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Surveys of Breeding Cliff-nesting Seabirds, Ground-nesting Seabirds and Burrow-nesting Seabirds in Western Scotland.

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Final report to:

afbi AGRI-FOOD & BIOSCIENCES INSTITUTE

Executive Summary

- This report summarises a series of counts of cliff-nesting seabirds, ground-nesting seabirds, burrow-nesting Petrels, and burrow-nesting Shearwaters made by multiple teams at various locations in northwest Scotland.
- Work was co-ordinated under contract issued by Agri-Food and Biosciences Institute Northern Ireland by the University of Exeter as part of the Marine Protected Areas Management and Monitoring (MarPAMM) project and its results will feed into the development of regional management plans for a number of MPAs in the area.
- Surveys were undertaken by teams from the University of Exeter, Shiants Auk Ringing Group and Sanda Island Bird Observatory and Field Station Trust.
- The work was originally contracted to run during the summer of 2020, but the COVID pandemic prevented this. Mitigating COVID restrictions in 2021 presented substantial logistical and financial challenges but all contracted survey work (and more) was successfully completed between early May and mid-July 2021.
- Cliff nesting counts were made at 111 sites in the Western Isles, the entire island of Skye (including offshore islands) and the entire islands of Rum, Muck and Little Cumbrae.
- Ground nesting skuas were counted across all suitable areas of north Lewis resulting in almost 400 km^2 of habitat surveyed.
- Surveys of Leach's and European storm petrels were made on North Rona, the Flannan Islands, Shillay and Sanda using the latest distance sampling approaches.
- The team also undertook the most comprehensive census ever made of the Rum Manx Shearwater colony surveying over 100,000m^2 of habitat on the island.
- A total of 72,071 breeding pairs & individuals of 13 species of cliff-nesting seabirds were recorded during the surveys (3502 in Lochaber, 7899 in Skye and Lochalsh, 60,246 in the Western Isles and 424 in Cunninghame).
- Over 1100 breeding pairs and individuals of 9 species of ground-nesting seabirds were recorded during surveys on the Isle of Lewis.
- Our surveys produced estimates of 1465 pairs of European Storm Petrels across 4 sites and estimates of 7336 pairs of Leach's Storm Petrels across 2 sites.
- Our Manx Shearwater survey on the Isle of Rùm produced an estimate of 288,894 breeding pairs.

Introduction

Background

MarPAMM is a €6.4 million EU INTERREG VA funded project that will develop a series of monitoring and management tools for several protected coastal marine environments in Ireland, Northern Ireland, and Western Scotland. Its cross-border nature recognises the fact that to protect and manage highly vagile species administrative and regional designations are often irrelevant and cooperation between states is needed. The work packages described in this report were originally identified by the environmental statutory bodies of the three regions within the MarPAMM area as priorities for the MarPAMM project and were contracted to the University of Exeter by Agri-Food and Biosciences Institute Northern Ireland (AFBINI) after a competitive tender process. While MarPAMM is multifaceted covering a range of issues and taxa, this report refers to work undertaken relating to the aim of collecting data on abundance and distribution of seabirds. The Exeter team successfully bid for two of the five work packages offered in the original call. The first package focused on a survey of breeding cliff nesting seabird species at colonies in Western Scotland, this also included ground nesting Skuas and Gulls in North Lewis. The second package was a Survey of breeding Shearwaters and Petrels in Scotland. The surveys cover sites in Highland Region, the Western Isles (Na h-Eileanan an Iar, hereafter referred to as the Western Isles) and two locations in the Firth of Clyde. These data will inform management decisions and contribute to the development of the habitat and conservation models being developed by other researchers on the project.

Covid-19

The project was originally scheduled to run during the summer of 2020 but was suspended due to the COVID pandemic with a plan to revisit in 2021. However, this did present a problem, as the project manager (Richard Inger) had already been involved in setting up the first parts of the project and some training. It did however give us the opportunity to reschedule/optimise some plans for the burrow nesting seabird survey work after the steering group requested we undertake some additional fieldwork. The University of Exeter managed to keep the project manager employed during the hiatus meaning that the team were ready to hit the ground running when the restrictions were lifted and the team at AFBI agreed to some additional funding to support the overlap associated with re-planning a field season. The logistics involved in running such a programme as we emerged from the pandemic were considerable and impacted the finances of the project. However, the various teams involved in delivering the huge amount of work described here were exemplary in this respect, taking all the precautions requested and respecting the sensitivities of local communities and other team members. There were no instances of COVID during the surveys (despite having 52 people involved in the surveys).

Region And Scope

The west coast of Scotland holds breeding seabirds in numbers that are of both national and international significance (e.g. Mitchell et al. 2004). Gathering data on abundance and distribution of these birds is a central aim of the Seabird modelling work within the MarPAMM project and essential for parameterising the management tools that are one of its key deliverables. The fourth large scale breeding census of seabirds in the British Isles, Seabirds Count, has been in operation in the region since 2015. As such, many of the seabird colonies had already been counted. The project covered here focussed on a subset of sites identified by the MarPAMM team and the project steering group because they were omitted during the initial Seabirds Count surveys sites, many of which were relatively minor assemblages of cliff nesters. Exceptions to this are the Shearwater colony on Rùm, which is likely the largest single Manx Shearwater *Puffinus puffinus* colony in the world, comprising some 120,000 apparently occupied sites (Murray et al. 2003, Jackson 2018), the large mixed skua colony on Lewis which holds regionally important numbers of both Arctic *Stercorarius parasiticus* and Great Skuas *Stercorarius skua* (Mitchel et al. 2004) and the two largest Leach’s Storm Petrel *Hydrobates leucorhous* colonies outside the St Kilda archipelago, North Rona and the Flannan Isles (Mitchel et al. 2004).

Cliff-nesting Seabirds.

The main objective of this work was to gather data on seabird populations from colonies where data is deficient. These data will help in the assessment of seabird population sizes, trends, distributions, and the threats they may face. This information will then inform a series of MPA Management Plans that will be produced by the MarPAMM project. The last complete census of seabirds in the region was conducted as part of Seabird 2000. As outlined above the counts of cliff nesters were made on a subset of generally smaller colonies, including some that had not been covered in earlier large-scale surveys. Species covered under this category were as follows: Northern Fulmar *Fulmarus glacialis* (hereafter Fulmar), Great Cormorant *Phalacorcorax carbo* (hereafter Cormorant), European Shag *Gulosus aristotelis* (hereafter Shag), Black-legged Kittiwake *Rissa tridactyla* (hereafter Kittiwake), Atlantic Puffin *Fratercula arcitica* (hereafter Puffin), Common Guillemot *Uria aalge* (hereafter Guillemot) and Razorbill *Alca torda*. For Fulmar, Cormorant, Shag and Kittiwake the census units were either Apparently Occupied Site/Nest (AOS/AON). In the case of Puffin Apparently Occupied Burrows (AOB) were counted, whereas for Guillemots and Razorbills the number of individuals (IND) were counted. Large gulls Larus spp and Skuas were also counted during these surveys and in these instances the sampling units were Apparently Occupied Territory (AOT). Surveys were carried out between mid-May and early July, census units matched those used during the previous Seabird 2000 surveys and were carried out according to the standard approaches outlined in Walsh et al. 1995. We also investigated the utility of the use of digital photography and the use of unmanned aerial vehicles (UAVs) for the surveying of cliff-nesting seabirds on the Isle of Skye. Locations surveyed were as follows: Skye (entire island), Rùm, Muck, and 111 Sites within the Western Isle, including a number of additional sites not included in the original remit.

Ground-nesting Seabirds.

Given that previous Seabirds Count surveys had already been carried out on many of the ground nesters, there were only a few parts of the survey region lacking in data for ground nesting seabirds. In this respect the work largely focussed on Skuas nesting in Northern Lewis. Large gulls along with Black-headed Gulls *Chriococephalus ridibundus* and Common Gulls *Larus canus* were also counted during the Lewis surveys, although some of the larger colonies had been counted relatively recently (Robin Reid, RSPB warden pers comm). Likewise Arctic Skuas had been counted during windfarm surveys (18/5/21-23/6/21) and many of the territories are regularly monitored by RSPB. In all cases census units were AOTs and for skuas additional information on how AOT was assessed was also collected (see Furness 1986, Walsh et al. 1995).

Burrow-nesting Seabirds.

As with Lot 1, the objective of Lot 3 was to gather data from burrow-nesting seabird populations at colonies where data is deficient. This component presented the greatest logistical and analytical challenges and involved three species: Manx Shearwater, Leach's Storm Petrel and European Storm Petrel *Hydrobates pelagicus*. As with the cliff nesters, many of the small colonies that were visited had not been surveyed since Seabird 2000. The Rùm Manx Shearwater colony has long been recognised as an extremely difficult survey task, and despite two surveys since 2000 that have better defined the extent of the colony, there is still a huge amount of uncertainty around the size of this population and it is probably larger than currently thought (Murray et al. 2003, Jackson 2018). Recent developments (Arneill et al.

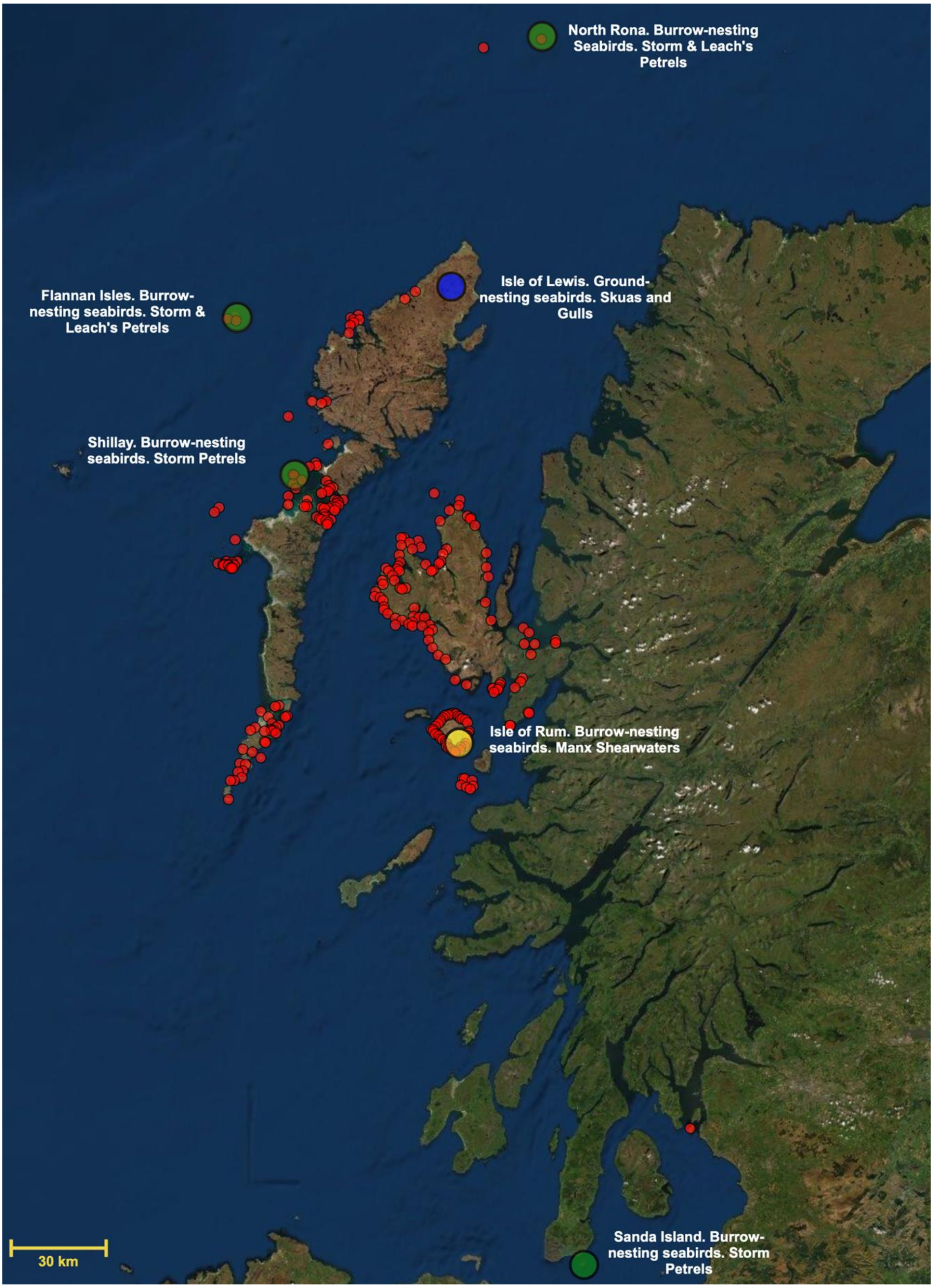
2019, Deakin et al. 2021), meant that we were able to combine the latest thinking on data collection with sophisticated analytical approaches for all three burrow nesting species to try and reduce some of the uncertainty that has featured in these censuses in the past. This also allowed us to think about best practice for future surveys of this nature in colonies of different sizes or where densities are more heterogeneous.

Outline.

This report details the seabird survey work outlined above that was carried out during May-July 2021 covering the locations visited, the species counted, and the methods used. We discuss our findings in relation to previous counts and outline some of the methodological amendments that could be made to future studies.

Methods

Figure 1. Map of all study sites. Small Red circles are cliff-nesting seabird sites. Blue circles are ground-nesting seabirds sites. Green circles are burrow nesting seabirds - Petrels. Yellow circles are burrow-nesting seabirds – Manx Shearwaters.



Cliff-nesting Seabirds

Sites

Skye and Lochalsh

All sites holding cliff-nesting seabirds were surveyed by boat between 16/6/21 and 21/6/21 over 6 days. The survey was carried out during a full circumnavigation of the Isle of Skye and associated islands starting and finishing at Armadale Pier in the south of the island. The survey was carried out in a counter clockwise direction. The location, start and finish grid references of all sites were provided by Daisy Burnell of JNCC. All sites were marked to OS Explorer series maps before the survey commenced, and the location of sites were identified using these maps along with the OS maps app on a smartphone. New sites and notable sighting were recorded using the OS maps app.

Cliff-nesting seabird counts using species-specific methodologies were carried out as described in the JNCC handbook under 'Whole colony counts' and 'Counts from the sea, from the air, or from photographs'. The boat was manoeuvred as close to each site as was safe as determined by the skipper. All counts were made using high quality binoculars, with 8-10 times magnification. At least 2 counts per species were carried out at each site. In the case of large or dense colonies repeat counts were made by multiple (2 or 3) observers. One team member collated all the observations, recording them into a notebook before they were subsequently transferred to a spreadsheet. Visibility, sea stare, wind and rain were also recorded at each site. A full list of sites surveyed can be found in the Appendix in Table A1. Full details of the survey can also be found in Appendix.

Lochaber

The Islands of Rùm and Muck were surveyed on the 17/5/21 and 18/5/21 respectively. Both islands were surveyed by a full circumnavigation of each island. Protocols were as described within the Skye methodologies. A full list of sites surveyed can be found in the Appendix in Table A2 (Rùm) and A3 (Muck). Full details of the survey can also be found in the Appendix.

Cunninghame

Little Cumbrae was surveyed on 6/6/21. The survey was completed during a single circumnavigation of the island following standard JNCC protocols as outlined within the Skye methodology. A full list of sites surveyed can be found in the Appendix in Table A4. Full details of the survey can also be found in the Appendix.

Western Isles

In addition to the sites identified in original tender specification additional counts were carried out on Lewis (Arnol, Barvas, Bearasay, Campay, Floday, Harsgeir, Mas Sgeir, Old Hill), Harris (Dun-aarn, Ensay, Gilsay, Greine Sgeir, Groay, Killegray, Langay, Renish Island, Suem, Taransay, Toe Head, Sleicham, Saghay Islands, Scarp Island) Sound of Harris (Bhacasaigh, Gousman, Greineam, near Laimhrig More, Sgeir Sine, Taghaigh), and Shillay. Surveys were carried out between 28/5/21 and 26/6/21 following standard JNCC protocols as outlined within the Skye methodology. A full list of sites surveyed can be found in the Appendix in Table A5. Full details of the survey can also be found in the Appendix.

Species Specific Methodologies

All methods are taken directly from the JNCC handbook.

Cormorant.

The generally recommended unit is the AON. This includes birds that appear to be incubating, unattended broods of young, and other attended, well-built nests including empty ones apparently capable of holding eggs. Nests at a lesser stage of construction are not included in the standard AON figures but should be noted separately. At some colonies, the majority of nests are not visible from any vantage point and minimum counts of nests and visible adults may be all that can be achieved (if aerial or sea-based surveys are not possible).

Shag.

The generally recommended unit is the AON. This includes active nests (bird sitting tight whether or not eggs or young were seen, or an unattended brood of young) and other attended, well-built nests (apparently capable of holding eggs). Nests at a lesser stage of construction should be recorded separately, as they are often abandoned, or destroyed by other pairs stealing nest material (Harris & Forbes 1987).

Fulmar.

The generally recommended unit is the AOS. A site is counted as occupied only when a bird appears to be sitting tightly on a reasonably horizontal area judged large enough to hold an egg. Two birds on such a site, apparently paired, count as one site. (This should exclude birds which are sitting or crouching on sloping sections of cliff.)

Kittiwake.

The generally recommended unit for counts and population monitoring is the AON, defined as a well-built nest capable of containing eggs with at least one adult present. (Poorly built 'trace' nests with adults in attendance are more likely to involve non-breeding birds, but additional counts of these can be useful, as a high proportion of trace nests may indicate a late breeding season or, possibly, a decrease in the proportion of adults breeding.) Late in the season, large numbers of apparent trace nests may indicate that many nests have failed and subsequently deteriorated.

Gulls.

Gulls included in the survey were Herring gull, Great black-backed gull, Lesser black-backed gull, Common gull and to a lesser extent Black-headed gull. The recommended census unit is an AON, i.e. a well-constructed nest, attended by an adult and capable of holding eggs, or an adult apparently incubating if, for example, actual nests are obscured by vegetation. Some count methods use slight variations on this (e.g. so- called active nests', containing eggs or with other signs of use, counted during transect or quadrat surveys, when attendance by adults is not possible to record). Some counts or estimates are made as AOTs, based on the spacing of birds or pairs viewed from a vantage point, if actual nests or incubation cannot be discerned. Counts of individual adults may also prove necessary on occasion.

Common Guillemot.

Here after called Guillemot. The recommended census unit is IND. Counts of breeding pairs are virtually impossible without highly intensive observations of mapped study-plots.

Razorbill.

The recommended unit is IND at a colony. Counts of AOSs are sometimes possible, but are difficult to define unambiguously and, in general, are not recommended.

Puffin.

The best count unit is the AOS, usually an AOB. At cliff colonies, individual birds may be all that can be counted.

Great Skua / Arctic Skua.

The recommended unit for counting both species is the AOT (Furness 1982; Ewins et al. 1988). An AOT is scored if any of the following are recorded: a) nest, eggs, or chicks; b) apparently incubating or brooding adult; c) adults distracting or alarm-calling; d) pair or single bird in potential breeding habitat, apparently attached to area.

Digital Photography

To examine the feasibility of using digital photography as a method for counting seabirds a series of digital photographs were taken during the Skye cliff-nester survey. A Sony Alpha A7R Mk2 full frame mirrorless camera body with a 43 mega pixel 35mm BSI CMOS sensor and 5-axis image stabilization, along with a Sony 70-300mm F4.5-5.6 G OSS lens was used for photography. Multiple photographs were taken at each survey site to provide an overview of the area. Additional photographs were also taken covering areas which contained birds and nest sites. The photograph number was recorded and assigned to each survey location.

Unmanned Aerial Vehicles (UAVs)

To test the utility of using UAVs (also known as drones) to carry out surveys of cliff-nesting seabirds a small subset of sites on the Isle of Skye were selected to be surveyed using UAVs. Before fieldwork commenced a detailed protocols, guidelines and restrictions were agreed with NatureScot as additions to a licence to cause disturbance to Schedule 1 birds under the Wildlife and Countryside Act 1981. Full details of this can be found in the Appendix (Page 15), but in summary the guidelines aimed to minimise any disturbance to cliff-nesting seabirds, mainly by staying at a reasonable distance away from the cliff face. An arbitrary distance of 40m was chosen as the maximum approach distance to the cliff-face.

UAV flights were carried out using two UAVs, a DJI Mavic Pro fitted with a fixed (non-zoom) lens and a 20 mega pixel camera, and a DJI Mavic Zoom fitted with a 4 times zoom lens and a 12 mega pixel camera. Both UAVs were controlled using the Litchi App on an iPad mini. Flight missions were planned using ESRI satellite data within QGIS software for each section of the coast to be surveyed. Full details of the mission planning methodology and more detailed field notes can be found in the Appendix (Page 16). All flights (Table A6) were piloted by a qualified and licenced UAV pilot with an additional qualified and licenced pilot acting as a spotter. All flights were conducted within line of site of the UAV.

Ground-nesting Seabirds

Sites

Isle of Lewis

Ground-nesting seabirds were surveyed on the Isle of Lewis between 25/6/21 and 30/6/21 over 6 days. The main survey area was the moorlands in the Northwest of the island. The area East and South of the A857 road, and North of the B895 and the Eye Peninsula were the focus of the surveys (Figure 2). Additional surveys were also carried out at sites identified by previous surveys. Species surveyed were Great Skuas, Arctic Skuas, Great Black-backed Gulls, Lesser Black-backed Gulls, Herring Gulls, Common Gulls, Black-headed Gull, Arctic Tern and Common Terns. In addition, 27 1km grid squares were surveyed by Robin Reid of RSPB as part of their Wimbrel survey.

Surveys were carried out as described in the JNCC handbook. Transects of the survey area were walked with team members spread out at 500m intervals whilst scanning for birds. Every 200-300m a team member would stop and carry out a detailed scan of the surrounding area. Navigation through the survey area was carried out using OS Explorer series maps and compass along with the OS maps application on a smartphone. Observations were noted in field notebooks before they were subsequently transferred to a spreadsheet. Further details of the fieldwork are contained in the Appendix (Page 18).

Figure 2. Survey area on the Isle of Lewis for Ground Nesting Seabirds. Approximate survey areas are outlined in yellow.

Species Specific Methodologies

All methods are taken directly from the JNCC handbook.

Arctic Skua / Great Skua.

The recommended unit for counting both species is the AOT (Furness 1982; Ewins et al. 1988). An AOT is scored if any of the following are recorded: a) nest, eggs, or chicks; b) apparently incubating or brooding adult; c) adults distracting or alarm-calling; d) pair or single bird in potential breeding habitat, apparently attached to area.

Gulls.

The recommended census unit is an AON, i.e. a well-constructed nest, attended by an adult and capable of holding eggs, or an adult apparently incubating if, for example, actual nests are obscured by vegetation. Some count methods use slight variations on this (e.g. so- called active nests', containing eggs or with other signs of use, counted during transect or quadrat surveys, when attendance by adults is not possible to record). Some counts or estimates are made as AOTs, based on the spacing of birds or pairs viewed from a vantage point, if actual nests or incubation cannot be discerned. Counts of individual adults may also prove necessary on occasion.

Burrow-Nesting Seabirds

Sites

North Rona
European Storm Petrels and Leach's Storm Petrels were surveyed on North Rona from 15/7/21 – 17/7/21.

Flannan Islands
European Storm Petrels and Leach's Storm Petrels were surveyed on the Flannan Isles from 19/7/21 – 23/7/21.

Shillay
European Storm Petrels were surveyed on Shillay on the 24/7/21.

Sanda Island
European Storm Petrels were surveyed on Sanda Island on the 16/7/21, 24/7/21 and 25/7/21.

Isle of Rùm
Manx Shearwaters were surveyed on the Isle of Rùm between 10/5/21 and 28/5/21.

Species Specific Methodologies

European Storm & Leach's Storm Petrel.
Petrel surveys were carried out using a hierarchical distance sampling (HDS) approach. Methods were based on those developed by Deakin et al. (2021) for the Leach's Storm Petrel survey of the St Kilda archipelago. Survey transects were designed to cover as much of the available burrow nesting habitat as possible within logistic constraints. Most of the islands surveyed were remote, uninhabited, and difficult to land on, therefore available survey time was limited. Only suitable breeding habitat was surveyed. This was estimated using a combination of previous survey data, aerial photography (provided by Nature Scot) and initial exploratory survey of the islands.

At 10m intervals along the transects survey points were marked and mixed sex calls for both European Storm and Leach's Storm Petrels were played through a portable speaker (MIFA A1) at a volume of approximately 75db (This was the maximum volume, and the same setting were used for all surveys). Full details of the recordings and best practice to maximise response rates are described in Deakin et al. (2021). MP3 recording of the mixed sex calls of each species were provided by Mark Bolton of RSPB. Once the playback was complete responses to the call from burrows surrounding the survey point were recorded in 0.5 m distance bands up to 4m around the survey area. Hence the total area surveyed for each playback was a circle of radius 4m giving an area of 50.27m^2. At each survey point the playback for Leach's Storm Petrel was performed first and responses recorded, after which the calls for European Storm Petrel were played and responses recorded. HDS sampling requires that a multiple transects are repeated, therefore a number of transects were assigned as calibration transects and were repeated either 2 or 3 times depending on logistical constraints.

The position of each survey point was recorded using GPS and recorded as either a UK grid reference or latitude and longitude. Altitudinal data was subsequently extracted from a digital elevation model provided by www.gpsvisualizer.com. The predominant habitat surrounding the survey area was also recorded for each site as either vegetation, rock, scree, or stone wall, or as a mixture of vegetation and rock, vegetation and scree or vegetation and wall. For each sampling occasion (to account for different conditions at repeated calibration transects) date, time, wind speed and the observers were recorded. All data was recorded onto datasheets in the field before being subsequently transferred into spreadsheets. More detailed methods and protocols are contained in the Appendix (Page 24).

North Rona

Both European Storm Petrel and Leach's Storm Petrel were surveyed on North Rona. 31 transects were carried out producing a total of 922 survey points. 12 of the transects were repeated either 2 or 3 times, producing a total of 1214 surveys. Full details of the transects including a map can be found in the Appendix (Table A7, Figure A1).

Flannan Isles.

Both European Storm Petrel and Leach's Storm Petrel were surveyed on the Flannan Isles. 33 transects were carried out producing a total of 278 survey points. 6 of the transects were repeated either 2 or 3 times, producing a total of 363 surveys. 16 transects were carried out on the island of Eilean Mor, 12 transects were carried out on Eilean Tighe and 5 were carried out on Roaiream. Full details of the transects including a map can be found in the Appendix (Table A8, Figure A2, Roaiream & Figure A3, Eilean Mor & Eilean Tighe). An aerial UAV photograph of the site is provided in Figure 3.

Figure 3. UAV photograph of Eilean Mor (foreground) and Eilean Tighe. Copyright Nigel Spencer

Shillay

Only European Storm Petrels were surveyed on Shillay. 31 transects were carried out producing a total of 143 survey points. 2 of the transects were repeated twice, producing a total of 174 surveys. Full details of the transects including a map and can be found in the Appendix (Table A9, Figure A4). An aerial UAV photograph of the site is provided in Figure 4.

Figure 4. UAV photograph of Shillay. Copyright Nigel Spencer

Sanda Island

Only European Storm Petrels were surveyed on Sanda. 20 transects were carried out on Sanda with a total of 112 survey points. 9 of the transects were repeated two or three times, producing a total of 190 surveys. Full details of the transects including a map can be found in the Appendix (Table A10, Fig A5).

Data Analysis

Hierarchical distance sampling (HDS) models were constructed following the methods in Deakin et al. (2021). All analyses were carried out in the R statistical language and environment (R Core Team 2020). HDS models were built using the 'gdistsamp' function of the 'unmarked' package (Fiske & Chandler 2011). The package requires 3 data frames, one containing all the responses to the calls which need to be in a wide format, such that each repeat is structured left to right within the data frame. It is also important that all the repeated transect points are in the same order within the data frame. Secondly a data frame is required which holds the site covariates with one row for each of the survey points. Finally, a data frame is required which holds the observer data such that there is one row for each actual survey.

Null models were then constructed to assess which detection function best described the detection process and which distribution best described abundance. All combinations of four detection functions (hazard rate, half-normal, exponential, and uniform) and abundance distributions (Poisson and negative binominal) models were constructed, and the best most parsimonious models selected using an information-theoretic approach based on Akaike's Information Criteria (AIC) (Burnham & Anderson 2004). Models with the two lowest AIC scores were selected as the best models and the parameter estimates were used subsequently. Despite the AIC results we also included the best model with a uniform distribution (where detection probability doesn't decrease with distance) because firstly, the distribution of responses amongst the distance bands did not visually appear to decay with increasing distance from the survey point (Appendix Figure A6), and secondly the uniform models have one less parameter to estimate and so their inclusion seems appropriate given the low number of responses in our datasets. Abundance estimates from these models are calculated on a log-scale and were therefore back-transformed prior to the calculation of densities and whole population estimates. Confidence intervals (0.025 & 0.975) were calculated using the function 'confint' and the 'profile' method. Goodness of fit tests for the models were carried out using Freeman-Tukey tests using the 'parboot' function.

Initially we planned to use the covariate data for each survey point and survey occasion to allow the models to predict the abundance by habitat type and altitude. However, response rates at all sites were too low to allow for the construction of these models as there was not enough variation across the range of habitats and altitudes within the surveys. Therefore, the null models were used to produce a single abundance estimate, along with the associated uncertainty around the estimate. The abundance estimate calculated was per survey unit i.e. the area of a $4m^2$ circle ($50.27m^2$). Abundance estimates were multiplied by the amount of available Petrel nesting habitat. For both North Rona and the Flannan Islands the available habitat was calculated by constructing convex polygons which encompassed the area covered by the transects and the area between the transects. For North Rona four polygons where produced to cover the transects in the South of the island, in the middle of the island, within the Northern peninsular and around the lighthouse (Appendix Figure A1). An example of this approach can be found in Figure 5. For the Flannan Isles six polygons were produced covering the surveyed area on Roaiream (Appendix Figure A2), three areas on Eilean Mor, and two areas on Eilean Tighem (Appendix Figure A3).

Figure 5. Diagram outlining how the area of available habitat was calculated. Southern transects on North Rona representing an area of 12.8 hectares or $128000m^2$.

For Shillay and Sanda these areas were expanded to include other potential breeding habitat not included in the surveys. Estimates of available breeding habitat were produced by the team leaders on both islands.

In order to test the robustness of the HDS approach and to provide an approximate comparison we calculated abundance estimates using a method analogous to previous surveys. We summed all recorded responses within all the distance bands. This was then divided by the total areas surveyed (i.e. the area of a circle of radius 4m multiplied by the number of surveys) to give a density/m^2. This value was then adjusted by the response rate as reported in Murray 2009 (0.422 for European and 0.355 for Leach's Storm Petrel) and multiplied by the estimated total habitat (using the same figures as for the HDS methods).

Manx Shearwater. Puffinus puffinus

The Isle of Rùm was surveyed to estimate the Manx Shearwater population between 10th May and 28th May 2021. The areas of the island known to be occupied by Manx Shearwaters (based on previous surveys; Murray et al. 2003, Jackson 2018) were surveyed using ground counts of burrows and play-back surveys by a team of 8–10 fieldworkers. Protocols are outlined below. Further details of the fieldwork are contained in the Appendix (Page24).

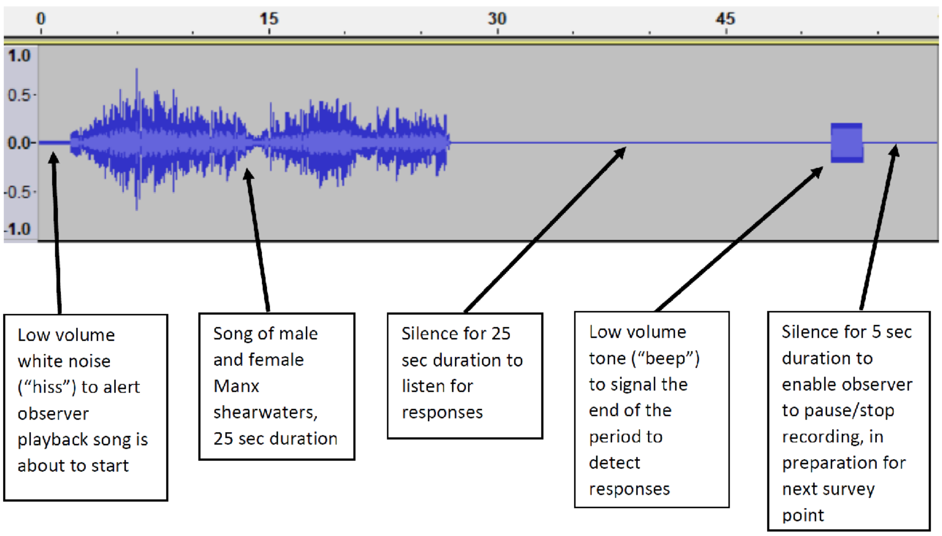
Prior to the start of the field survey, existing shapefiles and maps of the extent of the Manx Shearwater colony (Murray et al. 2003, Jackson 2018; Appendix Figure A7) were used to divide the colony into 1,568 survey grid squares measuring 100 x 100 m. A random sample of these grid squares were then surveyed by a team of 8–10 people, travelling on foot, in two phases. In Phase One we conducted an initial habitat survey to assess the habitat heterogeneity and to group survey strata into density bins (high, medium, and low density). A quasi-random sample of 200 grid squares were selected, based on the relative size of the three main breeding areas (the slopes of [1] Barkeval, [2] Hallival & Askival combined, and [3] Trollabhal; Figure 8).

The field team worked in pairs and used the GPS functionality on an Android Smart phone (model – Ulefone Armor X5) to navigate to the South-East corner of the selected grid squares. Once there, an initial visual survey of each grid square was carried out to determine whether the square was safe to survey and whether the habitat was suitable for Manx Shearwater burrows. Grids with dangerous cliffs or excessively steep slopes were eliminated from the survey on safety grounds. Transects that would run over entirely waterlogged soil or solid rock were eliminated on the grounds that the habitat was not suitable. If a grid square was deemed safe to survey, a 50 m measuring tape was used to measure to a point 25 m from the South-East corner along the Southern edge of the survey grid. From that point, a 100 m transect was measured using a 50 m measuring tape and yellow plastic pegs placed at 10 m intervals. Where possible, transects were pegged out in a northerly direction and walked in a southerly direction. Where this was not safe or possible, due to the nature of the terrain, transects were pegged out to run parallel to the contour of the slope for safety reasons. Each transect was walked slowly by both fieldworks of the pair, holding each end of a 4m piece of parachute cord, marked at the mid-point. All burrows within 2 m either side of the transect line (so falling within the length of the parachute cord) were counted.

Once the burrow count had been completed, a random selection of at least 20 burrows were tested for occupancy using playback methods. If there were fewer than 20 burrows within the 4 m along the transect, then all the burrows were assessed with playback. At each of these burrows, a recording of the calls of Manx Shearwaters was played and a record kept of whether a bird responded to the tape or not. The recording was a 'duet 'call containing both male and female songs, which has been shown to increase the response rate of Manx Shearwaters, reduce its daily variability, and improve the precision of population estimates relative to male only calls historically used in Shearwater surveys (Perkins et al. 2017). The recording sequences consisted of a few seconds of white noise to let the observer know that the call playback is about to start, the duet 'call containing both male and female songs for 25 seconds, a period of 25 seconds of silence during which responses from within the burrow should be listened for, a low volume tone ("beep") to denote the end of the period to listen for responses, followed by silence for 5 seconds to allow the observer to pause/stop the recording in preparation for the next playback trial (Figure 6). An MP3 recording of the call sequence was played (at approximately 80 dB) at the entrance to each burrow (the speaker pointing into the burrow) through a portable Sony® SRS-XB12 waterproof (IP67) speaker connected to an Oakcastle MP100 MP3 player by a 3.5 mm audio cable, with the volumes set at the maximum on both devices.

For each grid through which a transect was run, the following habitat covariates were also recorded: estimated slope of the grid (in degrees), estimated grass cover, estimated boulder cover, estimated suitable habitat (all in %), estimated vegetation height (ordinal: none, low, medium, high), and approximate weather details (rain: none, light, heavy; wind: light, medium, strong). All data were input into a bespoke QGIS database on an Android Smart phone and recorded into waterproof notebooks (as a back-up).

Figure 6. Labelled sonogram describing the Manx Shearwater duet call used in the playback methods. MP3 file and sonogram provided by Mark Bolton (RSPB).

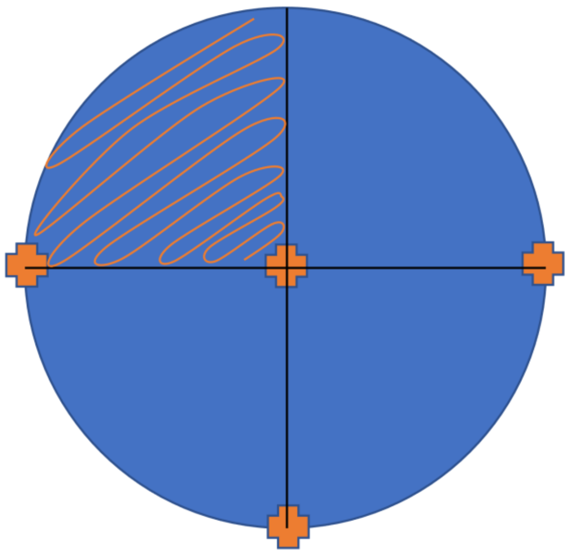


In Phase two, we conducted a multi-strata survey, informed by the habitat survey, to determine burrow density and apparent occupancy, and we carried out a series of repeated playbacks at burrows that were known to be occupied to determine an island and year specific calibration factor that would be used in the analysis to correct for non-responding birds (Ratcliffe et al. 1998, Mitchell et al. 2004). For the multi-strata survey, each of the 1,568 survey grids was assigned to one of three burrow-density categories (High, Medium, or Low), after the removal of any grids deemed to be in unsuitable habitat or unsafe to survey during the original habitat survey. A quasi-random sample of 120 grid squares was then selected, based on a target of 80 High density, 26 Medium density 14 Low density grid squares, as well as the relative size of the three main breeding areas (the slopes of [1] Barkeval, [2] Hallival & Askival combined, and [3] Trollabhal). Boulder fields were included if they fell within the grid squares, but here burrows could not be systematically defined. Instead, we searched crevices and conducted playback trials at these if there were clear signs of seabird activity (digging, guano, or vegetation pulled into crevices). Only small areas of the boulder fields seem to be suitable for low density breeding by Manx shearwaters (Murray et al. 2003). In our experience, this was where they were immediately contiguous with greens. As in Phase 1, the field team worked in pairs and used the GPS functionality on an Android Smart phone and a pre-installed QGIS layer to navigate to the centroid of each of the grid squares. In some instances, the centroid could not be reached (i.e. it was on or over a cliff) or it was deemed unsafe to attempt to access the centroid of some survey grid squares. In this instance, a nearby replacement grid square was selected from a pre-selected list (also based on a quasi-random sample as outlined above). In a few instances, it also proved impossible to reach the centroid of a replacement grid square. In this case, a heuristic rule was used to find a replacement which stated that the team should try to access the centroid immediately to the South, then West, then North and then East until an accessible centroid was found.

Once a target centroid was safely reached, the survey team used a series of large plastic tent pegs and 10 m of pre-measured parachute cord to mark out a 10 m radius circle, divided into 4 quarter circles. Each quarter was searched systematically by one of the pair of fieldworkers in a zig-zag pattern, starting at the centre of the circle and moving out to the edge (Figure 7) to identify Manx Shearwater burrows. To avoid double-counting where nest density was high, wooden plant markers were used to mark burrows close the boundaries of the quarter circles as they were counted. Burrows with double entrances are not uncommon (Murray et al. 2003), so where burrow entrances occurred in close proximity to others, these were checked carefully to avoid double counting as far as possible. The total number of burrows in each survey circle was recorded. While the burrows were being counted, the other fieldworker in the pair carried out playback trials as described above. If the 10 m radius circle contained 20 burrows or fewer, then a playback trial was conducted at every burrow in the circle. Where a circle contained more than 20 burrows, playback trials were conducted at every 4th burrow encountered by the fieldworker, until at least 20 burrows or at least a quarter of the burrows in the circle had been sampled. There was evidence of social facilitation in some of the dense colonies (i.e. multiple burrows responding to a single playback), hence why we reduced the playbacks to every 4th burrow.

Lastly, to determine an island and year specific calibration factor to correct for non-responding birds, we selected 30 survey grid squares that were relatively easy to access multiple times and set up calibration burrows. Time and logistical constraints, particularly travel time on foot to Trollabhal, meant it was not possible to set up calibration plots in all three of the main breeding areas, or to set up calibration plots in proportion to the multi-strata survey plot densities. At each of the 30 squares selected to be calibration plots, we used an Inskam LCD handheld digital endoscope, fitted with a 5m scope, to check burrows for occupancy. Starting at the centroid of the survey grid, one fieldworker checked burrows using the endoscope, working outwards from the centroid in a circular fashion, until birds were confirmed visually in 2 burrows per square (giving a target of 60 burrows). The scope was inserted into the burrow slowly and carefully by one fieldworker whilst constantly monitoring the output from the camera on the LCD display. As soon as a bird was seen on the screen, the scope was immediately removed from the burrow. Once an occupied burrow was located it was given a unique identification number and marked by staking a wooden plant marker in the ground close to the burrow entrance (but not in such a way as to impede the entry or exit of the occupying birds). The GPS position of each calibration burrow was recorded into a bespoke QGIS database on an Android Smart phone and recorded into waterproof notebooks as a back-up. Once the burrow had been marked, a playback trial was conducted at the burrow entrance, as described above and whether or not the bird occupying the burrow responded was noted. Each marked burrow was visited on a total of 1–6 occasions between 22/05/2021 and 28/05/2021 and the playback trial was repeated. The date, time, and weather conditions (rain, approximate wind conditions) were recorded for each playback trial.

Figure 7. The survey circles were 10 m radius, divided into quarters, and searched for burrows in a zig zag pattern originating from the centroid.



Data Analysis

The data from the field surveys were downloaded from the Android Smart phones to a laptop computer running QGIS and then extracted from QGIS into CSV files. The data from Phase 1 (the initial habitat survey) were not analysed further. For the data from Phase 2 (the multi-strata survey), the burrow counts in each survey circle were converted to a measure of density (burrows.m^{-2}) using the area of a 10 m radius circle (314 m^2; except in two grid squares where for safety reasons a semicircle, or 157 m^2, was surveyed). And the data from the playback trials were converted into a series of Bernoulli trials with a response to the playback = 1 and no response = 0. Using these data and the data from the calibration burrows (already recorded as a series of Bernoulli trials with a response to the playback = 1 and no response = 0), we estimated the number of apparently occupied Manx Shearwater burrows on the Isle of Rùm ($\widehat{N}_{AOB}$) as:

$$\widehat{N}_{AOB} = \sum_{j=1}^{3,419} \hat{A}_j \times \hat{B}_j \times \hat{P}_j \times \frac{1}{\hat{R}_j}$$

(equation 1)

were $\hat{A}_j$ is an estimate of the area (m^2) of suitable habitat within sampling unit *j*, $\widehat{B}_j$ is an estimate of the mean burrow density within sampling unit *j*, $\hat{P}_j$ is an estimate of the mean proportion of burrows that would be expected to respond to playback within sampling unit *j*, $\hat{R}_j$ is an estimate of the predicted mean response from occupied burrows within sampling unit j, and j denotes a matrix containing data on the slope-corrected area and predicted burrow density for 16.9 m x 30.9 m pixels from a spatial raster of the predicted breeding area of Manx Shearwaters on the Isle of Rùm (see below).

To estimate the area used by breeding Manx Shearwaters ($\hat{A}$) and the expected burrow density ($\hat{B}$), we used a spatial modelling framework incorporating topography and the observed relationship between burrow density and environmental covariates within our survey circles to build a predictive model of burrow density and calculate topographically corrected area. To define the extent of the Shearwater colony, we used GIS shapefiles from surveys of the extent of the colony in 2001 and 2018 (Murray et al. 2003, Jackson 2018) to set an absolute lower limit of the colony based on an altitude cut-off of 450 m above sea level, below which burrows are very rare or absent (Jackson 2018). We also included an additional section on the north-east face of Barkeval (above 450 m elevation) that was not occupied in any of these previous surveys, but that we found to be occupied in our survey (a number of calibration burrows were also located here).

To measure topography within the colony, we downloaded the SRTMGL1 (SRTM GL1 30 m) digital elevation model (DEM) from OpenTopography (https://opentopography.org/) API global datasets (Figure A8 in the Appendix contains a topographic map of the colony area). This contained elevation values at a resolution of 1 arc-second, which translates to a resolution of 16.9 m x 30.9 m for the Isle of Rùm. From this DEM we were able to derive the slope (in degrees) and the 'true' surface area, accounting for the 3D topography, for each of the *j* = 3,419 pixels in the Shearwater colony using the 'terrain' function in the package *raster* package (v. 3.5.2; Hijmans 2021) for programme R (v. 4.1.2; R Development Core Team 2021). This 'true' surface area calculated for each pixel was taken as our estimate of $\hat{A}_j$.

To determine the relative density of burrows across the 3,419 pixels in the Shearwater colony, we also used data on the Normalised Difference Vegetation Index (NDVI), a spectral index used to measure vegetation greenness, to measure the vegetation structure within each pixel. The rationale behind this approach is that the major colonies are visually obvious – both on the ground and in some aerial photographs – as 'Shearwater greens' due to the manuring effect of the birds' droppings enriching the surrounding vegetation (Murray et al. 2003). NDVI (N) was calculated from images taken by the Sentinel-2A satellite on 31 May 2021 (closest cloud free day to the survey) as:

$$N = \frac{NIR - IR}{NIR + IR}$$

(equation 2)

where NIR is the reading from the near infrared band and IR is the reading from the infrared band. Using a ratio of two bands helps to correct for differences in surface reflectance associated with terrain and aspect. The resolution of the NDVI data was 20 m x 20 m so we transformed it to have the same resolution as the topographic data (16.9 m x 30.9 m).

Using these environmental datasets, we then extracted the elevation, slope, and NDVI values for each of the (i = 129) 10 m radius survey circles sampled in the Phase 2 multi-strata survey (Figure 8). We overlaid these plots onto our environmental datasets and corrected the 10 m radius for topography (as on the ground the 10 m was measured on a 3D slope while the environmental data are on a 2D plane) by extracting the slope at the centre of the density plot and then converting to a distance on a 2D plane as:

$$r_{T,i} = 10 \times cos\, S_i$$

(equation 3)

where $r_{T,i}$ is the topographically-corrected radius in survey circle i and S_i is the slope of survey circle i. The values for the environmental variables (slope, elevation, and NDVI) for each survey circle i were calculated as a weighted mean of the values from all of the J pixels contained (even partially) within the survey circle, weighted by the proportion of the survey circle area (w) that overlapped with each pixel (j) (shown for slope as an example):

$$S_i = \frac{\sum_{j=1}^{J} S_j w_j}{\sum_{j=1}^{J} w_j}$$

(equation 4)

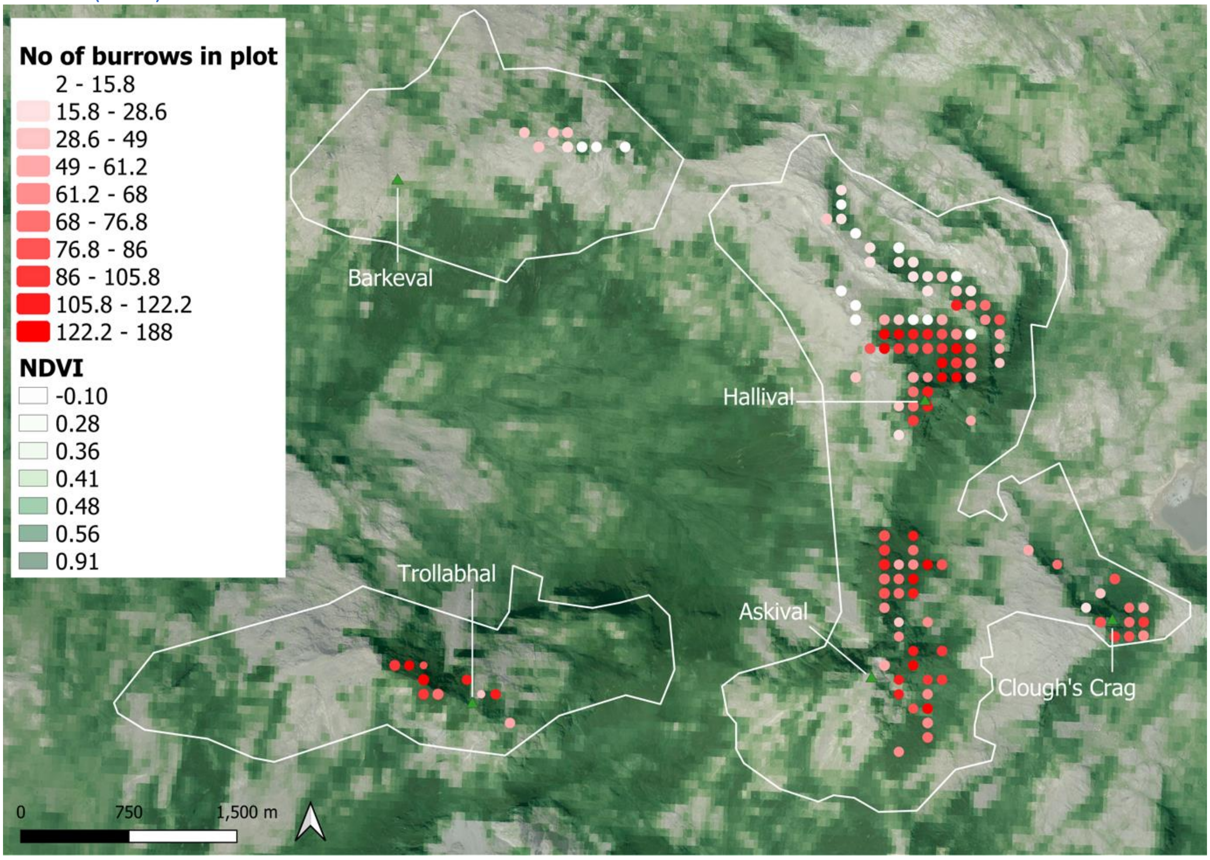
With these data, we could now predict the expected burrow density ($\hat{B}_j$) for each pixel in the Shearwater colony in two steps. First, we modelled the relationship between the environmental variables (slope, elevation, and NDVI) and the observed burrow density in each of our i = 129 survey circles (B_i) using a generalized linear model with a Beta error structure and a logit link function:

$$\begin{gathered} B_i \sim Beta(a_i, b_i), \\ a_i = \theta \times \rho_i \\ b_i = \theta \times (1 - \rho_i) \\ log\left(\frac{\rho_i}{1 - \rho_i}\right) = \beta_0 + \beta_1 N_i + \beta_2 S_i + \beta_3 E_i \end{gathered}$$

(equation 5)

where the β's are the coefficient estimates for the fixed effects, N_i, S_i and E_i are covariate vectors containing (respectively) the NDVI, Slope and Elevation values extracted for the i = 129 survey circles (as described above), a and b are the two shape parameters that define a Beta distribution, which are linked to the linear predictor via a mean ρ_i and an overdispersion parameter θ estimated from the data. Multi model inference was used to determine if all or any of these predictors were important in explaining variation in burrow density (Harrison et al. 2018). We could then combine the extracted values for NDVI, slope, and elevation for each of the j = 3,419 pixels within the Shearwater colony with the regression coefficients (the β's) from eqn. 5 to predict $\hat{B}_j$, the mean burrow density (in burrows.m^{-2}) for each pixel.

Figure 8. The centroids of the 129, 10 m radius survey circles (points) visited in the Phase 2 multi-strata survey overlaid on a raster of the Normalised Difference Vegetation Index (NDVI) data extracted for the Isle of Rùm. The number of burrows counted in each survey circle is indicated approximately by the colour of the point. The colours of the dots are matched by the colours in the legend. The white outlines show the 450 m contour, which denotes the limit taken as the lowest elevation of the Manx Shearwater colony after Murray et al. (2003) and Jackson (2018).



Similarly, to estimate $\hat{P}_j$, the mean proportion of burrows expected to respond to playback in pixel j, and $\hat{R}_j$, the expected response from occupied burrows in pixel j, we first modelled both parameters as a function of the observed burrow density in each of our i = 129 survey circles (B_i). To do this, and to derive our final estimate of $\hat{N}_{AOB}$, we used a Bayesian framework based on Markov Chain Monte Carlo (MCMC) estimation in JAGS (v. 4.3.0; Plummer 2003), implemented via the *jagsUI* package (v. 1.5.2; Kellner 2021) for program R. The proportion of burrows responding in each survey circle was modelled as a function of the observed burrow density using a generalised linear model with a Bernoulli (or binary logistic) error structure and a logit link function as:

$$Y_{i,l} \sim Bernoulli(\varphi_l),$$
$$log\left(\frac{\varphi_l}{1-\varphi_l}\right) = b_i + \alpha_P + \beta_P B_l$$
$$b_i \sim Normal(0, \sigma^2)$$

(equation 6)

where $Y_{i,l}$ are the observed responses (0,1) for each of l= 3,653 playback trials within each of the i = 129 survey circles, φ_l is the mean probability of a response (estimated from the data) that defines the Bernoulli distribution, α_P is the intercept, β_P the coefficient to be estimated for the effect of burrow density, b_i denotes a random effect to account for the non-independence of burrows within survey circles, and B_i is a vector denoting the observed burrow density associated with each playback trial (each trial was assigned the burrow density of the survey circle in which it occurred), and σ^2 is the variance terms for the random effect which was estimated from the data.

Likewise, the probability of an occupied burrow in the calibration plots responding to a playback trial (the calibration factor) was modelled as a function of the observed burrow density using a generalised linear mixed model with a Bernoulli (or binary logistic) error structure and a logit link function as:

$$Z_{k,m,o} \sim Bernoulli(p_o),$$
$$log\left(\frac{p_o}{1-p_o}\right) = b_k + b_{k,m} + \alpha_R + \beta_R B_k$$
$$b_k \sim Normal(0, \sigma_1^2), b_{k,m} \sim Normal(b_k, \sigma_2^2)$$

(equation 7)

where $Z_{k,m,o}$ are the observed responses (0,1) for each of o = 367 playback trials, at m = 62 burrows, in k = 31 calibration plots, p_o is the mean probability of a response (estimated from the data) that defines the Bernoulli distribution, α_R is the intercept, β_R the coefficient to be estimated for the effect of burrow density, b_k and $b_{k,m}$ denote the nested random effects to account for repeated sampling of burrows within each of the calibration plot, B_k is a vector denoting the observed burrow density in each calibration plot, and the σ^2s are the variance terms for the random effects which were estimated from the data.

Finally, the estimated coefficients from eqn. 6 and 7 were combined with the $\hat{B}_j$ values (mean burrow density for each pixel covering the colony) in logit space and then back-transformed (via an inverse-logit transformation) to probability space to estimate $\hat{P}_j$ and $\hat{R}_j$:

$$\hat{P}_j = \frac{exp(\alpha_P + \beta_P \hat{B}_j)}{1 + exp(\alpha_P + \beta_P \hat{B}_j)}$$

(equation 8)

$$\hat{R}_j = \frac{exp(\alpha_R + \beta_R \hat{B}_j)}{1 + exp(\alpha_R + \beta_R \hat{B}_j)}$$

(equation 9)

and the $\hat{B}_j$, $\hat{P}_j$, $\hat{R}_j$and $\hat{A}_j$ values were combined following eqn. 1 to generate a posterior distribution of apparently occupied burrows for each pixel ($\widehat{N}_{AOB,j}$), which were summed to yield a posterior distribution for the total estimated number of apparently occupied burrows:

$$\widehat{N}_{AOB} = \sum_{j=1}^{3,419} \widehat{N}_{AOB,j}$$

(equation 10)

from which we report the median and 95% highest posterior density interval (HDI) as our final estimate of the number of Manx Shearwaters breeding on the Isle of Rùm and the associated uncertainty in that estimate.

To implement the model in JAGS, we used vague normal priors: $Normal(0, 10^{-3})$ (where 10^{-3} is precision) for all coefficient estimates and vague Gamma priors: $Gamma(1.01005, 0.1005012)$(which yields a distribution with a mode ≈ 0.1 and standard deviation ≈ 10) for the standard errors (σ), with precision specified as σ^{-2}. We ran three chains of 250 000 samples, discarded the first 125 000 as burn-in, and thinned the chains to every 5th observation to increase the effective MCMC sample size for the same amount of computer memory. The models were checked for convergence visually and using Gelman-Rubin diagnostics, and all unambiguously converged (all $\hat{R}$ values < 1.03).

Results

Cliff-nesting Seabirds

Overall Species Summaries

Cormorant

A total of 420 Cormorant AONs were recorded during the survey (Table 1; Figure 9). Cormorants were recorded at one site in Lochaber (Table 2), one site in Cunninghame (Table 5), seven sites in Skye and Lochalsh & 30 sites in the Western Isles (Table 4).

Shag

A total of 1323 Shag AONs / individuals were recorded during the survey (Table 1; Figure 10). Shags were recorded at 21 sites in Lochaber (Table 2), one site in Cunninghame (Table 5), 55 sites in Skye and Lochalsh (Table 3) & 34 sites in the Western Isles (Table 4).

Fulmar

A total of 8094 Fulmar AOSs were recorded during the survey (Table 1; Figure 11). Fulmars were recorded at six sites in Lochaber (Table 2), one site in Cunninghame (Table 5), 15 sites in Skye and Lochalsh (Table 3) & 38 sites in the Western Isles (Table 4).

Kittiwake

A total of 4737 Kittiwake AONs were recorded during the survey (Table 1; Figure 12). Kittiwakes were recorded at four sites in Lochaber (Table 2), one site in Cunninghame (Table 5), 11 sites in Skye and Lochalsh (Table 3) & 12 sites in the Western Isles (Table 4).

Great Black-backed Gull

A total of 365 Great Black-backed Gull AONs / AOTs were recorded during the survey (Table 1; Figure 13). Great Black-backed Gulls were recorded at eight sites in Lochaber (Table 2), one site in Cunninghame (Table 5), 33 sites in Skye and Lochalsh (Table 3) & 60 sites in the Western Isles (Table 4).

Lesser Black-backed Gull

A total of 162 Lesser Black-backed Gull AONs / AOTs were recorded during the survey (Table 1; Figure 14). Lesser Black-backed Gulls were recorded at one site in Lochaber (Table 2), one site in Cunninghame (Table 5), two sites in Skye and Lochalsh (Table 3) & eight sites in the Western Isles (Table 4).

Herring Gull

A total of 792 Herring Gulls AONs / AOTs were recorded during the survey (Table 1; Figure 15). Herring Gulls were recorded at 15 sites in Lochaber (Table 2), one site in Cunninghame (Table 5), 35 sites in Skye and Lochalsh (Table 3) & 43 sites in the Western Isles (Table 4).

Common Gull

A total of 379 Common Gulls AONs / AOTs were recorded during the survey (Table 1; Figure 16). Common gulls were recorded at one site in Cunninghame (Table 5), six sites in Skye and Lochalsh (Table 3) & 12 sites in the Western Isles (Table 4).

Guillemot

A total of 38655 individuals were recorded during the survey (Table 1; Figure 17). Guillemots were recorded at nine sites in Lochaber (Table 2), 10 sites in Skye and Lochalsh (Table 3) & 12 sites in the Western Isles (Table 4).

Razorbill

A total of 11386 Razorbill individuals were recorded during the survey (Table 1; Figure 18). Razorbills were recorded at eight sites in Lochaber (Table 2), one site in Cunninghame (Table 5), 15 sites in Skye and Lochalsh (Table 3) & 14 sites in the Western Isles (Table 4).

Puffin

A total of 5659 individuals / AOBs were recorded during the survey (Table 1; Figure 19), of these 467 AOBs were recorded on North Rona. Puffins were recorded at one site in Lochaber (Table 2), three sites in Skye and Lochalsh (Table 3) & 10 sites in the Western Isles (Table 4).

Great skua

Great Skuas are a ground-nesting species, but several AOT were noted during the cliff-nesting surveys so included here. A total of 96 Great Skua AOTs were recorded during the survey (Table 1; Figure 20). Great Skuas were recorded at one site in Lochaber (Table 2), 5 sites in Skye and Lochalsh (Table 3) & 17 sites in the Western Isles (Table 4).

Arctic skua

Arctic Skuas are a ground-nesting species, but several AOT were noted during the cliff-nesting surveys so included here. Three Arctic Skuas AOTs were recorded during the survey at a single site in the Western Isles (Table 1 & Table 4; Figure 21).

Site Based Breakdowns

Table 1. Cliff-Nesting Seabird Species Summaries by Area (as defined in the SMP database).

Area	Cormorant	Shag	Fulmar	Kittiwake	Great Black-backed Gull	Lesser Black-backed Gull	Herring Gull
Lochaber	0	77	187	704	20	6	119
Cunninghame	0	22	11	0	5	132	250
Skye and Lochalsh	121	816	1114	1049	111	6	206
Western Isles	299	408	6782	2984	229	18	217
Total	420	1323	8094	4737	365	162	792

Area	Common Gull	Guillemot	Razorbill	Puffin	Great Skua	Arctic Skua
Lochaber	2	2117	250	19	1	0
Cunninghame	4	0	0	0	0	0
Skye and Lochalsh	90	2964	924	491	7	0
Western Isles	283	33574	10212	5149	88	3
Total	379	38655	11386	5659	96	3

Table 2. Cliff-Nesting Seabird Species Summaries by Master Site. Lochaber.

Master Site	Cormorant	Shag	Fulmar	Kittiwake	Great Black-backed Gull	Lesser Black-backed Gull	Herring Gull
Muck	0	23	175	4	9	6	77
Rùm	0	54	12	700	11	0	42

Master Site	Common Gull	Guillemot	Razorbill	Puffin	Great Skua	Arctic Skua
Muck	0	319	51	19	1	0
Rùm	2	1798	199	0	0	0

Table 3. Cliff-Nesting Seabird Species Summaries by Master Site. Skye & Lochalsh.

Master Site	Cormorant	Shag	Fulmar	Kittiwake	Great Black-backed Gull	Lesser Black-backed Gull	Herring Gull
East Trotternish	15	57	1	0	6	0	53
Eilean Creagach and South Ascrib	0	1	0	0	3	0	0
Fladda Chuain to Gearran Island	20	85	254	464	17	0	2
Kyleakin to Portree	28	37	0	4	11	0	7
Loch Eishort	0	0	0	0	7	0	4
Rubha Hunish	0	143	601	266	9	6	23
Skye	58	320	22	203	32	0	102
Skye - Eilean Maol to Point of Sleat	0	0	0	0	1	0	1
Skye - Strathaird	0	31	2	50	4	0	6
Skye: Hoe Point to Meanish	0	121	234	62	6	0	3
Skye: Meanish Pier to Druim Slachaidh	0	21	0	0	5	0	5
Staffin	0	0	0	0	10	0	0

Master Site	Common Gull	Guillemot	Razorbill	Puffin	Great Skua	Arctic Skua
East Trotternish	3	0	0	0	1	0
Eilean Creagach and South Ascrib	0	0	12	100	0	0
Fladda Chuain to Gearran Island	11	2564	622	376	2	0
Kyleakin to Portree	73	0	0	0	1	0
Loch Eishort	0	0	0	0	0	0
Rubha Hunish	2	112	104	0	1	0
Skye	1	170	153	15	2	0
Skye - Eilean Maol to Point of Sleat	0	0	0	0	0	0
Skye - Strathaird	0	0	5	0	0	0
Skye: Hoe Point to Meanish	0	118	13	0	0	0

Skye: Meanish Pier to Druim Slachaidh	0	0	15	0	0	0
Staffin	0	0	0	0	0	0

Table 4. Cliff-Nesting Seabird Species Summaries by Master Site. Western Isles.

Master Site	Cormorant	Shag	Fulmar	Kittiwake	Great Black-backed Gull	Lesser Black-backed Gull	Herring Gull
Arnol - Lewis	0	0	0	0	0	0	0
Barra & Vatersay	0	16	41	0	2	4	30
Barvas - Lewis	0	0	0	0	0	0	0
Bearasay - Lewis	21	10	132	0	0	0	1
Berneray, Sound of Harris	0	0	0	0	0	0	0
Campay - Lewis	0	22	20	0	2	0	5
Causamul, Haskeir, Boreray and Spuir	5	36	309	222	21	3	4
Coppay	0	5	3	195	3	0	2
Dun-aarn - Harris	125	0	0	0	0	0	0
Ensay - Harris	0	0	0	0	0	0	0
Flannan Isles SPA	0	68	3066	825	10	4	9
Floday - Lewis	0	8	11	0	1	0	0
Gilsay - Harris	0	0	0	0	4	0	2
Greine Sgeir - Harris	0	0	0	0	1	0	22
Groay - Harris	0	0	0	0	1	0	0
Gumersam Bheag - Harris	0	0	0	0	1	0	0
Harsgeir - Lewis	0	20	0	0	3	1	0
Islands South of Barra - Tysties	0	0	0	0	1	0	0
Killegray - Harris	0	0	0	0	3	0	0
Langay - Harris	0	0	0	0	5	0	7
Lewis and Harris - Tysties	0	3	15	0	12	0	0
Liungaigh - Harris	0	0	0	0	1	0	0
Mas Sgeir - Lewis	0	0	0	0	0	0	2
Mingulay and Berneray SPA	0	38	756	750	16	2	11
Monach Isles SPA	35	0	39	0	24	1	18
North Rona and Sula Sgeir SPA	0	42	2210	712	49	0	2
North Uist	17	0	0	0	0	0	12
Old Hill - Lewis	0	3	54	93	0	0	0
Pabay Mor	0	52	18	0	0	2	2
Pabbay	0	0	0	0	1	0	3
Renish Island - Harris	0	0	0	0	0	0	1
Saghay Islands - Harris	0	0	0	0	1	0	1
Scaravay - Harris	0	3	0	0	3	1	0
Scarp Island - Harris	0	20	0	0	3	0	1

Sleicham - Harris	0	0	0	0	1	0	0
Sound of Barra	68	23	0	0	20	0	73
Sound of Harris	7	0	0	0	23	0	8
Sound of Pabbay	21	32	105	0	14	0	1
Suem - Harris	0	0	0	0	1	0	0
Taransay - Harris	0	5	0	0	2	0	0
Toe Head - Harris	0	2	3	187	0	0	0

Master Site	Common Gull	Guillemot	Razorbill	Puffin	Great Skua	Arctic Skua
Arnol - Lewis	11	0	0	0	0	0
Barra & Vatersay	34	0	0	0	1	0
Barvas - Lewis	38	0	0	0	0	0
Bearasay - Lewis	0	0	5	0	1	0
Berneray, Sound of Harris	13	0	0	0	0	0
Campay - Lewis	0	0	0	0	0	0
Causamul, Haskeir, Boreray and Spuir	21	1809	104	2	6	3
Coppay	0	0	0	0	0	0
Dun-aarn - Harris	0	0	0	0	0	0
Ensay - Harris	9	0	0	0	0	0
Flannan Isles SPA	0	5632	1143	1742	11	0
Floday - Lewis	0	0	0	0	0	0
Gilsay - Harris	0	0	0	0	1	0
Greine Sgeir - Harris	0	0	0	0	0	0
Groay - Harris	0	0	0	0	0	0
Gumersam Bheag - Harris	0	0	0	0	0	0
Harsgeir - Lewis	0	0	0	0	0	0
Islands South of Barra - Tysties	0	0	0	0	0	0
Killegray - Harris	2	0	0	0	0	0
Langay - Harris	0	0	0	0	0	0
Lewis and Harris - Tysties	0	0	0	25	2	0
Liungaigh - Harris	0	0	0	0	0	0
Mas Sgeir - Lewis	0	0	0	0	0	0
Mingulay and Berneray SPA	0	18406	8537	79	17	0
Monach Isles SPA	119	0	0	0	0	0
North Rona and Sula Sgeir SPA	0	7727	396	3301	37	0
North Uist	0	0	0	0	2	0
Old Hill - Lewis	0	0	27	0	0	0
Pabay Mor	0	0	0	0	0	0
Pabbay	0	0	0	0	0	0
Renish Island - Harris	0	0	0	0	0	0
Saghay Islands - Harris	0	0	0	0	0	0

Scaravay - Harris	2	0	0	0	1	0
Scarp Island - Harris	0	0	0	0	0	0
Sleicham - Harris	0	0	0	0	0	0
Sound of Barra	8	0	0	0	1	0
Sound of Harris	6	0	0	0	0	0
Sound of Pabbay	0	0	0	0	8	0
Suem - Harris	2	0	0	0	0	0
Taransay - Harris	18	0	0	0	0	0
Toe Head - Harris	0	0	0	0	0	0

Table 5. Cliff-Nesting Seabird Species Summaries by Master Site. Cunninghame

Master Site	Shag	Fulmar	Great Black-backed Gull	Lesser Black-backed Gull	Herring Gull	Common Gull
Little Cumbrae (Master)	22	11	5	132	250	4

Refer to the Appendix (Page 27) for details of the raw data for Cliff-nesting Seabird surveys.

Maps

Figure 9. Cormorant distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

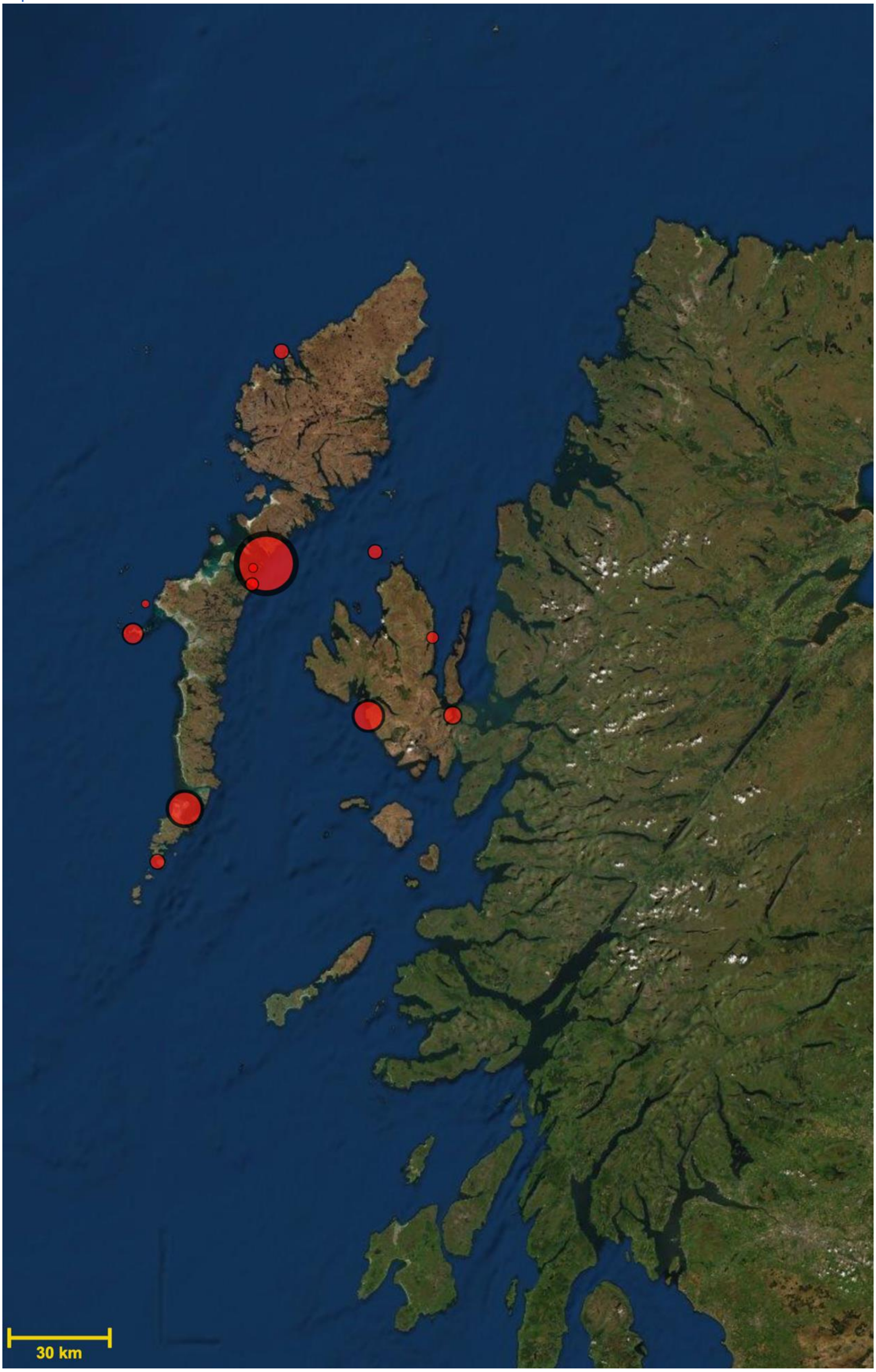


Figure 10. Shag distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

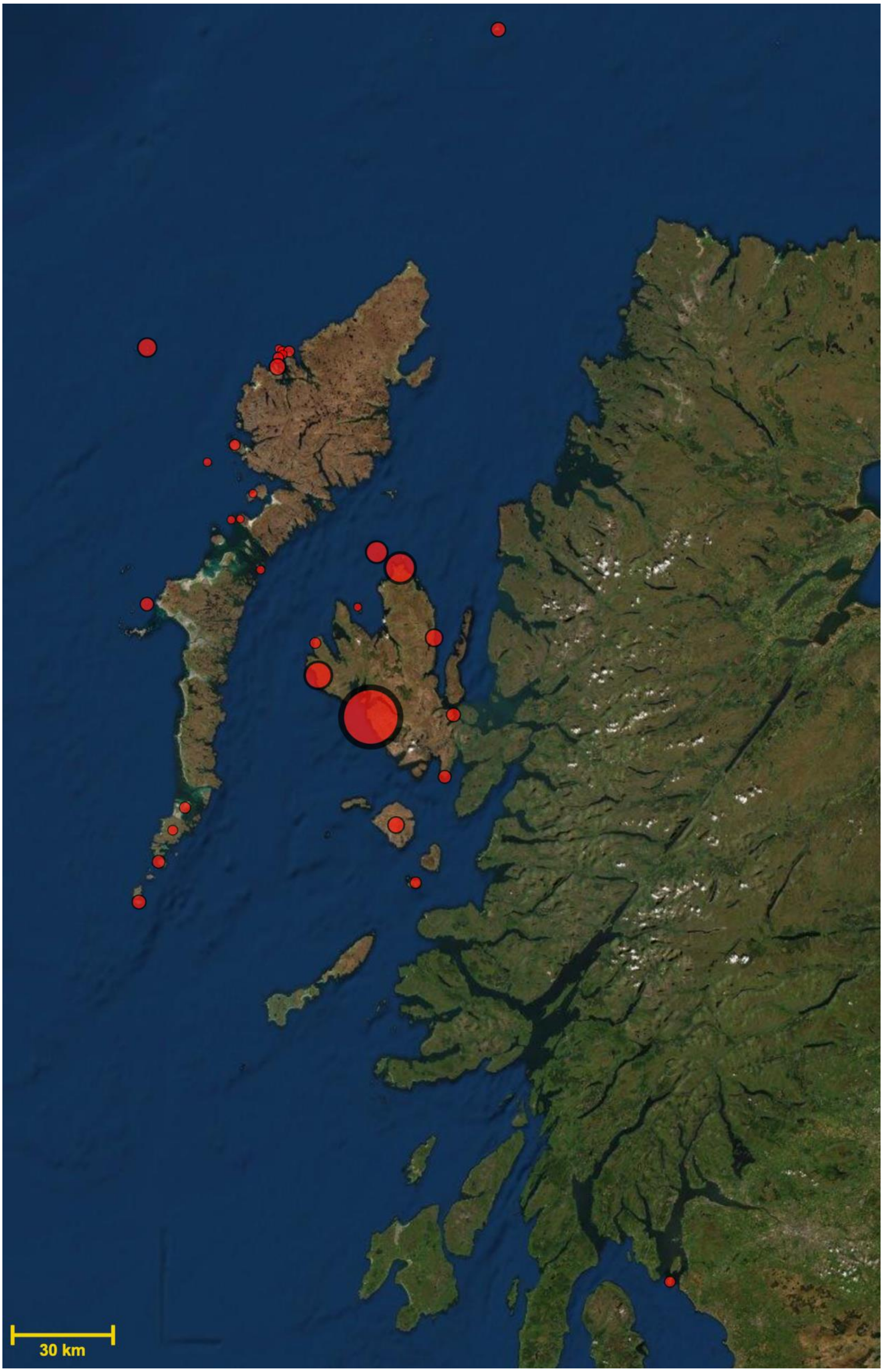


Figure 11. Fulmar distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

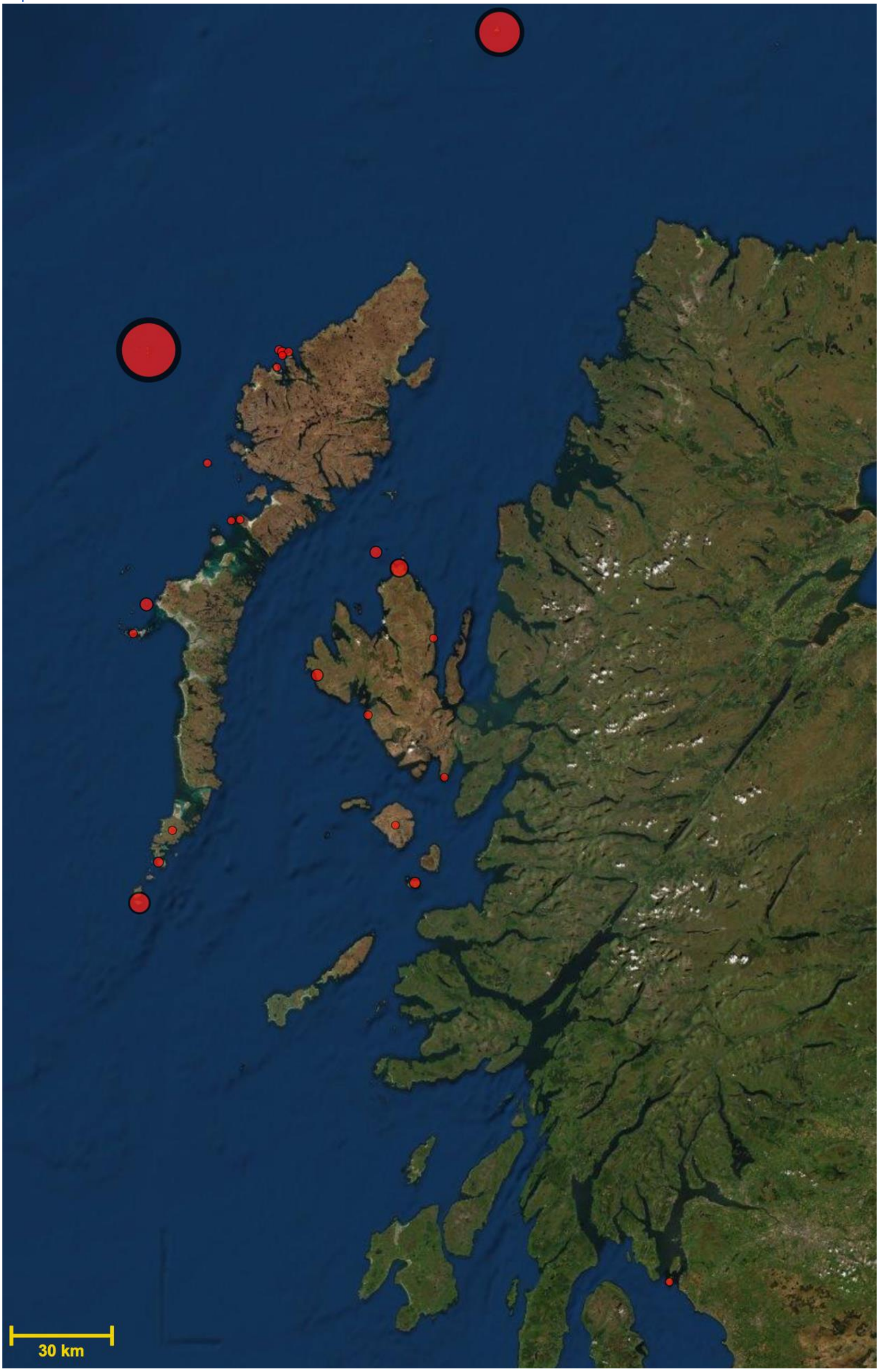


Figure 12. Kittiwake distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

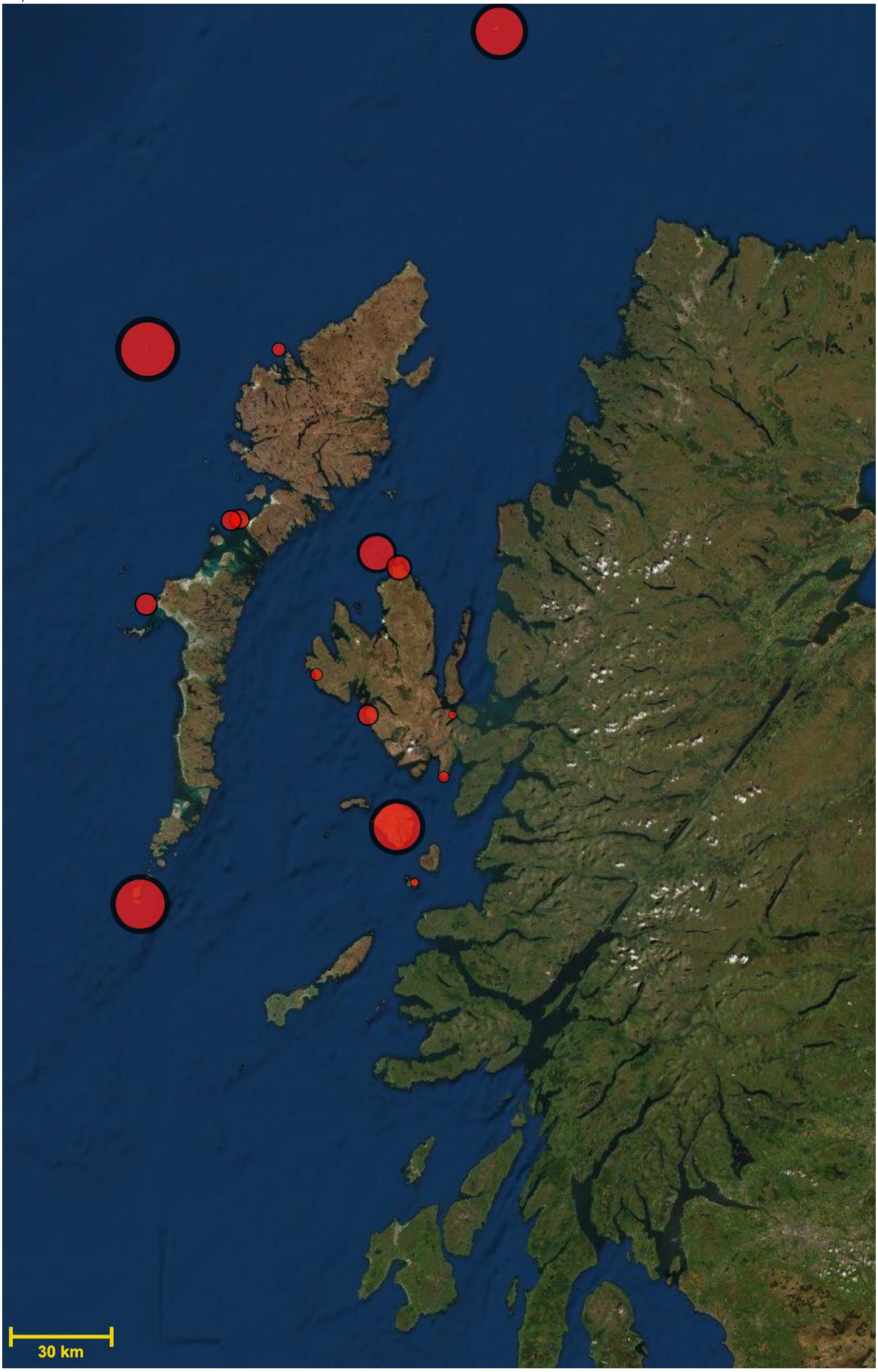


Figure 13. Great Black-backed Gull distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

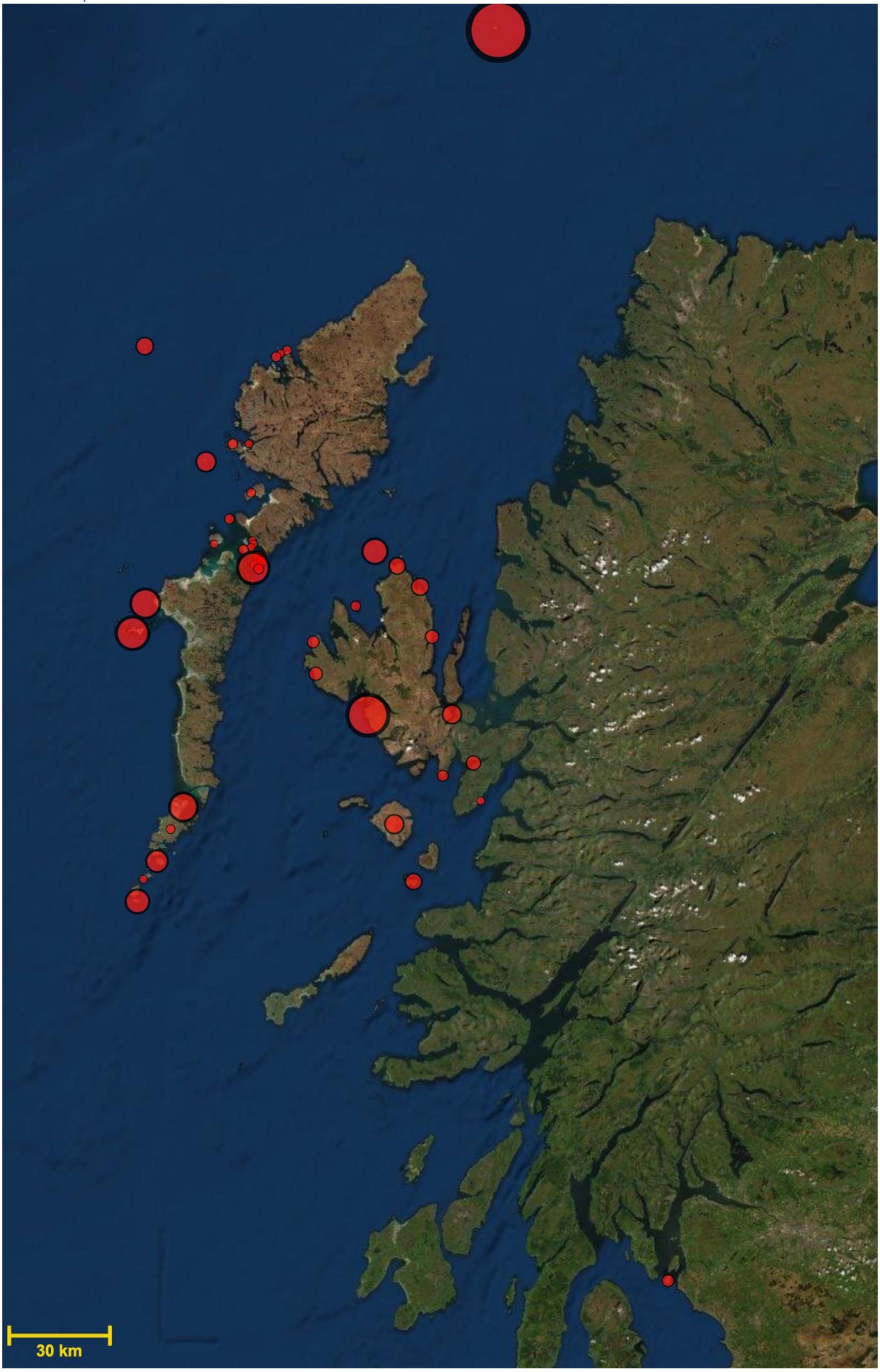


Figure 14. Lesser Black-backed Gull distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

Figure 15. Herring Gull distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

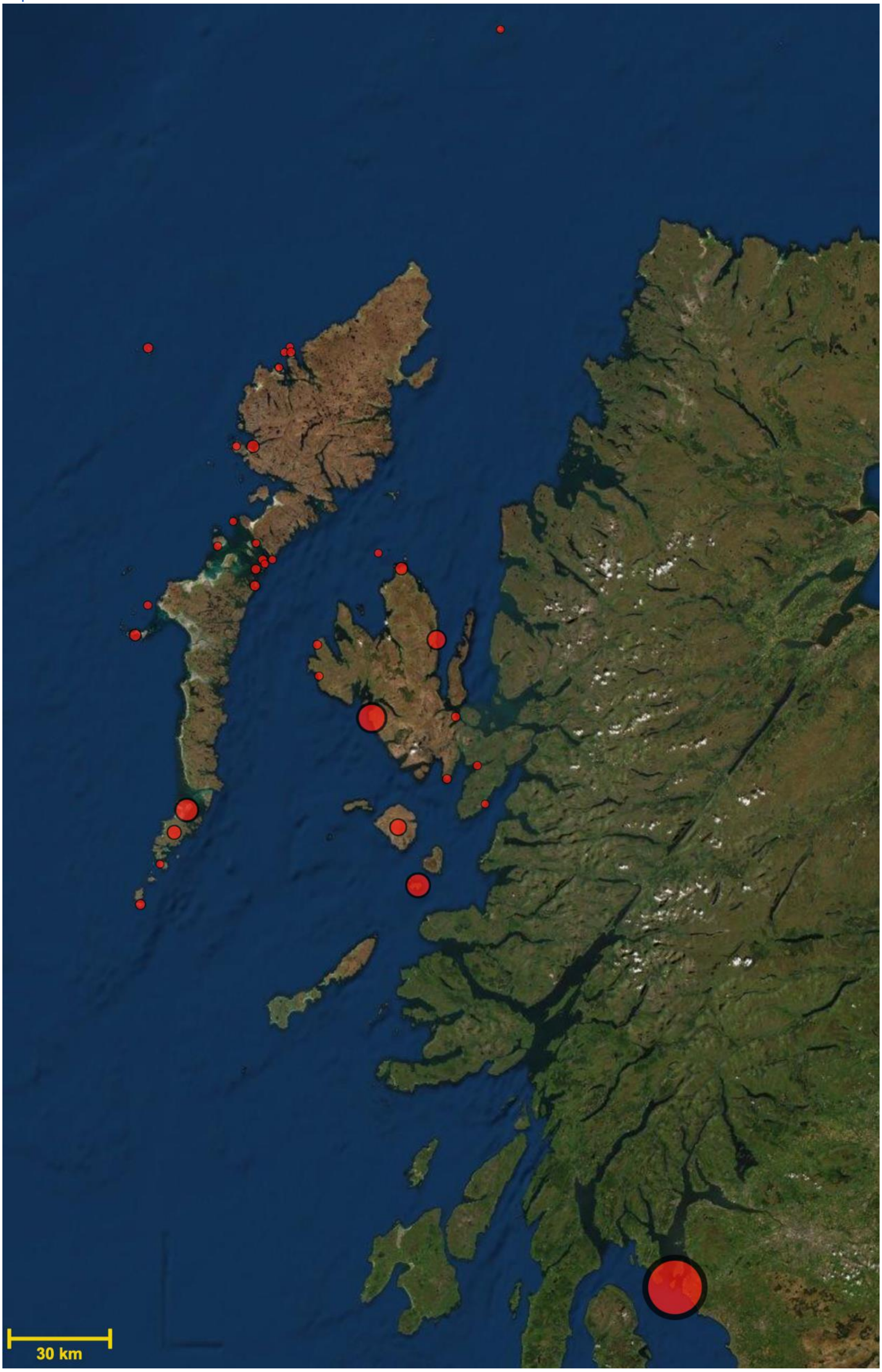


Figure 16. Common Gull distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

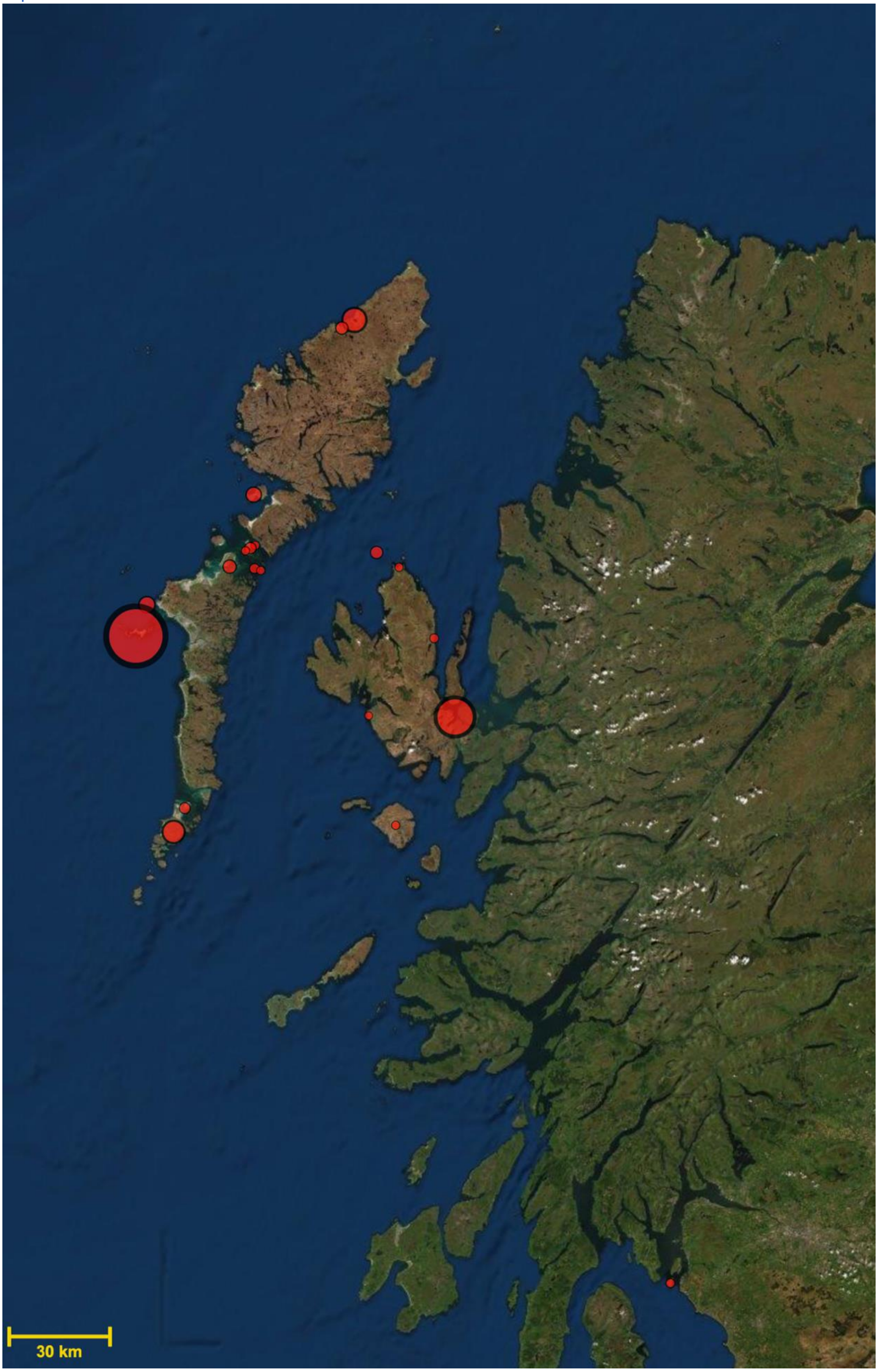


Figure 17. Guillemot distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

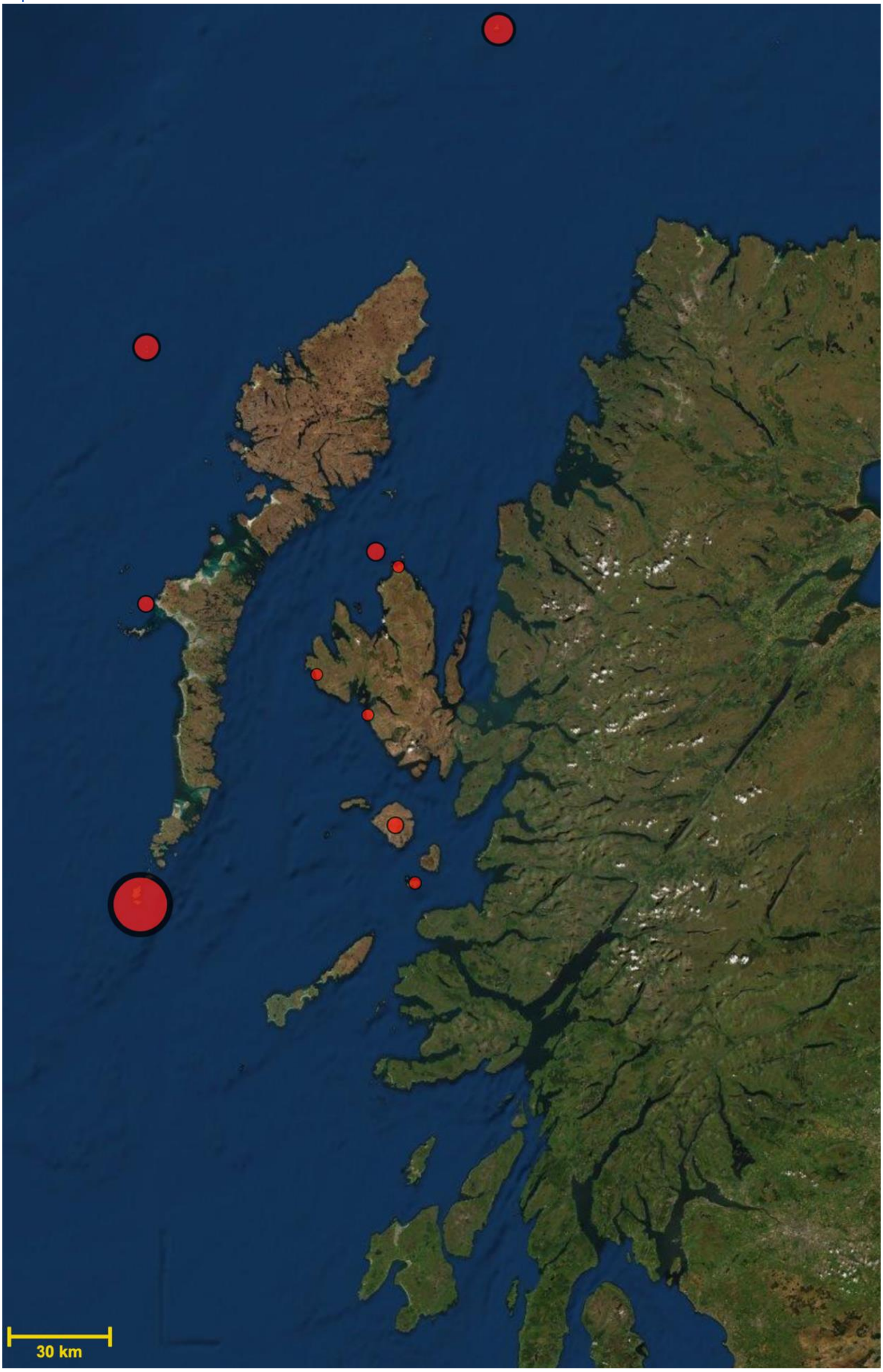


Figure 18. Razorbill distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

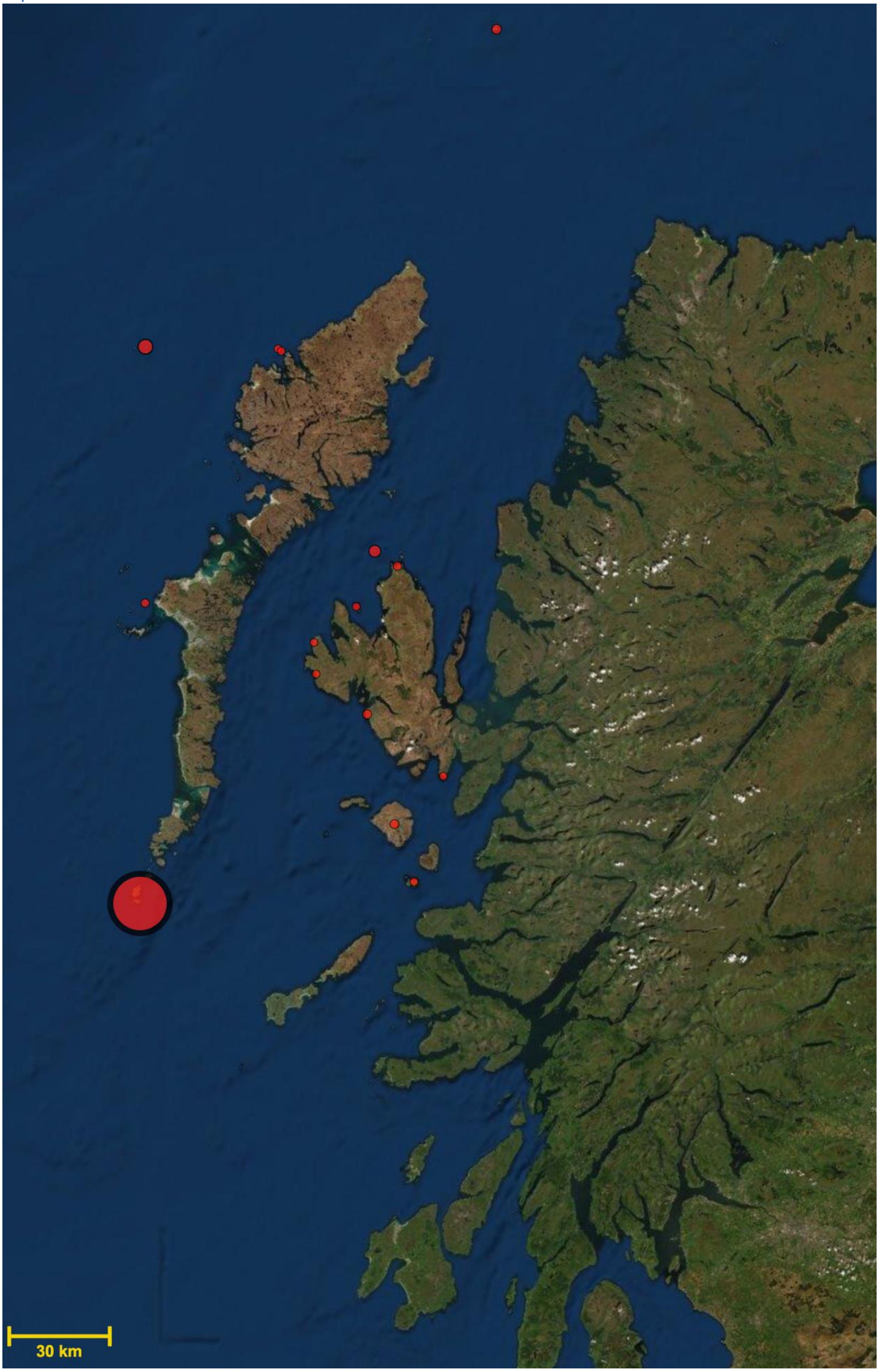


Figure 19. Puffin distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

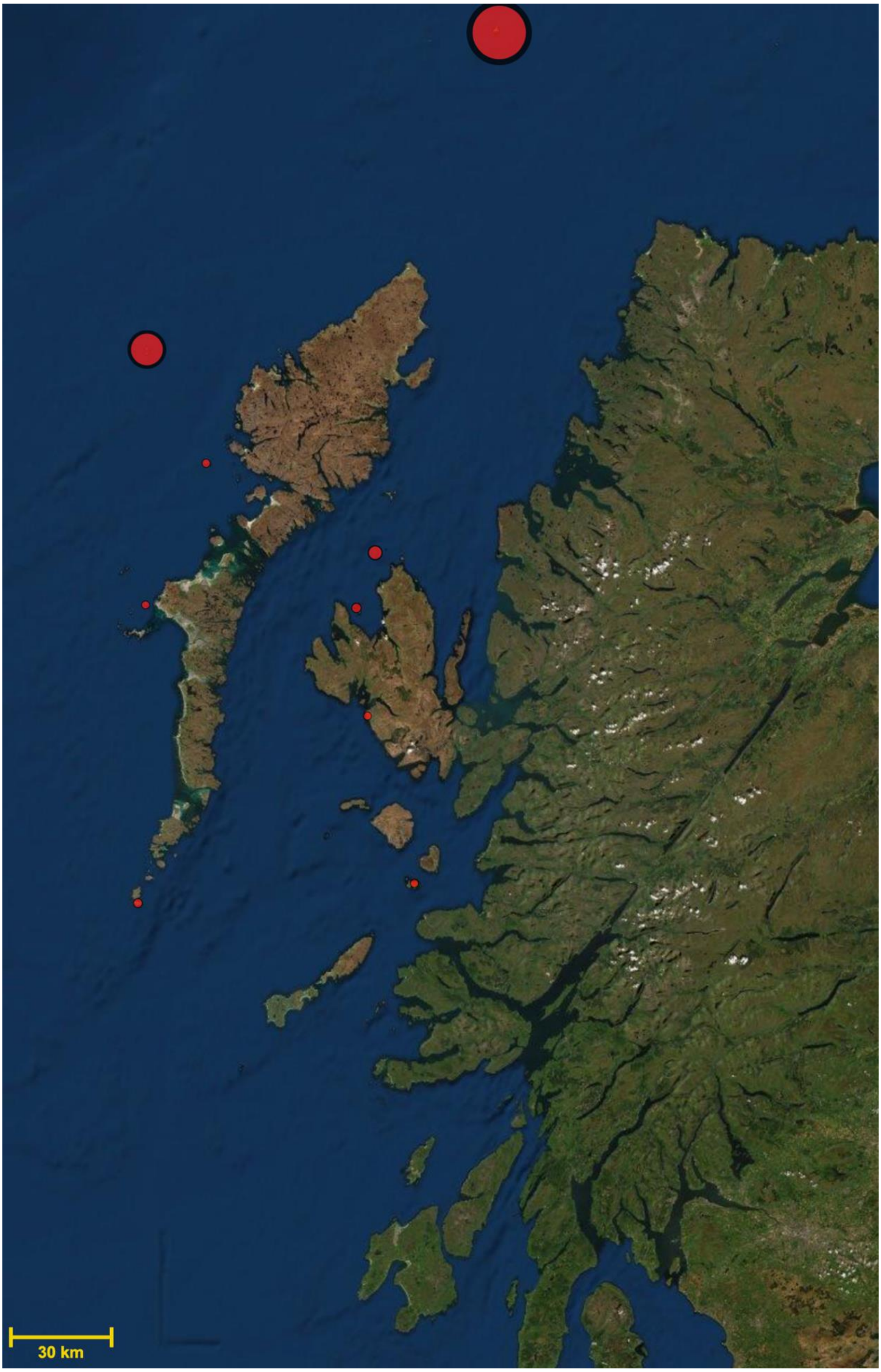


Figure 20. Great Skua distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

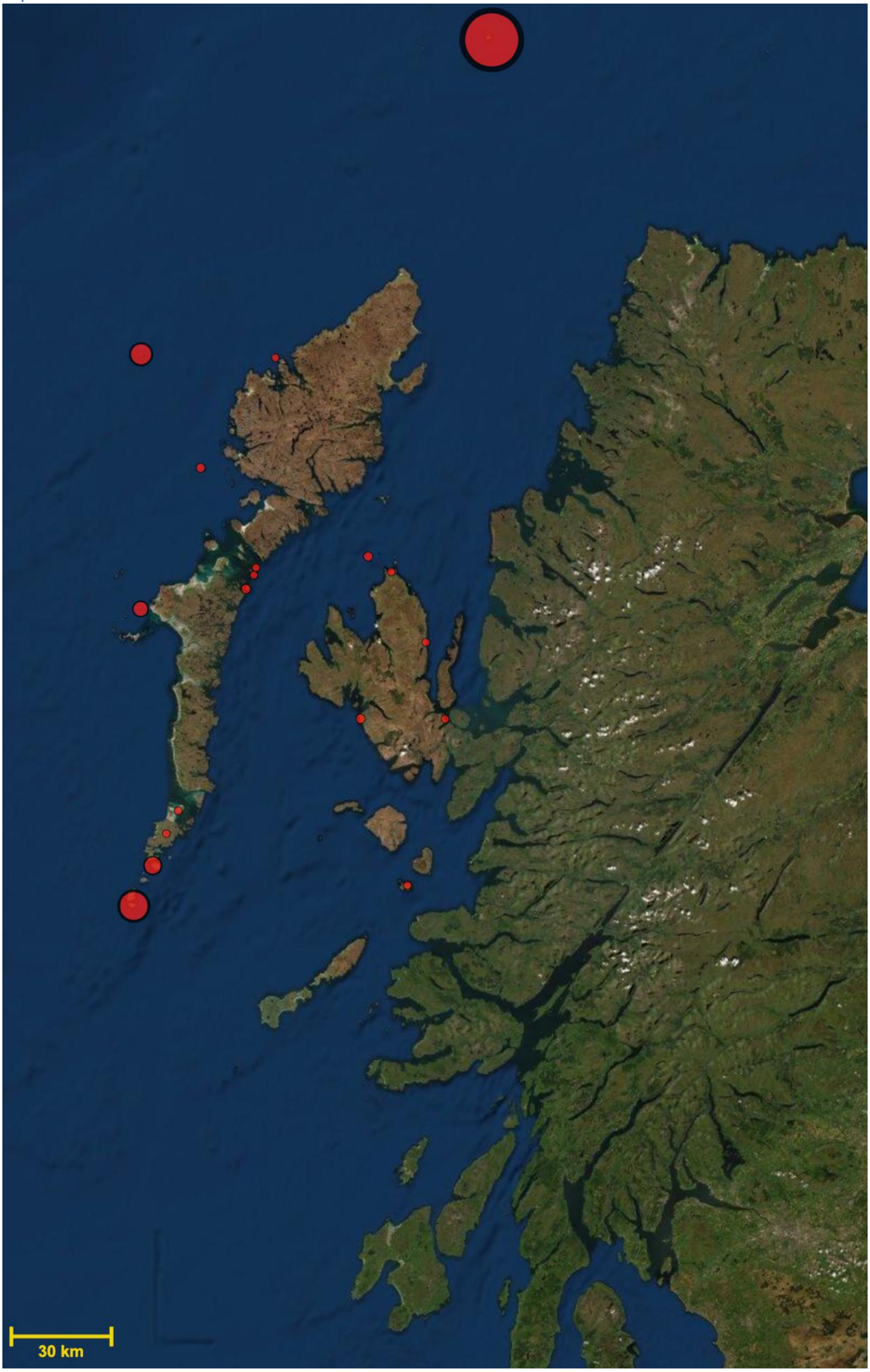


Figure 21. Arctic Skua distribution by main site. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 1-4 for exact abundance. Maps only represent the sites surveyed, and do not represent the total distribution within Western Scotland.

Cliff-Nesting Seabirds: Digital Photography

Digital photographs of cliff-nesting seabird sites were taken at 59 of the 90 sites surveyed on the Isle of Skye. A total of 663 photographs were taken. We have not carried out any formal analysis of the utility of using digital photography for the counting of cliff -nesting seabirds. However, the images will be made available and will be stored with Marine Science Scotland. The images may provide a useful guide to the sites for future surveys.

The quality of the images varied significantly but when good quality, sharp, in focus images were obtained they could be used to identify seabirds to species level (Figure 22 and 23). Whist the images in Figures 22 & 23 have been selected as a best example of what can be achieved with a digital camera taking images from a boat approximately 75% of the images taken were of sufficient quality to identify most birds to species level. Shags and cormorants can readily be discerned for the most part as can most of the gulls, although Common Gulls and Herring Gulls might be difficult in certain cases. Guillemots and Razorbills can also be separated although this does depend on the birds being in a favourable orientation within the images, if only the rear of the birds are visible identification might not be possible. Kittiwakes and Fulmars are also fairly easy to identify in decent quality images.

Figure 22. Digital photograph of cliff at site 'Waterstein Head to Camas na h Annait'. Section contains Guillemots and a single Razorbill.

Figure 23. Zoomed in version of digital photograph in Figure 35. Single Razorbill can be seen in the far right of the image (yellow circle). A bridled form of the guillemot with a white eye ring can also be seen in the image (red circle).

Cliff-nesting Seabirds. UAVs

A total of 17 UAV flights were conducted on the Isle of Skye at 5 different sites. Most of the flights were conducted at Bornessketaig around 6 miles to the North of Uig (Figure 24). Additional flights were also conducted at Duntulm, Rubha na h-Aiseng, Meall Raineach and Wiay. Full details of the flights can be found in the Appendix (Table A6).

The focus of the UAV work was to build flight planning methodologies to enable the UAVs to follow the edge of the cliffs, maintaining a distance of 40m from the cliff-face, whilst filming video to enable cliff-nesting seabirds to be identified. Full details of these methodologies and field notes can be found in the Appendix (Page 14).

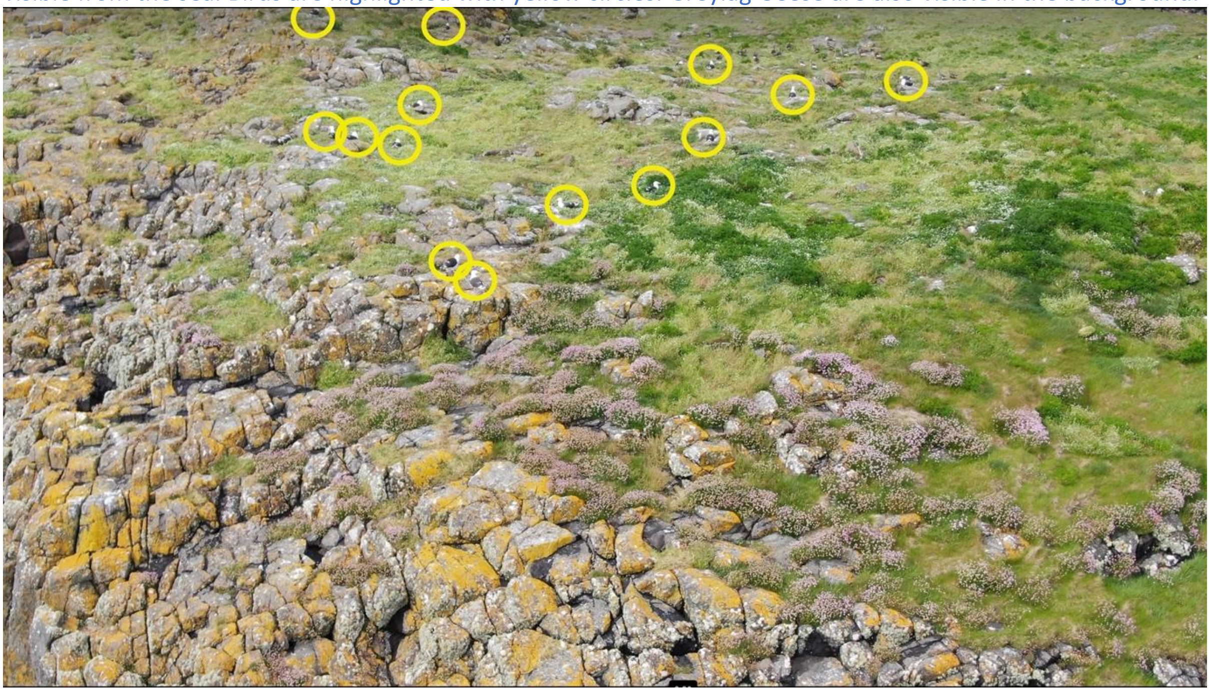
No formal analysis of the video collected has been undertaken, but the quality of the video taken even at 40m away from the cliff-face enabled birds to be fairly easily identifiable, although, as with the digital photography identification relied on the birds being in a favourable orientation on the cliff-face (e.g. Figure 25). The resolution of the sensors and the size of the lens on the UAVs was considerably lower than that of the camera used for the digital photography however identification to species level was still possible, although the same caveats noted for digital photography also apply here.

Figure 24. Location of 6 sub-transects (each used as a template for UAV flights) at Bornessketaig. Grid lines show 1 km grid squares. Lines approximately 40 m from cliff edge.

Figure 25. Still image taken from video shot from a UAV of the cliff-face at Duntulm. This section contains two Fulmar nest sites highlighted by the yellow circles. A third bird can be seen in flight just after leaving the left and lower nest.

In addition to the cliff-face scanning flights an additional flight was made over the island of Wiay located in Loch Bracadale on the Western coast of Skye. The flight over the island enabled us to identify and count a large colony of Great Black-backed gulls which would not have been visible from the sea (Figure 26). The only way these individuals could have been counted without a UAV would be to land a boat on the island and count the birds from the land, a considerably more logistically challenging proposition that a single UAV flight. At no time during any UAV flight did we observe any signs of disturbance to any Schedule 1 species. Indeed, the only signs of disturbance that appear to be from the UAV was that a flock of Greylag Geese appeared to run away as the UAV flew nearby.

Figure 26. Greater Black-backed gulls on the top of a cliff on Wiay Island. These individuals would not have been visible from the sea. Birds are highlighted with yellow circles. Greylag Geese are also visible in the background.



Ground-nesting Seabirds

Overall Species Summaries

Great Skuas

138 AOTs / AONs were recorded during the survey. Their distribution can be found in Figure 27. Great Skuas generally occupied locations near the cost on the East coast of Northern Lewis and the Eye Peninsular, with aggregations of nest sites at Tolsta Head, Creag Fhraoch and around Loch Innis on the Eye Peninsular. There were also a number of more isolated nest sites at more inland sites to the North of the Lewis moorlands. Raw data can be found in the Appendix (Table A11).

Arctic Skua

166 AOTs / AONs were recorded during the survey. Their distribution can be found in Figure 28. Arctic Skuas were distributed throughout much of the moorlands of North Lewis with a slightly higher density is the areas to the Southwest of North Tolsta and an aggregation to the South of the Eye Peninsular. Raw data can be found in the Appendix (Table A12).

Great Black-backed Gulls

144 AOTs / AONs were recorded during the survey. Their distribution can be found in Figure 29. Great Black-backed Gulls were mostly found at more coastal locations, although we a few nest sites were found further inland. There were more dense aggregations around Back on the East Coast of North Lewis and around Chicken Head and Loch Cuilc to the south of the Eye Peninsular. Raw data can be found in the Appendix (Table A13).

Lesser Black-backed Gulls

119 AOTs / AONs and 37 probably breeding were recorded during the survey. Their distribution can be found in Figure 30. Only one aggregation of nest sites was found in the actual survey area near Shader on the West Coast of North Lewis. We did however also locate further aggregations to the South of the main survey area. Raw data can be found in the Appendix (Table A14).

Herring Gulls

462 AOTs / AONs and 173 probably breeding individuals were recorded during the survey. Their distribution can be found in Figure 31. Small aggregations of Herring Gulls were located near to coastal sites on the East Coast South of Tolsta Head, on the West Coast near Shader and at the Butt of Lewis. Larger aggregations were found to the South of the Main Survey area. Raw data can be found in the Appendix (Table A15).

Common Gulls

45 AOTs / AONs and 16 probably breeding individuals were recorded during the survey. Their distribution can be found in Figure 32. Common gulls were generally found around the Northwest Coast and two small aggregations on the Eye Peninsular. Another aggregation of individuals was also located near Barvas. Raw data can be found in the Appendix (Table A16).

Black-headed Gulls

23 AOTs / AONs were recorded during the survey. Their distribution can be found in Figure 33. The main aggregation of Black-headed Gulls was located near Loch Eileabhat, with smaller aggregations near to Swainbost and Knockaird to the North of Lewis. Raw data can be found in the Appendix (Table A17).

Arctic Tern

150 Individuals were recorded during the survey. Their distribution can be found in Figure 34. A single colony of Arctic Terns was located at the Butt of Lewis. Raw data can be found in the Appendix (Table A18).

Common Terns

34 AOTs / AONs were recorded during the survey. Their distribution can be found in Figure 35. Only one small colony was found in the survey area around Loch Sgeireach Mòr. A further small colony was found to the South of the main survey area. Raw data can be found in the Appendix (Table A19).

Maps

Figure 27. Great Skua distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 12 pixels maximum). See Table 19 for exact abundance.

Figure 28. Arctic Skua distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 12 pixels maximum). See Table 19 for exact abundance.

Figure 29. Great Black-backed Gull distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 19 for exact abundance.

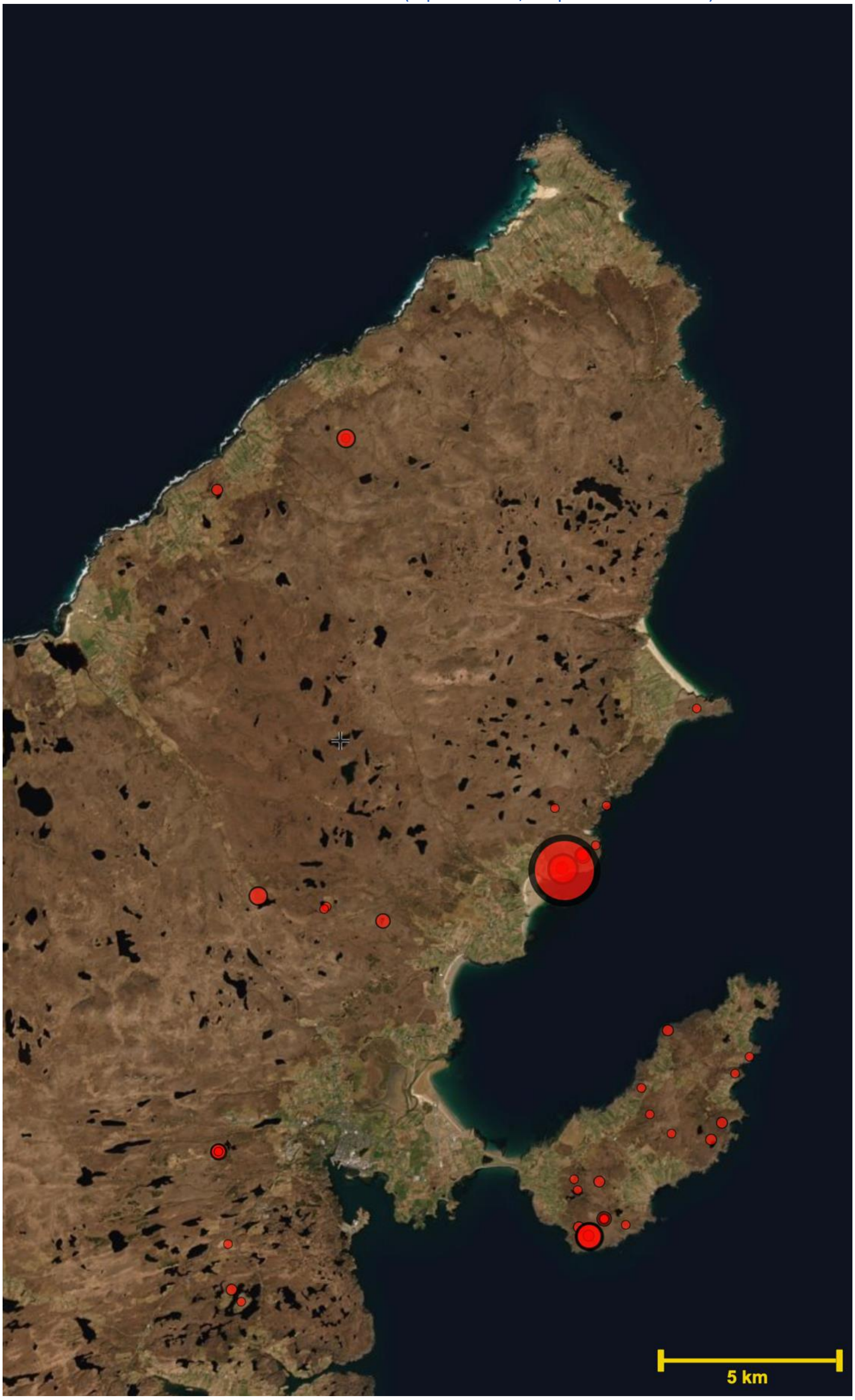


Figure 30. Lesser Black-backed Gull distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 19 for exact abundance. Red dots indicate AOT /AONs Blue dots indicate individuals.

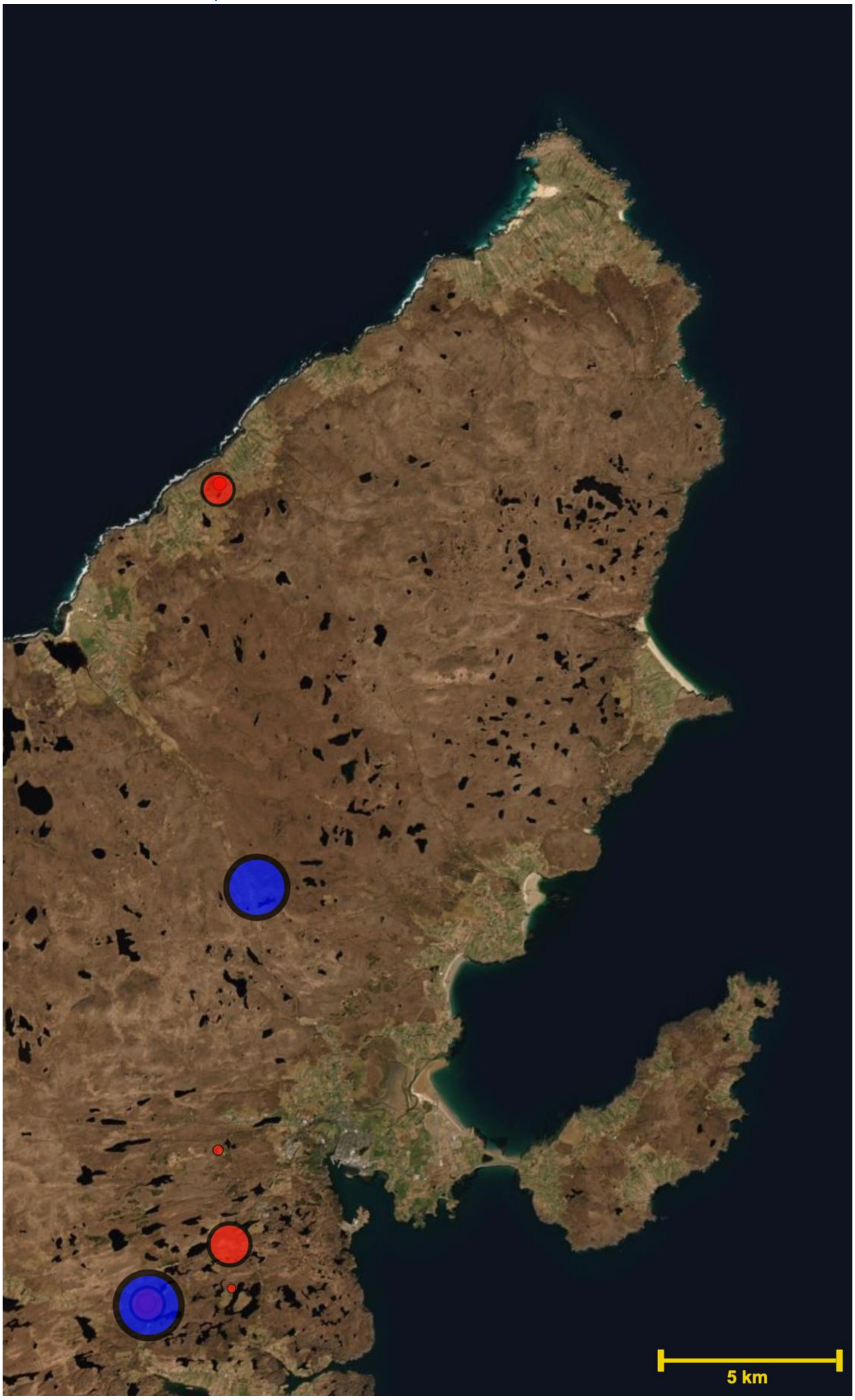


Figure 31. Herring Gull distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 19 for exact abundance. Red dots indicate AOT /AONs Blue dots indicate individuals.

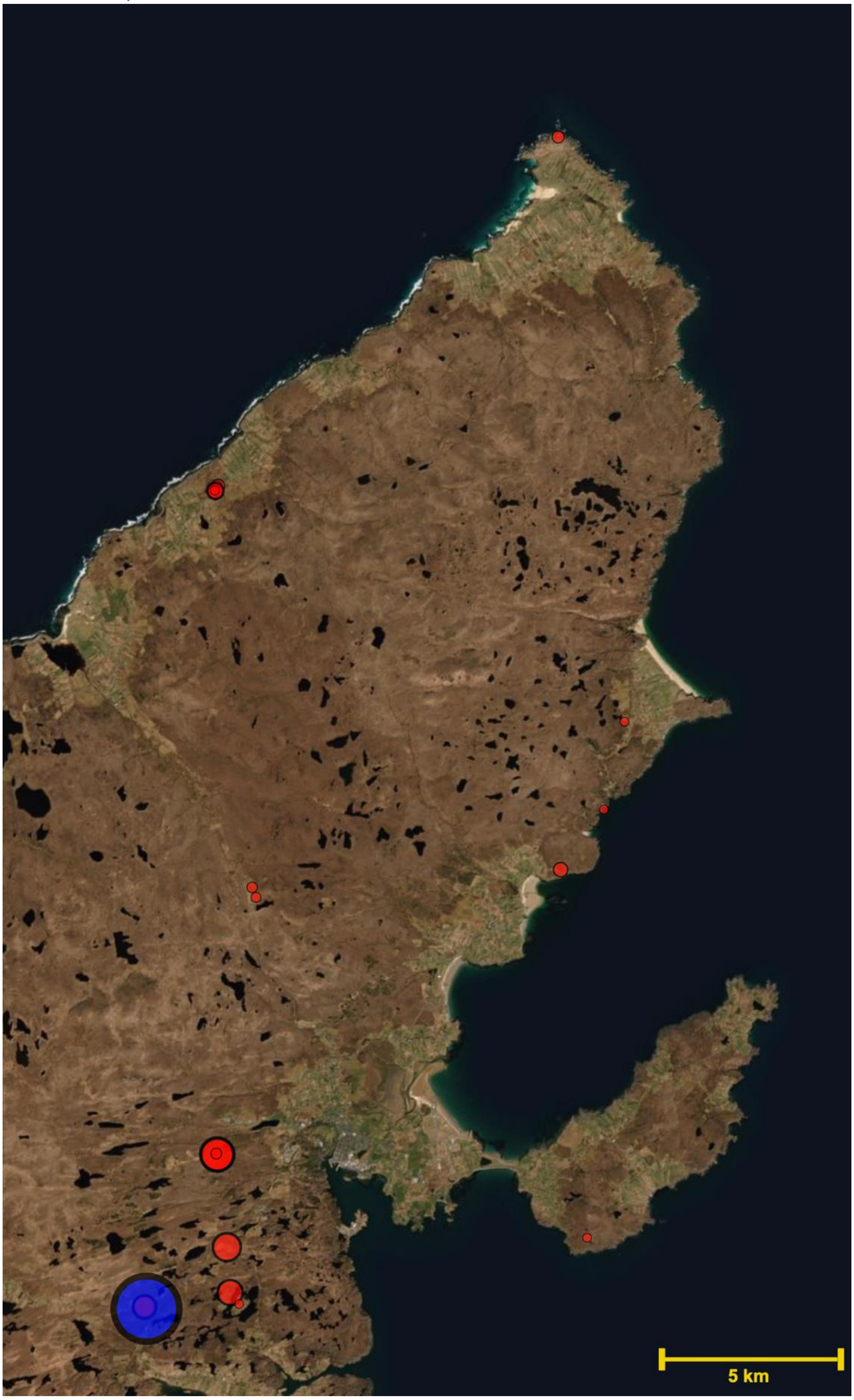


Figure 32. Common Gull distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 19 for exact abundance. Red dots indicate AOT /AONs Blue dots indicate individuals.

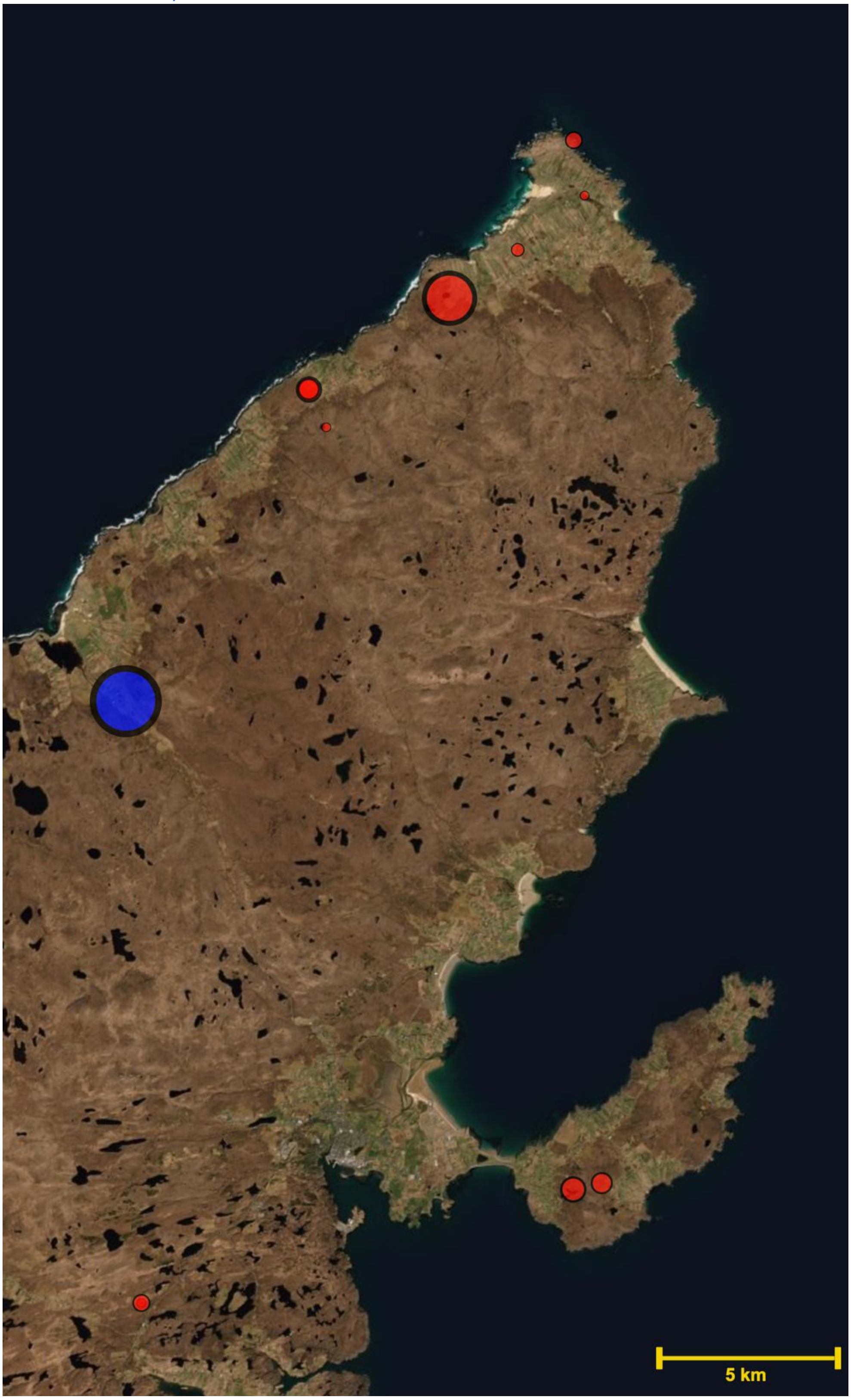


Figure 33. Black-headed Gull distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 19 for exact abundance. Red dots indicate AOT /AONs Blue dots indicate individuals.

Figure 34. Arctic Tern distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 19 for exact abundance. Blue dots indicate individuals.

Figure 35. Common Tern distribution on the Isle of Lewis Northeast Moorlands and Eye Peninsula. Size of the dots are scaled to reflect abundance (4 pixels min, 30 pixels maximum). See Table 19 for exact abundance. Red dots indicate AOT /AONs Blue dots indicate individuals.

Burrow-Nesting Seabirds

Overall Species Summaries

European Storm Petrel

Four sites were surveyed for European Storm Petrels with 1941 separate playback surveys being carried out over 1455 survey points. The total number of positive responses from playbacks was 93 over the four sites (Table 6).

Survey results for North Rona are summarised in Tables 6. A total of 1214 surveys were carried out with 62 positive responses being recorded. The best HDS model used a hazard detection function and a negative binominal distribution, whilst the second best model used an exponential detection function. Full details of all the HDS models are provided in the Appendix (Table A20). The best model produced an estimated European Storm Petrel density of 0.526 (0.138-1.768) per survey area (50.27m^2). The second best model produced an estimated density of 0.28 (0.1321-1.7546) per survey area (50.27m^2). The best model with a uniform detection function had a negative binominal distribution and produced an estimated density of 0.147 (0.0489-1.7191) per survey area (50.27m^2). The Freeman-Tukey goodness of fit p-values for all models were greater than 0.05 suggesting the models were an adequate fit to the data (Table A26). Calculations of available breeding habitat produced an estimate of 341540m^2. Abundance estimates based on the density and the estimated breeding habitat were 3574 (938-12013) for the best model, 1902 (897-11921) for the second best model and 999 (332-11680) for the best model with a uniform distribution (Table 6).

Survey results for the Flannan Isles are summarised in Table 6. A total of 363 surveys were carried out with 10 positive responses being recorded. The best HDS model used a hazard detection function and a negative binominal distribution, whilst the second best model used an exponential detection function. Full details of all the HDS models are provided in the Appendix (Table A21). The best model produced an estimated European Storm Petrel density of 0.569 (0.106 - 4.815) per survey area (50.27m^2). The second best model produced an estimated density of 0.443 (0.0787-5.0924) per survey area (50.27m^2). The best model with a uniform detection function had a negative binominal distribution and produced an estimated density of 0.242 (0.0094-4.5951) per survey area (50.27m^2). The Freeman-Tukey goodness of fit p-values for all models where greater than 0.05 suggesting the models were an adequate fit to the data (Table A26). Calculations of available breeding habitat produced an estimate of 78140m^2. Abundance estimates based on the density and the estimated breeding habitat were 884 (165-7484) for the best model, 689 (122-7916) for the second best model and 376 (15-7143) for the best model with a uniform distribution (Table 6).

Survey results for Shillay are summarised in Table 6. A total of 174 surveys were carried out with 15 positive responses being recorded. The best HDS model used a uniform detection function and a Poisson distribution, whilst the second best model used an half normal detection function. Full details of all the HDS models are provided in the Appendix (Table A22). The best model produced an estimated European Storm Petrel density of 0.049 (0.021–0.095) per survey area (50.27m^2). The second best model produced an estimated density of 0.049 (0.021–0.1022) per survey area (50.27m^2). The Freeman-Tukey goodness of fit p-values for all models where greater than 0.05 suggesting the models were an adequate fit to the data (Table A26). Calculations of available breeding habitat produced an estimate of 80334m². Abundance estimates based on the density and the estimated breeding habitat were 78 (34-151) for the best model and 78 (34-163) for the second best model (Table 6).

Table 6. Total number of positive responses recorded during surveys of European Storm Petrel. Details of HDS models, outputs and subsequent abundance results. Results for the first and second best models (based on AIC) and best model with a uniform detection function are reported. For Shillay and Sanda the best fitting model contained a uniform detection function. All area measurements are in m². Abundances and confidence intervals are in bold. . Abundance estimates are reported as AOS (apparently occupied sites).

				Back Transformed from Log Scale				
	Responses		**Model**	**Estimate**	**SE**	**0.025 CI**	**0.975 CI**	
North Rona	62	Best Model	Hazard Neg Binominal	0.526	0.509	0.138	1.768	
North Rona	62	Second Best Model	Exponential Neg Binominal	0.28	0.114	0.1321	1.7546	
North Rona	62	Best Uniform Model	Uniform Neg Binominal	0.147	0.156	0.0489	1.7191	
Flannan Isles	10	Best Model	Hazard Neg Binominal	0.569	0.444	0.106	4.815	
Flannan Isles	10	Second Best Model	Exponential Neg Binominal	0.443	0.362	0.0787	5.0924	
Flannan Isles	10	Best Uniform Model	Uniform Neg Binominal	0.242	0.441	0.0094	4.5951	
Shillay	15	Best Model	Uniform Poisson	0.049	0.019	0.021	0.095	
Shillay	15	Second Best Model	Half Normal Poisson	0.049	0.019	0.021	0.1022	
Sanda	6	Best Model	Uniform Poisson	0.0699	0.053	0.018	2.829	
Sanda	6	Second Best Model	Half Normal Poisson	0.0699	0.053	0.0178	2.8291	
	Responses			**Survey Area**	**Survey Area/Plot Size**	**Count**	**0.025 CI**	**0.975 CI**
North Rona	62	Best Model	Hazard Neg Binominal	341540	6794	**3574**	**938**	**12013**
North Rona	62	Second Best Model	Exponential Neg Binominal	341540	6794	**1902**	**897**	**11921**
North Rona	62	Best Uniform Model	Uniform Neg Binominal	341540	6794	**999**	**332**	**11680**
Flannan Isles	10	Best Model	Hazard Neg Binominal	78140	1554	**884**	**165**	**7484**
Flannan Isles	10	Second Best Model	Exponential Neg Binominal	78140	1554	**689**	**122**	**7916**
Flannan Isles	10	Best Uniform Model	Uniform Neg Binominal	78140	1554	**376**	**15**	**7143**
Shillay	15	Best Model	Uniform Poisson	80334	1598	**78**	**34**	**151**
Shillay	15	Second Best Model	Half Normal Poisson	80334	1598	**78**	**34**	**163**
Sanda	6	Best Model	Uniform Poisson	8560	170	**12**	**3**	**482**
Sanda	6	Second Best Model	Half Normal Poisson	8560	170	**12**	**3**	**482**

Survey results for the Sanda are summarised in Table 6. A total of 190 surveys were carried out with 6 positive responses being recorded. The best HDS model used a uniform detection function and a Poisson distribution, whilst the second best model used an half normal detection function. Full details of all the HDS models are provided in the Appendix (Table A23). The best model produced an estimated European Storm Petrel density of 0.0699 (0.018-2.829) per survey area (50.27m²). The second best model produced an estimated density of 0.0699 (0.0178-2.8291) per survey area (50.27m²). The Freeman-Tukey goodness of fit p-values for all models where greater than 0.05 suggesting the models were an adequate fit to the data (Table A26). Calculations of available breeding habitat produced an estimate of 8560m^2. Abundance estimates based on the density and the estimated breeding habitat were 12 (3-482) for both the best and second best models (Table 6).

Leach's Storm Petrel

Two sites were surveyed for Leach's Storm Petrels with 1577 separate surveys being carried out over 1200 survey points. The total number of positive responses from playbacks was 110 over the two sites (Table 7).

Table 7. Total number of positive responses recorded during surveys of Leach's Storm Petrel. Details of HDS models, outputs and subsequent abundance results. Abundances and confidence intervals are in bold. Results for the first and second best models (based on AIC) and best model with a uniform detection function are reported. All area measurements are in m^2. Abundances and confidence intervals are in bold. Abundance estimates are reported as AOS (apparently occupied sites).

				Back Transformed from Log Scale				
	Responses		**Best Model**	**Estimate**	**SE**	**0.025 CI**	**0.975 CI**	
North Rona	79	Best Model	Hazard Neg Binominal	1.82	0.98	0.742	4.065	
North Rona	79	Second Best Model	Exponential Neg Binominal	0.924	0.334	0.5554	4.0752	
North Rona	79	Best Uniform Model	Uniform Neg Binominal	0.334	0.392	0.1119	3.976	
Flannan Isles	31	Best Model	Exponential Neg Binominal	3.26	3.81	0.212	15.852	
Flannan Isles	31	Second Best Model	Hazard Neg Binominal	3.26	3.81	0.2123	15.852	
Flannan Isles	31	Best Uniform Model	Uniform Neg Binominal	3.26	3.81	0.2123	15.852	
	Responses		**Best Model**	**Survey Area**	**Survey Area/Plot Size**	**Count**	**0.025 CI**	**0.975 CI**
North Rona	79	Best Model	Hazard Neg Binominal	341540	6794	**12365**	**5042**	**27618**
North Rona	79	Second Best Model	Exponential Neg Binominal	341540	6794	**6278**	**3773**	**27688**
North Rona	79	Best Uniform Model	Uniform Neg Binominal	341540	6794	**2269**	**760**	**27013**
Flannan Isles	31	Best Model	Exponential Neg Binominal	78140	1554	**5067**	**330**	**24641**
Flannan Isles	31	Second Best Model	Hazard Neg Binominal	78140	1554	**5067**	**330**	**24641**
Flannan Isles	31	Best Uniform Model	Uniform Neg Binominal	78140	1554	**5067**	**330**	**24641**

Survey results for North Rona are summarised in Tables 7. A total of 1214 surveys were carried out with 79 positive responses being recorded. The best HDS model used a hazard detection function and a negative binominal distribution, whilst the second best model used an exponential detection function. Full details of all the HDS models are provided in the Appendix (Table A24). The best model produced an estimated Leach's Storm Petrel density of 1.82 (0.742-4.065) per survey area (50.27m^2). The second best model produced an estimated density of 0.924 (0.5554-4.0752) per survey area (50.27m^2). The best model with a uniform detection function had a negative binominal distribution and produced an estimated density of 0.334 (0.1119-3.976) per survey area (50.27m^2). The Freeman-Tukey goodness of fit p-values for all models where greater than 0.05 suggesting the models were an adequate fit to the data (Table A26). Calculations of available breeding habitat produced an estimate of 341540m^2. Abundance estimates based on the density and the estimated breeding habitat were 12365 (5042-27618) for the best model, 6278 (3773-27688) for the second best model and 2269 (760 - 27013) for the best model with a uniform distribution (Table 7).

Survey results for the Flannan Isles are summarised in Table 7. A total of 363 surveys were carried out with 31 positive responses being recorded. The best HDS model used an exponential detection function and a negative binominal distribution, whilst the second best model used an hazard detection function. Full details of all the HDS models are provided in the Appendix (Table A25). All three models produced almost exactly the same estimated Leach's Storm Petrel density of 3.26 (0.212-15.852) per survey area (50.27m^2). The Freeman-Tukey goodness of fit p-values for all models where greater than 0.05 suggesting the models were an adequate fit to the data (Table A26). Calculations of available breeding habitat produced an estimate of 78140m^2. Abundance estimates based on the density and the estimated breeding habitat was 5067 (330-24641) (Table 6).

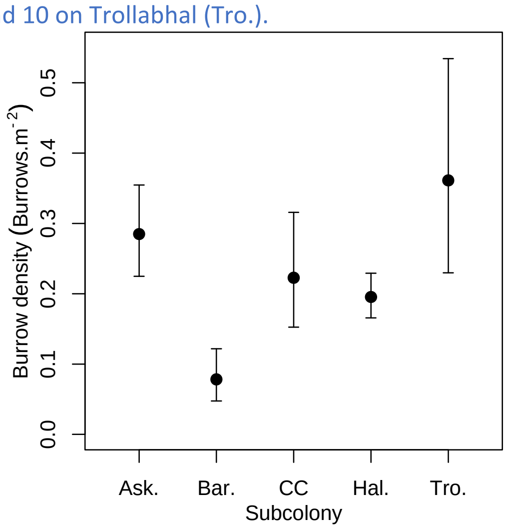
Robustness Testing of HDS models

Abundance calculations produced using methods analogous to previous surveys produced estimates which all fell within the confidence intervals of the estimates from the best HDS model with a uniform detection function, apart from European Storm Petrels on Shillay were the estimate was higher than the upper confidence interval from the HDS results Full results can be found in the Appendix (Table A27).

Manx Shearwater

The Phase 1 habitat survey was carried out between 11 May 2021 and 20 May 2021. We carried out 167 transect surveys (covering 61,920 m^2), counted 2,344 burrows, and carried out 1,0145 playback trials. Using the information from the Phase 1 survey, we then visited 129 survey grid squares in Phase 2 (the multi-strata survey) between 20 May 2021 and 28 May 2021; 33 on Askival, 8 on Barkeval, 13 on Clough's Crag, 65 on Halival and 10 on Trollabhal (Figure 8). The median (95% HDI) burrow density was lower on Barkeval 0.08 (0.05–0.12) burrows.m^{-2}, than at the other 4 subcolonies, which were all similar and varied between 0.20 (0.17–0.23) burrows.m^{-2} on Hallival and 0.36 (0.23–0.53) burrows.m^{-2} at Trollabhal (Figure 36).

Figure 36. The mean (95% highest posterior density interval, HDI) burrow density (burrows.m^{-2}) based on the observed burrow counts from the 129-survey circles; 33 on Askival (Ask.), 8 on Barkeval (Bar.), 13 on Clough's Crag (CC), 65 on Halival (Hal.) and 10 on Trollabhal (Tro.).

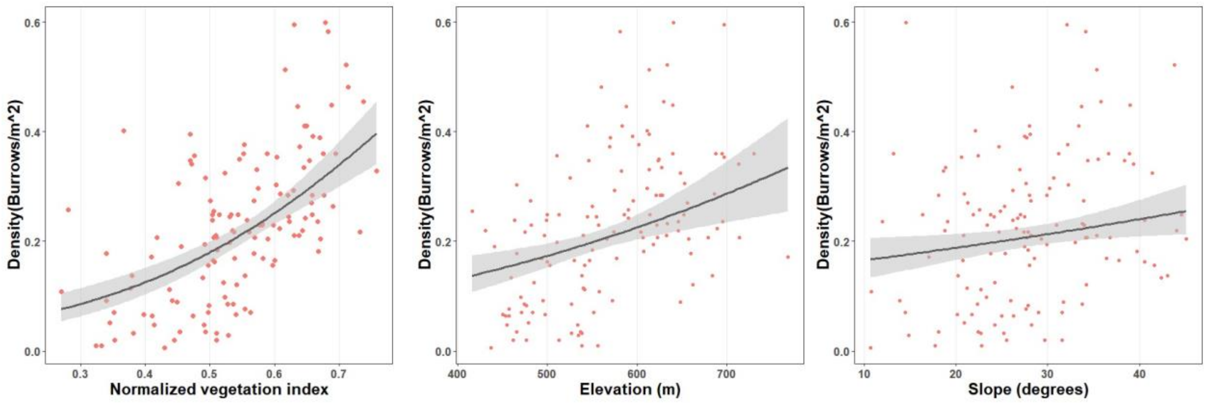


Burrow density in the 129-survey circles was positively related to NDVI, Slope and Elevation (Figure 37). The best-support model contained the additive effects of these three environmental covariates and differed from the next best supported model by a ΔAICc > 3 (Table 8). Subcolony was not retained in the best-supported model, and neither were any interaction terms between the covariates (Table 8). Using these relationships in combination with the topographically corrected estimate of the 'true' surface area of the colony ($\hat{A}_j$ = 2,089,611 m^2 or 208.96 ha), yielded an expected burrow density ($\hat{B}_j$) for each of the 3,419 pixels making up the raster of the Manx Shearwater colony. The expected burrow density ($\hat{B}_j$) across the colony ranged from 0.022 to 1.03 burrows.m^{-2}; the upper limit is outside the range in our observed data (Figure 38), but the predictions for >99.99% of the 3,419 pixels was a burrow density <0.599 burrows.m^{-2}, the maximum observed burrow density in the 129 survey circles.

Table 8. Model selection table for models exploring how environmental covariates (NDVI, Elevation and Slope) and subcolony affect burrow density in the survey circles. All possible sub-models of the full model were created and ranked using AICc. Those retained in the top set (below) were those that were not nested versions of models with lower AICc, i.e. more complex version of models with a lower AICc, and those that were within 6 AICc points of the top ranked model (Burnham et al. 2011, Harrison et al. 2018). Notes: df = model degrees of freedom (number of estimated parameters), logLik = the model log-likelihood, NDVI = Normalized vegetation index, * indicates an interaction term.

Intercept	Subcolony	Elevation	NDVI	Slope	Colony*NDVI	df	logLik	AICc	ΔAICc
−1.34 [−1.45–1.23]	NA	0.25 [0.14–0.36]	0.44 [0.32–0.56]	0.12 [0.02–0.22]	NA	5	130.02	−249.56	0.00
−1.33 [−1.44–1.22]	NA	0.27 [0.16–0.38]	0.44 [0.33–0.56]	NA	NA	4	127.25	−246.18	3.38

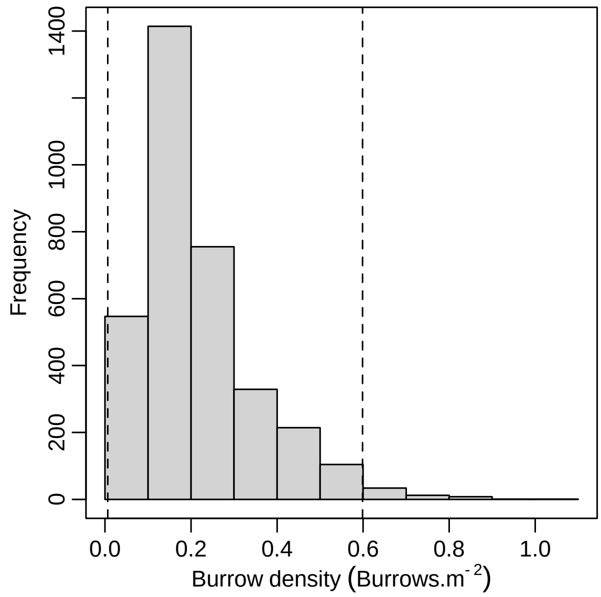
Figure 37. The modelled relationship between burrow density (burrows.m^{-2}) in the 129-survey circles and (left) Normalized vegetation index (NDVI), (middle) Elevation (m above sea level) and (right) Slope (degrees). The black line shows the fitted relationships from a generalised linear model (beta errors, logit link function), the grey polygons show the 95% confidence intervals around the fit, and the red points are the observations.



Response rates from the dual-sex call playback trials showed a negative relationship with the observed burrow density in both the 129 survey circles and the calibration burrows (Figure 39). However, the slopes were relatively shallow (Figure 61), and the coefficient estimates only differed from zero with about 85% probability (i.e. they would not be considered "significant" at the 5% level in a frequentist analysis). The median probability of getting a response ranged from 0.39 (0.32–0.47) at high burrow density to 0.45 (0.40–0.50) at low burrow density in the survey circles (were burrow occupancy was unknown), and from 0.55 (0.24–0.85) to 0.79 (0.65–0.91) in the occupied burrows used for the calibration factor. For the calibration burrows, the raw mean ± SE response rate was 0.68 ± 0.02 (approx. 95% CI: 0.63–0.72), and the modelled mean ± SE response rate was 0.73 ± 0.05 (95% HDI: 0.63–0.83). Both are comparable to response rate from a dual-sex call playback experiments undertaken previously at Rùm by Perkins et al. (2017) who reported a response rate of 0.67 ± 0.07 (95% CI: 0.54–0.79).

Based on the coefficient estimates from the response rates models (β_P and β_R), the expected burrow density ($\hat{B}_j$) for each of the 3,419 pixels, we were able to estimate $\hat{P}_j$, the mean proportion of burrows expected to respond to playback in each of the 3,419 pixels, and $\hat{R}_j$, the expected response from occupied burrows in each of the 3,419 pixels. Averaging across the colony, the median (95% HDI) probability of getting a response at any burrow ($\hat{P}$) was 0.43 (0.38–0.47) and the median (95% HDI) probability of getting a response at an occupied burrow ($\hat{R}$) was 0.74 (0.49–0.86), giving a calibration factor of 1/0.74 = 1.35 (1.16–2.04).

Figure 38. The distribution of predicted burrow densities (burrows.m^{-2}) for the 3,419 16.9 m x 30.9 m raster pixels covering the Manx shearwater colony. The vertical dashed lines show the minimum and maximum burrow densities (burrows.m^{-2}) observed in the maximum observed burrow density in the 129 survey circles; >99.99% of the predicted distribution lies within these values.



Finally, combining the $\hat{B}_j$, $\hat{P}_j$, $\hat{R}_j$and $\hat{A}_j$ following eqn. 1 yielded a direct estimate of the number of AOBs expected in each of the 3,419 spatial pixels making up the Manx Shearwater colony (Figure 62). The median (95% HDI) number of burrows per pixel was 63.6 (9.2–212.1), at a median burrow density of 0.10 (0.02–0.33) burrows.m^{-2}, but the individual pixel values ranged from 6.5 burrows per pixel (0.01 burrows.m^{-2}) to 683 burrows per pixel (1.05 burrows.m^{-2}). This average value of 0.10 burrows.m^{-2} across the whole colony is slightly higher than the estimate from the 2001 survey of 0.081 burrows.m^{-2} (Murray et al. 2003). The resulting map (Figure 40) of the spatial distribution of the breeding population over the known footprint of the colony provides a direct mechanism by which our estimates could be ground-truthed in further surveys. Summing the AOBs over all 3,419 pixels (following eqn.

10), gave a total (posterior median) of 288,894 AOBs (95% HDI: 226,010–403,915) in an area of 208.96 ha (Figure 41).

Figure 39. The modelled relationship between the probability of getting a response to a playback trial and burrow density (burrows.m^{-2}) in (A) the 3,653 playback trials carried out in the 129-survey circles during the multi-strata survey and (B) the 367 playback trials at 62 burrows known to be occupied in 31 calibration plots. The coefficient estimates (in logit space) for the slopes (β_P and β_R respectively) and the upper and lower limits of the 95% HDI (separated by a comma) are shown at the top left-hand corner of each plot.

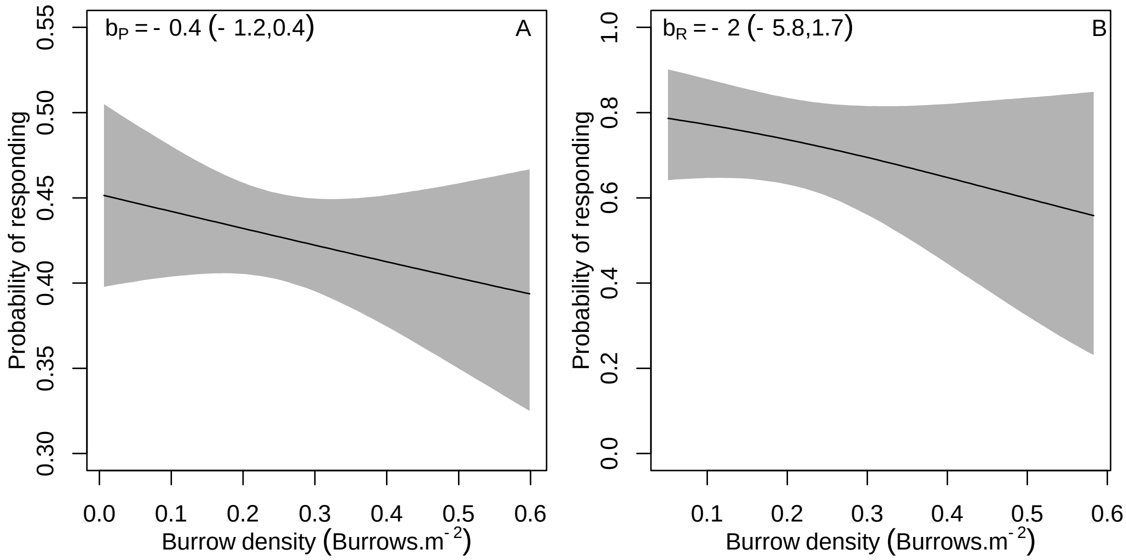


Figure 40. The predicted number of apparently occupied Manx Shearwater burrows in each 16.9 m x 30.9 m spatial pixel covering the known footprint of the colony. The five subcolonies, named after the main peaks (green triangles) that occur within the spatial extent of the colony, are labelled. The white outlines show the 450 m contour, which denotes the limit taken as the lowest elevation of the Manx Shearwater colony after Murray et al. (2003) and Jackson (2018).

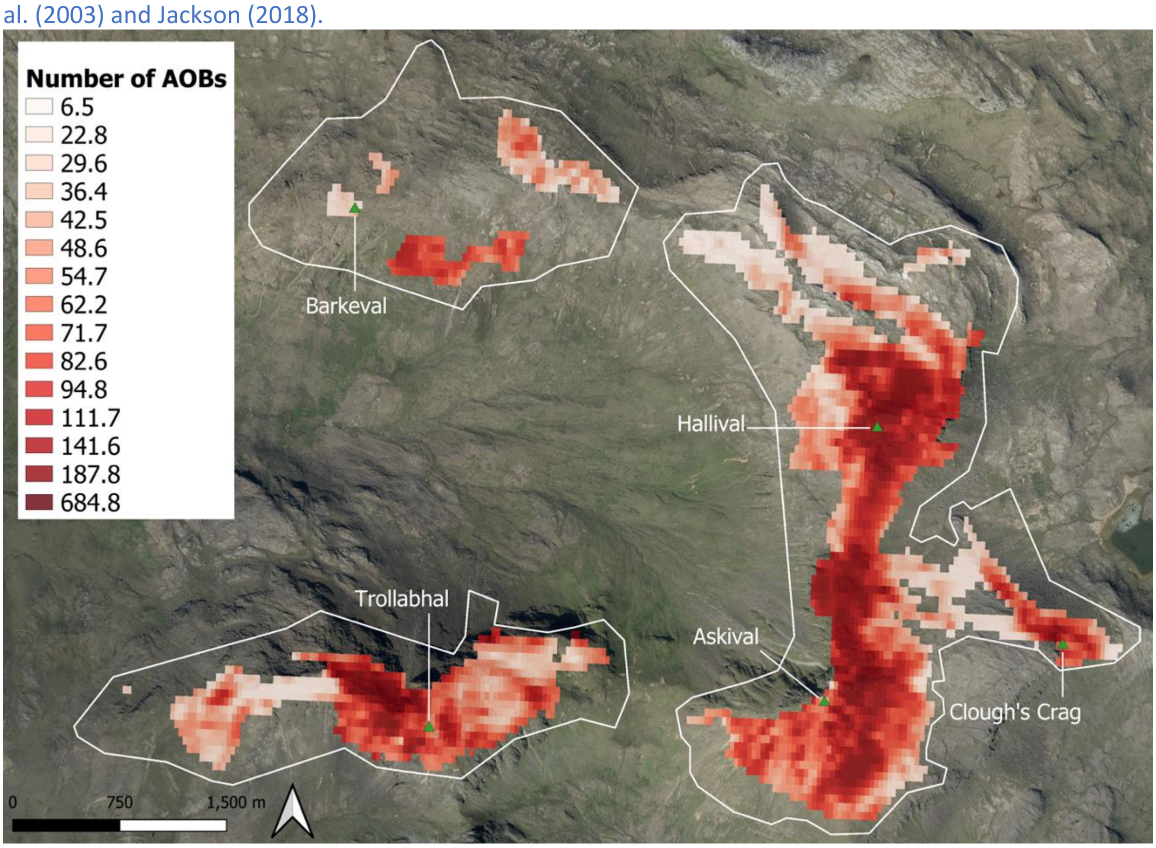
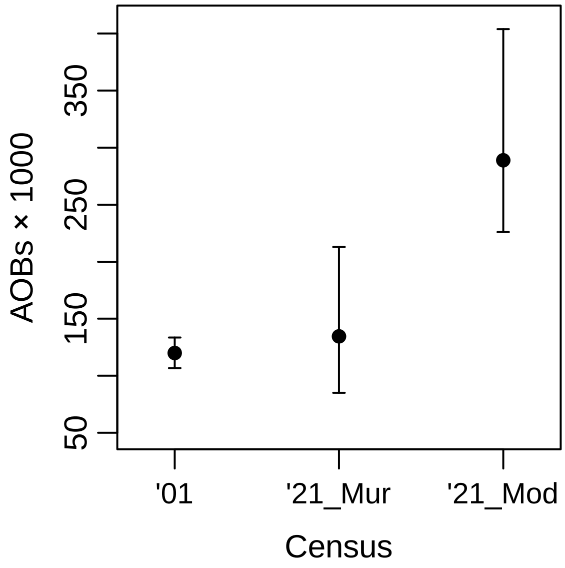


Figure 41. The estimated number of apparently occupied burrows (AOB) of Manx Shearwater on the Isle of Rùm from the 2001 census ('01; Murray et al. 2003, mean and 95% confidence intervals), based on our estimate of the density of AOBs but using the area of the colony estimated in the 2001 census of 148 ha ('21_Mur; Murray et al. 2003, median and 95% highest posterior density intervals, HDI), and based our best estimate ('21_Mod; median and 95% HDI) using an area of colony of 208.96 ha and the spatial distribution of AOBs shown in Figure 61. See methods text for details of how this estimate was derived.



Refer to the Appendix (Page 35) for details of the raw data for all Burrow-nesting Seabird surveys.

Discussion

Cliff-nesting Seabirds

The rationale for carrying out the cliff-nesting seabird surveys reported here was the need to survey areas which had not been surveyed for a number of years, or would not form parts of other surveys to be carried out in 2021 as part of the latest UK seabird survey. As such it is important to note that the abundances reported here only represent a subset of all cliff-nesting seabirds within Western Scotland. It is also important that population trends should not be implied from the results presented here. This is because firstly, our sites are not representative of the total seabird populations within Western Scotland. Secondly, as many of our sites are difficult to survey, mainly because they require a boat to get to, previous surveys may not be temporally or spatially matched i.e. different sites may have been surveyed in different years. Comparisons across years are only valid when the same sites are surveyed between years, or mathematical corrections are made to account for this, which is beyond the scope of the current report.

Generally, the methods carried out here were the same as in previous years and we still believe that counting of cliff-nesting seabirds by eye, using multiple trained observers is the preferred approach. Both digital photograph and the use of UAVs do have potential to supplement standard approaches however, and some of the advantages and disadvantages are discussed below.

Digital Photography

There were a number of issues with the use of digital photographs for cliff-nesting seabirds. Firstly, given that that the photographs are being taken from a boat, it is difficult to get stable images even when the camera has optical stabilisation. Multiple photographs of each site need to be taken to maximise the likelihood of usable images being captured. Secondly, at most sites it was difficult, if not impossible to capture the whole area within a single image. Therefore, multiple images need to be taken at each site, which can be difficult to subsequently compile to provide a comprehensive representation of the site. On our survey of Skye, we had one team member who was acting as a scribe recording the data, also taking the photographs. In future if digital photographs are to be used during surveys, we would recommend that a separate team member be used whose sole responsibility would be to take the photographs and record the location of number of images taken. A further problem is that digital photography may not capture all of the three-dimensional features of the cliff. Crags and outcrops which hold birds might only be visible from certain angles and hence multiple photographs are needed to represent this. In addition, we found that the digital images were particularly poor at discerning the insides of caves which often contain Shags. Birds could clearly be seen inside of caves using binoculars, but the same birds could not be seen in the photographs. Finally, for a survey the size of the Skye survey the number of photographs generated means that the amount of time and manpower required to analyse the photographs comprehensively makes their utility questionable, particularly when the use of digital photographs offer no real benefits over carrying out counts in the traditional manner. That said, it might be possible to develop citizen science schemes which would allow members of the public to count the number of birds found within images and report the results back. A number of such studied are currently hosted on the Zooniverse platform (https://www.zooniverse.org) and have been reasonably successful (Wood et. al. 2021). Despite the problems with digital photography there are likely to be circumstances when digital photographs might be useful, particularly for very large and dense colonies of seabirds where it is difficult to obtain an accurate count using traditional methods. Unfortunately no such colonies are found on the Isle of Skye hence we were unable to test this.

UAVs

UAV technology has improved considerably in recent years and the cost of the devices has also come down making the use of UAVs for cliff-nesting seabirds a realistic method to consider. A large amount of planning is however required before surveys are undertaken and it is not realistic (or safe) to arrive at a site and expect to carry out a survey without prior planning and training. Also given that disturbance of Schedule One species is possible with the use of UAVs it is important to know what species are to be found at particular sites (for e.g. to avoid flights near to eagle nests) and to ensure that all appropriate licences are in place before survey work commences. We worked with NatureScot to put together a set of guidelines before our survey work in which we set a 40m approach limit to the cliff-face. At this distance we did not observe any disturbance, and it may be that this is too conservative and closer approaches may be possible. At 40m with the UAV models utilised here birds were generally identifiable to species level by the trained eye, but the resolution was still quite poor in comparison to the digital images taken with a high specification standard camera. This issue with resolution may be address by using closer passes to the cliff-face. That said, rapid advances in UAV technology, including the size of the sensors used and the quality of the lenses will very probably mean that much higher resolution images will be feasible at a distance of 40m (which we have shown to be safe) as new models become available.

We found that by far the best approach was to undertake pre-flight planning before surveys were undertaken. This enables a route to be flown which ensures comprehensive coverage of the site, and that the maximum approach distance (40m) is always maintained. This also means that flights are repeatable, and here lies one of greatest potential uses for UAVs in the future, that is repeat surveys of the same site. Once the groundwork has been done at a particular site and the desired flight route planned, the exact same survey could be very easily and inexpensively carried out in future years. Repeated measurements of abundance at a selection of key sites could provide a very useful indicator of changes in the population size of cliff-nesting seabirds into the future.

We have a number of other recommendations for those planning UAV surveys in the future. We recommend that ground-based take-off and landing sites be used, which facilitates the use of pre-planned flights. Launching UAVs from mobile platforms such as boats is problematic as it is difficult for the boat to maintain position during the UAV flight and so pre-planned return flights may result in the UAV missing the boat. We did conduct one manual flight from a boat and managed to return the UAV safely onto the boat, but this was with two experienced UAV pilots in control (one flying the UAV and another acting as a spotter). Even then, we very nearly lost the UAV to sea whilst trying to return it to the boat. If boat launching is the only option, the UAV manufacturer DJI recommend the older phantom 4 as more appropriate due to the inbuilt hand launch function and safer holding area on the UAV. However, this UAV is believed to disturb birds more readily than the Mavic UAVs we used, probably due to their white colour (J. Duffy & L. DeBell personal communication).

Other considerations relate to battery life and memory. UAVs are quite power hungry and the video they capture produces quite large file sizes, and this will only increase as the resolution of the images increases in the future. We found that having multiple UAV batteries, along with a method to charge them was essential. We found portable solar generators consisting of a lithium-ion battery pack connected to a solar panel offered an excellent solution and enabled us to keep UAVs charged whilst in the field. Several manufacturers supply such battery packs, including Goal Zero (which we used) and Jackery. Having a good supply of SD cards to record the video onto is also essential as each minute of flight generates near to one GB of data.

Finally, weather is another factor to be considered. We managed to fly the UAVs without a problem with 20km/h base winds and gusts of up to 25km/h, although above this flights may become more erratic and so more dangerous.

Ground-nesting Seabirds

As with the cliff-nesting seabirds, it is not easy to make assessments of trends in the population sizes of the ground-nesting seabirds we surveyed due to a lack of consistence in past counts. Much of the moorlands of North Lewis have only been surveyed sporadically if at all in the past. The traditional methods of survey ground nesting seabirds worked well, and we have nothing to add here apart from the utility of GPS apps on smartphones which greatly helped us in navigating the survey areas and for recording the location of the birds. We found the OS maps app to be very useful as it allows maps to be downloaded to the device before fieldwork commences and so will work without a mobile phone signal.

Burrow-nesting Seabirds

European and Leach's Storm Petrels

We once again advise caution when comparing the results of the surveys reported here to previous surveys, in the case of the Petrels because of the different survey methods used. Previous surveys have followed the calibration plot method as outlines by Radcliffe et al. (1998), whereas the surveys reported here follow a Hierarchical Distance Sampling approach (Deakin et al. 2021). The HDS approach was used here, after discussion with the scientific steering committee, as it had recently been successfully applied on the large Leach's Storm Petrels colonies on St Kilda in Scotland and on the Vestmannaeyjar archipelago in Iceland (Deakin et al. 2021). The HDS approach has the advantage that a much larger area of habitat is surveyed at each playback point than in the calibration plot method. Also, the hierarchical nature of the surveys means that it is possible (with enough data) to produce density estimates for different habitat types and hence produce a more accurate overall population estimate. Given that some of the sites we intended to survey are particularly difficult to travel to and prone to bad weather, logistical constraints meant that time on the islands could be very limited, therefore the use of HDS would maximise the amount of habitat that could be surveyed in the time available.

At all four of our survey sites, we did not collect enough data to enable us to produce density estimates for different habitat types. This was not due to insufficient surveys of the available habitats, as we believe that the surveys covered the majority of available breeding habitat, particularly for North Rona and the Flannan Isles were coverage was comprehensive. We simply did not record enough responses to the playbacks to provide enough data within each habitat type for the models to produce estimates for each habitat. We did however collect enough data for the models to produce density estimates for each island. On Shillay and Sanda Island however the very low number of responses recorded (15 & 6 respectively) means that we have less confidence in these abundance estimates, and the results presented here should be treated with caution.

The HDS models proved to be very sensitive to the detection function used. The best supported HDS models (based on AIC score) produced much higher estimated abundances for a given response rate that the calibration plot methods which have previously been used (differing by an order of magnitude in some cases). However visual inspection of the distribution of responses across all the distance bands suggest that the use of a uniform detection function, were the probability of detection does not change with distance from the payback point, would be more appropriate. While these estimates are higher than those from previous surveys they are more in agreement with the previous surveys than the most parsimonious models which used non-uniform detection functions. Murray et.al. calculated 713 AOSs from 253 responses for Leach's Storm Petrel and 313 AOSs from 132 responses for European Storm Petrel on North Rona. (Murray et al. 2009; Tables 2 &5). The current surveys based on the best HDS models with a uniform detection function produced estimates of 2269 AOS for 79 responses for Leach's Storm Petrel and 999 AOS for 62 responses for European Storm Petrel on North Rona.

We also carried out further calculations to produce abundance estimates analogous to previous surveys. These calculations produced abundance estimates which all fell within the confidence interval from the HDS methods, apart for Shillay, where the estimates were higher than those from the HDS methods (Appendix Table A27). We also applied these methods to the abundance estimates for Leach's Storm Petrel found in Deakin et al. (2021) and where able to accurately recreate the estimates for Ellidaey were we calculated an estimate of 5352 compared to the HDS estimate of 5356 (4296-6678) and for St Kilda where we calculated an abundance of 14917 compared to the published estimate of 15140 (11315-25412). Additionally, goodness of fit tests did not identify evidence of any significant lack of fit of the HDS models to the data (Appendix Table A26), hence we are reassured that the models are sensible. However, that the two methods produce such different abundance estimates per response remains a cause for concern. The discrepancy is largely due to our survey producing substantially more responses per unit area than the earlier ones, back calculation of the Murray et al. (2009) data show the 2021 figures being around 10 times higher. It is very hard to speculate on why such a large difference might exist, but it is clear that more validation work is needed using direct comparisons of two methods simultaneously at the same colony.

Adopting a precautionary approach we would strongly suggest that the HDS estimates based on the best fitting model with a uniform distribution be favoured for inclusion in the Seabird Monitoring Program database. All the data and our analyses suggest that there are more European and Leach's Storm Petrels on North Rona and the Flannan Isles than has previously been reported, although the magnitude of these difference remains unclear.

For medium to large Petrel colonies the HDS approach offers clear advantages over the calibration plot methods. We have provided full details of all the survey transects including GPS data along with detailed protocols which should allow repeat surveys to be carried out in the future utilising the exact same protocols. This will facilitate the detection of any changes in population size within these colonies. For the smaller colonies however, we do not believe the HDS approach is appropriate, and the tradition approaches may be more useful. Also, for smaller (or low density) colonies alternative methods utilising night vision optics, trail cameras and thermal imaging techniques might be more appropriate. A further consideration when deciding on which survey method to use is the level of analytic expertise required to analyses the HDS data. This is much more complex than for the calibration plot methodology and requires a solid foundation in advances statistics and the R statistical language and environment. We also suggest examining Deakin et al. (2021) for a more detailed description of the HDS approach and its advantages and disadvantages. Finally, there is a question as to whether any method is able to accurately estimate population size in such cryptic nesters. There is clearly an argument for moving to an index-based approach to detecting population change and the transects and data provided in these surveys could be used as a starting point.

Manx Shearwater

Our estimate of 288,894 AOBs (95% HDI: 226,010–403,915) is far higher than the 119,950 (95% CI: 106,730–133,500) estimated to be on the island in 2001 (Murray et al. 2003). However, as outlined above, our average burrow density across the whole island (0.10) is similar to the value estimated in the 2001 survey (0.08), and our playback response rates are also similar to earlier work. The major difference between our survey and the 2001 survey is in the area considered to make up the available area for breeding. Murray et al. (2003)

considered the extent of the colony to be 148 ha compared to our estimate of 209 ha; if we apply our burrow density and response rate estimates to a breeding area of 148 ha, our estimate of the number of AOBs would be 134,514 (95% HDI: 85,122–212,886), similar and not statistically differentiable from the 2001 estimate of 119,950 (95% CI: 106,730–133,500) AOBs. Earlier surveys, before the 2000/2001 survey, considered the colony to occupy a much smaller area – or at least focused only on the obvious shearwater greens. Wormell (1976) calculated the extent of the colony as 771.3 sq chains, or 31 ha, but estimated that these greens held ~116,065 AOBs in 1976. Subsequent estimates in 1978–1979 of 124,000-146,000 AOBs (Thompson and Thompson 1980) and ~79,000 in 1982 (Philips 1982) also used Wormell's (1976) map of the greens. And a later survey using Earthwatch volunteers also considered that the greens occupied about 30 ha, but apparently produced only a "crude map of doubtful accuracy" (Furness 1990, Murray et al. 2003). Furness (1997), used this map and estimated a population of ~62,800 AOBs in 1995.

It is worth noting that on-the-ground surveys since the 2000/2001 surveys, notably Jackson (2018) and our own survey work, have identified areas where burrows are (now) present that were not included in the defined survey area in Murray et al. (2003). For example, our survey work confirmed areas on Barkeval and west Trollaval that contained at least medium density shearwater greens and Jackson (2018) reports that the 2000 survey recorded one "high density" green on Barkeval. But Murray et al. (2003) described these as "areas where burrow densities were so low that a disproportionate number of quadrats would have been required to obtain sufficient data to allow robust estimates to be calculated" and did not include any of Barkeval in their defined survey area. To constrain our estimate of the coverage of the colony, we used shapefiles of "areas where burrows have been confirmed" produced by NatureScot following the Jackson (2018) report that combined the information from the 2000, 2001 (Murray et al. 2003), and 2018 (Jackson 2018) surveys as well as information from NatureScot productivity surveys (see Jackson 2018). These represent the most up-to-date information on the extent of the shearwater colony. We then applied our model based on NDVI, slope and elevation to these areas only. The approach predicted areas of at least medium AOB density on the south slopes of Barkeval and the west of Trollaval, but as with previous surveys, we were unable to spend much time surveying these areas because of their relatively inaccessibility (due to distance and terrain respectively).

It is possible that the use of NDVI might be producing misleading results in these two areas in particular; the slopes surrounding the upper reaches of Glen Harris are on the track of weather systems coming in from the west it may not be the presence of shearwaters driving apparently lush vegetation in these areas. We recommend an on the ground estimate of the densities of AOBs in these areas as a key short-term priority – if such a survey could be carried out in the short term (i.e. 2022 or 2023) then the results could be used to improve our population estimate. However, crucially, these areas do not contain enough AOBs to account for the difference of ~168,000 AOBs between our estimate and that from 2001. For example, the section on the south slope section on Barkeval (Figure 62) is predicted to contain 9,740 AOBs, or about 3.4% of the total estimated number of AOBs.

Nevertheless, this demonstrates the importance of gaining good data on the extent of the colony in future years. This could be done through a combination of fieldworkers travelling on foot to areas of the colony and ground truthing the burrow density estimates, and burrow numbers shown on our map of the colony (Figure 61) and high-resolution aerial photographs from UAV surveys to delineate the extent of the Shearwater greens. In addition, although Phase 1 of our survey, the habitat survey, helped us to stratify the multi-strata survey by burrow density in Phase 2, it was very costly in terms of time in the field and the data has so far contributed little to our ability to estimate the population size. In future, our map (Figure 56) could be used to stratify future surveys and the time of fieldworkers on the ground could be better spent increasing the estimates of burrow density and doing a greater number of calibration playback trials, whilst UAV were used to conduct an updated habitat survey.

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