A census of breeding Manx Shearwaters *Puffinus puffinus* on the Pembrokeshire Islands of Skomer, Skokholm and Midland in 2018

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Abstract
We present the results of a census of the Manx Shearwaters *Puffinus puffinus* nesting on the three Pembrokeshire islands of Skomer, Skokholm and Midland (formerly Middleholm), Pembrokeshire, undertaken in 2018. The breeding population estimates were largely in line with those made in 2011–2013, but differed markedly from 1998; this difference seems to be due to the different methods used in 1998 rather than any marked change in population size. Despite attempts to refine the estimation of response rate to call playback, the error of the population estimates remains large, illustrating the logistical and analytical challenges of making seabird censuses using call playback. Nonetheless, the population estimates are large and the spatial distribution of occupied burrows is consistent between censuses, and thus Wales may hold more than half of the world's breeding population of Manx Shearwaters.

Introduction
Useful estimates of population size are important components of population monitoring, to confirm the stability or increase of protected populations and signal the requirement for conservation strategies to be enacted in response to population declines. To this end, frequent sub-population monitoring is conducted (Walsh *et al*. 1995). Estimating the total population size of a breeding seabird colony is useful to 'ground-truth' sub-population estimates and to account for changing distributions, but is not always easy.

One group of birds which present particular difficulties is the burrow-nesting seabirds; these include a number of species such as some auks Alcidae and petrels and shearwaters Procellariiformes. Their nest-sites may be real burrows, such as those in soil or cavities, or crevices in rocky scree. Estimating the numbers of nesting pairs presents a number of difficulties; the nesting sites may be difficult or dangerous to access, the nesting chambers may be inaccessible, and they may be

 ***SEABIRD 32* (2019): 106–118**

empty or occupied by a species other than the target one. An added problem confronting the surveyor is that many of the petrels and shearwaters only visit the colony at night; a daytime visitor may see no birds at all, the birds are either present in the nest-chamber or at sea.

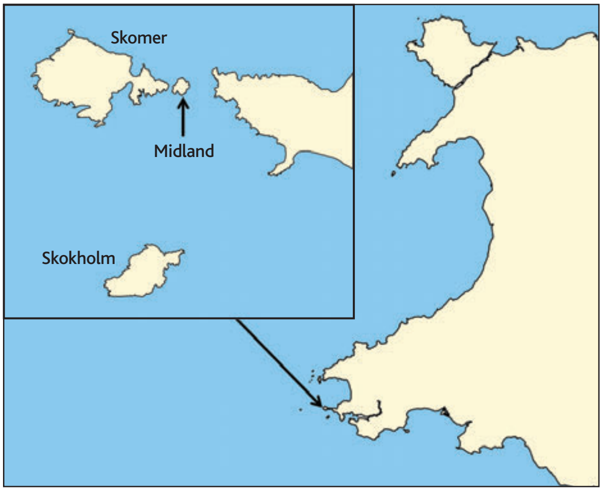

Figure 1. Map showing the location of the three Pembrokeshire islands, Skomer, Skokholm and Midland, where the study took place.

Increasingly in recent years workers studying these species have been using call playback to estimate population size. Each species has specific calls and by playing the calls at the burrow entrances some idea of the numbers may be obtained. An added advantage is that the work can be carried out in the day, making it much safer. While this method has made it possible to estimate numbers, it is not without its own difficulties; the work has to be carried out during the incubation period, not all individuals respond to the tape, in some neither parent may be present at the time of the visit, and there are differences in the calls — and the response to them — of the two sexes.

This paper describes studies on the Manx Shearwater, carried out as part of Seabirds Count 2015–2020 coordinated by the Joint Nature Conservation Committee. The aims of this study were to census the breeding Manx Shearwater population on each of the three islands of Skomer, Skokholm and Midland (51°44’N 5°5’W) (Figure 1), by use of call playback and, if possible, to improve on the estimates made on Skomer in 2011 (Perrins *et al*. 2012) and Skokholm in 2012–13 (Perrins *et al*. 2017). These most recent censuses of the two islands estimated the number of breeding pairs on Skomer as 316,065 (95% CI: 83,534) and Skokholm as 63,564 (95% CI: 15,943). A previous census in 1998 produced markedly lower results, with 101,274 breeding pairs on Skomer, 46,021 on Skokholm and 2,990 on Midland (Smith *et al*. 2001). Variations in response rates between different sites were examined, and as a final aim of this paper, we re-analysed the 1998 data to make them retro-comparable with the later censuses. The census results are compared with the earlier studies.

Methods

The basic methods used are described in Perrins *et al*. (2012). The islands were divided into hectare squares (100 m x 100 m, 10,000 m^2). In each square, the location of a plot (a circle of 10 m radius, and thus area 314 m^2) was pre-selected without reference to the terrain. Many of the coastal squares extend into the sea; in the 1998 census an attempt was made to estimate the percentage of each square that was in the sea. These estimates were made by island wardens (on Skomer by S. Smith and on Skokholm by G. Thompson). Although these estimates were approximate (sometimes because parts of the area could not be safely viewed), they were retained in 2011–13 and 2018 censuses to allow like-for-like comparisons. Later, we discuss changes to these area estimations. In 2018, 11 plots/squares were visited on Midland and 288 on Skomer; on Skokholm 172 plots were visited in 86 squares (two plots per square).

During the period from 1–20 of June 2018, each of these plots was thoroughly searched for burrows, and at each of these burrows a tape of the calls of Manx Shearwaters was played and a record kept of whether or not a bird responded to the tape. The recording, a 'duet' call, contained both male and female calls (Perkins *et al*. 2017, and see below). The period chosen is one which over a series of years has been that when almost all the birds were incubating their egg and so one or other of the parents was likely to be present in the burrow.

***A**: An estimate of the number of responding birds*

By the end of the census we have for each hectare square i, and hence each island, N_r, the estimated number of responding birds:

$$N_r = \sum \frac{A_i}{314} \times n_{ri}$$

Where:

N_r = total estimated responders summed across all squares

A_i = area of square i (m^2) (10,000 m^2 multiplied by the proportion that is land)

n_{ri} = number of burrows for which a response was recorded for square i

***B**: An estimate of the Response Rate*

In parallel with the whole island estimate of the number of responding birds, a series of burrows was opened and a hatch placed over the nest so that the contents could be examined easily. During the same period that the tapes were being played across all plots, each of these nests where an egg was laid was visited every other day (10 visits per nest) and the call was played. After noting whether or not there was a response the hatch was opened and the presence/absence of an occupant recorded. This enabled us to establish the actual Response Rate from a sample of burrows and use this to "correct" the number of responses in each plot to estimate the number of breeding pairs in that plot.

***C**: The estimate of the total number of breeding pairs for the whole island.*

The number of breeding pairs, N, is estimated from the sum of the estimates of each square multiplied by the reciprocal of the response rate, R:

$$N = \sum \frac{A_i}{314} \times n_{ri} \times \frac{1}{R}$$

Variances, standard error and hence confidence intervals were computed by measuring variance between adjacent squares and combining this with variance measured in response rate (see Perrins *et al*. 2012). First, the global variance is computed:

$$Var(N) = \left(\frac{Var(N_r)}{R}\right)^2 \times \left(\left(\frac{Var(N_r)}{N_r}\right)^2 + \left(\frac{Var(R)}{R}\right)^2\right)$$

And hence the standard error is:

$$S.E. = \sqrt{Var(N)}$$

Method refinements in 2018: The methods used are described in more detail in Perrins *et al*. (2012); some modifications to these are described in the study on Skokholm in Perrins *et al*. (2017). The differences were that a) instead of opening up many burrows early in the season and using those in which an egg was laid, in this study the burrows were opened in late May and only those containing an egg were used for obtaining the response rates, and b) Skokholm being smaller than Skomer, it was possible to measure results in two plots per square as opposed to only one on Skomer.

In 2018, a further change was implemented; a different playback call was used, the earlier recording being outdated. There were several reasons for this: first, the old tapes were wearing out which might affect response rates (Brown 2006). Second, both they and the tape-players were becoming increasingly hard to replace. Third, previous censuses had used the calls of male shearwaters and recorded the number of burrows from which males responded (a very high proportion of the males respond to the call of a male). However, the same is also true for female responses to female calls (Brooke 1990). By playing a recording containing both male and female calls (a 'duet' call), a higher and less variable Response Rate was achieved on nearby Ramsey Island (Perkins *et al*. 2017). This recording was used in all the playback studies in 2018 and will hopefully be used in all future censuses. Whilst a higher response rate does not influence the estimate in any particular direction, it should reduce uncertainty around the estimate.

The 1998 census estimate revisited: The first attempt to census the shearwaters on all three islands was made in 1998 (Smith *et al*. 2001). It was made in a way which was very labour intensive - and hence unlikely to ever be repeated. In essence, it involved:

a) Counting all the burrows on each island (in mid-winter when the vegetation was low)
b) When the shearwaters were incubating, visiting at least 5% of the burrows in each square, playing the tape and recording the number of those burrows where there was a response
c) Adjusting this figure by the response rate.

So,

$$N = n_b \times \frac{n_r}{n_s} \times \frac{1}{R}$$

Where:
N = total estimated occupied burrows
n_b = number of burrows counted during winter
n_r = number of burrows for which a response was recorded
n_s = number of burrows sampled
R = the response rate for an occupied burrow

The burrows to sample were selected by throwing a cane in each square and playing the tape down every burrow in a circle of 200 m^2 centred on the position where the cane landed. If the 5% criterion was not reached, the operation was repeated (sometimes with a smaller circle) until it was. A record was kept of the area of each square sampled in this way.

The 2011 and subsequent censuses have been made, as outlined above, by

$$N_r = \sum \frac{A_i}{314} \times n_{ri} \times \frac{1}{R}$$

Where:
N_r = total estimated responders summed across all squares
A_i = area of square i (m^2) (10,000 m^2 multiplied by the proportion that is land)
n_{ri} = number of burrows for which a response was recorded for square i
R = the response rate for an occupied burrow

Because the workers in 1998 recorded the area of each square that they sampled, we can repeat their calculations using the 2011 formula above to allow comparison between the three whole island censuses.

Results

2018 estimates of the number of breeding pairs

A: Estimates of the number of responding birds

Table 1 gives the estimated number of responding birds on each of the three islands in 2018.

Table 1. The number of breeding Manx Shearwaters *Puffinus puffinus* responding to call playback on each of the three islands in 2018.

Skomer (all)	175,786*
Skokholm (all)	63,545*
Midland	16,548

* Note: in order to obtain a measure of variance (see 2012 paper) these counts involve pairing squares and adding the means of the pairs. This will result in some small differences from adding the numbers of responses in each square separately. There were too few squares on Midland for this to be meaningful.

B: Estimates of the Response Rate

The measurement of Response Rates (Table 2) has a major effect on both the estimated number of breeding pairs and the estimate of Confidence Intervals (CI) of this; a larger sample of Response Rate calibration burrows markedly reduces the CI.

One informal recommendation from the earlier studies was that both the number of study burrows and the number of sites where they are located should be increased. Unfortunately, the 2018 census indicates that considerable variation in Response Rate remains between and within islands. We have no *a priori* reasons for using one of these rates over any others (though the lowest, North Valley on Skomer, seems very low and the highest, Quarry Track on Skokholm, could be explained as a result of the small sample).

The final column of Table 2 shows the CI as a percentage of the actual estimate for each area. The calculations based on combining all the data for each island yield the lowest percentage, and the CI for the combined data from both islands produce the lowest CI of all. We have used the within-island averages of Response Rate in calculations of the number of breeding pairs for Skomer and Skokholm, and for Midland (which is not inhabited and thus repeat playback calibrations were not feasible) used the Response Rate from neighbouring Skomer Island.

C: The estimate of the total number of breeding pairs.

The estimate of the total number of breeding pairs is the sum of A x B for all squares (Table 2). We conclude that the estimate of the breeding population of Manx Shearwaters on Skomer is, "of the order of 350,000 breeding pairs", that for Skokholm is, "in the region of 90,000", and that for Midland, "in the region of 16,000 breeding pairs", but we stress that these should not be quoted without the large Confidence Intervals associated with them - over 90,000 on Skomer and around 22,000 on Skokholm.

Table 2. Response Rates and estimated numbers of burrows with responding birds for all three islands 2018.

Island	Area	Resp Rate	N	E(x)	SD(x)	Var(y)	Var(z)	Estimate	CI(z)	Low CI	High CI	Error %
Skomer	North Haven	0.56	39	175,786	9,514	0.00632	2273790642	320,228	93,461	226,767	413,689	58.37
Skomer	North Valley	0.42	20	175,786	9,514	0.01218	12608532089	447,439	220,083	227,354	667,522	98.37
Skomer	All	0.51	59	175,786	9,514	0.00424	2267899089	349,663	93,340	256,323	443,003	53.39
Skokholm	Lighthouse	0.7	21	63,545	5,768	0.00877	215308428	92,404	28,759	63,644	121,163	62.24
Skokholm	Crab Bay	0.72	23	63,545	5,768	0.01000	214433272	89,961	28,701	61,259	118,662	63.81
Skokholm	Quarry Track	0.8	6	63,545	5,768	0.02667	314875555	82,742	34,779	47,962	117,521	84.06
Skokholm	All	0.72	50	63,545	5,768	0.00403	124757867	88,945	21,892	67,053	110,837	49.23
Skomer	All, both islands	0.6062	109	175,786	9,514	0.00219	747478520	291,709	53,586	238,123	345,296	36.74
Skokholm	All, both islands	0.6062	109	63,545	5,767	0.00219	311810091	105,451	34,609	70,841	140,061	65.64
Midland								16,548				

Key to Columns: A: Island, B: Area, C: Response Rate, D: Number of tested nests, E: Estimated numbers of responses, F: Standard Deviation of E, G: Sampling variance of responding burrows, H: Sampling variance of the estimate E, I: Estimated number of breeding pairs, J: 95% Confidence Interval, K: Lower Confidence Interval, L: Upper Confidence Interval, M: Range of Confidence Interval as % of I.

Note: Skomer: the North Haven estimate falls very close to that for 2011, but the North Valley one is far higher than the Upper CI. Skokholm: the 2018 estimate is just above the Upper CI of the 2011 census (79,507).

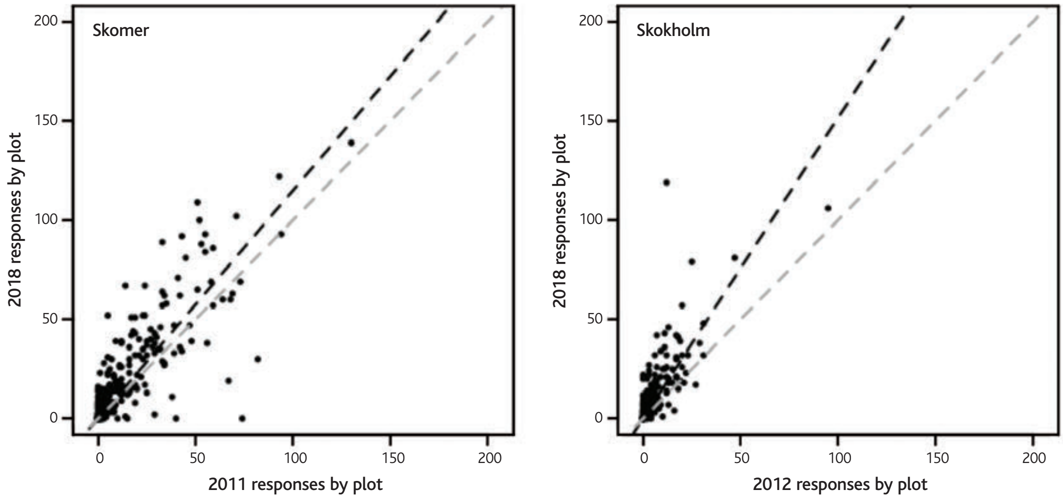

Figure 2. A comparison of plot-wise responses between the 2011 Skomer census and 2012–13 Skokholm one, respectively, and the 2018 census for both islands. The black dashed line shows the regression of the data presented. The grey line shows what might be expected if Manx Shearwaters were at the same density and had the same response rate (a 1:1 ratio).

Plot repeatability between censuses: Figure 2 shows the number of responses recorded from each plot in 2018 plotted against the number of responses in the same plot in the Skomer 2011 census and the Skokholm 2012–13 census respectively (2011 and 2018 for Skomer, r^2 = 0.78; 2012–13 and 2018 for Skokholm. r^2 = 0.68). There are a number of reasons why we would not expect to find the same number of responses at the same plot between censuses: plot locations were revisited using handheld GPS which carries an error of approximately 3 m, so slightly different plot areas will have been surveyed, and the playback calls used were different.

Departure from the grey line indicates either a difference in response rate or total occupied burrows for each plot, between 2011–12 and 2018. Response rates were significantly different between the two survey years for both Skomer and Skokholm (Skomer: paired $t_{1,270}$ = 6.44, P < 0.0001; Skokholm: paired $t_{1,163}$ = 7.88, P < 0.0001).

Both the high consistency in relative plot density between the two surveys, 5–7 years apart (see r^2 reported above), and visual inspection of the spatial clustering in density of Apparently Occupied Burrows across all three island censuses on Skomer and Skokholm (Figure 3) suggest that survey techniques used are producing robust and comparable results.

1998 comparability with 2011–2013 and 2018: The results of recalculating an estimate from the 1998 data using the 2018 formula are shown in Table 3. As can be seen, the results of the two calculation methods differ greatly on all three islands. One reason for supposing that the 2018 census calculation method is more appropriate comes from simple arithmetic. In 2018 the workers visited 281 squares

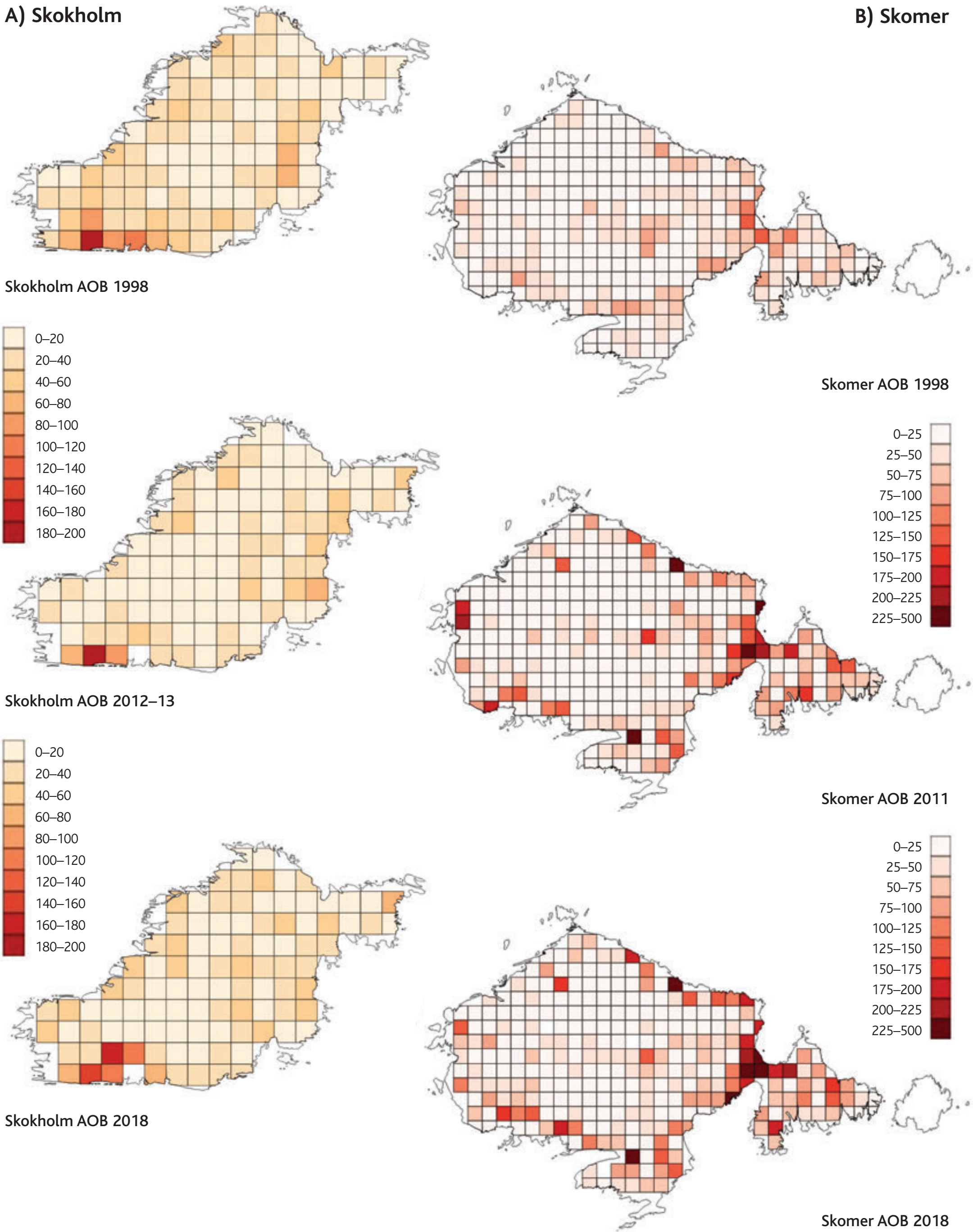

Figure 3. Maps showing the spatial distribution of the estimated number of Apparently Occupied Burrows (AOB) of breeding Manx Shearwaters *Puffinus puffinus* on A) Skokholm and B) Skomer Island, from the three whole-island censuses carried out in 1998, 2011–13, and 2018. The spatial distribution of occupied burrows is consistent. Midland was not surveyed in 2011–13, and thus is not shown here. Island maps are shown at different scales: each grid square represents one hectare (100x100 m).

Table 3. Estimated number of breeding Manx Shearwaters *Puffinus puffinus* on the three islands using different calculation methods.

Island	Formula used	Estimated no. of responses	Adjusted for Response Rate (0.4301)
Skomer	1998	43,558	101,274
	2011/18	155,708	362,027
Skokholm	1998	19,794	46,021
	2011/18	53,401	124,159
Midland	1998	1,247	2,899
	2011/18	3,471	9,296

Note: for each island, the data recorded in 1998 have been used; for each island, the two rows show the results when the formulae used in 1998 and 2011/18 are applied to the same set of 1998 data.

containing some 266 ha of land. They carried out playback to all the burrows in 8.82 ha (281 plots x 314 m^2) and recorded 6,113 responses; expanding the latter density to the whole 266 ha area yields 6113 x (266/8.82) or 184,360, a figure similar to the 173,355 derived from the more detailed calculation. If this reasoning is correct, we still lack an explanation for why the method used in 1998 was incorrect. On the face of it, the 1998 method seems reasonable, yet the numbers of burrows recorded is only about half of the number of pairs of shearwaters estimated. There are also empty burrows, and others containing rabbits and puffins. One point to note, however, is that there is an inconsistency within the 1998 data. Namely, that given the number of burrows counted in the winter count, not enough area was searched to find a similar number of burrows during the summer survey. This means that probably one or both densities were systematically mis-recorded. We therefore suggest our revised figure for the 1998 should be used for comparison, both here and in future.

Assuming this to be correct, the three censuses — 1998, 2011 and 2018 — have largely overlapping confidence intervals and thus are not statistically distinguishable. The good news from this is that, within the order of accuracy that these surveys permit, we have not detected large changes in populations over the last 20 years, and the spatial distribution of occupied shearwater burrows on the islands is consistent between census efforts (Figure 2). The less-good news is that smaller changes, while less worrying, would not be detected with the methods presently available. However, Procellariiform population changes in response to invasive species (e.g. rats) can be rapid and substantial and so even having the power to detect only large changes in population size is useful for conservation management of this species (Arneill *et al*. 2019). Further, it is worth noting the similarity of the most likely estimates for population size over the three surveys.

Discussion

A total of approximately 456,000 breeding pairs of Manx Shearwaters were estimated to be present on the three islands of Skomer (350,000), Skokholm

Manx Shearwater
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(90,000) and Midland (16,000) – more than 900,000 breeding adults. A crude addition of the known confidence intervals associated with these figures is 112,000 (excluding Midland). With the addition of an unknown number of non-breeding birds, it is likely that more than a million adult Manx Shearwaters are present in the Pembrokeshire Special Protection Area during the breeding season. However, we stress the large confidence intervals associated with these island population estimates — over 90,000 on Skomer and around 22,000 on Skokholm — which reflect the challenges of call playback surveys (Arneill *et al.* 2019).

Because of the great difficulty of censusing a bird that lives largely on uninhabited islands, nests in burrows and is only active at the colony at night, arriving at even an approximate size for the world population may be more a case of 'guestimate' than estimate. The last full census of the Manx Shearwater in the UK and Ireland, (Seabird 2000, Mitchell *et al*. 2004), put the world population at a maximum of 410,000 pairs (Newton *et al.* 2004); however, the current estimates for Skokholm (90,000), Skomer (350,000) and Midland (16,000) exceed this figure. Together with Bardsey (16,000, now perhaps 25,000, S. Stansfield pers. comm.), and Ramsey (5,000), the total Welsh population could be in the region of 500,000 breeding pairs. Seabird 2000 (Mitchell *et al*. 2004) estimated the Scottish population at 126,000 pairs, but that included 120,000 for Rum which has since been estimated at 76,000 (Murray *et al*. 2003). By far the largest source of error is likely to be the estimate for Ireland, put at 37,000 in Seabird 2000 (95% CI between 23,643 and 54,558, Cummins *et al*. 2019) but this number includes guesses for some inaccessible islands, especially in the south-west, which have not been fully censused but where large numbers of birds can be observed offshore. Of these, three estimated to hold 765 during Seabird 2000 have since been more carefully surveyed and are currently estimated to hold 4,280 pairs (Arneill 2018). Were that degree of discrepancy similar for the other islands, the 37,000 might easily be as high as 200,000 pairs. However, it remains a possibility that some island populations in Seabird 2000 were overestimated and therefore the Irish population size remains to be established with certainty (J. Quinn pers. comm.). Outside the UK and Ireland, there may be only some 50,000 pairs of Manx Shearwaters (25,000 Faeroes, 10,000 Iceland, and small numbers in France, Spain, Portugal and perhaps elsewhere – Mitchell *et al*. 2004).

Putting these all together yields of the order of: Scotland 100,000, Ireland 200,000, Wales 500,000 and outside UK 50,000; some 850,000 breeding pairs. These figures emphasise the central importance of Wales to the Manx Shearwater; well over half of the world population breed in Wales. For only one other species of bird, the Northern Gannet *Morus bassanus,* is the UK and Ireland home to half the world's population (Mitchell *et al*. 2004).

Future census using call playback: As described above, not all the areas falling within a hectare square are suitable for shearwaters to nest in; most commonly, this is because coastal squares extend into the sea. However, inland squares may also include areas where nesting is impossible: sections of rock, ponds or boggy ground.

In 2017, the whole of Skomer Island was surveyed by use of an unmanned aerial vehicle (UAV or 'drone'; Alexander & Bellamy 2018). Areas of sea, rocky or boggy ground were measured for each hectare square; while not applied in the census analysis presented here, removing these from each square results in a much more accurate measurement of the land potentially available for nesting by shearwaters. Further, it was possible to use the drone to locate and examine 45 other small coastal patches, hitherto omitted from censuses because they were either too dangerous to visit or difficult to observe. These data are available only for Skomer and have not been used in this paper where the aim was to establish the status of the populations on the three islands. In the long-term it would be valuable to have them for Skokholm and Midland.

There are two caveats which need to be applied to any comparisons made between the Skomer shearwater census data and the areas that were acquired from the drone study. First, the initial area estimations made in 1998 were based on hectare squares of the British National Grid, located on the island using an established Trig point and a compass and measuring tapes. This is imprecise, but for continued use to study population change such errors do not matter greatly. However, the drone study was done to a much greater accuracy. Inevitably the two sets of hectare squares will not match exactly. Second, the drone measurements are taken vertically whereas the measuring tapes were laid on the ground and so where there is a steep slope (as often occurs in the coastal strip), there is a 'parallax' problem.

The data from the 2011 Skomer census (which contained estimates of land area for each of the squares censused) were based on 284 squares which were estimated to cover 268.7 ha. However, using the drone measurements, these same squares yielded an estimate of 245.7 ha, some 9% smaller. This may seem a small difference, but it is most serious in the coastal plots where both the largest discrepancies arise and where the largest densities of shearwaters occur. Examining the 72 plots which were scored as 'coastal', the 2011 census estimated the area in these plots as 57.5 ha compared with 45.2 ha for the drone survey. This reduced the estimated number of responses in these squares from 64,068 to 52,899 and when the Response Rate was included, resulted in an over-estimate of the number of pairs of some 28,000. Against this, the drone survey showed that the 45 small coastal slopes in total covered 5.04 ha. Assuming that these areas contain densities similar to those in the other coastal plots, there could have been about 5,900 responses or 14,600 breeding pairs in these areas. Neither of these corrections has been made to the figures presented here since they can only be made to Skomer. In future census work, we recommend the use of more accurate estimations of suitable breeding habitat by using aerial imagery, such as that provided by drone, to improve the accuracy of population estimates. Although we detected no decline in Response Rate with date as Response Rate calibration trials continued, the potential for pseudoreplication resulting from the use of the same call for all playbacks (Kroodsma *et al*. 2001) might also be explored. These methods can be retro-applied to extant census data for comparability in future censuses.

Acknowledgements

This study could only have been undertaken with the help of many people. We are particularly grateful to the following for doing most of the fieldwork: Jack Barton, Aude Boutet, Alice Cousens, Nicci Cox, Sarah du Plessis, Connor Walsh and Tom Lloyd; and on Skokholm: Kirsty Franklin, Stephen Vickers, Amy Sherwin, Alys Perry and Zoe Deakin. The census received funding contributions from the National Trust (Wales), Natural Resources Wales (NRW), and The Seabird Group. Lizzie Wilberforce (Wildlife Trust of South and West Wales) and Patrick Lindley (NRW) assisted with funding applications and logistical support.

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