



Framework for mapping key areas for marine megafauna to inform Marine Spatial Planning: The Falkland Islands case study



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ABSTRACT

Marine Spatial Planning (MSP) is becoming a key management approach throughout the world. The process includes the mapping of how humans and wildlife use the marine environment to inform the development of management measures. An integrated multi-species approach to identifying key areas is important for MSP because it allows managers a global representation of an area, enabling them to see where management can have the most impact for biodiversity protection. However, multi-species analysis remains challenging. This paper presents a methodological framework for mapping key areas for marine megafauna (seabirds, pinnipeds, cetaceans) by incorporating different data types across multiple species. The framework includes analyses of tracking data and observation survey data, applying analytical steps according to the type of data available during each year quarter for each species. It produces core-use area layers at the species level, then combines these layers to create megafauna core-use area layers. The framework was applied in the Falkland Islands. The study gathered over 750,000 tracking and at-sea observation locations covering an equivalent of 5495 data days between 1998 and 2015 for 36 species. The framework provides a step-by-step implementation protocol, replicable across geographic scales and transferable to multiple taxa. R scripts are provided. Common repositories, such as the BirdLife International Tracking Database, are invaluable tools, providing a secure platform for storing and accessing spatial data to apply the methodological framework. This provides managers with data necessary to enhance MSP efforts and marine conservation worldwide.

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1. Introduction

Marine ecosystems worldwide face increasing pressures from maritime activities, coastal development, resource exploitation and pollution that threaten ecosystem health and biodiversity, and require a holistic management approach to mitigate threats [20,32,49]. During the last decade, the use of Marine Spatial Planning (MSP) to inform sustainable development and protection of the marine environment has grown worldwide [21,24,31,52]. MSP provides a spatial context for managing and planning the coordination of human uses of the sea. Spatial data are therefore one of the critical building blocks for MSP to map the physical environment, human activities, cultural values, and also distribution and habitat use of marine wildlife [11,3,74,75]. Marine megafauna (here defined as seabirds, pinnipeds and cetaceans) have long been used as indicator species because their distributions reflect those of their prey, and potentially wider marine biodiversity and ecosystem processes [36,43]. Hence, mapping key marine areas for these species can provide important inputs to MSP.

An increasing number of studies worldwide have investigated different approaches to analyse the available data and identify key areas for marine megafauna (also called important, priority conservation or critical areas; [30,2,44,84,33,14,29,40,42,53,51,12,23,79,76]). Of particular importance, BirdLife International has developed a methodological framework to analyse and incorporate tracking data for multiple seabird species which can be used to define Important Bird and Biodiversity Areas (IBAs), both regionally and globally [41]. Most studies focus only on identifying hotspots at the species level and few studies have attempted to present a standardised methodology that could be applied across taxa and seasons. An integrated multi-species approach to identifying key areas is important for MSP because it allows managers a global representation of an area, enabling them to see where management can have the most impact for biodiversity protection. However, multi-species analysis often requires the integration of data from different sources (such as at-sea observations and biologging data), which remains challenging.

Habitat modelling has been used to combine at-sea observations from ships and tracking data (e.g. [44]). However, the time, resources and data required to undertake such analyses are often outside the scope of management organisations. Sufficient data required for such analyses are also available for only a very few species. It is evident that combining tracking and at-sea observation data improves knowledge of the ecological significance of marine areas [14]. Hence, a methodological framework that can combine multi-taxa tracking and observation data to map key areas in a repeatable and simple way would provide a valuable tool for MSP efforts. This paper presents a methodological framework that builds on the methodology of Lascelles et al. [41] to analyse tracking data at the colony level, and incorporate these analyses within the framework which extrapolates results to other colonies and incorporates ship-based survey data. The framework incorporates data from a large number of species across seasons to define key areas for megafauna, and its steps and results are illustrated with a case study in the Falkland Islands.

The Patagonian Shelf surrounding the Falkland Islands is a productive and biodiversity-rich marine area ([27]; Fig. 1). Seventy seabird species and 29 marine mammal species have been recorded in Falkland Islands waters [56,82]. Most species are relatively well studied, and 17 species of seabirds and four pinnipeds have been tracked in these waters (48% of common and regularly occurring species in Falkland Islands waters; [80,81,64,65,67,69,68,70,63,9,37,16,13,61,46,47,48,34,35,15,45,17,73,6,7,71]). One third of the seabird species using the Falkland Islands waters breed on the Falkland Islands [84]. At least 17% of the marine mammals found in Falkland Islands waters breed there but knowledge of their distributions is currently limited. Falkland Islands waters are also important for a large number of migrants that breed elsewhere but visit the region during their non-breeding season or as juveniles [18,19,22,38,54–57,78,8]. Due to the importance of the

Patagonian Shelf for marine megafauna (Table 1) and the social and economic value accorded to these species, in particular for tourism and cultural identity [1], the identification and mapping of their key areas is a priority for input into local MSP development.

The aims of the study were to develop the methodological framework that provides a consistent approach for mapping the intensity of use and species diversity for marine megafauna within a defined marine region. Part of the framework included the development of a scoring system for species and for data quality. The application of the framework to the Falkland Islands data produced:

- A single map for 33 species of seabirds and 3 species of pinnipeds, reflecting their core-use areas in Falkland Islands waters throughout the year.
- Composite maps illustrating the distribution of all marine megafauna (presenting a megafauna biodiversity index and a megafauna core use intensity index) in the marine area around the Falkland Islands by combining all species layers, with the use of a scoring system to reflect conservation and ecological importance.

The methodological framework is discussed in the context of applications to other areas and the results for the Falkland Islands are considered in the context of MSP and how they can later be used to assist this process.

2. Material and methods

2.1. Study area

The study area is the Exclusive Economic Zone (EEZ) of the Falkland Islands, locally known as Falkland Islands Conservation Zone that covers 453,897 km² of ocean around the islands (Fig. 1). This area is administered by the Falkland Islands Government which includes the licensing of activities (e.g. fisheries, oil exploitation). All data analyses were conducted in the EEZ with an added 50-km buffer to avoid a boundary effect. Then, the results were clipped back to the EEZ for presentation. A grid of 10 × 10 km cells was created for the entire study area and was used as a template for all results. Some results were produced at a coarser scale of 30 × 30 km and resampled later based on this grid.

2.2. Data collation and formatting

The initial step of the framework is data search and collation, focusing on any spatial data available on the distribution of marine megafauna species occurring within the study area along with colony, life cycle and environmental data. The sections below describe sources, formatting and manipulation of these data for homogenisation across all species for our Falkland Islands case study.

2.2.1. Tracking datasets

Existing tracking data for seabirds and pinnipeds were identified from a range of sources, including scientific publications, published reports, the Atlas of the Patagonian Sea [22], the list of all wildlife research permits provided by the Falkland Islands Government to scientists conducting work on the islands, and the BirdLife International Seabird Tracking Database (<http://www.seabirdtracking.org/>). The BirdLife database was used to house all additional tracking datasets obtained for seabirds as part of this study. Any tracking locations overlapping with the EEZ were included in the study (Appendix 1 summarises all identified datasets and their owners/providers and Appendix 2 the details of each dataset used in the analyses following data suitability assessment).

GPS (Global Positioning System), PTT (Platform Terminal Transmitter) and GLS (Global Location Sensing) should be considered in the context of the methodological framework described in this paper.

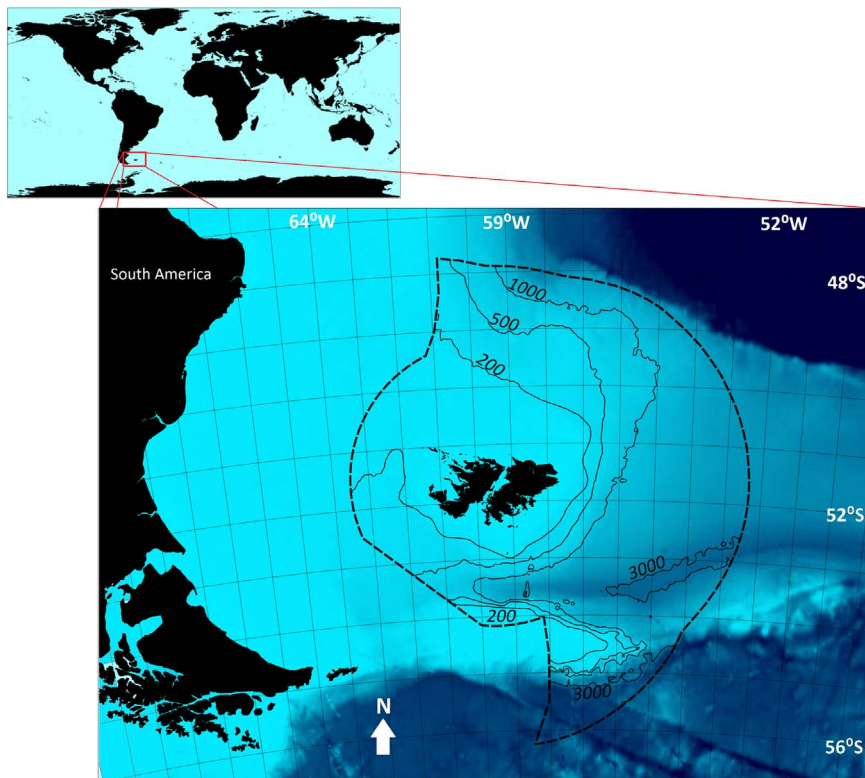


Fig. 1. Location of the Falkland Islands and the study area (dashed line) on the Patagonian Shelf (lighter blue indicates shallower depths corresponding to the shelf; bathymetry contours displayed with depths). Data sources: GEBCO and Falkland Islands Fisheries Department. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

However, after exploratory analyses we opted to use only GPS and PTT data for our case study in the Falkland Islands due to the large spatial error associated with GLS data (186 ± 114 km; [62]) in comparison to the size of the study area. Nevertheless for larger areas where GLS errors would satisfy assumptions, the same analytical steps can be applied to GLS data.

2.2.2. At-Sea observation datasets

The main source of at-sea observations (ASO) data was the Joint Nature Conservation Committee (JNCC) large-scale surveys conducted from 1998 to 2001 throughout the EEZ of the Falkland Islands. These surveys followed the European Seabird At Sea (ESAS) protocol [82]. Several other ASO datasets were found which consisted of opportunistic observations, or observations from fishing vessels or oil platforms; most had no effort data, were spatially-restricted or had records likely biased due to bird attraction [10]. Therefore, only the JNCC data were included in the study.

A total of 57 seabird species was recorded during the JNCC survey (50 species of flying seabirds; 7 species of penguins). The observation rate for pinnipeds and cetaceans was very low, so ASO data were not included for these species. Species classified as rare (i.e. few sightings) in White et al. [82] were also excluded from the study due to the very low encounter rate, reducing the number of species with ASO data to 33.

2.2.3. Colony data

Sizes (number of breeding pairs) and locations of penguin, albatross and giant petrel colonies were obtained from the latest island-wide census undertaken by Falklands Conservation as part of their long-term seabird monitoring programme (Falklands Conservation, unpublished data). Locations of breeding colonies of other species and breeding areas for those species with no distinct colonies (e.g. Magellanic penguins) were digitised from Woods and Woods [84] as one point in each 10×10 km cell, and population size estimated for sections of the coasts where the species is known to breed (at that 10×10 km cell size). Pinniped colony locations and abundance (numbers of pups born) were

obtained from Baylis et al. [4,5] and the Elephant Seal Research Group (Filippo Galimberti, unpublished data).

2.2.4. Bathymetry mask

Bathymetry was obtained from the General Bathymetric Chart of the Oceans (GEBCO) dataset at a 4 km resolution (http://www.gebco.net/data_and_products/gridded_bathymetry_data/). Bathymetry values were extracted for each location along each individual foraging trip for each species. A bathymetric threshold was defined for each species as the depth beyond which < 1% of all available locations for that species were found. This threshold was used to create a species specific bathymetric mask that included only the areas where depth was less than that threshold.

2.2.5. Annual life cycle table

For species with tracking data, the timing of the different phases of the annual cycle was determined from available information on a weekly basis across the year. These data enabled calculation of the duration of each phase within each season or year and, in particular, indicated when animals breeding on the Falkland Islands are tied to their breeding colonies. The annual cycles for 11 species for which tracking data were available are illustrated in Fig. 2 [26,58,66,84].

2.3. Methodological framework

The methodological framework involves producing year-quarter (YQ) layers for each species to generate a core-use index of the area by the species over that quarter. The quarters provide a temporal component to the analyses because the use of the marine environment varies greatly across seasons according to the life cycle (e.g. some species migrate out of the zone over winter). The quarters were designed to fit best the majority of the life cycles of species in the Falkland Islands and are YQ1 (December-February), YQ2 (March-May), YQ3 (June-August) and YQ4 (September-November). Depending on the data (quantity and type) available for the species, the analytical steps set out below are taken (see Fig. 3 for the conceptual model of the

Table 1

Species included in the study and their IUCN status, breeding (if % of world population is known and > 1%, it is indicated in brackets), presence in the Falkland Islands' waters, and types of data available for modelling distribution (ASO: At-Sea Observation).

Species – Common name	Species – Latin name	IUCN status	Breeding in Falklands*	Presence in Falklands*	Data available
Atlantic petrel	<i>Pterodroma incerta</i>	EN	No	Regular	ASO
Black-bellied storm-petrel	<i>Fregetta tropica</i>	LC	No	Regular	ASO
Black-browed albatross	<i>Thalassarche melanophris</i>	NT	Yes (76% of world pop.)	Common	Tracking, Colonies, ASO
Blue petrel	<i>Halobaena caerulea</i>	LC	No	Regular	ASO
Brown skua	<i>Stercorarius antarcticus</i>	LC	Yes	Common	Tracking, ASO
Cape petrel	<i>Daption capense</i>	LC	No	Common	ASO
Common diving petrel	<i>Pelecanoides urinatrix</i>	LC	Yes	Common	ASO
Dolphin gull	<i>Leucophaeus scoresbii</i>	LC	Yes (30% of world pop.)	Scarce	Tracking, ASO
Fairy prion	<i>Pachyptila turtur</i>	LC	Yes	Regular	ASO
Falkland steamer duck	<i>Tachyeres brachypterus</i>	LC	Yes (100% of world pop.)	Regular	ASO
Gentoo penguin	<i>Pygoscelis papua</i>	NT	Yes (21% of world pop.)	Common	Tracking, Colonies, ASO
Great shearwater	<i>Puffinus gravis</i>	LC	Yes	Common	ASO
Grey-backed storm-petrel	<i>Garrodia nereis</i>	LC	Yes	Common	ASO
Grey-headed albatross	<i>Thalassarche chrysostoma</i>	EN	No	Regular	Tracking, ASO
Imperial shag	<i>Phalacrocorax atriceps</i>	LC	Yes (35%)	Common	Tracking, Colonies, ASO
Kelp gull	<i>Larus dominicanus</i>	LC	Yes	Common	ASO
King penguin	<i>Aptenodytes patagonicus</i>	LC	Yes	Scarce	Tracking, Colonies, ASO
Long-tailed jaeger	<i>Stercorarius longicaudus</i>	LC	No	Regular	ASO
Magellanic penguin	<i>Spheniscus magellanicus</i>	NT	Yes (8% of world pop.)	Common	Tracking, Colonies, ASO
Northern giant petrel	<i>Macronectes halli</i>	LC	No	Regular	Tracking, ASO
Northern royal albatross	<i>Diomedea sanfordi</i>	EN	No	Regular	Tracking, ASO
Rock shag	<i>Phalacrocorax magellanicus</i>	LC	Yes (5% of world pop.)	Regular	Tracking, Colonies, ASO
Slender-billed prion	<i>Pachyptila belcheri</i>	LC	Yes	Common	ASO
Soft-plumaged petrel	<i>Pterodroma mollis</i>	LC	No	Regular	ASO
Sooty shearwater	<i>Puffinus griseus</i>	NT	Yes	Common	Tracking, Colonies, ASO
South American fur seal	<i>Arctocephalus australis</i>	LC	Yes (4% of world pop.)	Common	Tracking, Colonies
South American tern	<i>Sterna hirsudinacea</i>	LC	Yes	Common	ASO
Southern elephant seal	<i>Mirounga leonine</i>	LC	Yes	Common	Tracking, Colonies
Southern fulmar	<i>Fulmarus glacialisoides</i>	LC	No	Common	ASO
Southern giant petrel	<i>Macronectes giganteus</i>	LC	Yes (42% of world pop.)	Common	Tracking, Colonies, ASO
Southern rockhopper penguin	<i>Eudyptes chrysocome</i>	VU	Yes (36% of world pop.)	Common	Tracking, Colonies, ASO
Southern royal albatross	<i>Diomedea epomophora</i>	VU	No	Common	Tracking, ASO
Southern sea lion	<i>Otaria flavescens</i>	LC	Yes (2% of world pop.)	Common	Tracking, Colonies
Wandering albatross	<i>Diomedea exulans</i>	VU	No	Regular	Tracking, ASO
White-chinned petrel	<i>Procellaria aequinoctialis</i>	VU	Yes	Common	Tracking, ASO
Wilson's storm-petrel	<i>Oceanites oceanicus</i>	LC	Yes	Common	ASO

* From Falabella et al. [22] with smaller estimate used when range given; ** From [82]. For full description of tracking data ownership and deployment details used in this study, see Appendix 1 and Appendix 2.

methodological framework). All the analytical steps were conducted in R 3.2. R core Team [72]. The R scripts for each step below can be found in the [Supplementary material](#) provided with this paper.

Step 1.1: Tracking data analyses

When tracking data were available for a species during a life cycle stage, the type and amount of data were first assessed for suitability and representativeness. Tracking data were only used for analyses when at least 10 individual tracks were available for each stage of the annual life cycle for one colony, or 10 tracked animals for an entire species that does not breed in the Falkland Islands, or for a quarter when they do not use their breeding colonies.

The tracking data were formatted and standardised following the procedures provided at www.seabird.tracking.org (attributes required: (1) species, (2) colony, (3) stage of annual cycle, and (4) date-time), and split into datasets (unique combination of tracking data collected for each species' colony, in a certain breeding stage). The methodology described in details in Lascelles et al. [41] was applied to each tracking dataset to calculate the core-use areas at sea of each individual. In summary, this consisted of 1) estimating the core-use area of each individual's foraging trip as the Kernel utilisation distribution 50% isopleths, then overlapping all trips to obtain the individual's core-use area – step *batchUD* in Lascelles et al. [41]; 2) mapping the intensity of use of each 10 × 10 km grid cell within the area (expressed as % of the population using each cell as their core-use area, hereafter %birds; step *polyCount* in [41]). An example of the application of these functions to a dataset is illustrated in Fig. 4a,b.

Step 1.2: Extrapolation to other colonies (without tracking data)

The relationship between the percentage of the core-use areas used by each individual that fell within each cell, and the distance to the colony of origin was estimated using a modified Gompertz curve. The Gompertz curve models the relationship between distance from shore and the proportion of animals from the colony using the cell. The proportion of animals using each grid cell was calculated as an average across tracked colonies during each breeding stage for the species (Fig. 4c). The Gompertz curve was used because it accounts for the principle of central place foraging ecology and provides a way to model the decrease in use from the colony point as an average function. The use of the Gompertz curve is conducted under the same assumptions as the foraging radius concept (maximum distance individuals reach at sea from the colony) that has been used in other studies [29,76]. The average function was then applied to all known colonies of each species without tracking data in another breeding stage, to create a map presenting the modelled percentage of animals' core-use areas of each colony covering each 10 × 10 km cell during each breeding stage, then represented after applying the bathymetric mask (Fig. 4d, e).

Step 1.3: Creation of the year-quarter layers from tracking data

For each breeding stage, maps obtained for each colony were combined based on the percentage of the Falkland Islands population in each colony. This assigned the percentage of individuals of the entire population of the Falkland Islands that have core-use areas in each cell (Fig. 4f). The layers were then standardised to obtain values from 0 to 100. Maps for each breeding stage were then combined to produce year-quarter layers by taking into account the overlap between each breeding stage and year quarters (see Fig. 2). In the example of the

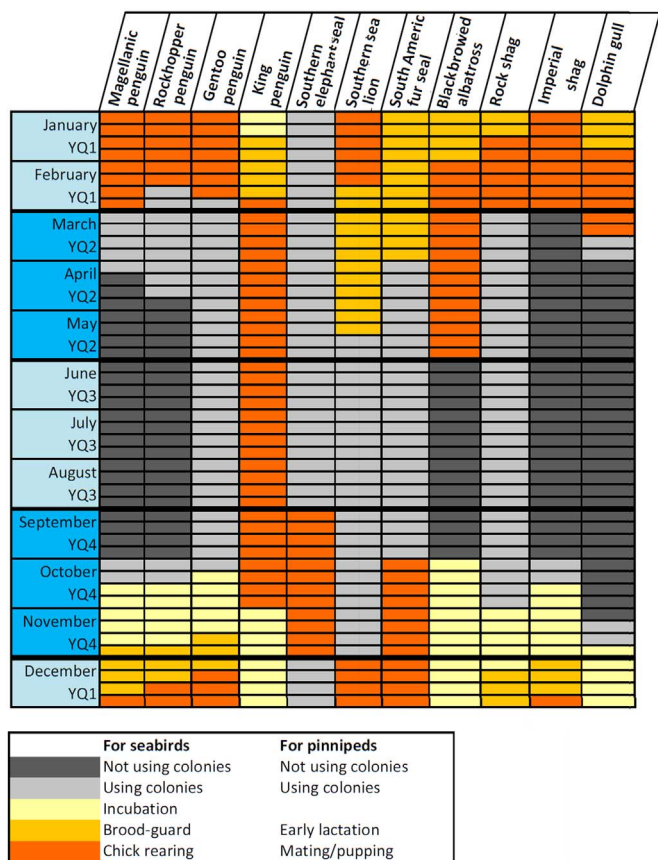


Fig. 2. Annual life cycle stages of the species where tracking data was available in the Falklands' waters. YQ: year-quarter.

black-browed albatross *Thalassarche melanophris* (Fig. 5), YQ1 is made from the incubation stage (1 month), brood-guard stage (1 month), and the post-guard stage (1 month), so the final map for YQ1 was calculated with weighted average incubation * 1/3 + brood-guard * 1/3 + post-guard * 1/3.

Step 1.4: Creation of the year-quarter layers from At Sea Observation data

When no tracking data were available for a species during one quarter, the distribution of the species was mapped using the ASO data. The grid cell size for analysis was defined to minimise the number of empty cells (i.e., cells with no sampling effort) and maximize the number of ASO unit samples per cell, without oversimplifying the final result. After testing the size chosen was 30 km * 30 km (i.e. similar to the size used by [82])). To create quarter layers the steps were (a) Calculate the density of birds (*dens*; birds/km²) based on the 300 × 300 m cell sampling effort unit (see [82] for more details), taking into consideration the counts of 0 where effort occurred but no animals of that species were seen; (b) Average the density values within each 30 km * 30 km grid cell; (c) Apply an interpolation modelling (kriging with function *krige*, R package *gstat* with a value equivalent to the average radius of the core area as per methodology in [41]) to fill in values of cells with no effort; (d) Standardise the values to a 0–100 scale, based on the maximum density value (after logarithmic transformation).

This step produced the remaining quarter layers from ASO data and, after this step, each species had 4 quarter layers, each assigned a data type (tracking or ASO). Examples of quarter layers for 3 selected species (a long-range flying seabird, a short-range penguin and a pinniped) are shown in Fig. 5.

Step 2: Combining year-quarter layers to a species layer

The year-quarter layers for each species were combined in this step

to produce a single species-layer using the quarter scores comprising two types of weights: data type and Intensity of use. Data from tracking were given twice as much weight as ASO data because ASO data were one-off sightings during single surveys that could have been affected by local short-term environmental conditions more than the tracking data. The relative intensity of use of the Falkland Islands waters by a species during each quarter, in comparison to other quarters, was classified using the ratio of the highest density value (in number of individuals per km²) of the quarter compared to the highest value across all quarters as calculated from the analyses of the JNCC ASO data for the seabird species with the classification (weight from 0 to 3, respectively): Almost none (< 0.01), Low (0.01–0.2), Medium (0.2–0.5) and High (0.5–1). For pinniped species, weights for intensity of use were all given the same value of 1 for all quarters. The weights for both criteria were multiplied to give a final quarter score. Appendix 3 contains the weights and final quarter scores for each quarter of each species. We calculated these layers with weighted averages using the final quarter scores applied to each related quarter of the species. Each species layer maps the intensity of use of each 10 * 10 km cell by the species across the year, with the value defined as the intensity use index.

Step 3: Combining species layers to megafauna layers

The megafauna key area layers were created by averaging the values across all 36 species layers. The species layers, however, all depict the relative and standardised use for the species, and do not reflect either conservation (threat status) or ecological (numbers or biomass) importance. Therefore, two options to create megafauna layers using a scoring system reflecting the characteristics of each species are also presented (Table 2). The scores were applied to the species layers to calculate: 1. a conservation-focus megafauna key area layer (with scores based on IUCN status, irreplaceability and data quality); and 2. an ecologically-focussed megafauna key area layer (with scores based on population estimate, average individual mass and number of year-quarters present in Falkland Islands waters). The two scoring systems were created, respectively, based on a sample of simplified IUCN's Key Biodiversity Area criteria and categories [39] that were edited from consultation and agreement with the Falkland Islands environmental managers, and based on the biomass concept (number of individuals multiplied by the average mass). The similarity of indices between the two scoring systems was assessed with a Pearson correlation coefficient (R²).

The megafauna layers were created from the weighted average across all species using the respective scores as weights. The conservation and ecological scores assigned to each species are provided in Appendix 4. These two scored layers can be compared to determine if the identified key areas are similarly highlighted in both resulting maps (using the top 10% and 20% of the cell values in each map).

A biodiversity richness index was also mapped using the species layers. Values of over 50% (therefore capturing the cells that an estimated half of the population of the species uses across the year) were selected in each species layer to create a core-use polygon for each species. The number of species core-use areas overlapping each cell was summed to calculate a megafauna biodiversity richness index.

3. Results

3.1. Species layers

The methodological framework was applied to 36 species (33 seabirds; 3 pinnipeds). In total, the chosen methodology for each species (across the four quarters) corresponded to ASO only (16), tracking only (3), tracking + ASO (8), tracking + extrapolation (5), tracking + extrapolation + ASO (4) (see Table 1). Appendix 2 describes in details all the tracking datasets collated in this study and included in the analyses. In total, the analyses included 591,003 tracking locations covering a total of 5495 data days between 1998 and 2015. The ASO data analysed were made of 157,700 recorded locations of observations

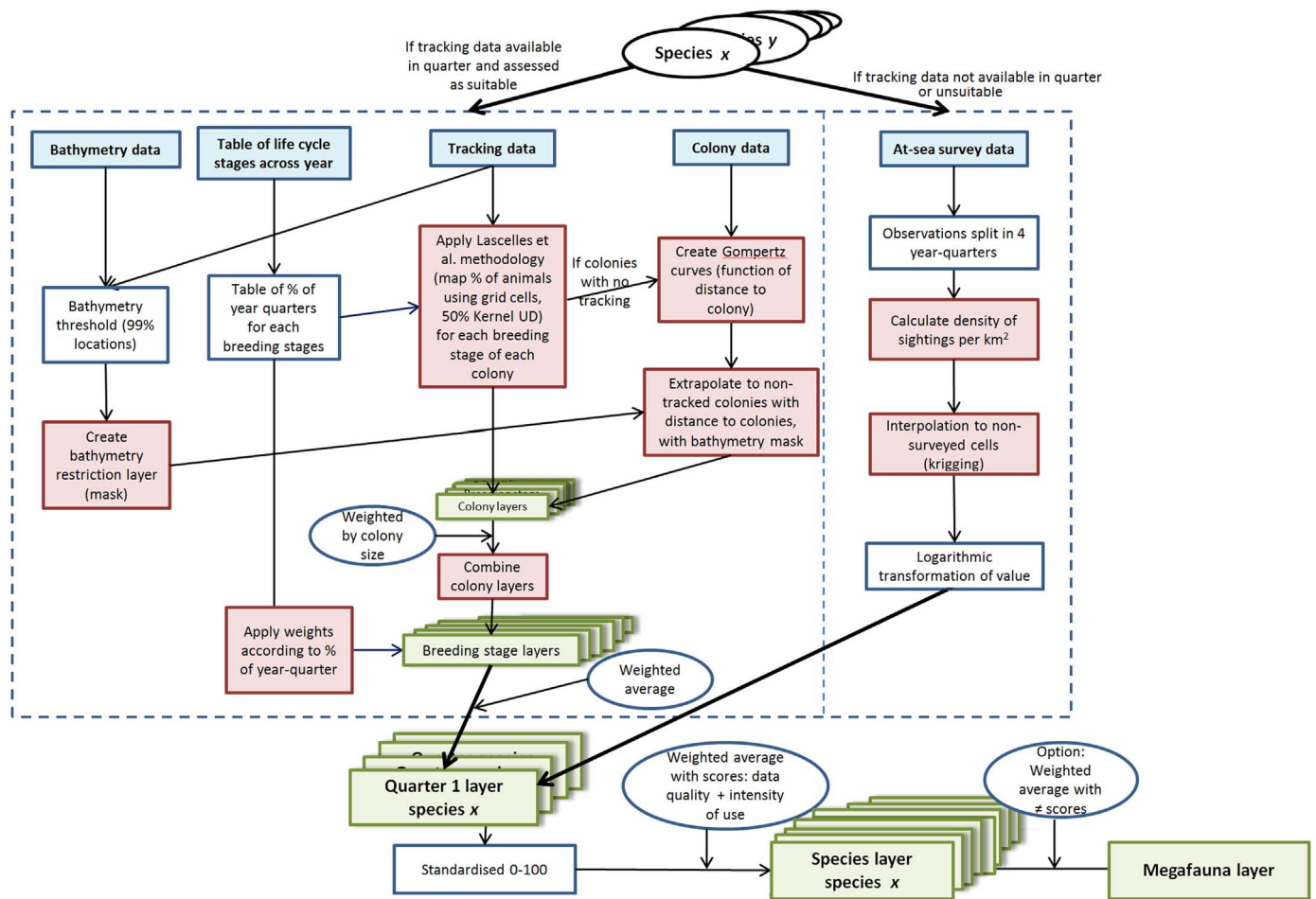


Fig. 3. Methodological framework to map key areas for marine megafauna.

of seabirds over a 4-year period. All species layers can be visualised online on a custom-made Falkland Islands Marine Spatial Planning webGIS focussed on marine megafauna at the link: http://148.251.22.181/saeri_webgis/lizmap/www/index.php/view/map/?repository=v05&project=webGIS20160801.

3.2. Megafauna layers

The megafauna key area layers (conservation and ecological) give an overview of the distribution of use of the Falkland Islands EEZ by marine megafauna using two sets of criteria (Fig. 6). The index ranges from 0 to 1 and depicts the intensity of use by all species, based on the species layers. The conservation and ecological key area layers harbour similar overall patterns of distribution of usage by all species with a high similarity between conservation and ecological index values for each cell ($R^2 = 0.95$; Appendix 5). The overall pattern of distribution of the high value core-use areas remained similar with the different set of scores, in particular when selecting the cells with the highest index values covering 10% of the Falkland Islands EEZ (Fig. 7). This indicates that both conservation and ecological importance follow a similar pattern of distribution. The key areas are the near-shore and coastal areas. The overlap between the top areas based on the different scores is, however, lower when selecting the cells with the highest index value covering 20% of the EEZ.

The megafauna species richness layer displays a Biodiversity Index that is the total number of core-use areas of the 36 species that overlapped with each 10-km cell across the year (Fig. 8). A similar pattern to the key areas emerged with the coastal areas displaying the highest values (up to 20 species with core-use areas in one cell), while the

offshore area east of the islands has very low values of one or two species only. No cell had a value of 0.

4. Discussion

This paper presents a methodological framework to map the spatial use patterns of marine megafauna and to identify key areas. Crucially, the framework enables the inclusion of multiple taxa, different types of data (associated with different degrees of error), uses a simple extrapolation model to include non-studied colonies, and retains species information in the form of intermediate species layers (breeding stage, quarter and species layers). In summary, the framework constitutes seven steps: 1) study area definition, 2) data collation, 3) data classification and formatting, 4) species-level analyses by year-quarter (using decision tree and methodology summarised in Fig. 3), 5) creation of layers indicating intensity of use by each species, 6) species scoring, 7) creation of megafauna layers (eg. biodiversity and core-use intensity). The resulting maps can be incorporated as a decision-support tool or in spatial and prioritisation analyses for MSP. The methodological framework, combined with simple data formatting and R scripts will enable updates with minimal resources in terms of time when new data are available, which is essential as part of the regular recommended review required in assessing the continued efficiency of MSP.

The framework was applied to the most common species of marine megafauna within the Falkland Islands EEZ. The process of identifying and gathering data for numerous species across many providers was streamlined by the use of the Birdlife International Tracking Database. Data providers had the assurance that their data would be shared and used only for specific analyses towards marine conservation

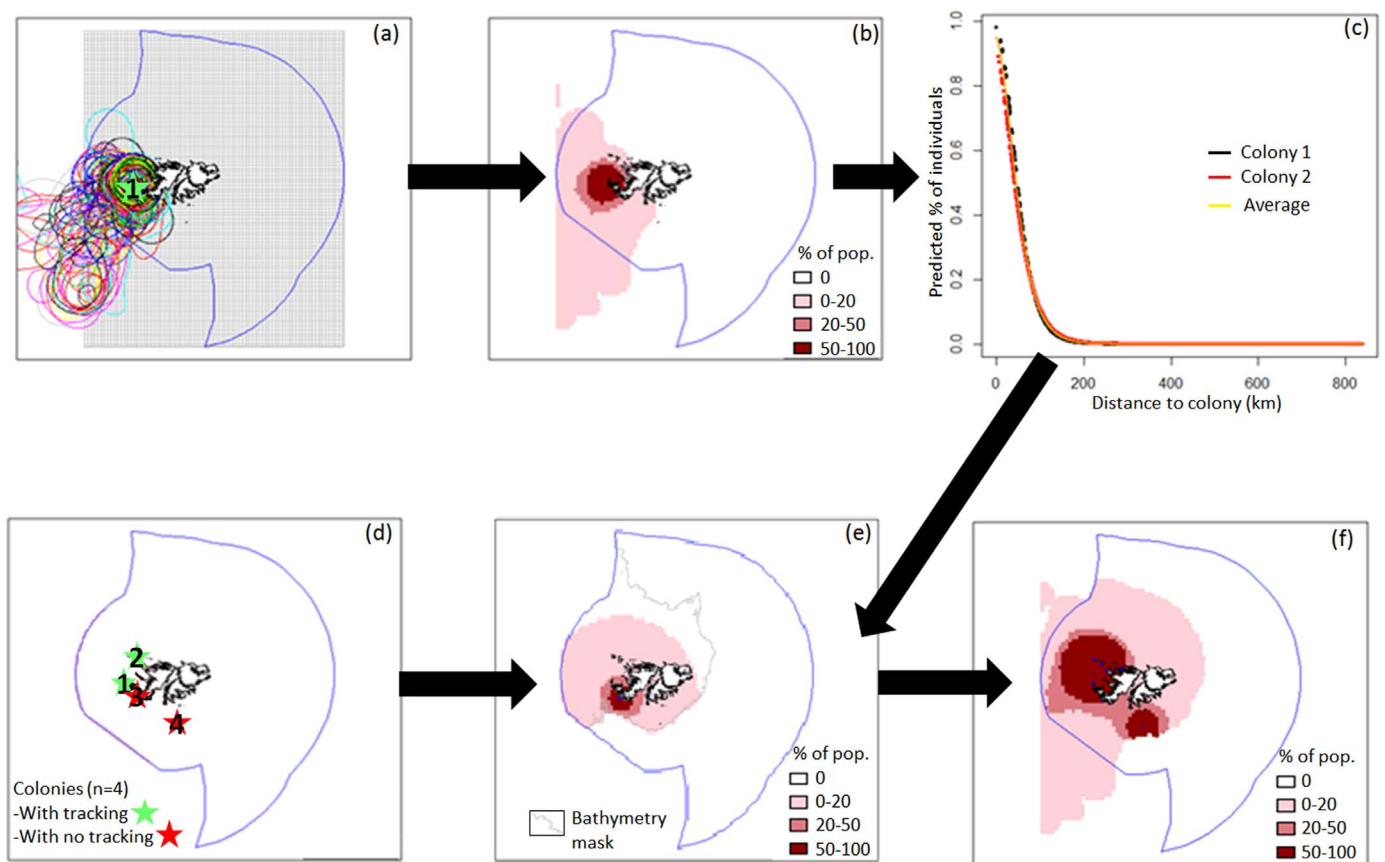


Fig. 4. Illustration of the methodology to produce the species quarter layers using the example of the black-browed albatross during the brood-guard stage (tracking data source: Falklands Conservation, J.P. Granadeiro, P. Catry). (a) Core-use areas (50% Kernel utilisation distribution) for each individual track as per methodology in Lascelles et al. [41] from colony 1, (b) % of core-use area found in each cell for colony 1 from tracking data (c) Relationship between % of core-use areas and distance to colony (Gompertz Curve), (d) location of 4 example breeding colonies, (e) extrapolated colony layer for colony 3, (f) breeding stage layer for the species accounting for all colonies weighted by colony numbers.

improvement goals due to well established legal protocols, agreements and data protection of this database. This was very successful in obtaining a large dataset with information for 36 species. The megafauna maps are illustrative of the final products from the methodological framework. In particular, the conservation key area layer and the species richness layer could be used in the context of MSP to (1) identify areas for potential protection of key sites for multiple species (e.g. areas with the highest values for the conservation or biodiversity indices; [85]), (2) manage particular activities (e.g. shipping, oil extraction) within highlighted key areas to minimise their impacts, (3) identify areas that require more detailed assessments or more stringent requirements in terms of Environmental Impact Assessments (EIAs) if new developments are proposed. The ecological key area layer, on the other hand, could be used in the context of wider fishery spatial management and potential impacts on megafauna food resources through increased understanding of energy transfer in the marine systems underlying the MSP effort. The intermediate species layers produced during the process can also be used for finer-scale studies on single species in the context of EIA or risk assessments from current or proposed activities or development, for cumulative impact analyses for MSP, and for identification of major gaps in data availability and research needs. The framework therefore provides a series of layers depicting the use of a study area by marine megafauna. Decision makers can use them to inform MSP analyses and to design a range of management options as part of MSP, for example shipping lanes to avoid areas with highest concentration, or designating a network of Marine Protected Areas (MPAs).

It is, however, important to emphasise that, depending on the intended application, managers would need to review the criteria and

assumptions involved in the results presented for the Falkland Islands to understand the potential biases due to data availability, criteria and score choices. For example, while the scoring criteria and the weights used to create the conservation key area layer were based on internationally-accepted guidelines and had inputs from local managers, there may be other local criteria for conservation and distribution of weights that should be explored prior to application (e.g. cultural significance, national red list, importance for tourism). In addition, the treatment of raw location data is simplified to allow integration of a wide variety of data types. While basic data quality is included as a weight within the framework, there is scope to add a parallel analysis to produce a simple way of mapping data accuracy and to assess whether tracking data is representative for each species or colony (e.g. nonlinear asymptotic regression analysis, previously used by [41,77,50]). This would give managers an easily understood visual way of assessing potential risks associated with their decisions for MSP due to uncertainty from the raw location data fed in the framework. Finally, the Falkland Islands is one of the most data-rich parts of the ocean in terms of marine megafauna, with the exception of cetaceans for which data are deficient. Therefore cetaceans were not included in the analysis presented here (but the methodological framework was designed to incorporate cetacean data when available). The Falkland Islands is an important habitat for migrating baleen whales and resident delphinids [38,56]. When data become available for these species, their integration in the methodological framework will be possible for future MSP review. Integrating cetacean distribution data will be particularly important as whale populations worldwide are recovering and whale sightings have been increasing around the Falkland Islands in the last decades [25]. Therefore, efforts are required to obtain fine-scale distribution data for

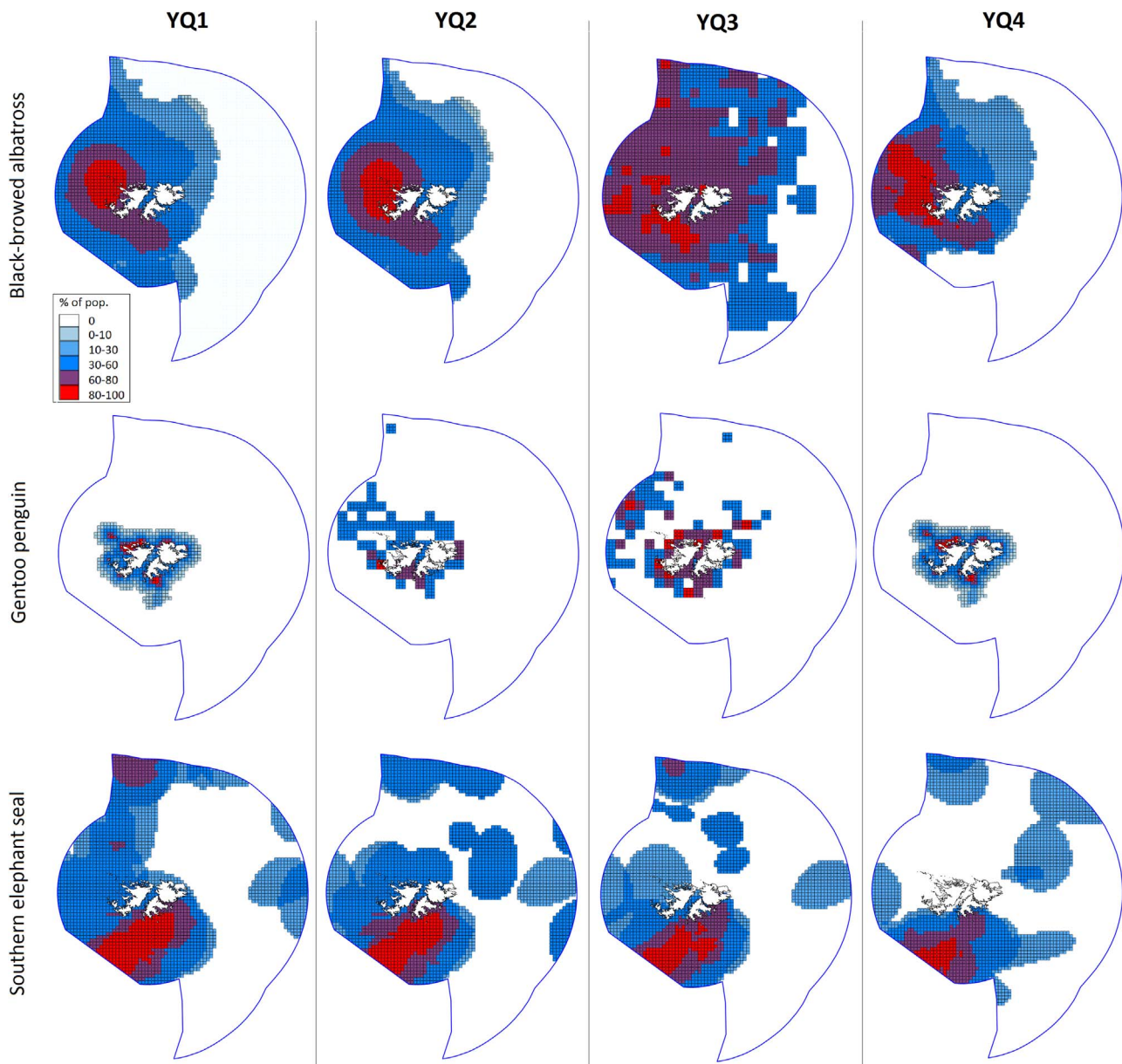


Fig. 5. Examples of the 4 quarter layers for 3 species for each year quarter (YQ1: Dec-Feb (summer), YQ2: Mar-May (autumn), YQ 3: Jun-Aug (winter), 4: Sep-Nov (spring)), black-browed albatross (data quality for YQ1 and YQ2: tracking + extrapolation; YQ3: ASO only; YQ4: tracking only), Gentoo penguin (data quality for YQ1 and 4: tracking + extrapolation; YQ 2 and 3: ASO only), and southern elephant seal (data quality all tracking only).

cetaceans for incorporation into the framework and for MSP efforts in the Falkland Islands.

The range of scoring criteria presented in this study is given as a general guide. The criteria and their weights were developed for the Falkland Islands, from consultation with stakeholders and managers for an MSP application towards identifying potential areas for protection. Criteria need to be customised for specific practical MSP applications. Therefore, the application of the methodological framework in the Falkland Islands and other regions with different sets of species, and different MSP or conservation aims, will need to include the step of creating scoring criteria. Methodology to define a scoring system will be region-specific and the decision should be made by managers with advice from expert knowledge for defining thresholds. For the Falkland Islands case study, two scoring options are presented for the species layers to illustrate the impacts of using alternative criteria in generating the final layers, and how the results could be used for different aspects of MSP. The areas with the highest index of density use were consistent across scoring systems; the areas with lower values did vary between

scoring systems. Managers, however, often require the identification of key areas (i.e. areas with an index of highest values) and therefore the differences should not affect the utility of the framework for the identification of key areas.

The results of the application of the framework to the Falkland Islands indicated that the key areas for marine megafauna included all coastal waters around the islands and, overall, the shallower areas (< 200 m depth). This is mostly due to the large concentration of breeding colonies of seabirds and pinnipeds on the islands. The pattern was consistent with both scoring systems, whereas there is almost no correlation between the scores calculated for each species in the two scoring systems. The coastal areas around breeding colonies are where the highest concentration of animals occurs because individuals of the colony must use this area (for rafting before returning to nest in flying seabirds, and for accessing the breeding or hauling out areas for pinnipeds and penguins). A recent study has also highlighted the importance of near-shore areas for black-browed albatross spending significant time on near-shore waters before departing to sea [28]. Other

Table 2
Methodology to assign scores to species for combining species layers to a megafauna layer.

	Criteria & Descriptions	Classification	Score
Ecological scores = (a × b) + c	(a) Average mass of an individual (kg)	> 500	5
		50–500	4*
		2–50	2
		0.5–2	1
		< 0.5	0
	(b) Estimated population using Falkland Island waters (number of individuals)	> 500,000	5
		> 100,000	4
		10,000 to 100,000	3
		< 10,000	2
		< 1000	1
	(c) Number of year quarters the species uses Falklands Island waters	1	1
		2	2
		3	3
4		4	
Criteria for Data Quality scores = d	(d) Data available and modelling methodology	Tracking for all colonies (in FI and overseas) known to use the FI waters	4
		Tracking some colonies + extrapolation to > 50% colonies (if Falklands and overseas) known to use FI waters	3
		Tracking < 50% of colonies only, no extrapolation	2
		ASO based distribution only	1
			By case
Criteria for Conservation scores = e + f	(e) Irreplaceability based on endemism and % of world population using FI waters	Endemic	5
		Very high (> 90% of population)	4
		High (10–90% of population)	3
		Medium (1–10% of population)	2
		Low (< 1% of population)	1
	(f) IUCN threat status	Critically endangered (CR)	3
		Endangered (EN)	3 ^a
		Vulnerable (VU)	2
		Near-Threatened (NT)	1
		Least Concern(LC)	0
		Data deficient (DD)	By case

The scores calculated for each species are available in Appendix 4. *Score value of 3 was skipped due to the significant difference in mass between the categories.

^a Critically endangered and endangered species were given the same value because they both require full protection for survival.

studies have also shown that coastal areas are often key areas for marine megafauna [51,59,79]. It is, however, also important to note that, for wide ranging species (for instance southern elephant seals), the overall species core use areas may be found outside of the Falkland Islands EEZ most of the year. MSP within a country's waters can improve sustainable marine management and conservation at the national level. Nonetheless, for protection of wide-ranging species to be effective, cross-nation MSP will also be required. The framework presented here could provide a way to conduct analyses to inform cross-nation MSP.

5. Conclusion

In conclusion, this paper presents a replicable simple methodological framework that incorporates a wide range of data types to map megafauna key areas. The illustration of this framework in the Falkland Islands demonstrated its applicability and potential uses for MSP while highlighting its limitations that managers need to understand. The methodological framework provides a simple step-by-step implementation protocol, replicable across geographic scales and transferable to multiple taxa. The results of the framework provide a range of

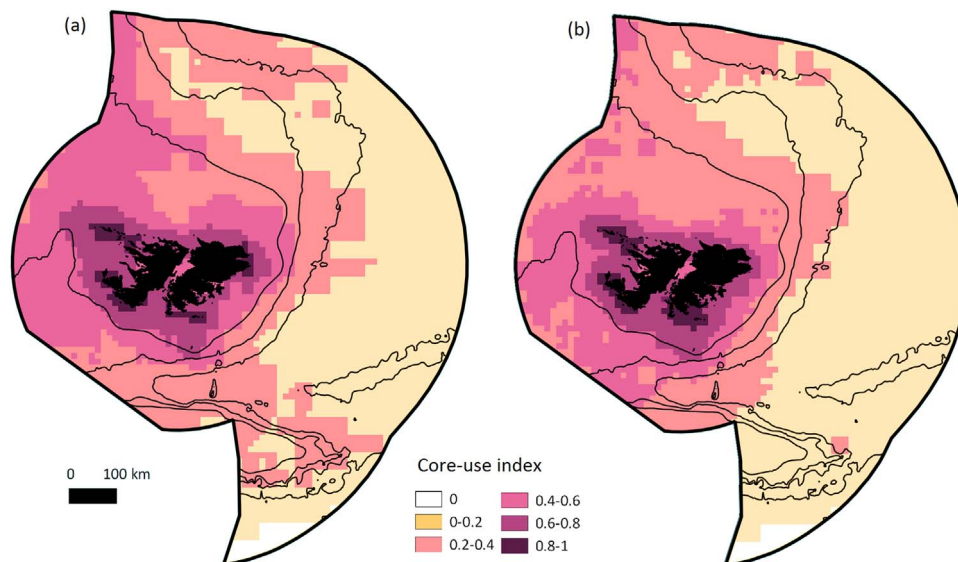


Fig. 6. Core-use areas by marine megafauna In the Falkland Islands Economic Exclusive Zone; a) with conservation scores and b) with ecological scores.

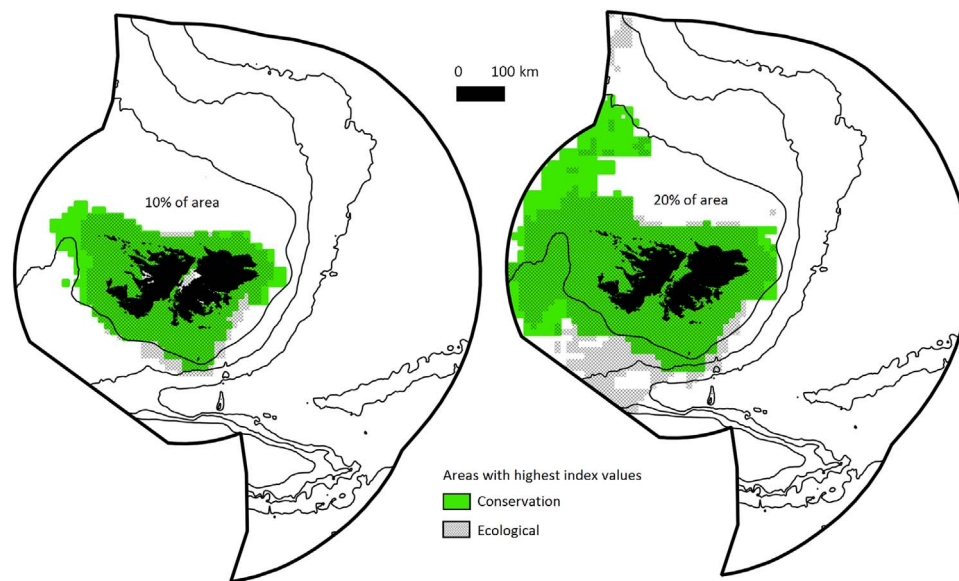


Fig. 7. Areas with the highest marine megafauna core-use index values with conservation and ecological scores, for 10% of the Falkland Islands Economic Exclusive Zone) left) and for 20% of this EEZ (right).

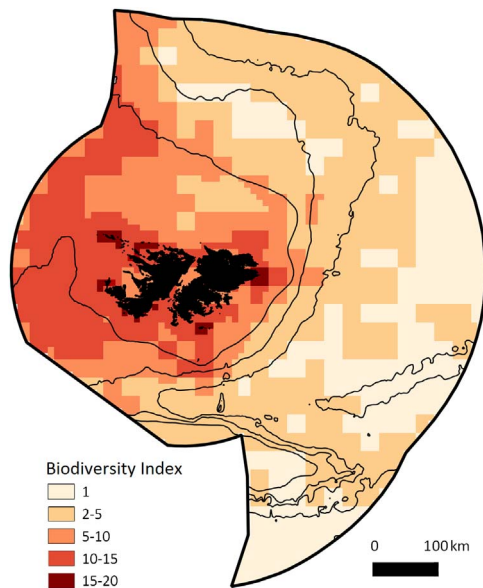


Fig. 8. Map of megafauna species richness displayed as the biodiversity index in the Falkland Islands Economic Exclusive Zone. The index is the number of species' core-use areas (50% Kernel distribution) out of the 36 study species including in the analysis that are contained within each 10 km cell.

spatial tools for MSP and decision support tools for marine management and opportunities. New data can be added relatively easily to re-run the analyses during MSP review process for instance. Other areas of the world have sufficient data to apply such a framework for creating maps to inform MSP (e.g., Bay of Biscay, [60], or other UK Overseas Territories). Gathering the data available is, however, still an obstacle for such studies. It can be very time-consuming and difficult to find where data are stored and who to contact, in particular for tracking data from species that use but do not breed in an area, from wide-ranging species, or data from scattered at-sea surveys that may be conducted by consultants, researchers or tourism operators. Initiatives such as the Bird-life International Tracking Database will provide invaluable tools for this step in the future. Funding agencies, universities and governments should ensure that data are stored and made available in such a database to provide required data for the success of MSP efforts and to

improve marine conservation worldwide.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.marpol.2018.02.017>.

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