previous surveys agree that the southwestern slopes are characterised by the highest density of burrows and most found that they contained the majority of the Puffin population (Table A6; but note Tasker *et al*. 1988). The surveys all involved estimating the densities of AOB in sample areas and multiplying these up by estimates of the total colony area. However, the sample areas and the precise methods varied widely between surveys. The surveys in 1975, 1980 and 1987 (e.g. Harris & Murray 1978) were confined entirely to the southwestern slopes, with extrapolations or estimates made for the other areas.

Mitchell *et al.* (2000), whose zonation system we have attempted to replicate, used a combination of sample quadrats (in zones BOR1 and BOR4) and total burrow counts (in all other areas) to estimate AOB in each zone (Table A1). The totals for our 2019 survey and that of Mitchell *et al.* (2000) are comparable, though Mitchell *et al.* (2000) gave higher totals in some zones (BOR1, BOR4, BOR8 and BOR11) and lower in others (BOR2, BOR7 and BOR10). Some of the differences may have been due to difficulties in identifying the zone boundaries (see Table A7).

Mitchell *et al*. (2000) only calculated population density for two zones: BOR1 and BOR4 (see Figure A1). We obtained their original data for these zones and recalculated the average densities using the same bootstrapping techniques (Table A7). Our burrow density for zone BOR1 was higher than that obtained by Mitchell *et al.* (2000) while that for zone BOR4 was lower. It is likely that both of these discrepancies were influenced by differences in zone boundaries. Our estimate of the area of BOR1 was 48,164 m^2 while Mitchell *et al*. estimated it to be 63,636 m^2 and it seems likely that this included some of the zone that we identified as BOR2. Similarly, we had difficulty in delimiting the boundary between BOR4 and zones BOR5 and BOR6. Mitchell *et al.* (2000) may have included in BOR4 some portions of our BOR5 and BOR6 where the burrow density was higher. This highlights how small differences in zone boundaries can make substantial differences in estimates of colony size.

The densities recorded by earlier surveys for the southwest slopes are also similar. Harris & Murray (1978) recorded 0.61 AOB/m^2 (on the basis of only six quadrats), Duncan *et al.* (1982) recorded 0.52 AOB/m^2 (from 12 quadrats 'laid down haphazardly across the length of the main colony') and Tasker *et al.* (1988) recorded 0.39 AOB/m^2 for 'the denser section of the colony' and 0.18 AOB/m^2 for the 'less dense section'. While it is impossible to make direct comparisons because it is not known where these samples were taken, if we assume that they are representative of the main part of the colony (BOR1 and BOR2), the density has not changed greatly.

There is some evidence that the population may have declined in the less dense, southern part of the Boreray colony. Moore (2022) analysed a photograph taken by Cherry Kearton in 1896 near to Cleitean MacPhaidean (in BOR4, near the boundary of BOR5 and BOR6; Figure A1). He counted 335 Puffins in Kearton's photograph but found only 29 AOB in the same area in 2019. Harris & Murray (1977) reported that they had photographed 'a similar number of Puffins to that which can be seen in [Kearton's] photograph'.

The other zone that showed a substantial difference was Sunadal, on the eastern side of the island. Our estimate was derived from only four sample transects while a whole colony count of this zone was carried out in the Seabird 2000 survey. It is therefore not possible to produce a statistical comparison, though it is notable that the Seabird 2000 estimate was close to our upper confidence limit (Table A1).

2.1.2 Soay

There have been only three previous land-based attempts to count the Puffin population of Soay. Brooke (1972) estimated a population of 77,000 AOB on the basis of two horizontal transects 'across the entire breadth of the colony', sampling one 1 m^2 quadrat at intervals of 15 paces. He counted 39 AOB in 222 1 m^2 quadrats, giving an average density of 0.175 AOB/m^2, which he then extrapolated to an estimated total colony area of 440,000 m^2 ('drawn by hand without the use of mapping techniques'). He considered this to be a maximum population estimate. Harris & Murray (1977) assessed it from the sea in 1975 and counted 'tens of thousands of Puffins sitting on the grass and boulders', concluding that 'Brooke's estimate is reasonable, although it may have been too small'. They later, in 1977, estimated the population to be 150,000 pairs (Harris & Murray 1978), although they subsequently acknowledged that this was based on 'an optimistic estimate of Puffin areas not borne out by subsequent visits' (Murray 2002).

Moore & Rothe (1989) spent nine days on the island in 1989 and estimated burrow density from 64 30 m^2 quadrats, spread across five zones, to be 0.312 AOB/m^2, giving a total of 39,500 AOB. These data were later reanalysed by Mitchell *et al.* (2000) who provided a revised total of 40,018 AOB (95% CLs: 26,447–54,606).

Mitchell *et al.* (2000) spent seven days on the island in 2000 and decided that the distribution of Puffin burrows was so patchy that the use of sample quadrats was inappropriate. Consequently, they traversed the slopes attempting to count every burrow. The results of this survey are shown in Table A2, together with our counts from the same zones. They did not count burrows within the Tigh Dugan boulder field (SOY7) but estimated there to be about 2000 burrows. They did not visit two zones (SOY14 and SOY15) and estimated that each contained 500 AOB. Since these estimates are whole colony counts, they do not have confidence intervals. Limited time on Soay meant that we were unable to visit many of the sectors (SOY1, SOY2, SOY4, SOY5, SOY8, SOY11, SOY13) censused by Mitchell *et al.* (2000). Their estimate of the total colony size was 27,514, but if only the sectors we counted in 2019 are included (SOY3, SOY6, SOY7, SOY9, SOY10, SOY12), their total of 13,501 is similar to ours of 15,186, and is well within our confidence limits (Table A2).

It is also possible to look at the density of AOB/m^2 (Table A8). Mitchell *et al.* (2000) did not estimate burrow density but only gave the total number of AOB. We have applied the total area of sectors calculated in this study (210,958 m^2) to calculate an average density of 0.116 AOB/m^2. Although the total number of AOB varies widely, there is less variation in the density of burrows. Brooke (1972)

hugely overestimated the colony area, probably by a factor of two, and therefore his colony size is almost certainly a large overestimate. Correcting for area would bring Brooke's (1972) estimate more in line with Moore & Rothe (1989), suggesting that there had been little change between 1971 and 1989. In contrast, the density recorded in the present study, 0.130 AOB/m^2 (excluding the boulder field SOY7) is less than half of the density in 1989. As the estimates are based on a similar number of samples, this suggests that there has been a decline in the overall size of the colony between 1989 and 2019. It is more difficult to draw comparisons between 2000 and 2019 because of the different methods used, but there does not appear to be much difference in average AOB density.

There is still a substantial population of Puffins in Tigh Dugan boulder field, which we estimated to be 4,484 AOB (95% CLs: 3,217–5,863).

2.1.3 Dùn

Luxmoore *et al.* (2019) showed that the Seabird 2000 population estimate for Puffins on Dùn was substantially inflated due to an anomalous estimate of colony area. Once this was corrected, the population estimate on Dùn in 2018 was indistinguishable from that in 2000 (see Table 1, main text). Our brief survey of the high-density zones of the Puffin colony on Dùn showed an average density of 0.7303 AOB/m^2. This was very similar to the density of 0.7132 AOB/m^2 in 2018 (Luxmoore *et al.* 2019) and confirms that the 2018 estimate was not anomalous.

2.1.4 Hirta

All previous surveys of Carn Mòr boulder field have concluded that counts of AOB were impossible and have relied on counts of individuals visible on the surface or flying overhead. Previous counts have revealed 5,800 'sites' in 1969, 7,500 individuals in 1969–71, 3,000–3,350 in 1972 (all quoted by Harris & Murray 1977), 1,574 in 1999 (Mitchell *et al.* 2000) and 1,329 in 2018 (Luxmoore *et al*. 2019). Harris & Murray (1977) realised that counts prior to 1977 were underestimates and suggested that the real colony size was 5,000–10,000 by 'comparison of the numbers seen flying there with those at areas with known populations at Dùn'.

The survey of large (9.47 m x 9.47 m) quadrats in this census represents the first attempt to produce a direct estimate of AOB in Carn Mòr. Our estimate of 13,142 AOB (95% CLs: 11,549–14,779) suggests that even the higher estimate of Harris & Murray (1977) may have been conservative.

Estimates of the number of Puffin burrows in the grassy slopes below the Lover's Stone (sector 19) in previous surveys were 20–40 (Harris & Murray 1977) or 1,819 AOB (Mitchell *et al.* 2000), based on counts of AOB on 'accessible slopes between Mullach Bi and Rubha Mhuirich'. Our estimate of 0.0514 AOB/m^2 in sector 19 confirms that there is a substantial population here, though whether it is valid to extrapolate it to the full area of 67,783 m^2, giving a total of 3,414 AOB is debatable. Given that Mitchell *et al.* (2000) confined their survey to accessible slopes and that a large percentage of our burrows were in sections only accessible with rope access, the total seems not unreasonable.

These additional surveys require the estimate of Puffin numbers on Hirta given in Table 4 of Luxmoore *et al.* (2019) to be updated. The totals for sectors 19, 20 and 21 should be increased to 3,414, 559 and 13,142 respectively, giving a total for the island of 19,119.

2.2 European Storm-petrels

Our total population estimate for European Storm-petrels is lower than that from Seabird 2000 (Mitchell *et al.* 2000; Table 2, main text), but falls within the Seabird 2000 confidence intervals. The main difference is in the estimates for Hirta. While the Seabird 2000 survey systematically surveyed 'all areas of suitable habitat' on Hirta over two years, the resources available for the current survey did not enable us to cover all areas of Hirta and our surveys were restricted to Carn Mòr, Gleann Mòr

and the cleitean and walls within and above the village. This reduced survey area is likely to explain at least some of the difference in the estimates between the two surveys. In addition, the Seabird 2000 survey was conducted in mid-July, which is considered optimal for the species since it is thought to be the peak incubation period, and therefore maximum numbers of breeding birds are present in the nest site during the day and are available to respond to playback. Our survey was conducted in late June, and this may have contributed to the reduced population estimate. However, the more regular surveys of European Storm-petrels in Village Bay carried out by the NTS Seabird Ranger detected a substantial decline in the population between 1999 and 2004 (Lawrence 2019). The Ranger's survey in 2019 produced the highest population estimate since 2011, although this did not represent a statistically significant population increase (Lawrence 2019).

2.3 Manx Shearwater

Our total population estimate for Manx Shearwaters is lower than that from Seabird 2000, although our mean estimate falls within the Seabird 2000 confidence limits (Mitchell *et al.* 2000; Table 3, main text). The difference appears to be largely because of our estimate of only 414 AOS (95% CLs: 277–619) for Carn Mòr, compared to 3,443 AOS (95% CLs: 2,233–4,549) in the Seabird 2000 survey (which estimated Carn Mòr to be the largest colony in the archipelago). The Seabird 2000 survey was conducted in late May whereas ours was conducted in late June. Late May is generally considered optimal for surveying Manx Shearwaters since it is thought to be the peak incubation period. However, it is now believed that peak burrow occupancy occurs later at St Kilda than other colonies and it is recommended that surveys are conducted on St Kilda in early June (Hatsell 2018). The difference in survey timing, along with the differing survey methodologies, may partly explain the difference between the two survey estimates, but it appears likely that there has been a decline in the Manx Shearwater population at Carn Mòr. In contrast, the NTS Seabird Ranger's surveys of the permanent monitoring plots on the slopes above Carn Mòr indicate 482 Manx Shearwater AOS in 2022, a 99% increase since 2010 (Nisbet 2022; Table A9), and this may be a result of birds relocating from the Carn Mòr boulder field colony.

The Seabird 2000 survey estimated 222 AOS on the southeast section of Dùn (sector D; Mitchell *et al.* 2000) on the basis of only five responses. The rest of Dùn was not surveyed but it was concluded that there were unlikely to be 'more than double this number on the whole island'. Our survey suggests that Dùn contains more than twice as many Manx Shearwater AOS as estimated in Seabird 2000. Again, this could be a result of birds relocating from elsewhere in the archipelago.

Manx Shearwaters were not surveyed on Soay during the Seabird 2000 census since it was concluded that the island did not contain substantial numbers. Our survey estimated 598 AOS (95% CLs: 323–1,104) on Soay, with four out of the six detected responses coming from the Tigh Dugan boulder field (SOY7). If time is again limited in future surveys, the boulder field may be an important sub-colony to cover.

The increased estimates for Manx Shearwaters outside of Carn Mòr support the theory that birds may have relocated from the boulder field colony since Seabird 2000. If this is the case, there may be significant numbers outside of the surveyed areas. Although no Manx Shearwaters have been detected on Boreray in this survey or Seabird 2000, it is worth continuing to survey the species there in case of changes in their distribution.

Supplementary Tables

Table A1. Counts and population estimates (total apparently occupied burrows, 'AOB') for Atlantic Puffins *Fratercula arctica* in different survey zones on Boreray, St Kilda, in 2019 and in the 'Seabird 2000' survey of 1999/2000 (Mitchell *et al.* 2000). Some Seabird 2000 estimates were only available for combined zones. Densities and total numbers of AOBs are presented as means, with bootstrapped 95% confidence intervals given in brackets. For a map of different zones, see Figure A1.

Zone	Surveyed quadrats	AOB count	AOB density (m^2)		Zone area (m^2)	Total AOB estimate		'Seabird 2000' AOB estimate
BOR 1	136	1,664	0.40 73	(0.3507–0.4701)	48,164	19,6 15	(16,893–23,642)	23,242
BOR 2	38	450	0.39 19	(0.2702–0.5339)	11,078	4,34 1	(2,993–5,793)	2,578
BOR 3	2	15	0.24 74	(0.0667–0.4333)	10,866	2,68 0	(724–4,709)	
BOR 4	81	187	0.07 73	(0.0469–0.1177)	65,062	5,03 3	(3,052–7,658)	8,499
BOR 5	22	138	0.20 85	(0.1364–0.2946)	13,848	2,88 7	(1,888–4,218)	3,546
BOR 6	12	50	0.13 01	(0.0889–0.2028)	5,947	827	(529–1,296)	
BOR 7	50	7	0.00 48	(0–0.014)	113,170	542	(0–1,584)	117
BOR 8	30	77	0.08 53	(0.0544–0.1178)	15,988	1,36 2	(870–1,882)	2,492
BOR 10a	47	3	0.00 21	(0–0.0057)	13,392	28	(0–76)	179
BOR 10b	24	74	0.10 24	(0.0625–0.1458)	13,420	1,37 4	(839–1,957)	
BOR 11a	30	138	0.15 20	(0.0978–0.2178)	30,603	4,67 0	(2,991–6,665)	8,424
BOR 11b	30	13	0.01 44	(0.0033–0.0278)	59,057	853	(197–1,642)	
BOR 12								200
Total	502	2,816			400,596	44,2 20	(30,977–60,933)	50,999

Table A2. Counts and population estimates (total apparently occupied burrows, 'AOB') for Atlantic Puffins *Fratercula arctica* in different survey zones on Soay, St Kilda, in 2019 and in the 'Seabird 2000' survey of 1999/2000 (Mitchell *et al.* 2000). Not all zones were visited in 2019. Seabird 2000 estimates are total counts, except for those marked with * which are estimates for areas that were not counted. Only two quadrats were surveyed in SOY8a, so an estimated AOB density was preferred: survey data and estimate are shown below in both parts of the table, respectively sectors visited and sectors. Some Seabird 2000 counts were only available for combined zones. Densities and total numbers of AOBs are presented as means, with bootstrapped 95% confidence intervals given in brackets. For a map of different zones, see Figure A2.

Zon	Surveyed	AOB	AOB density (m^2)		Zone area (m^2)	Total AOB estimate		'Seabird 2000' AOB estimate
Sectors visited in 2019								
SOY	14	51	0.12	(0.0524–	43,565	5,23	(2,282–	4,547
SOY	7	10	0.04	(0.0048–	13,927	674	(66–1,724)	2,158
SOY	39	301	0.25	(0.1829–	17,589	4,48	(3,217–	*2,000
SOY	2	29	0.48	(0.3333–				
SOY	8	5	0.02	(0–0.05)	23,238	474	(0–1,162)	3,488
SOY	7	68	0.32	(0.1238–	4,761	1,53	(589–	
SOY	13	70	0.17	(0.1–	8,867	1,58	(887–	262
SOY	16	32	0.06	(0.0396–	17,929	1,19	(710–	1,046
Tota	106	566			129,876	15,1	(7,751–	13,501
Sectors not visited in 2019								
SOY					17356	*50		50
SOY					9874	*50		636
SOY			0.12	(0.0524–	19,026	2,28	(997–	3,192
SOY					13668	*50		574
SOY			0.02	(0–0.05)	27,851	568	(0–1,393)	7,576
SOY 8b			0.32 18	(0.1238–0.5335)	9,782	3,14 8	(1,211–5,219)	
SOY					12328	*70		798
SOY					6142	*25		187
SOY					20009			*500
SOY								*500
Total unvisited sectors					58659	8,00	(4,208–	14013
Whole island estimate					188,535	23,1	(11,959–	27,514

Table A3. Counts and population estimates (total apparently occupied burrows, 'AOB') for Atlantic Puffins *Fratercula arctica* in the two zones sampled on Dùn, St Kilda, in 2019. Densities and total numbers of AOBs are presented as means, with bootstrapped 95% confidence intervals given in brackets. For a map of different zones, see Figure A3.

Zone	Surveye quadrats	AOB count	AOB density (m^2)	Total area (m^2)	Total AOB estimate
DÙN B	35	694	0.6648 (0.5305–0.8038)	26,941	17,910 (14,292–21,655)
DÙN F	16	382	0.7958 (0.5313–1.0604)	26,098	20,769 (13,864–27,674)
Combined	51	1,076	0.7303 (0.722–0.7386)	53,039	38,734 (31,281–46,288)

Table A4. Number of playbacks and responses and estimated Apparently Occupied Sites (AOS) for European Storm-petrels *Hydrobates pelagicus* on each island of the St Kilda archipelago. Response density is corrected for the decline in detection with increasing distance from the observer, and a correction factor is applied to these values to give the AOS density. The correction factor used was the reciprocal of the response rate from a calibration in Village Bay between 16–23 July 2019 (mean response rate 0.441, 95% CI 0.319–0.562). Calibration plot, Head Dyke, and above Head Dyke are all within Village Bay and the head dyke and the calibration plot data are from Lawrence (2019). Densities and total numbers of AOS estimates are presented as means, with bootstrapped 95% confidence intervals given in brackets.

Island	'Seabird 2000' whole	Zone	Playbacks	Responses	Response density	AOS density	Total area	Total AOS estimate
Boreray	84 (62 – 171)	Cleitean	83	11	0.539 (0.258–	1.222 (0.959–	42	51 (40–71)
		Other areas	475	0				
Dùn			301	0				0
Soay	529 (387–1,071)	Tigh Dugan	53	13	0.02 (0.01–0.04)	0.045 (0.035–	17,589	791 (621–1,094)
		Other areas	63	1				
Hirta	508 (366–1,000)	Carn Mòr	171	1	0.0005 (0.00006–	0.001 (0.0008–	39,692	43 (33–59)
		H19 & H20	21	0	0	0		0
		Gleann Mòr/gullies		6				14 (11–19)
		Calibration plot		23				23
		Within Head Dyke		10				23 (18–31)
		Above Head Dyke		3				7 (5–9)
Total	1,121 (825–2,242)							952 (729–1,283)

Table A5. Number of playbacks and responses and estimated Apparently Occupied Sites (AOS) for Manx Shearwaters *Puffinus puffinus* on all islands of the St Kilda archipelago during the distance sampling survey. AOS estimates result from a hierarchical distance sampling model. A separate estimate is given for the SE sector of Dùn (Sectors B+F on Fig. A3) as this was the only part of Dùn surveyed in the Seabird 2000 census (Mitchell *et al.* 2000). The Seabird 2000 total excludes the NW sector of Dùn. Area estimates are from Deakin *et al*. (2021) and differ slightly from those used for Atlantic Puffins in this study. All surveys were conducted in 2019, except for zone H20a, which was surveyed in 2022 (see Methods). Densities and total numbers of AOS estimates are presented as means, with bootstrapped 95% confidence intervals given in brackets.

Island	Zone	Playbacks	Responses	Total Area (m^2)	AOS estimate	Seabird 2000 estimate
Boreray		511	0		0	No responses
Soay		116	6	227,687	598 (323–1,104)	Not substantial numbers
Dùn	All	953	147	154,567	983 (762–1,268)	Unlikely more than 444
	SE sector	83	15	73,214	481 (347–667)	222
Hirta	Carn Mòr	171	20	56,827	414 (277–619)	3,443 (2,233–4,549)
	H19 & H20	27	0		0	1,043
	H20a	314	147	27,448	1,640 (1,285–2,093)	
	Gleann Mòr/gullies		50		96 (89–104)	61
	H30 Oiseval					34
Total		>2,092	370		3,731 (2,736–5,188)	4,803 (3,593–5,909)

Table A6. Estimated number of Apparently Occupied Burrows (AOB) from six surveys of Atlantic Puffins *Fratercula arctica* on Boreray, St Kilda.

	Brooke (1972)	Harris & Murray (1978)	Duncan *et al.* (1982)	Tasker *et al.* (1988)	Mitchell *et al.* (2000)	This study
	11–18 July 1971	*5 July 1975*	*8–25 July 1980*	*13–20 June 1987*	*26 June – 4 July 2000*	*18–21 June 2019*
SW Slopes	41,000	c. 55,000	65,000	19,948	38,089	35,934
Sunadal	17,000	not given	c. 5,000	c. 42,500	9,474	5,532
Other areas	c. 19,000	not given	c. 10,000		3,236	2,764
Total	77,000	100,000	80,000+	63,000	50,999	44,230

Table A7. Comparison of estimates of the density and total estimates of Apparently Occupied Burrows (AOB) for Atlantic Puffin *Fratercula arctica* from this study and Mitchell *et al*. (2000) in zones BOR1 and BOR4 on Boreray, St Kilda (for a map of different zones, see Figure A3.).

	BOR1		BOR4	
	This study	Mitchell *et al.* (2000)	This study	Mitchell *et al.* (2000)
No. of quadrats surveyed	136	263	81	169
Bootstrapped mean AOB density (m^2)	0.4073	0.3042	0.0773	0.1858
UCL	0.4701	0.3384	0.1177	0.2116
LCL	0.3507	0.2702	0.0469	0.1619

Table A8. Estimated density of Atlantic Puffin *Fratercula arctica* Apparently Occupied Burrows (AOB) on Soay from Brooke (1972), Moore & Rothe (1989), Mitchell *et al*. (2000) and this study. *Colony area, and hence density, for 2000 was calculated from this study.

Year	Dates	AOB density (m^2)	Colony area (m^2)	Area sampled (m^2)	Total AOB estimate
1971	17–19 July	0.175	400,000	220	77,000
1989	June	0.312	75,160	2130	39,500
2000	5–12 July	*0.116	*210,958	-	27,514
2019 (excluding SOY7)	23 June	0.130	112,287	2010	18,705
2019 (including SOY7)	23 June	0.178	129,876	3180	23,189

Table A9. Estimated numbers of Manx Shearwater *Puffinus puffinus* AOS in monitoring plots within Sector H20a from 2007 to 2022 (Nisbet 2022).

	2007	2008	2010	2012	2015	2018	2021	2022
Responses	69	112	153	153	196	211	231	278
AOS	147		242	323	351	405	455	482

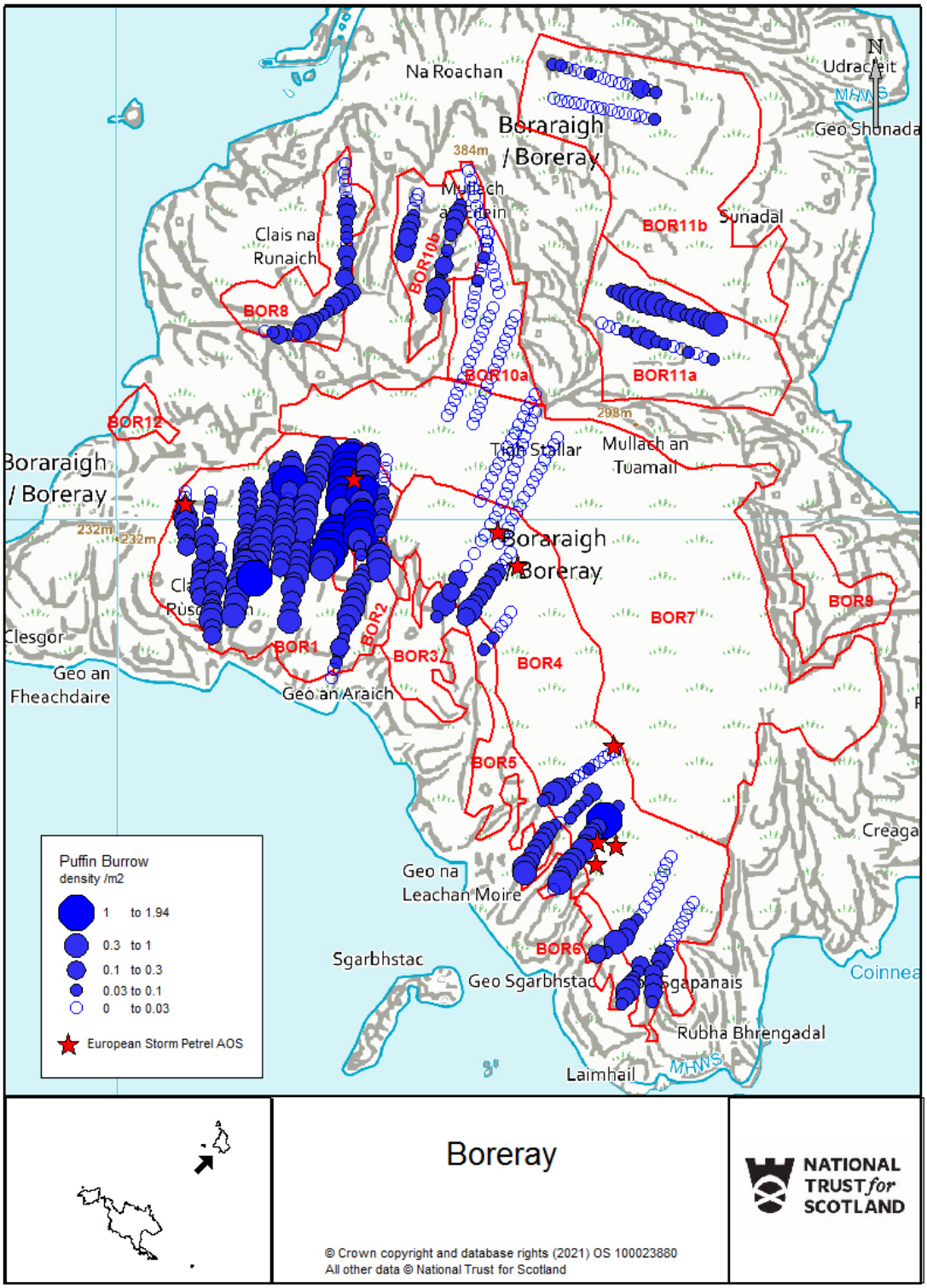

Figure A1. Map of transects surveyed for Atlantic Puffin *Fratercula arctica* on Boreray in 2019, also showing the zones used in the 1999/2000 'Seabird 2000' census as red lines (Mitchell *et al.* 2000). The density of Atlantic Puffin Apparently Occupied Burrows are shown (blue circles) together with detected responses from European Storm-petrels *Hydrobates pelagicus* (red stars). All detected European Storm-petrel responses were from a stone cleitean (a hut), which was surveyed in addition to the transects. Some sites had more than one Storm-petrel response.

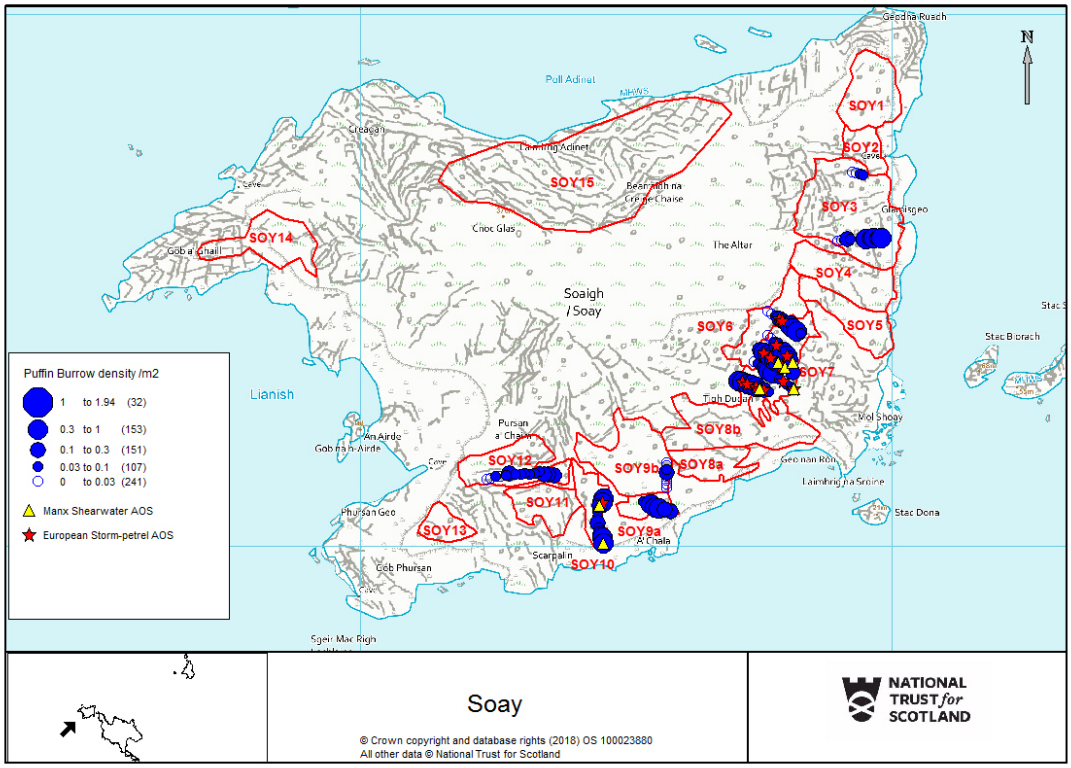

Figure A2. Transects surveyed on Soay in 2019 showing (red lines) the zones used in Seabird 2000 (Mitchell *et al.* 2000). The density of Atlantic Puffin *Fratercula arctica* Apparently Occupied Burrows is shown (blue circles) together with detected responses from European Storm-petrels *Hydrobates pelagicus* (red stars) and Manx Shearwaters *Puffinus puffinus* (yellow triangles). Some sites had more than one response.

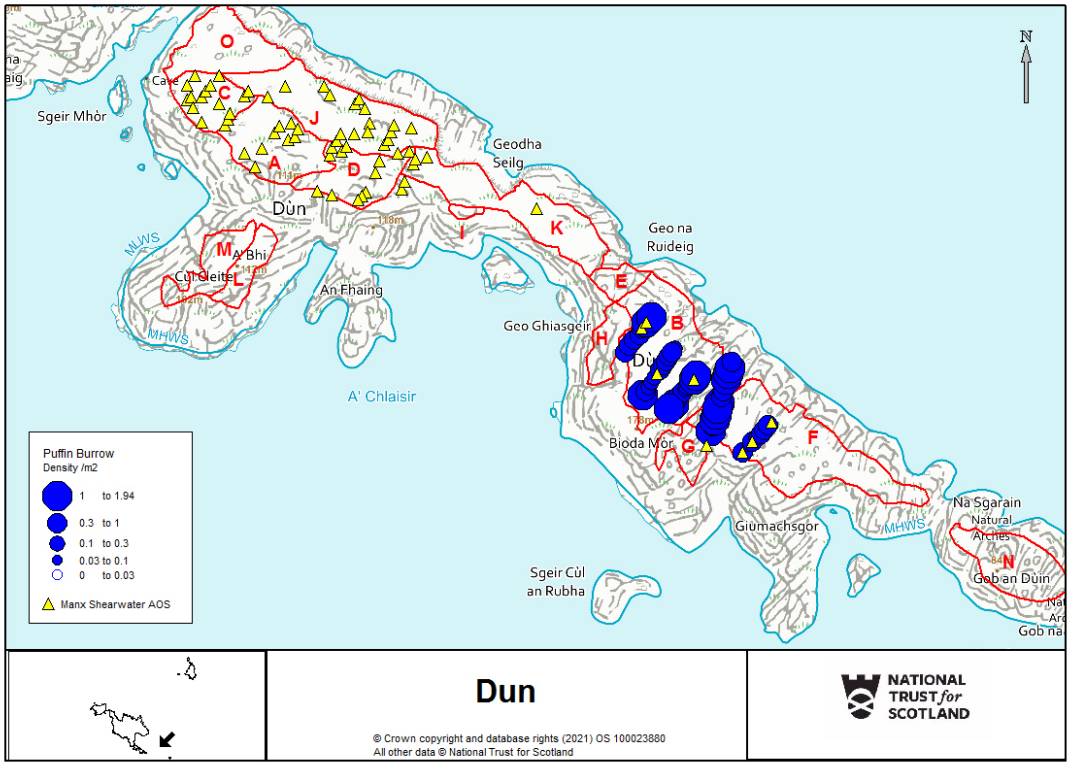

Figure A3. Transects surveyed on Dùn in 2019 showing (red lines) the zones used by Harris and Murray (1977). The density of Atlantic Puffin *Fratercula arctica* Apparently Occupied Burrows is shown (blue circles) together with detected responses from Manx Shearwaters *Puffinus puffinus* (yellow triangles). Only zones B and F were surveyed for Atlantic Puffin. No European Storm-petrels *Hydrobates pelagicus* were detected. For detail of the transects surveyed for European Storm-petrel and Manx Shearwater, see Deakin *et al.* (2020).

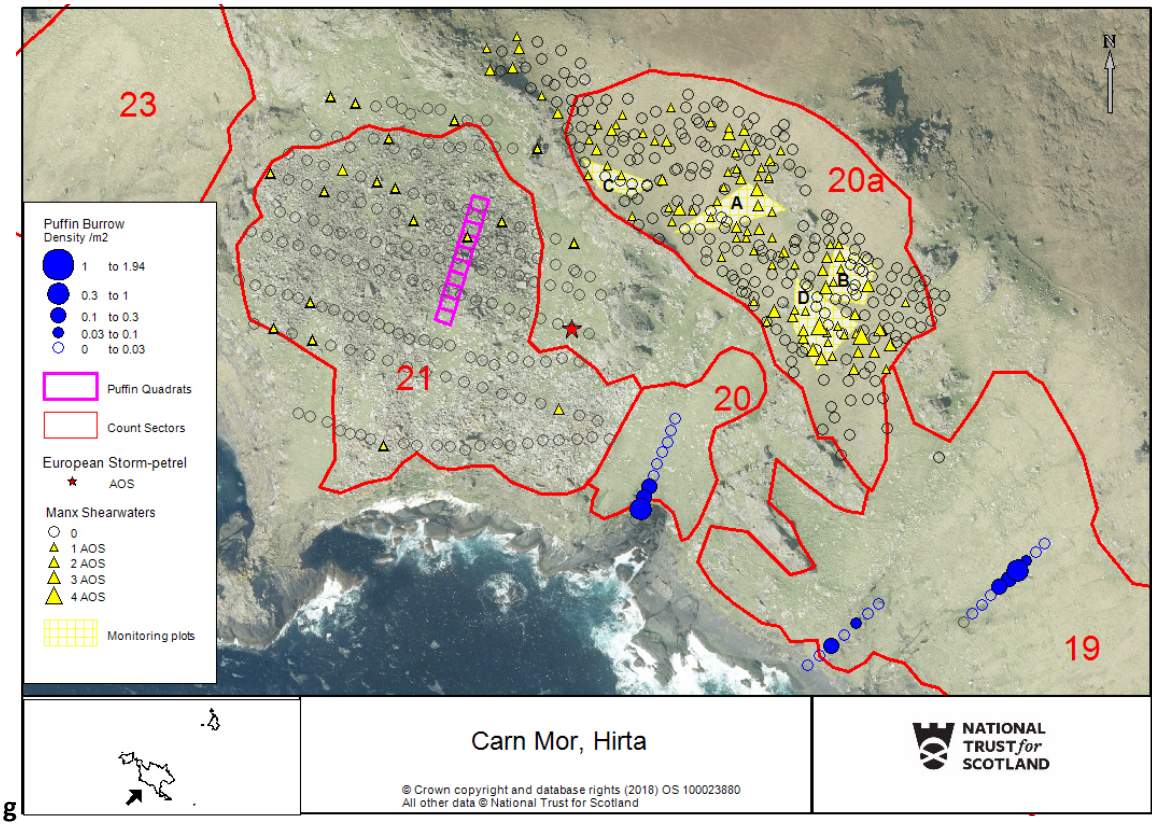

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Figure A4. Surveys of Atlantic Puffins (blue circles), Manx Shearwaters *Puffinus puffinus* (yellow triangles) and European Storm-petrels *Hydrobates pelagicus* (red star) in and around Carn Mòr on Hirta, St Kilda, in 2019 showing (red lines) the zones used in Seabird 2000 (Mitchell *et al.* 2000) and the long-term shearwater monitoring plots (Hatsell, 2018). The density of Atlantic Puffin *Fratercula arctica* Apparently Occupied Burrows (AOB) is shown (blue circles). The purple rectangles show the large (c. 9.5 m x 9.5 m) quadrats surveyed for Puffins.

Figure A5. Surveying for puffins in Carn Mòr boulderfield. Note the blue rope delimiting the quadrat.

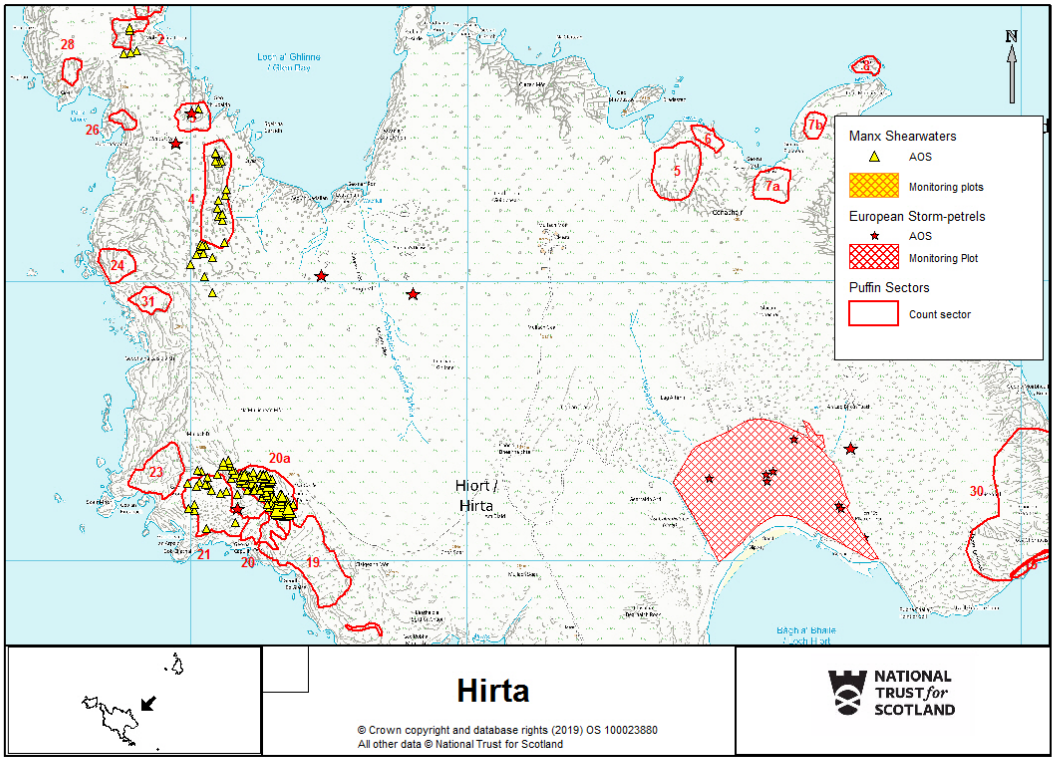

Figure A6. Responses to playback in Gleann Mòr and the Glen Bay gullies for European Storm-petrels *Hydrobates pelagicus* (red stars) and Manx Shearwaters *Puffinus puffinus* (yellow triangles) in 2019. Shapes are scaled by the number of responses detected in each location (1–3 for both species). The permanent monitoring plot for European Storm-petrels in the Village (see Lawrence 2019) is also shown.

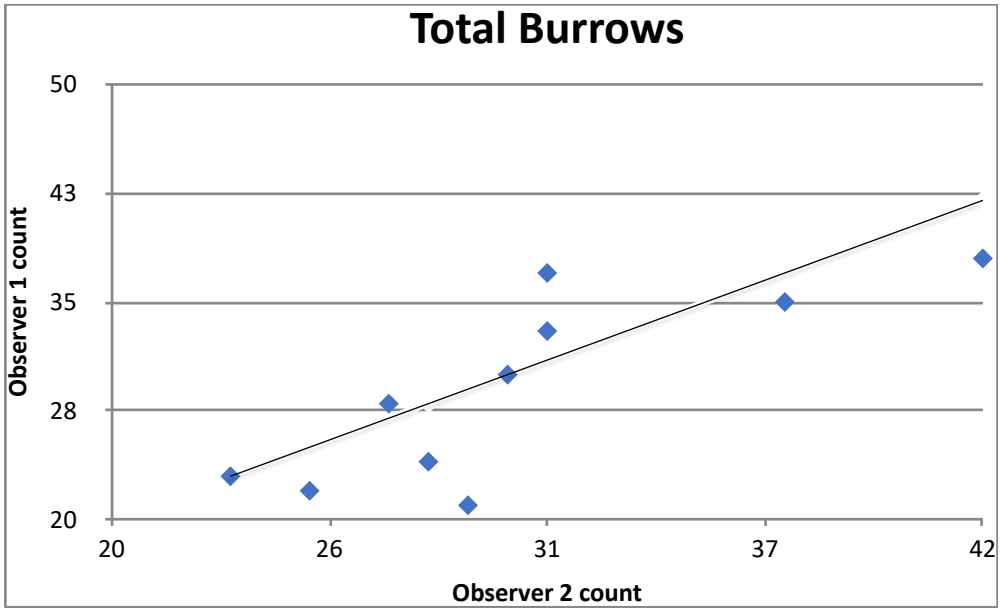

Figure A7. Comparison of counts of Apparently Occupied Burrows (AOB) in ten quadrats made by two different observers in Carn Mòr boulder field on Hirta, St Kilda, in 2019. 1:1 equivalence line shown.

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