The conservation value of the Channel Islands: a spatial evaluation using species distribution modelling

Ruth Dunn

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Declaration

All of the material within this thesis is my own work, with the following acknowledgements:

This dissertation was supervised externally by Melanie Broadhurst (Alderney Commission for Renewable Energy) and internally by David Orme (Imperial College London). After the initial suggestion as to the line of analysis (a general ecological review of the Channel Islands, with an emphasis on species of importance) I developed and attempted the statistical and spatial approaches chosen, on my own. Statistical advice was offered, although aside from one referenced piece of coding (‘*Species Set Cover Problem (SSCP) Function’* written by David Orme, 2015), all other analyses, and the write-up, are my own work.

Data was provided by Chris Wood (Seasearch), Paul Chambers (States of Jersey), Jessi Jennings (La Société Guernesiaise), Guernsey Sea Fisheries Section and Julia Henney (Guernsey Digimap Service Team), via Melanie Broadhurst. All further utilized data and software was assembled and processed by me and is cited appropriately throughout.

Contents

Abstract

The Channel Islands play host to a wide diversity of marine assemblages and unique communities. The islands mark a boundary between contrasting abiotic conditions that define two marine biotas: the northern limit of many species distribution ranges and the southern end of others. As Crown dependencies are exempt from protection by UK conservation legislation, there is consequently little modern literature addressing Channel Island marine ecology. Statistical and spatial analyses were performed on Seasearch data in order to assess the species richness and community structure of the Channel Islands, with a focus on physiological characteristics and the identification of areas for conservation implementation. Species richness was correlated with a number of physical parameters and varied between sample sites, while differing community structures were found to exist across the different islands. The richness of target species (those regarded as important in terms of their conservational value and/ or role as indicator species) was generally higher within coastal regions where marine conservation efforts should therefore be focussed. 34 potential grid cells were identified as having high irreplaceability for conservation action: 4 surrounding the coasts of Alderney, 3 at Jersey and 1 at Sark. The identification of sites of high irreplaceability, as well as the proposal of further structured surveying and monitoring, is advised as being necessary in regards to conserving the marine biology of the Channel Islands.

1. Introduction

1.1. The marine ecology of the Channel Islands

The Channel Islands are situated within the English Channel, a shallow, temperate sea positioned near the northern Boreal and southern Lusitanian biogeographical boundaries (Hawkins *et al*, 2003; Dauvin, 2014). It exhibits vast tidal ranges (over 12 m in some areas of Jersey (Renouf & James, 2011), and large sea and air temperature gradients: the average minimum annual sea surface temperature (SST) at St Peter Port, Guernsey was 6.4^{o}C in 1986, whilst the average maximum was 18.3^{o}C in 2014 (Guernsey Sea Fisheries Section, 2015). Due to these environmental characteristics, many marine species are present at the edge of their thermal tolerance ranges and geographical distribution limits (Hinz *et al*, 2011). As a result, Channel Island marine communities differ from those recorded within the United Kingdom (UK): they support species that more frequently inhabit southerly, warmer areas (Rombouts *et al*, 2012). For example, the northern limit of the green ormer (*Haliotis tuberculata*), a southern European mollusc species, is the island of Alderney (Fish & Fish, 2011). As such, the area supports a range of marine phyla such as algae, porifera, cnidarians, molluscs, arthropods, echinoderms, bryozoans, fishes and marine mammal species (Sheehan *et al*, 2011; McClellan *et al*, 2014).

1.2. Natural and anthropogenic pressures within the Channel Islands

Near-shore and sublittoral systems form harsh physical environments, exposed to dynamic oceanographic and hydrologic stresses (Dauvin, 2014). The marine ecosystems that surround the Channel Islands are particularly subject to physiological pressures (high wave action, tidal circulation, sediment transport, increased turbidity and intense weather conditions; Delebecq *et al*, 2012; Cohn *et al*, 2014) due their situation proximate to a significant ocean gyre (Pingree & Mardell, 1987; Salomon & Breton, 1993). Environmental driving pressures greatly affect the lives of marine organisms, potentially causing the dislodgment and breakage of some marine algae and fauna, for example (Denny, 2006; Nishihara & Terada, 2010). However, some organisms, such as bryozoan species, are more readily adapted (in terms of body form, feeding activities and reproduction efforts) to suit such high energy environments (O’Dea *et al*, 2008; Rouse *et al*, 2013). Perhaps due to this, sublittoral areas are known to support some of the most biologically diverse and productive communities on the earth (Siegal *et al*, 2008).

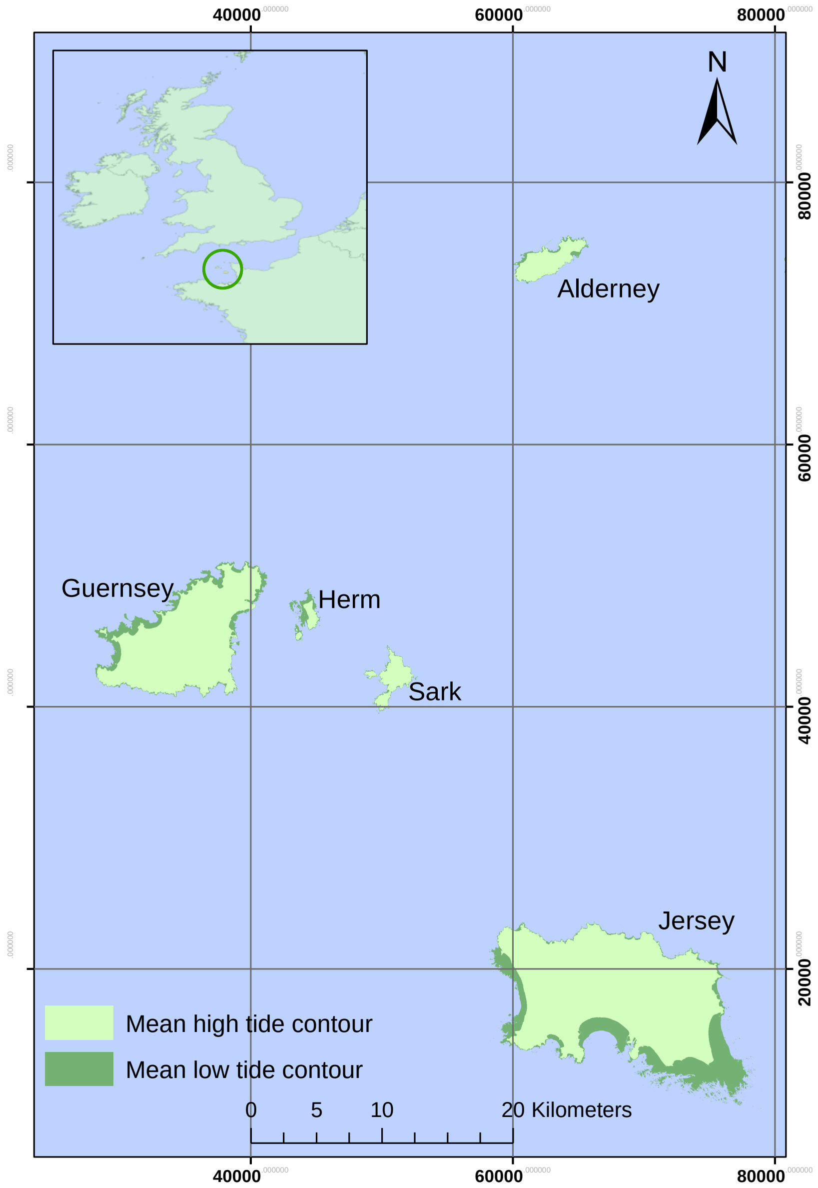

Fig. 1 Location of the Channel Islands, situated within the south of the English Channel, between the United Kingdom and France. Mean high and low tidal contours are depicted (provided by Guernsey Digimap Service Team, 2014).

The impacts and progression of climate change have had a profound effect on marine communities, causing species distribution shifts, range contractions, ocean acidification, and alterations in phenology and migration timings (Richardson *et al*, 2012). Because of the wide range of these influences, many marine species and habitats are at risk of severe degradation and potential extinction (Harley *et al*, 2006; IPCC, 2014).

1.3. Conservational importance within the Channel Islands

The Channel Islands play host to a unique assemblage of marine organisms, including nationally scarce and rare species, as well as those that do not inhabit mainland Britain (Chambers, n.d.). Numerous Channel Island species are UK Biodiversity Action Plan (BAP) priority species (Appendix 1; their populations are threatened within the UK). Although the Channel Islands are not part of the UK (the Bailiwicks of Jersey and Guernsey are Crown dependencies) such designations should still be taken into consideration (Hampton, 2007; JNCC, 2007). Further species are ‘threatened, rare or declining’ and therefore designated as ‘Features of Conservation Importance’ (FOCI) within Marine Conservation Zone (MCZ) planning (Ashworth & Stoker, 2010), whilst others are protected under the OSPAR Convention (OSPAR Commission, 2004).

Aside from climate, further anthropogenic stressors degrade marine biodiversity and contribute to the vulnerable statuses of many species (Halpern *et al*, 2007). Oceans provide the earth’s increasing human population with vital resources, however these are becoming progressively depleted, suffering degradation due to pollutant, freshwater, sediment and nutrient inputs, coastal development and engineering, and destructive fishing methods (Halpern *et al*, 2007; Gelcich *et al*, 2014). In recent years, there has been an emergence of further disruptions on these pressurised, natural ecosystems. In westerly areas of the English Channel, increases in aggregate extraction are a concern, while the Channels Islands themselves are proposed sites for the development of tidal power (Dauvin, 2014).

In order to combat biodiversity losses, international efforts have been made to maintain the world’s oceans (Cole-King, 1993). It is important that these systems and the goods and services that they provide are protected. In order to successfully do this, in-depth research must be done to facilitate understanding of the current ecosystems that exist, so that conservation effort can potentially be focused on areas that are of higher ecological value (Cognetti & Maltagliati, 2010). The ecology of the marine ecosystems that surround the Channel Islands remains relatively unstudied within modern scientific literature (Dauvin, 2014). This is concerning considering both their unique physical and ecological conditions, as well as the species and habitats of conservation importance that are present.

1.4. Aims and hypotheses

The marine ecology of the Channel Islands will be spatially evaluated by critically assessing marine life sightings data, collected during volunteer diver surveys through the Marine Conservation Society Seasearch programme.

Using statistical analyses, marine ecology will be evaluated alongside environmental characteristics (calcite concentration, chlorophyll-α concentration, cloud fraction, diffuse attenuation coefficient, photosynthetically available radiation (PAR), SST, dissolved oxygen, hydrology, light fraction, nitrate, ocean bottom, pH, phosphate, salinity, seabed landscape, silicate and wind speed and power density). Significant indicator species of these communities will be identified, as well as those of conservation importance. Upon identification, their geographic distributions will be modelled, in order to identify areas of high irreplaceability (the extent that they are valued to be a necessary part of a conservation area network, as defined by Shokri & Gladstone, 2012).

Essentially, the following hypotheses will be evaluated: 1) Species richness and community similarity differs between the sample sites and island regions; 2) Species richness is predicted by a range of environmental variables; 3) Coastal regions exhibit a higher level of target species richness and therefore represent areas of higher irreplaceability in regards to species conservation, in comparison to open water areas.

2. Material and Methods

2.1. Data acquisition and integration

Seasearch marine habitat inventories were obtained from the National Biodiversity Network gateway in order to extract Seasearch records of species occurrences within the Channel Island area. This data was collected across a monitoring programme comprised of volunteer divers who gathered scientific data. This was achieved by the compilation of observation forms that detailed information regarding seabed cover and marine life, alongside information as to the dive date, duration, depth and location (Seasearch, n.d.). This information could then be utilised in order to evaluate the marine environment (Cuthill, 2000).

Survey sites situated outside the Channel Island area (Fig. 1) were eliminated from the database. The geographic locations of the remaining data (collected using handheld GPS devices by Seasearch volunteers) were then recorded. In order to ensure the accuracy of the points' positions, annual Seasearch reports (Wood, 2007; Wood, 2008a-b; Sharrock, 2010; Wood, 2010) and copies of raw data collection forms (Chambers, 2014; Jennings, 2014) were consulted and subject to cross comparison. Finally, the points (9949 observations across 450 locations) were mapped upon a base layer of the Channel Islands (Guernsey Digimap Service Team, 2014), using *ArcGIS Desktop 10.2* (ESRI, Redlands, CA, USA), to ensure that none of their locations were anomalous.

Vector and raster data on the environmental conditions within the marine ecosystems that surround the Channel Islands were sourced online (Table 1) and compiled in *ArcGIS*. In order to allow their use within species distribution modelling in *Maxent* (version 3.3.3, Phillips *et al*, 2004 and 2006), the environmental layers were projected using the *Guernsey Grid* coordinate system, clipped to the Channel Island study area and converted into ASCII format, ensuring identical cell size and processing extent (using Data Management, Geoprocessing and Snap Raster tools in *ArcGIS*).

Table 1 List of the data sources used within the production of this report, and their publishers, points of access and resolutions. All are widely used sources, projected using the *WGS84 (EPSG: 4326)* spatial reference system.

Publishing Information and Points of Access	**Spatial Resolution**
Bio-ORACLE: calcite concentration, chlorophyll-α concentration, cloud fraction, diffuse attenuation coefficient, dissolved oxygen, nitrate, pH, PAR, phosphate, salinity, silicate and SST Tyberghein, L., Verbruggen, H., Pauly, K., Troupin, C., Mineur, F. & De Clerck, O. (2011) <http://www.oracle.ugent.be/download.html> [Accessed:2/12/14]	5 arc-minute
Fraction of Light at Seabed: North Sea and Celtic Marine Ecosystems Team, Joint Nature Conservation Committee. (2010) <http://www.emodnet-seabedhabitats.eu/default.aspx?page=1953> [Accessed:2/12/14]	4 km
French Marine Landscapes Maps Mapping European Seabed Habitats, (2008) <http://www.emodnet-seabedhabitats.eu/default.aspx?page=1953> [Accessed:10/11/14]	150 m to 1 km
Ocean Bottom Natural Earth. (2014) <http://www.naturalearthdata.com/downloads/10m-ocean-bottom/ocean-bottom-base/> [Accessed:2/12/14]	2.5 km
The GEBCO_2014 Grid General Bathymetric Chart of the Oceans. (2014) <www.gebco.net> [Accessed: 6/2/15]	30 arc-second
UK National Marine Landscape Maps Mapping European Seabed Habitats. (2008) <http://www.emodnet-seabedhabitats.eu/default.aspx?page=1953> [Accessed:10/11/14]	150 m to 1 km
Wind Data GIS Shapefiles Atlas of UK Marine Renewable Energy Resources, ABPmer. (2008) <http://www.renewables-atlas.info/> [Accessed:10/11/14]	12 km

2.2. Community structure

The species richness of the sample sites was calculated by combining the total number of species observed at each location (Mieszkowska & Lundquist, 2011). In order to determine whether there was a difference in richness between sites, a histogram of species richness was plotted in *R* (*R* Development Core Team, 2012).

Abundance data was recorded using the Marine Nature Conservation Review (MNCR) SACFOR Abundance Scale (JNCC, 2006). This was converted into a numeric format, as done by Howarth *et al*, 2011 (Table 2), in order to create a community data matrix. To evaluate the similarity that existed between the communities that inhabited the islands and open water areas, a one-way Analysis of Similarities test (ANOSIM) was applied to the Bray-Curtis dissimilarity community matrix (Chapman & Underwood, 1999).

Table 2 Numeric conversion of the MNCR SACFOR Abundance Scale (see JNCC (2006) for further details).

SACFOR Scale	Numeric Format
Superabundant	6
Abundant/ Superabundant	5.5
Abundant	5
Common	4
Frequent	3
Occasional	2
Rare	1
Present	0.5

This simple integer coding (Table 2) only captured the order of abundance and not the true scaling of abundance differences (Zeleny, 2014). Therefore, non-metric multidimensional scaling (nMDS) was used (Hale *et al*, 2011). The nMDS was performed (using the *MASS* and *vegan* statistical software packages in *R* (Venables & Ripley, 2002; Oksanen *et al*, 2014) over 100 runs, based on the Bray-Curtis dissimilarity matrix, using the *wisconsin* double standardisation method (Manjarrés-Martínez *et al*, 2011; Oksanen, 2013). An unconstrained ordination was created to allow a visual assessment of the relative similarities and differences in the communities present across the sample sites and islands (Goring *et al*, 2009). To facilitate interpretation, sites that had a species richness of 1 were removed from the plot (Sapra, 2010).

Further cluster analysis was conducted in order to evaluate the differing community structures that existed over spatial distributions, using the *R* package *vegan* (Gogina *et al*, 2010; Oksanen *et al*, 2014). The Bray-Curtis index was utilised in order to assess ecological dissimilarity between the clustered communities, whilst the average linkage method was used to fuse the most similar sites into a cluster, based on the distance between cluster centroids (Oksanen, 2014). Using the *labdsv* (Roberts, 2013) and *mgcv* (Wood, 2006) packages, the optimum number of clusters was revealed to be 26 (using the Euclidean metric and the Hellinger transformation). Tables of the frequency of species occurrence, as well as their mean abundances across the clusters, were then analysed (using the *IndVal* method; Dufrene & Legendre, 1997; Oksanen, 2014). The result of this was the identification of 69 significant Dufrene-Legedre indicator species. Only species where $P < 0.01$ (as opposed $P < 0.05$) and those that had enough observation points to create a species distribution model within *Maxent*, were selected as target species (Appendix 2). This was due to time constraints and the high quantity of indicator species that were initially revealed.

2.3 Predictors of species richness

Cell values of the environmental raster data layers (Table 1) were extracted at the specific points where species richness had been recorded (using the *Spatial Analysis* toolbox in *ArcGIS*; Burgert *et al*, 2014). 16 sites lay outside areas covered by environmental data, and were therefore excluded from further analysis. As the response variable (the species richness) was count data, a square root transformation was used in order to reveal a distribution approaching normality within a quantile-quantile plot (McDonald, 2014). Therefore, Pearson’s correlations were performed (Dytham, 2003), inferring whether there were relationships between species richness and the extracted environmental variables (see Weyhenmeyer *et al*, 2012). All correlated variables also had linear regressions calculated and plotted (Mieszkowska & Lundquist 2011).

2.4. Species distribution modelling

Maximum entropy modelling, using *Maxent* software (Philllips *et al*, 2004), was conducted in order to predict species presence within the Channel Islands. *Maxent* was utilised because the method was able to handle irregularly sampled, spatially biased data, such as that collected by Seasearch (Wood, 2008a; Kramer-Scadt *et al*, 2013). Wisz *et al* (2008) revealed that it was less sensitive to sample size, in comparison with other modelling algorithms: it yielded ‘high-quality’ species distribution predictions, in spite of small sample sizes. Furthermore, the fact that *Maxent* uses presence data equates to it being widely utilised within the marine setting, where rates of encounter can be low, and absence data would potentially result in ‘false negatives’ (Arcos *et al*, 2012).

The distributions of 37 target species, from a range of taxonomic groups, were modelled using *Maxent*. This included the 13 identified indicator species (Appendix 2) and a further 24 species of conservation value (e.g. UK or EU designated status, Appendix 1).

2.5. Identifying irreplaceability

Analyses were conducted to determine which areas of the Channel Islands’ marine systems were of a high conservational value. The ‘Maximum test sensitivity plus specificity’ threshold, generated in *Maxent*, was used as the predicted ‘suitable habitat cut-off point’ for each species. ASCII files of each species distribution were consequently extracted using the *raster* and *sp* packages in *R* (Hijmans, 2014; Pebesma & Bivand, 2005). Areas that contained the presence of at least one of the modelled species were selected (using Extract by Attributes, *ArcGIS*) and the centroids of the ASCII grid cells (250 by 512 metres) were combined with this data in order to form a binary presence-absence species distribution matrix (Benito *et al*, 2013). The matrix was used as a tool to solve the Species Set Cover Problem (SSCP): minimising the area of conservation investment whilst protecting all of the input target species (Underhill, 1994; Kincaid *et al*, 2008).

A SSCP function to select the smallest the number of sites, ensuring that at least one site was included for each of the species, was coded in *R* (Orme, 2015) and solved using the *lpsolve* package (Berkelaar & Buttrey, 2013). The target number of sites to represent each species was increased in quantities of 5 until a total of 100 solutions were reached; each representation covered all target species once. A baseline representation target of 5 was selected in order to cover a 0.64 km^2 area, almost a third of the area covered by the Upper Fowey and Pont Pill MCZ (2 km^2). The Upper Fowey and Pont Pill MCZ is a relatively proximate site, situated on the Cornish coast, which spans intertidal, coastal and estuarine habitats (DEFRA *et al*, 2013). This representation target was run in order to obtain 20 different, random solutions. The resultant solutions were then divided by 20 in order to reveal the number of cells, ranked by their irreplaceability within a conservation scheme focused on the target species. In order to display the results of this analysis, maps were drawn in *ArcGIS*.

3. Results

3.1. Channel Island ecology

Species richness across the 450 Channel Island sample sites ranged from 1 to 90 species and was right skewed (skew=1.24, Fig. 2) with a mean species richness of 22.34 and a median species richness of 18. The areas of L'Etac and Vingt Clos (Sark), and also Helon Wreck near Jersey had an observed richness of only 1 species, whereas a South of Bigorne site (Jersey) was documented as supporting a rich community of 90 species (the maximum observed species richness).

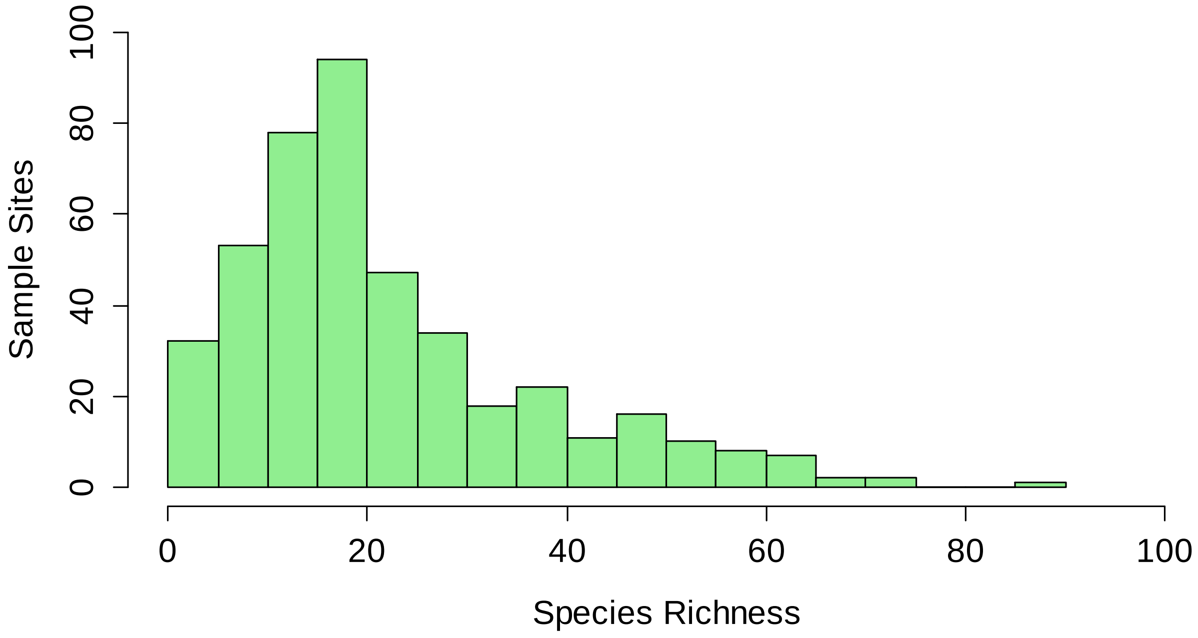

Fig. 2 Histogram of the species richness observed for the 450 Channel Island sites, sampled by Seasearch.

Multidimensional scaling analysis (Fig. 3) revealed that many of the sites appeared to perhaps be grouped into a single, large cluster, illustrating overall similarity and a lack of spatial distinction between islands. Within this agglomeration, however, there was evidence of ecological clustering within the islands (particularly Alderney, Sark and Jersey, although Guernsey and the open water areas also display evidence of this). This indicates that there was a high degree of similarity within the communities that existed throughout the Channel Island region, as well as within the distinct island areas. The nMDS plot (Fig. 3) had a stress level of 0.169, indicating that the plot is a 'fair' representation of how the clustering of community structure represents the data (Kruskal, 1964). An ANOSIM determined that there was a significant difference in community structure between the islands and sea groupings (ANOSIM, *Global R* = 0.251, *P* = 0.001).

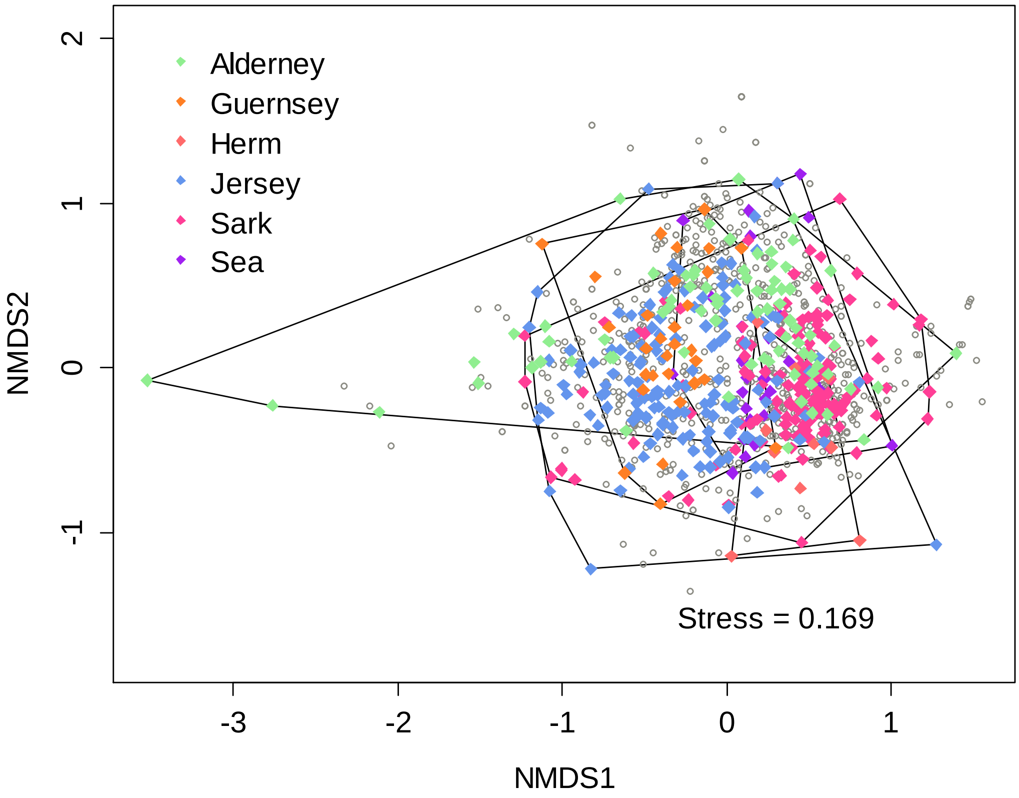

Fig. 3 A two dimensional nMDS ordination plot generated from a Bray-Curtis similarity matrix, omitting sites with only one species present. Species are depicted as hollow grey circles, whereas the sites are larger and coloured. Convex hulls encircle the sites from the different islands/ open water (Oksanen, 2013).

3.2. Environmental influences

Using univariate linear models, species richness was found to be predicted by the following environmental variables: calcite, chlorophyll-α concentration, cloud fraction, dissolved oxygen, maximum SST, minimum SST, nitrate, pH, phosphate, silicate, wind power density and wind speed (Fig. 4). However, these correlations were weak (see Table 3 for detailed results).

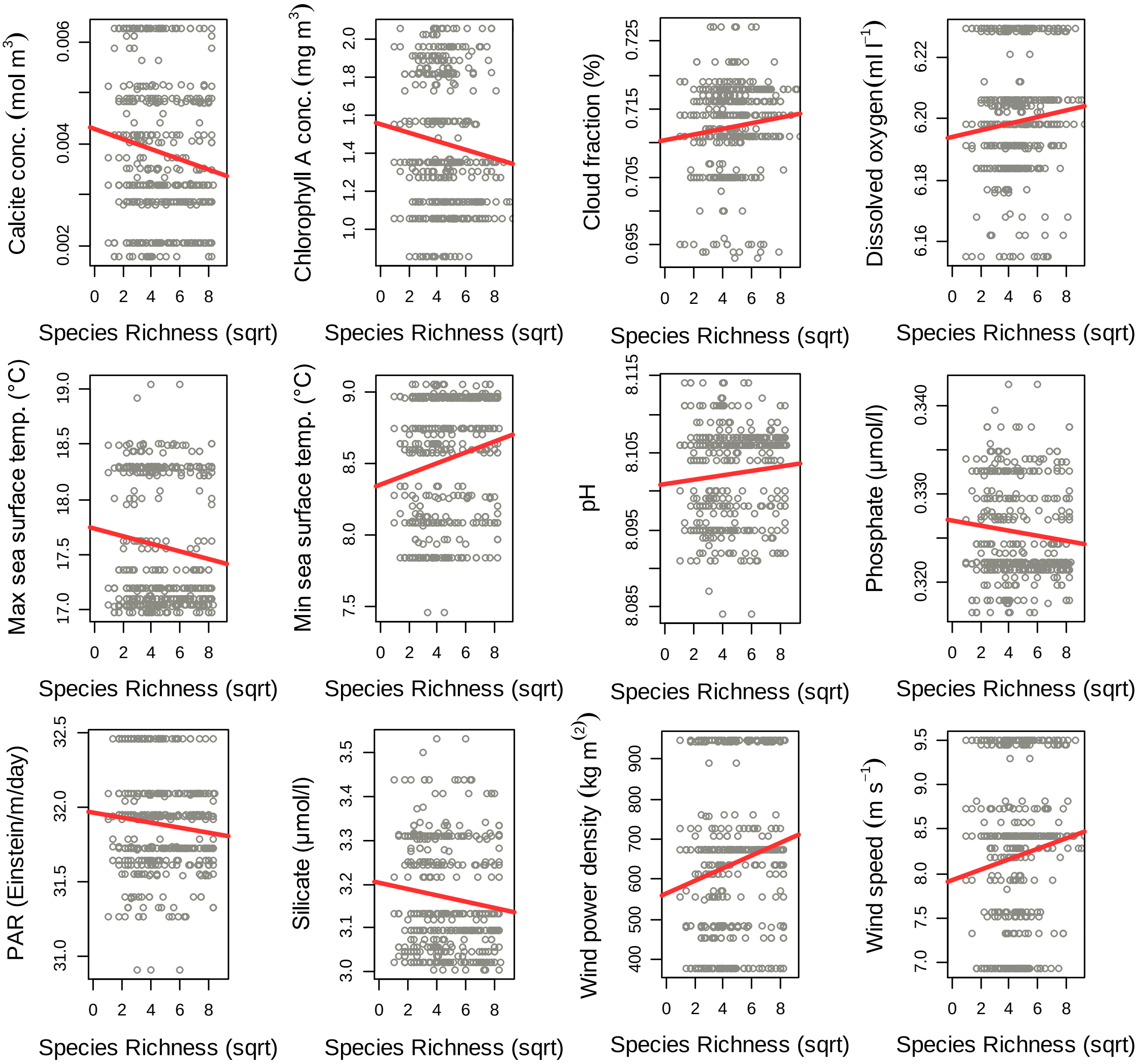

Fig. 4 The significant relationships between species richness (subject to a square root transformation) and the environmental variables of the Channel Islands (further depicted in Table 3). Lines of significant linear regression are shown.

Further environmental variables were not found to be significantly correlated (Pearson's correlation, $P > 0.05$). These were: ocean depth, fraction of light at the seabed, salinity, diffuse attenuation coefficient and PAR (see Table 3).

Table 3 Results of calculating Pearson's Correlations and Linear Regressions between different environmental variables and the square root transformed species richness observed over the Channel Islands.

Independent Environmental Variable	***Pearson's Rank Correlation***		***Linear Regression***			
	R_{434}	*P*	r^2	$F_{1\text{-}434}$	*P*	*Standard Errors*
Calcite (mol m^3)	-0.135	<0.01	0.018	8.405	<0.01	0.001
Chlorophyll α (mg m^3)	-0.104	0.027	0.011	4.94	0.027	0.349
Cloud fraction (%)	0.107	0.022	0.012	5.259	0.022	0.006
Dissolved oxygen (ml l^{-1})	0.095	0.044	0.009	4.075	0.044	0.018
Max sea surface temperature (^{o}C)	-0.118	0.012	0.014	6.361	0.012	0.570
Min sea surface temperature (^{o}C)	0.172	<0.01	0.030	13.71	<0.01	0.427
pH	0.095	0.044	0.009	4.082	0.044	0.006
Phosphate (µmol/l)	-0.101	0.032	0.010	4.602	0.032	0.006
PAR (Eintein/m^2/day)	-0.102	0.030	0.010	4.726	0.030	0.322
Silicate (µmol/l)	-0.114	0.016	0.013	5.901	0.015	0.122
Wind power density (kg m$^{(2)}$)	0.164	<0.01	0.027	12.38	<0.01	185.4
Wind speed (ms^{-1})	0.111	0.018	0.012	5.637	0.018	0.844
Diffuse attenuation coefficient (m^{-1})	-0.055	0.247	-	-	-	-
Fraction of light at seabed (%)	0.013	0.81	-	-	-	-
Mean sea surface temperature (^{o}C)	-0.010	0.838	-	-	-	-
Nitrate (µmol/l)	-0.086	0.067	-	-	-	-
Ocean depth (m)	0.009	0.860	-	-	-	-
Salinity (PSS)	0.087	0.063	-	-	-	-

3.3. Target species distribution and richness

The modelled species distributions of the target species are illustrated within Appendix 3. A range of distribution patterns were observed: *Caryophyllia inornata* had a large distribution, almost covering the study area, whereas *Raja undulata* was only present around the coast of Jersey and one small area of open water. The model for *Raspaillia ramosa* revealed a northern coastal distribution trend, demonstrating an affinity for sheltered bays; *Eunicella verrucosa* and *Carpomitra costata* had more widespread, yet westerly, distributions, inhabiting exposed rocky shores (see Appendix 3).

A histogram of species' log species ranges is shown in Fig. 5. These species' distributions were compiled to create a map of target species richness across the Channel Islands (Fig. 6).

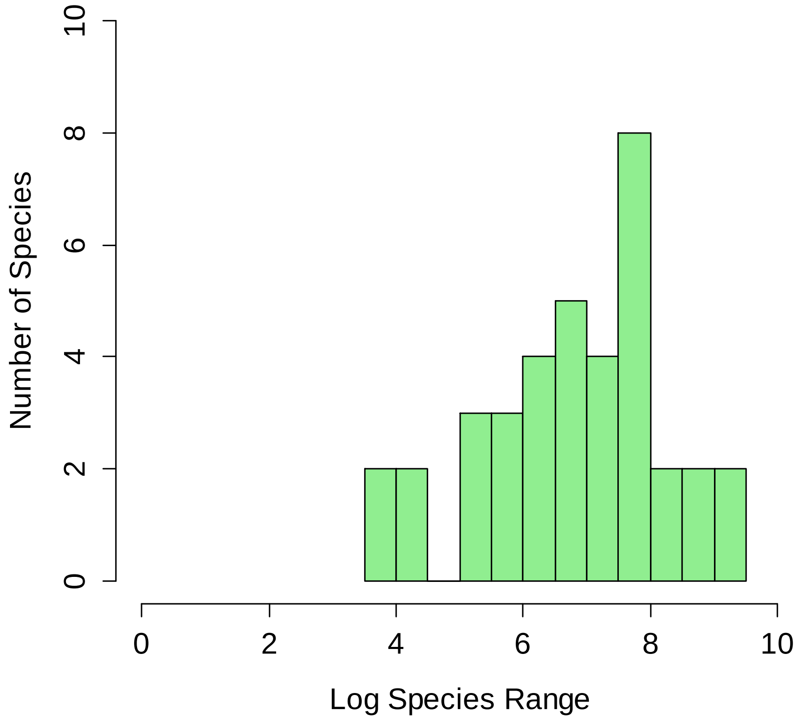

Fig. 5 The log range size distributions for the target species listed in Appendices 1 and 2, across the Channel Island area.

3.3. Areas of conservation value

It was determined that only 3 grid cells were required in order to represent each target species once: 2 near Alderney and 1 near Jersey (Fig. 7). Increasing the representation target of each species to 100 cells required 295 cells: cell count increased linearly with representation (Fig. 7). The majority of the selected study sites were in coastal areas; regions depicted to have a high species richness of target species (Fig. 6).

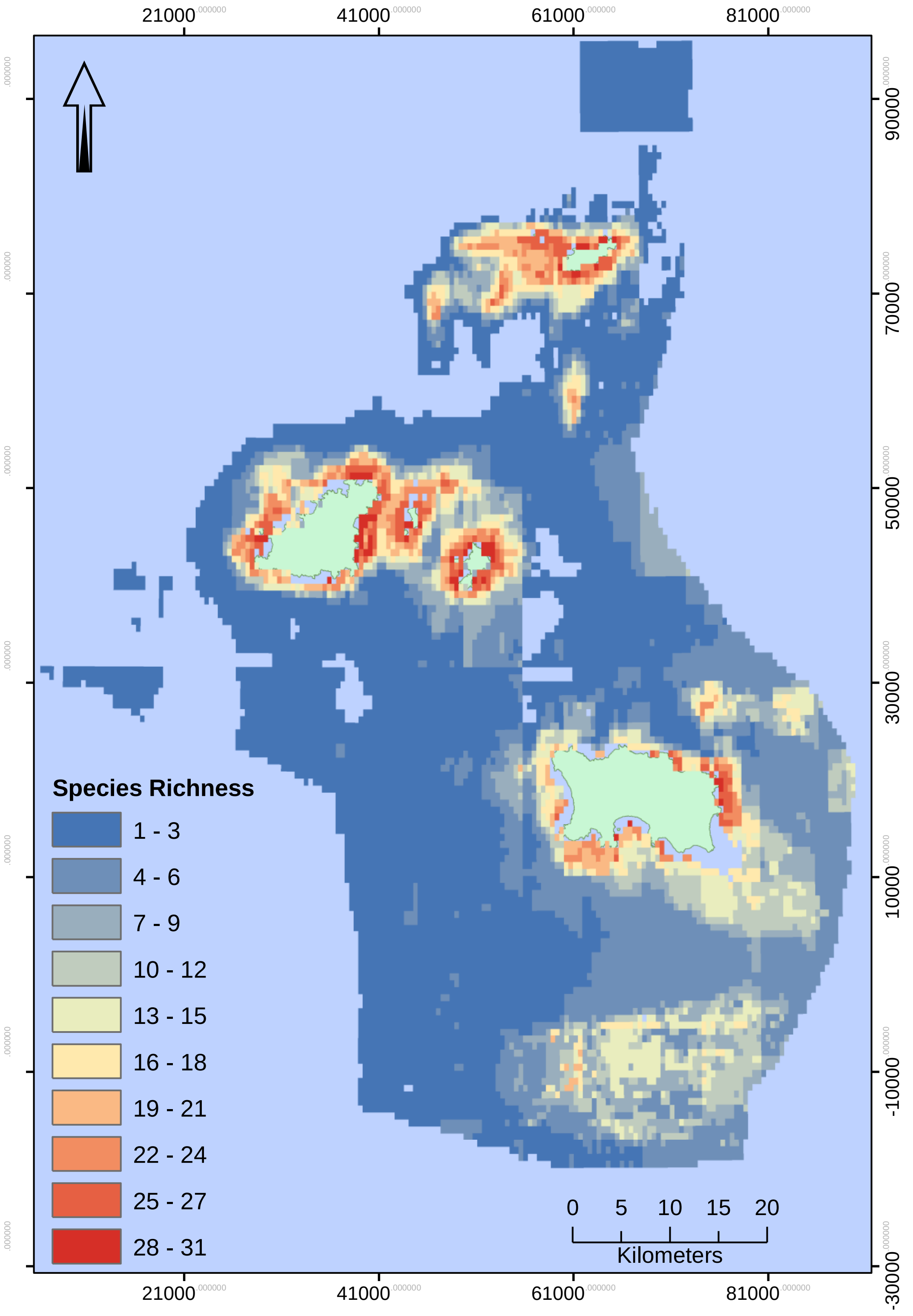

Fig. 6 Target species richness of the Channel Islands (inferred from species distribution models).

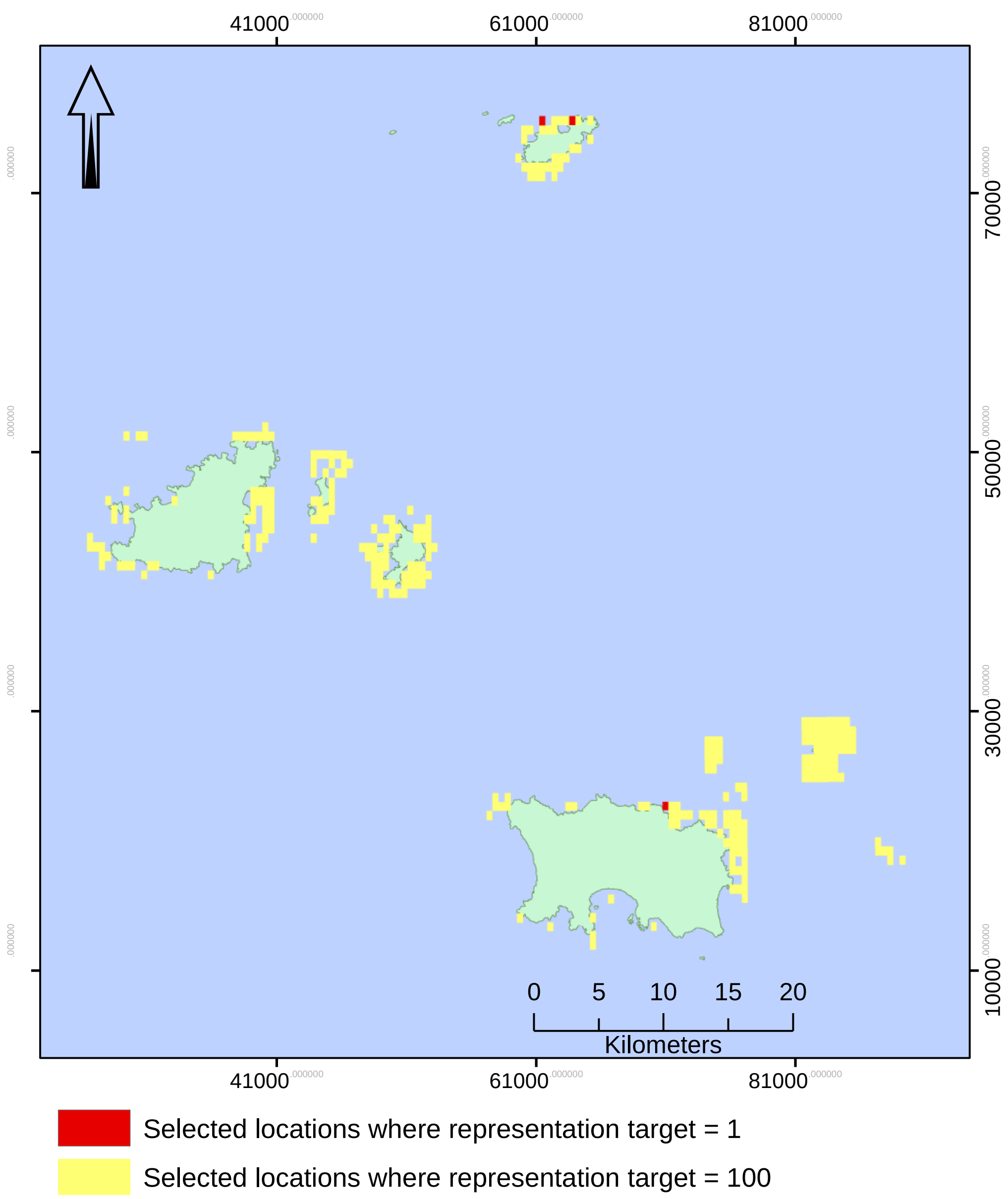

Fig. 7 The sites selected under the Species Set Cover Problem Algorithm when the representation target was first 1, and then 100, grid cells per target species.

Fig. 8 depicts areas of high irreplaceability and ecological importance within the Channel Island area. 34 cells were selected: 10 around the coasts of Alderney, 8 around Sark, 3 to the north of Herm, 11 around the coastal areas of Jersey, and 2 to the north-east. Of these sites, 8 were found to appear within over 17 of the solutions: 4 on the north-eastern coast of Jersey, 3 at north-western Alderney, and 1 to the east of Sark.

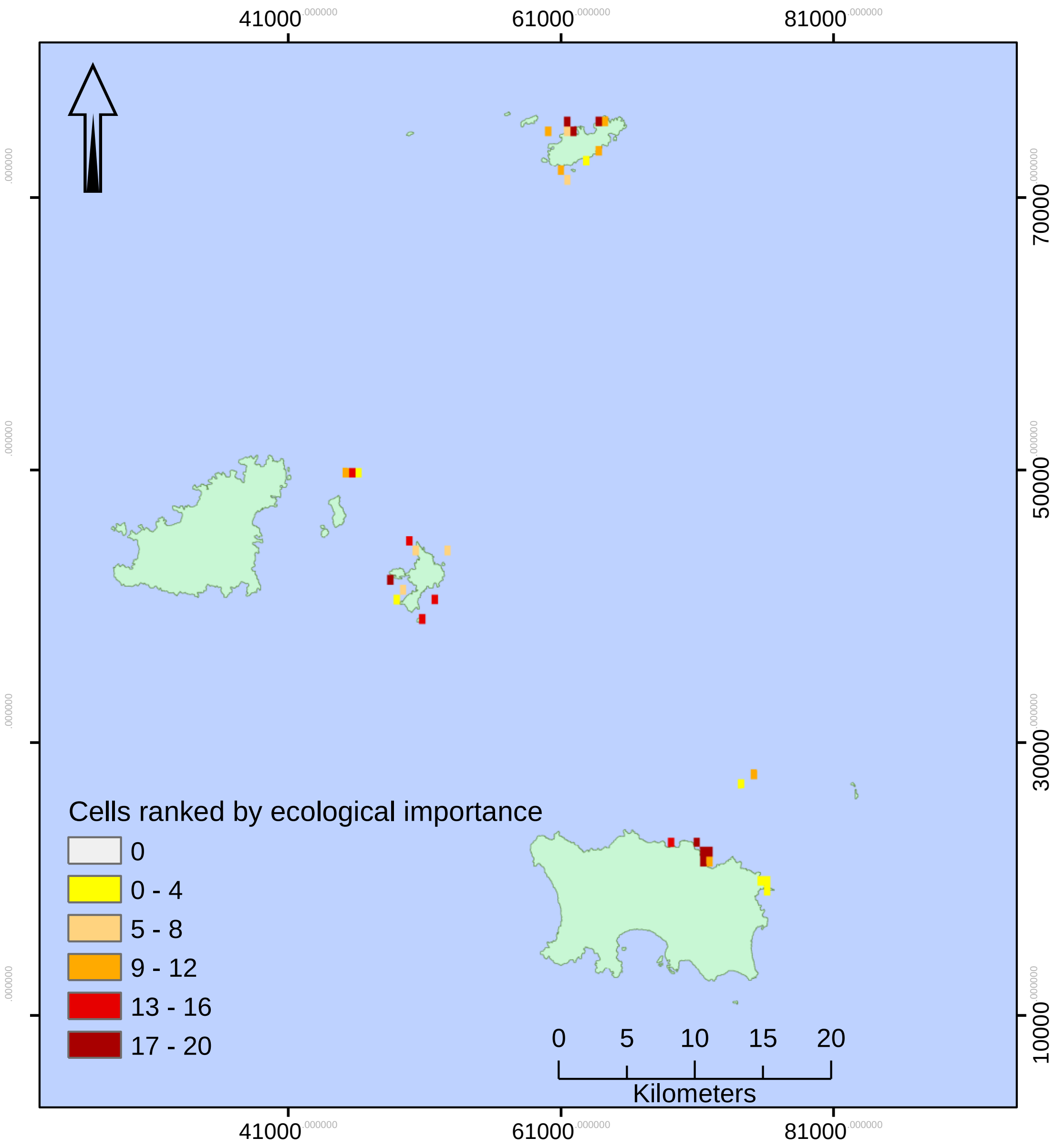

Fig. 8 The sites selected under the Species Set Cover Problem Algorithm when the representation target number of cells for each target species was 5, ranked by their occurrence when conducted for 20 repeats.

4. Discussion

4.1. Channel Island marine ecology

In order to successfully implement effective conservation strategies, it is essential to have an understanding of the present ecological conditions within the area of interest (Hiscock, 2014). Assessing species richness across the geographical regions is a key initial basis by which to initiate this process (Guisande *et al*, 2013). Within the 'Seasearch Survey of Alderney' report, Wood (2010) identified certain sites within the Channel Islands that provided diverse habitats for a range of ecologically important and threatened species: Longis Bay, Frying Pan Bay, Les Boufresses and Queslingue (Alderney). All of these sites additionally demonstrated high quantities of species richness within this study. Mapping within *ArcGIS* revealed that the seas around Alderney had an increased wind power density and wind speed, in comparison to the other islands – environmental characteristics found to be positively correlated with species rich areas (Figure 4; Table 3). This may be because high winds have been shown to increase nutrient enrichment in the euphotic zone (MacIsaac *et al*, 1985). This creates an optimal environment for diatoms, a key carbon source within planktonic food webs which in turn influences energy transfer within higher marine trophic levels (Fry & Wainright, 1991).

The Channel Islands marine environment exhibited high biological diversity and species richness due to the presence of key habitats: low-disturbance, minimal-exposure rocky areas and sublittoral seagrass beds, largely composed of *Zostera marina* (Wood, 2010). Seagrasses face a multitude of threats, including disease, physical disturbance, competition from invasive species (e.g. *Sargassum muticum*), pollution and nutrient enrichment (Maddock, 2008). Despite these threats (and their consequential decline elsewhere within the UK (JNCC, 2014), the Channel Islands are known to support numerous thriving habitats, particularly around the island of Jersey (Jackson *et al*, 2006). Seagrasses provide nursery habitats, act as a direct food source, participate in nutrient cycling and stabilise against sediment erosion (Phillips & Milchakova, 2003). Because of this, it is unsurprising that high species richness was observed within regions in which they are present. Species richness may vary temporally, however, due to some species favouring seagrass beds throughout particular stages of their life histories (Gratwicke & Speight, 2005). Further research into the effect of the sampling period on the obtained data should be conducted due to this variability within the reproductive timings of marine species (Lowerre-Barbieri *et al*, 2011). In addition, analysis into the habitats present across the Channel Islands is encouraged, due to the large effect that this has on the assemblages present, as well as their independent importance (Goble *et al*, 2012). Further insight into habitat presence may also help facilitate understanding as to why community similarity exists amongst the sites that surround individual islands (see Results section, Fig. 3). Perhaps it is due to the presence of *Zostera* seagrass beds across Jersey, Guernsey and Sark that has led to a clustering of similar community structure (Jackson *et al*, 2006; Sheehan *et al*, 2011).

Due to the nature of the data collection methods (volunteer recreational diver surveys) sampling bias may have occurred. Certain islands were subject to an increased survey effort (Appendix 4) and particular sites (such as a selection of rocky features and caves surrounding Sark) were selected due to their biologically interesting nature, and the provision of favourable underwater scenery. On occasion, survey effort may have been hindered due to time constraints, tides and weather conditions (Wood, 2008a; Wood, 2008b). This being said, the involvement of volunteers within biological surveying, often referred to as 'Citizen Science' (Schnoor, 2007), provides numerous benefits: reductions of costs otherwise required to establish a monitoring scheme, increased sampling effort and often a heightened sense of environmental stewardship (Pattengill-Semmens & Semmens, 2003).

The instatement of a regional Channel Island coordinator for future citizen science surveys, based on sound aims and objectives, is recommended. A more accurate and balanced review of the Channel Islands' marine region could therefore be conducted (taking into account the planning and implementation of future monitoring techniques), including a conservation review of seagrass habitats, due to their aforementioned ecological importance.

4.2. Physiological impacts on ecological communities

Despite the aforementioned overlap in clustering between some of the islands and open water areas, discrete clusters were also observed, indicating significant community dissimilarity between the study regions (see Results section, Fig. 3). Physiological factors create, transform and significantly influence the patterns that exist within marine ecosystems, and are likely to have caused diversity within the community structure present between the different Channel Islands (Kaiser *et al*, 2011). Yet, despite the influence that physiological factors have on marine communities, correlations between many of the researched variables and the species richness were found not to be significant. This was potentially due to the low spatial precision of the Seasearch observation data (resolution = 100 metres), which was of insufficient resolution to allow the differentiation between different communities (Mieszkowska & Lundquist, 2011). Any further monitoring should seek to address this issue.

Much of the environmental data was of relatively low resolution (see Table 1). It was perhaps as a result of the consequential, apparent reduced variation between sites, therefore, that the relationships between species richness and the investigated environmental parameters were found to either be weak or, in some cases, non-existent (see Fig. 4 and Table 3) (Wulder *et al*, 2004). A further explanation as to the lack of correlations could be that many of the environmental characteristics were perhaps almost homogenous across the extent of the study region, exhibiting almost negligible ranges, for example: dissolved oxygen (6.16 – 6.23 ml^{-1}), pH (8.08 – 8.11) and phosphate (0.317 – 0.342 µmol l^{-1}). It was potentially due to this that the individual islands and open sea areas seemed to be part of a larger cluster of similar community composition (Fig. 3). Despite the fact that many of the relationships between species richness and the physiological environment were small, those of importance are outlined briefly within Appendix 5.

4.3. The geographic ranges and habitats of target species

Species geographic range size demonstrated a left log-skew, as is a common phenomenon (Gaston, 1998). This pattern was similarly observed amongst the marine Channel Island target species (Fig. 5). This implies that disproportionately more of the modelled species have restricted ranges, being either indicators of particular communities, or threatened and rare species (Birand *et al*, 2012).

The most dominant obstacles, in terms of species geographic range expansions, are physical and topographical barriers (Gaston, 2003). Within marine systems, ocean currents (often within shoreline locations) fulfil a similar role, creating ocean fronts: gradients in temperature, salinity and nutrients (Gaylord & Gaines, 2000; Woodson *et al*, 2012). It is perhaps due to this that the Channel Islands coastal regions supported a higher richness of target species (see Results section, Fig. 6). Marine biodiversity is often high within coastal areas, largely because of the diversity of habitats present and the habitat complexity that they provide (Gray, 1997; Speight & Henderson, 2010). Further biotic factors, such as predation and competition, as well as anthropogenic impacts, may also restrict species ranges (Kaiser *et al*, 2000).

Despite the benefits of the coastal biome, the impacts of human disturbance are often greater and more amplified here, particularly upon certain species (Speight & Henderson, 2010). For example, the brown alga *Ascophyllum nodosum* (which demonstrated a coastal distribution; Appendix 3) grows within rocky, sheltered areas of the intertidal zone (Parys *et al*, 2009). *A. nodosum* is a UK BAP species and suffers increased susceptibility to the uptake of pollutants, caused by proximate developments of harbours and roads (JNCC, 2010). Because of such anthropogenic threats, monitoring and appropriate conservation measures should be undertaken in order to help to protect often-fragile marine ecosystems (Weaver & Johnson, 2012).

4.4. Anthropogenic impacts and conservation strategies

Despite the unique marine assemblages that the Channel Islands support, the area is far from void of the consequential threats of anthropogenic impacts (McClellan *et al*, 2014). Within the 2010 'Seasearch Survey of Alderney' report it is noted that one site particularly ('South of Rubbish Tip A-C', see Appendix 4) exhibited the effects of human disturbance: litter was recorded on the seabed (Wood, 2010). Furthermore, English Channel ecosystems are subject to additional large-scale anthropogenic degradation by fishing and aggregate extraction (Kaiser & Spence, 2002). Demersal fishing gear, particularly, has been linked to the deterioration of benthic communities (Kaiser *et al*, 2000). For example, target species *Ostrea edulis* (European flat oyster) has suffered decline due to the accumulative historic effects of habitat loss by dredging, trawling and the consequential impacts of sedimentation and disease (Beck *et al*, 2011). A further target species, *Eunicella verrucosa* (pink sea fan) suffers physical damage due to fishing activity (Holland *et al*, 2013), whilst English Channel *Pleuronectes platessa* and *Solea solea* populations are vulnerable to overfishing and discard mortality (Revill *et al*, 2013). In order to reverse the declines of these species (or at least reduce the rate of loss) a more conscientious approach to fisheries management, involving less destructive harvesting methods, is encouraged (Lenihan & Peterson, 2004). Further conservation action should also be considered within the discrete locations of high irreplaceability and ecological importance, identified within Fig. 8 (Smith *et al*, 2009).

Whilst anthropogenic impacts rise, an escalating human population determines that we are increasingly reliant on the ecosystem services that the ocean provides (Hiscock, 2014). It is because of this that the seas surrounding the Channel Islands are of high economic importance (Rombouts *et al*, 2012). Although it is a relatively small area of sea, it is subject to high volumes of concentrated maritime activity, including recreational and commercial fisheries, as well as trans-channel ferry crossings and commercial shipping (Minchin *et al*, 2013). These high levels of activity amount to the Channel being prone to marine pollution and playing host to introductions of alien species (Minchin & Eno, 2002). As a result, it is important to develop conservation strategies such as the designation of marine reserves, in conjunction with socioeconomic goals (Klein *et al*, 2008). Stakeholders should be consulted, as the effects of limitations (of activities such the aforementioned shipping, as well as mining, waste discharge, tourism, coastal development and differing levels of fishing) may impact lives and livelihoods (Hiscock, 2014). Suitable conservation approaches should accommodate the requirements of marine systems in terms of sustaining biodiversity, as well as reducing potential impacts on fisheries and the local economy (Lundquist & Granek, 2005). In terms of other anthropogenic effects (particularly those caused by chemical and biological pollution due to shipping lanes and coastal development) designating areas for marine conservation can be particularly difficult, because of the fluid, living nature of the seas, and the therefore superficial boundaries that exist (Boersma & Parrish, 1999).

Aside from the aforementioned impacts, which can often seem more tangible in comparison with the global phenomenon of accelerated climate change, the warming of the earth's atmosphere and oceans has been determined to have an unequivocal effect on natural systems (IPCC, 2014). Marine environments are predicted to witness changes in their chemistry, ocean circulation and increasing temperatures (Harley *et al*, 2006; Woehrling *et al*, 2005). In response to these physiological changes, the distribution of marine organisms (including North Sea fishes and English Channel invertebrates) have already demonstrated marked northward boundary extensions (Perry *et al*, 2005; Bates *et al*, 2014). Climate-mediated northern shifts are expected to continue in conjunction with further warming. Because of this, warm-water invasive species are also likely to become more evident within the English Channel, in addition to the foreign species which enter the English Channel via the heavy shipping traffic that the region observes (for example *Crepidula fornicata* and *Steyla clava* (Wade *et al*, n.d.; Philippart *et al*, 2011). *Crassostrea gigas*, the Pacific oyster, for example, was recorded at Gorey Castle, Jersey, within 2012 and 2013 despite previously been unable to inhabit northern European coasts, requiring temperatures of above 18^{o}C to spawn (Lejart *et al*, 2011). Due to these changes, additional monitoring as to the present ecological status of the area should be undertaken (further current information on the area was unavailable at the time of this report).

4.5. Conclusion

Due to the often numerous, confounding factors involved in planning marine conservation, it is encouraged that further research is undertaken to address the socioeconomic landscape of the Channel Islands (Agardy, 2000). In particular, this should take into account the busy commercial shipping route that the English Channel forms, as well as the future prospects of wind, wave and tidal energy developments and submarine electric cable links (McClellan *et al*, 2014). It is recommended that conservation approaches are considered, particularly within areas of high irreplaceability, focused on seagrass bed habitats and the target species with UK designations (Appendix 1). In order to successfully plan these actions, the appointment of a regional Channel Island Citizen Science Coordinator is encouraged, to ensure that future surveying and monitoring achieve their full potential.

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Appendices

5.1. Appendix 1

Table A.1 The 24 species chosen to have their distributions modelled, based designations, as well as their phylum, class and the reasons that they are of particular interest.

Species	Phylum and Class	Designations and listings
Adreus fascicularis	Porifera, Demospongiae	Nationally rare
Ascophyllum nodosum	Ochrophyta, Phaeophyceae	UK BAP Priority Species
Axinella damicornis	Porifera, Demospongiae	Nationally Scarce Marine Species
Balanophyllia regia	Cnidaria, Hexacorallia	Non common
Carpomitra costata	Ochrophyta, Phaeophyceae	Nationally scarce
Caryophyllia inornata	Cnidaria, Hexacorallia	Rare
Doris sticta	Mollusca, Gastropoda	Nationally Scarce Marine Species Rare/ scarce in the UK
Eunicella verrucosa	Cnidaria, Octocorallia	Feature of Conservational Importance IUCN Red List: Vulnerable (UNEP-WCMC, 1996) UK BAP Priority Species
Gracilaria bursa-pastoris	Rhodophyta, Florideophyceae	Nationally scarce
Haliotis tuberculata	Mollusca, Gastropoda	Not recorded on mainland Britain
Hexadella racovitzai	Cnidaria, Demospongiae	Recently identified and rarely recorded
Homaxinella subdola	Cnidaria, Demospongiae	OSPAR Species Uncommon, south-westerly species
Nucella lapillus	Mollusca, Gastropoda	UK BAP Priority Species
Ostrea edulis	Mollusca, Bivalvia	Feature of Conservational Importance OSPAR Species UK BAP Priority Species

Pachycerianthus indet	Cnidaria, Anthozoa	UK BAP Priority Species
Parazoanthus axinellae	Cnidaria, Hexacorallia	Nationally scarce
Periclimenes sagittifer	Anthropoda, Malacostraca	Rare, southern English coast
Pleuronectes platessa	Chordata, Actinopterygii	IUCN Red List: vulnerable to overfishing (Freyhof, 2014) UK BAP Priority Species
Raja clavata	Chordata, Elasmobranchii	IUCN Red List: Near Threatened (Ellis, 2005) OSPAR Species UK BAP Priority Species
Raja undulata	Chordata, Elasmobranchii	IUCN Red List: Endangered (Coelho *et al*., 2009) UK BAP Priority Species
Solea solea	Chordata, Actinopterygii	UK BAP Priority Species
Tripterygion delaisi	Chordata, Actinopterygii	Scarce/ rare in UK waters; Characteristic Channel Island species
Tritonia nilsodhneri	Mollusca, Gastropoda	Nationally scarce/ rare
Zostera marina	Angiospermophyta, Angiospermophyta	Nationally scarce and in decline IUCN Red List: Least concern; large-scale localised declines/ complete disappearance in some areas

Notes: The species within Table A.1 are those that were observed by Seasearch and crosschecked with lists of UK Biodiversity Action Plan (BAP) species (JNCC, 2014a), MCZ FOCI (JNCC, 2012) and OSPAR species (OSPAR Commission, 2004). In addition, annual Seasearch reports (Wood, 2007; Wood, 2008a-b; Sharrock, 2010; Wood, 2010) were interrogated for species that were thought to be ‘rare’ or ‘scarce’ in the seas that surround the Channel Islands and the British Isles. Some of the species had too few sample points to be suitably modelled, and therefore were removed from this list.

In addition to the species within Table A.1 being of conservational importance further species, *Eunicella verrucosa* (indicator value = 0.320; probability = 0.008) and *Tripterygion delaisi* (indicator value = 0.598; probability = 0.003) (See Table A.1) were also identified as indicator species.

5.2. Appendix 2

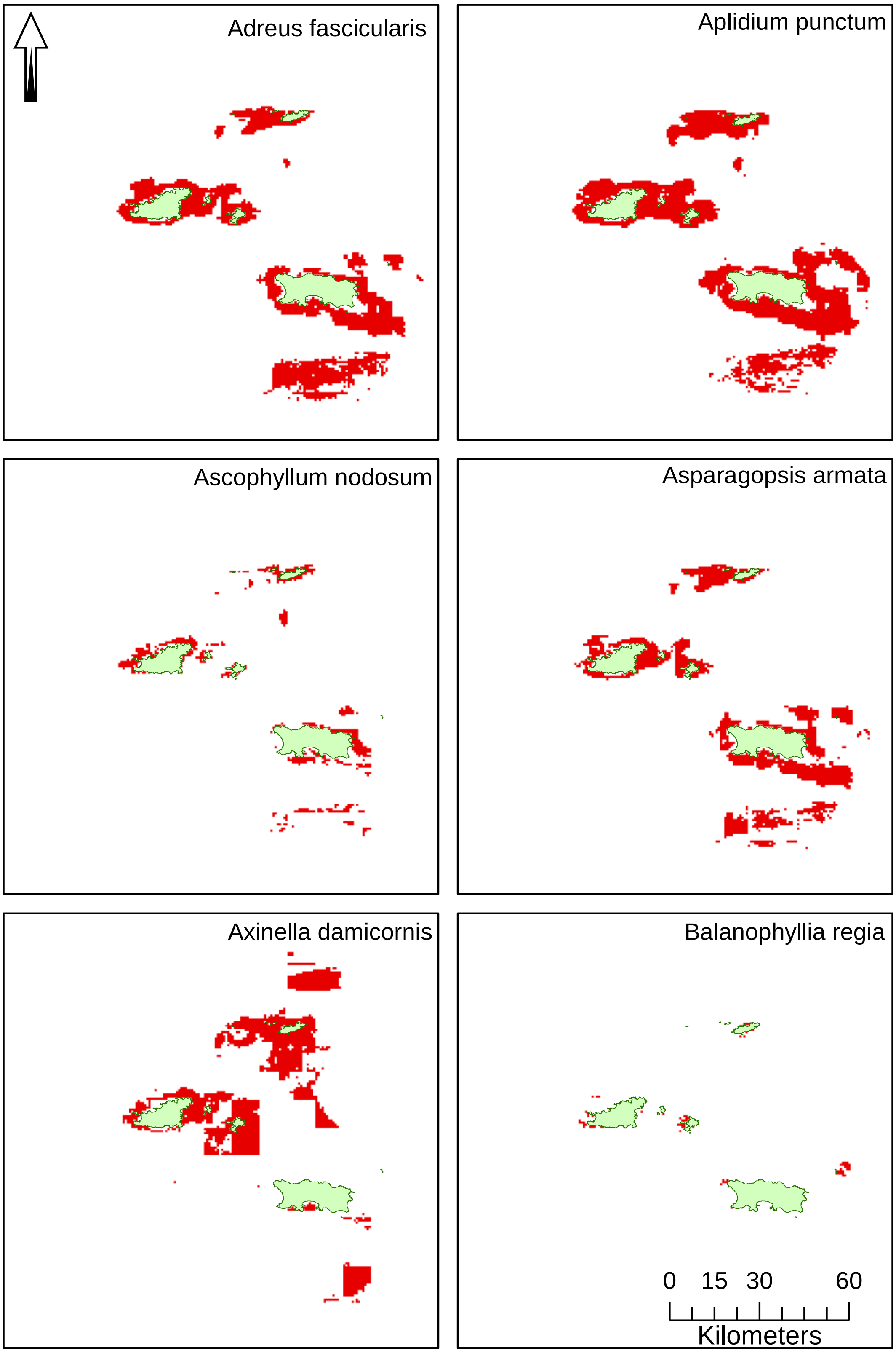
Table A.2 The 13 species determined as indicator species. Species phylum and class are listed, as well as their indicator value and probability.

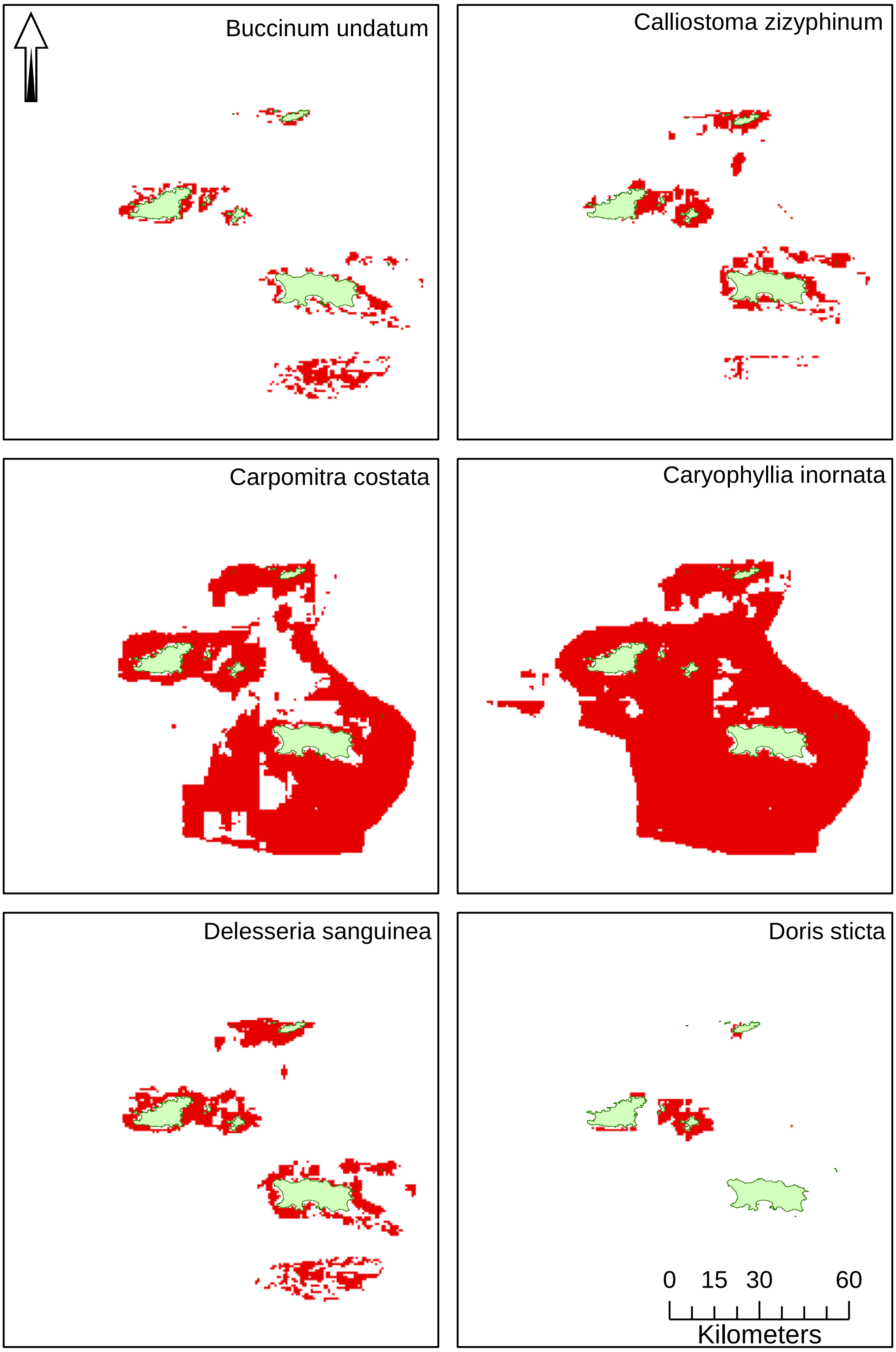
Species	Phylum and Class	Indicator Value	Probability
Aplidium punctum	Chordata, Ascidiacea	0.676	0.004
Asparagopsis armata	Rhodophyta, Florideophyceae	0.514	0.007
Buccinum undatum	Mollusca, Gastropoda	0.920	0.003
Calliostoma zizyphinum	Mollusca, Gastropoda	0.358	0.002
Delesseria sanguinea	Rhodophyta, Rhodophyta	0.722	0.001
Echinus esculentus	Echinodermata, Echinoidea	0.758	0.004
Galathea strigosa	Arthropoda, Malacostraca	0.830	0.004
Haliclona (Halichoclona) fistulosa	Porifera, Demospongiae	0.805	0.002
Haliclona (Rhizoniera) viscosa	Porifera, Demospongiae	0.914	0.005
Lissoclinum perforatum	Chordata, Ascidiacea	0.751	0.002
Omalosecosa ramulosa	Bryozoa, Gymnolaemata	0.855	0.006
Raspailia (Raspailia) ramosa	Porifera, Hadromerida	0.480	0.006
Tubularia indivisa	Cnidaria, Hydroidomedusa	0.855	0.001

Notes: Indicator value was calculated independently for each species and refers to how characteristic the species is of its group, in regards to how frequently it is found within the group, and it being present in the majority of sites that belong to the group (Dufrene & Legendre, 1997).

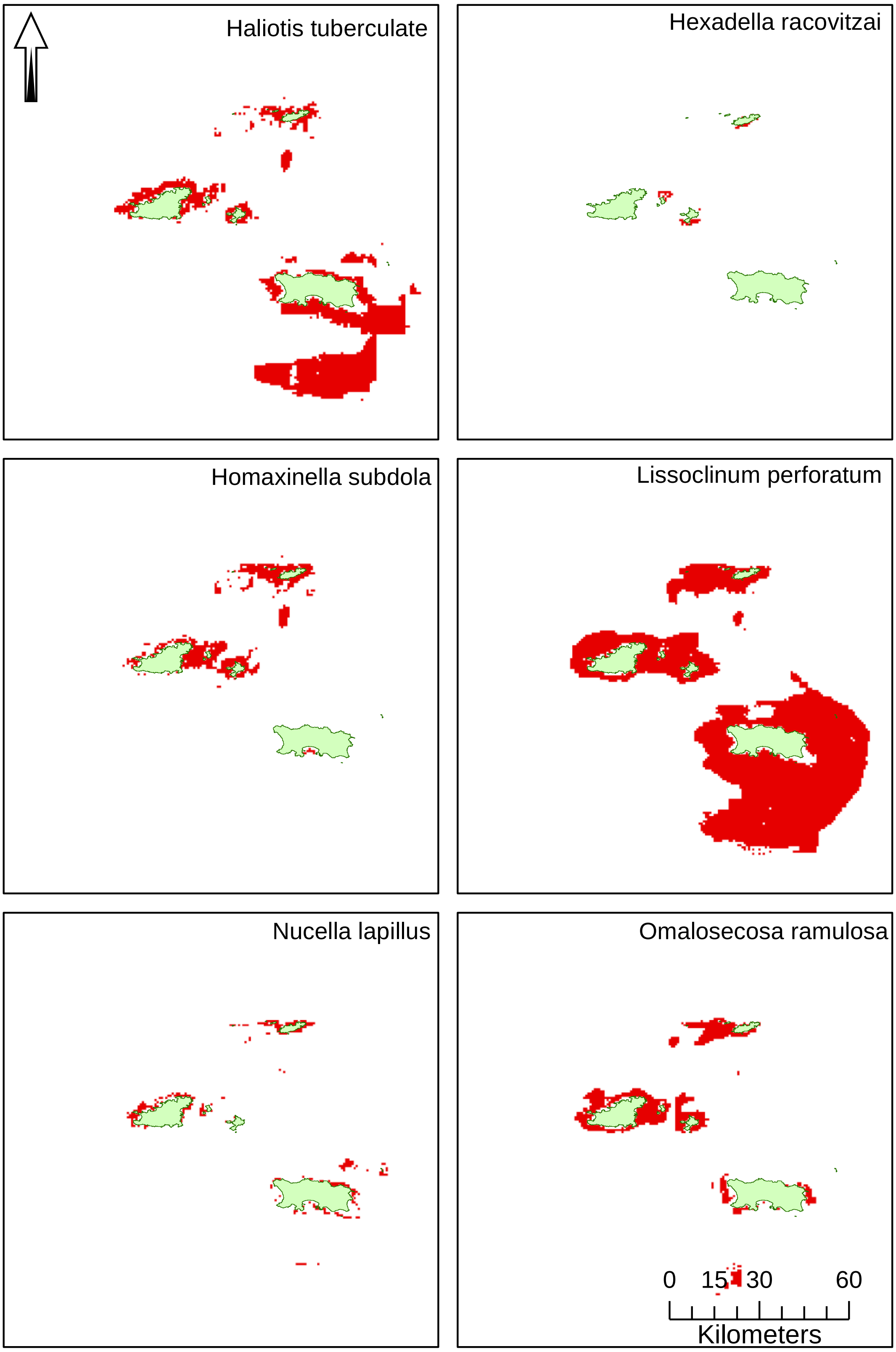
5.3. Appendix 3

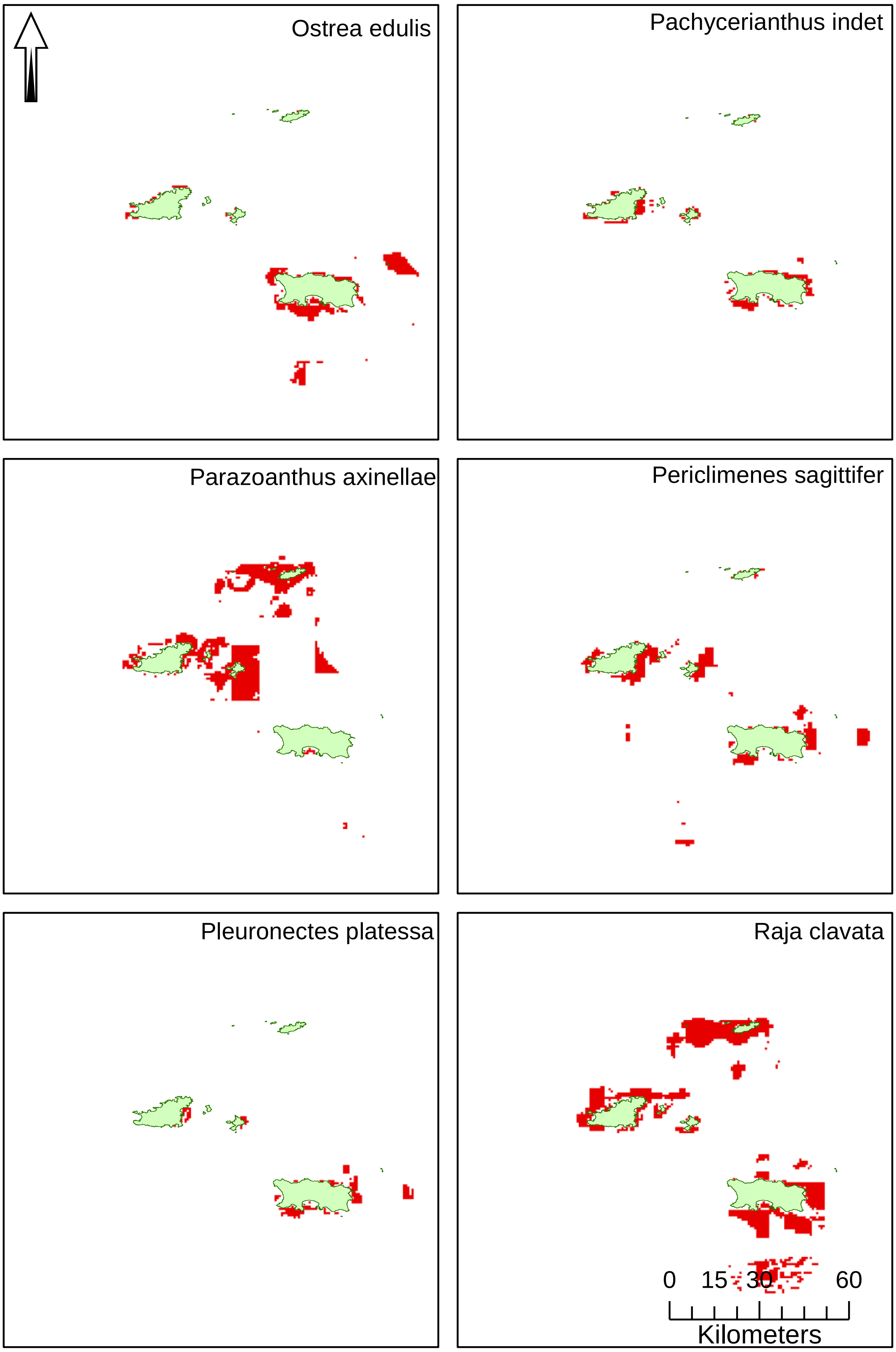
Fig. A.3 The modelled species distributions of the 37 conservation features across the Channel Islands, using the ‘Maximum test sensitivity plus specificity’ threshold, in *Maxent*.

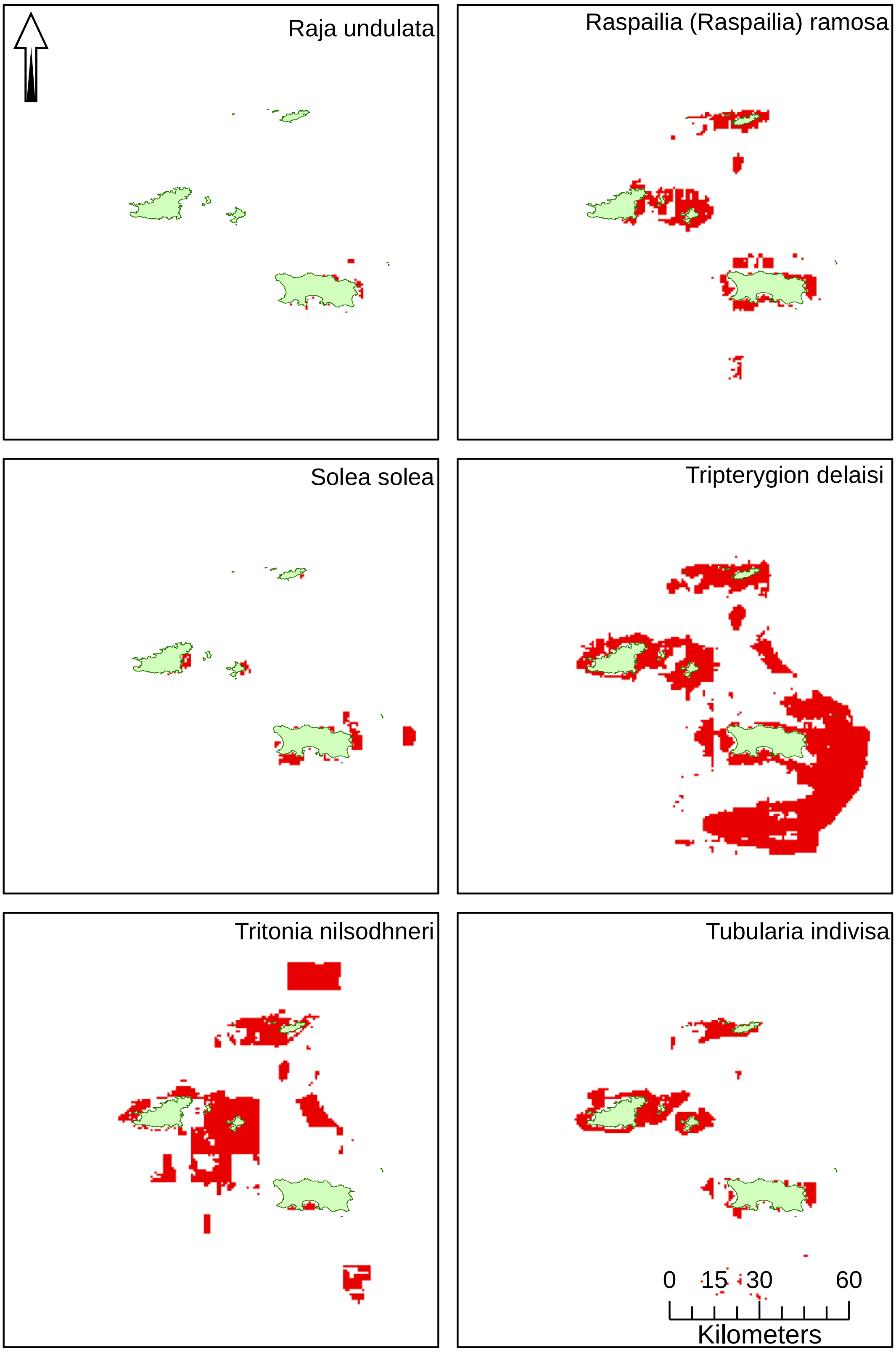


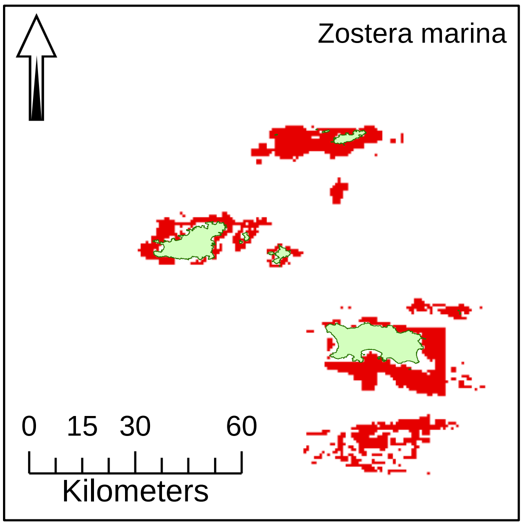

Buccinum undatum
Calliostoma zizyphinum
Carpomitra costata
Caryophyllia inornata
Delesseria sanguinea
Doris sticta
0
15
30
60
Kilometers


Echinus esculentus
Eunicella verrucosa
Galathea strigosa
Gracilaria bursa-pastoris
Haliclona (Halichoclona) fistulosa
Haliclona (Rhizoniera) viscosa
0
15
30
60
Kilometers


Haliotis tuberculate
Hexadella racovitzai
Homaxinella subdola
Lissoclinum perforatum
Nucella lapillus
Omalosecosa ramulosa
0
15
30
60
Kilometers

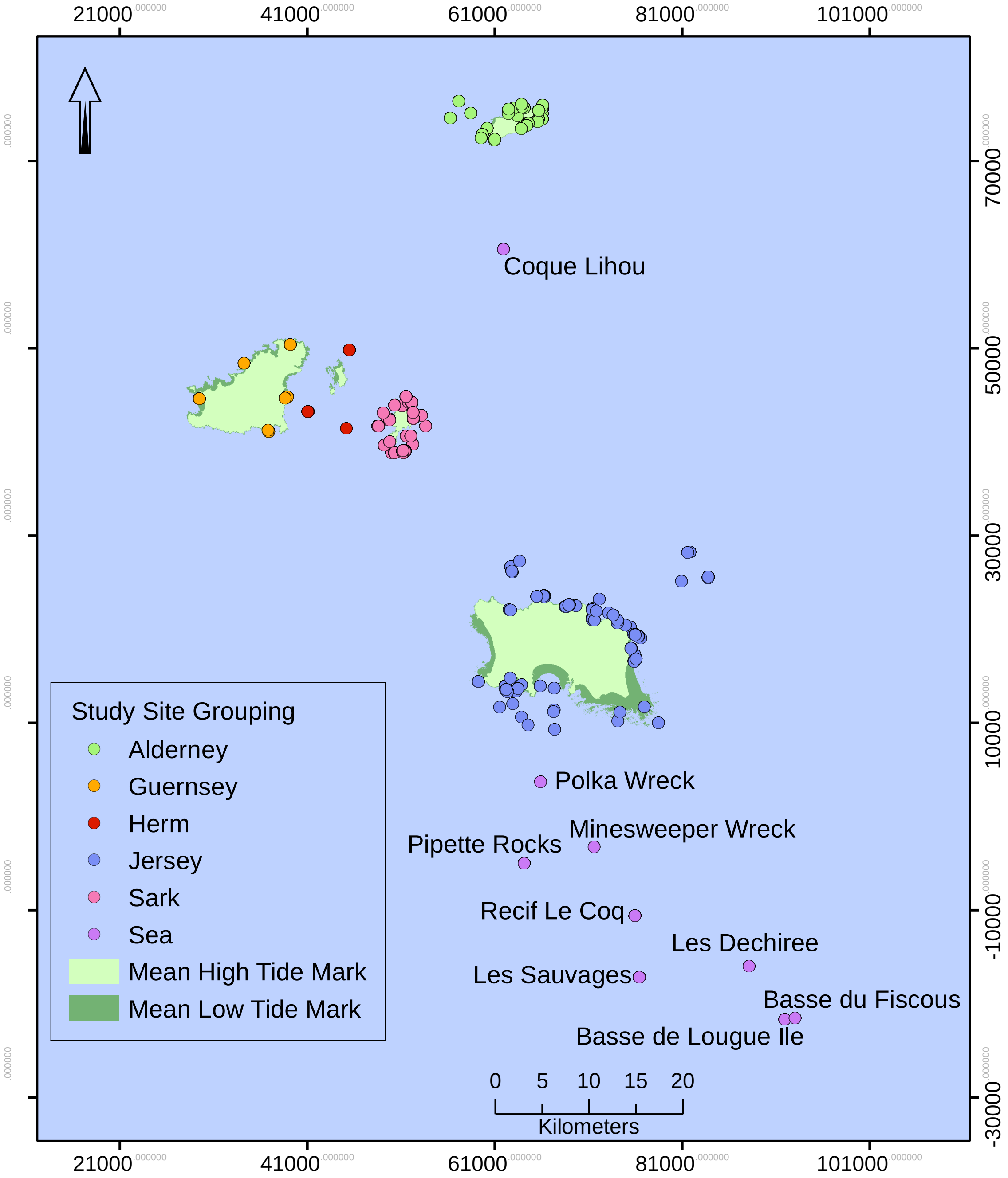

Ostrea edulis
Pachycerianthus indet
Parazoanthus axinellae
Periclimenes sagittifer
Pleuronectes platessa
Raja clavata
0
15
30
60
Kilometers


Raja undulata
Raspailia (Raspailia) ramosa
Solea solea
Tripterygion delaisi
Tritonia nilsodhneri
Tubularia indivisa
0 15 30 60
Kilometers


Zostera marina
0
15
30
60
Kilometers

5.4. Appendix 4

Fig. A.4.1 The location of the study sites surveyed by Seasearch volunteer divers. The sites were grouped by their location (the island areas and the open sea), to allow for nMDS analysis. The open sea sites are labelled.



Notes: Some of the islands were subject to an increased survey effort, for example Jersey has 147 sample sites (see Figure A.4.4), whereas Herm had just 10 (Figure A.4.3). Certain areas where surveyed over multiple depths and across a number of years, hence each of the 450 determined sites are not clearly visible within the figures.

Fig. A.4.2 A labelled map of the Seasearch study sites that surround the island of Alderney.

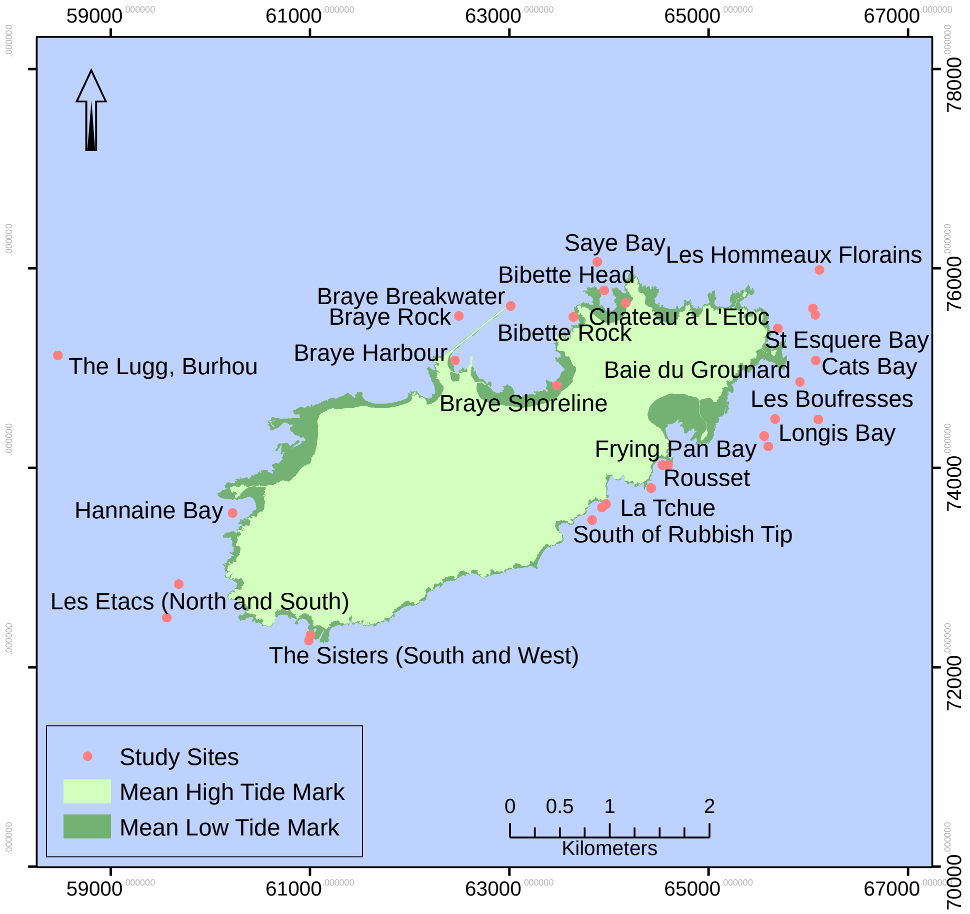


Fig. A.4.3 A labelled map of the Seasearch study sites that surround the islands of Herm (in the east) and Guernsey.

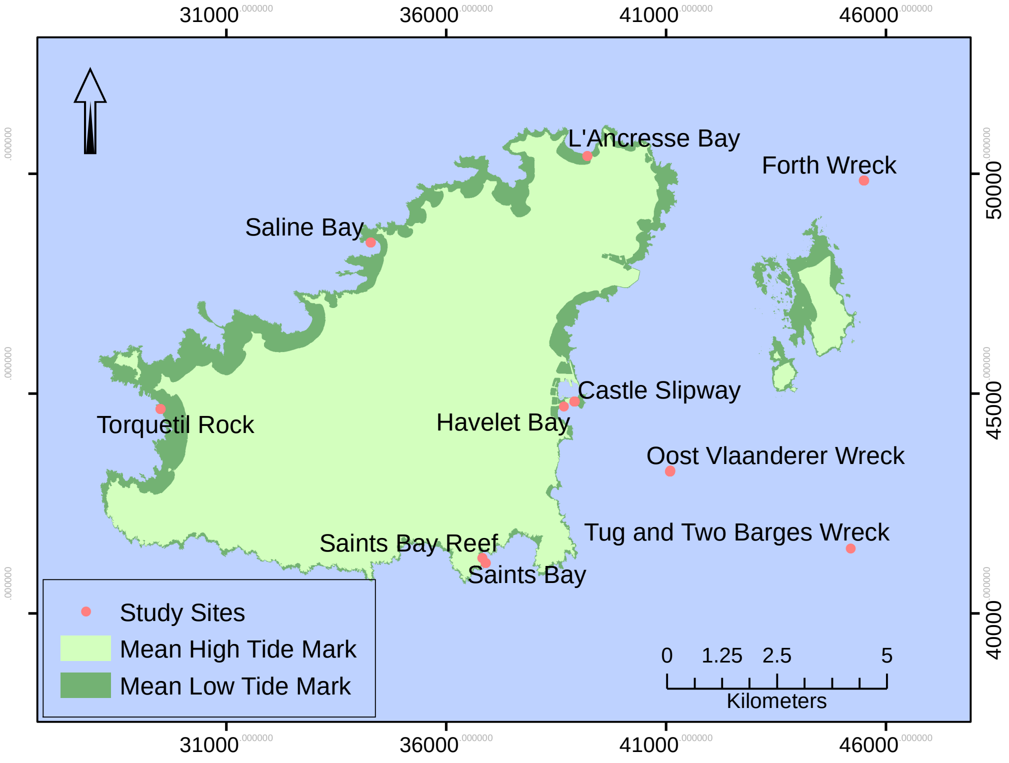


Fig. A.4.4 A labelled map of the Seasearch study sites that surround the island of Jersey.

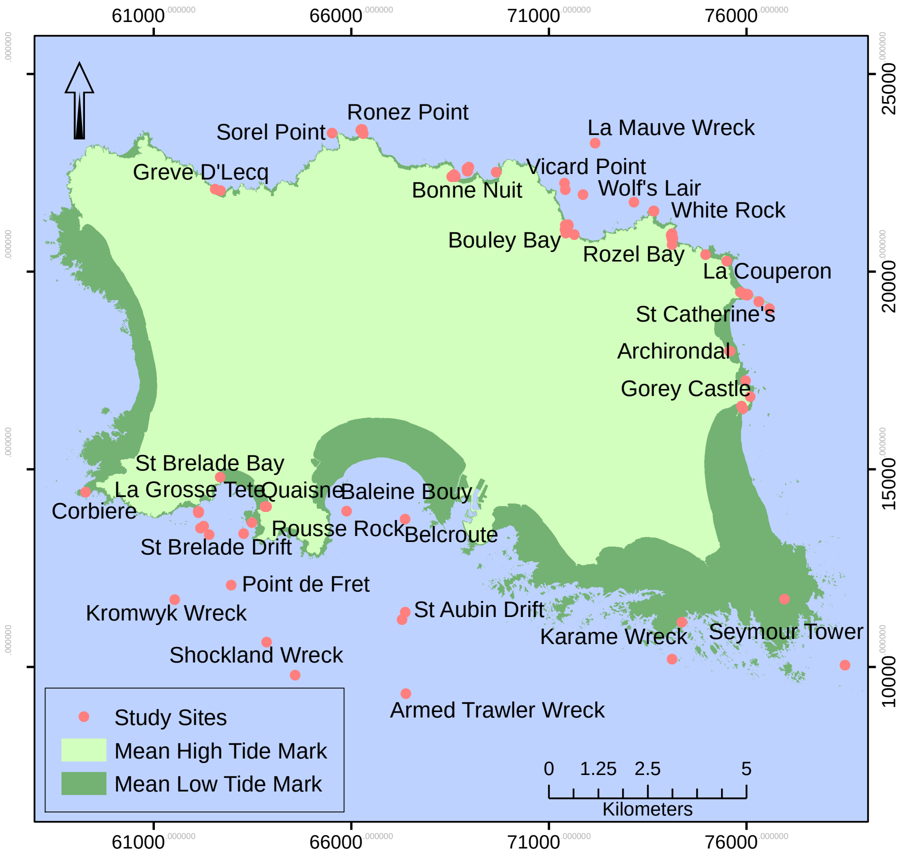
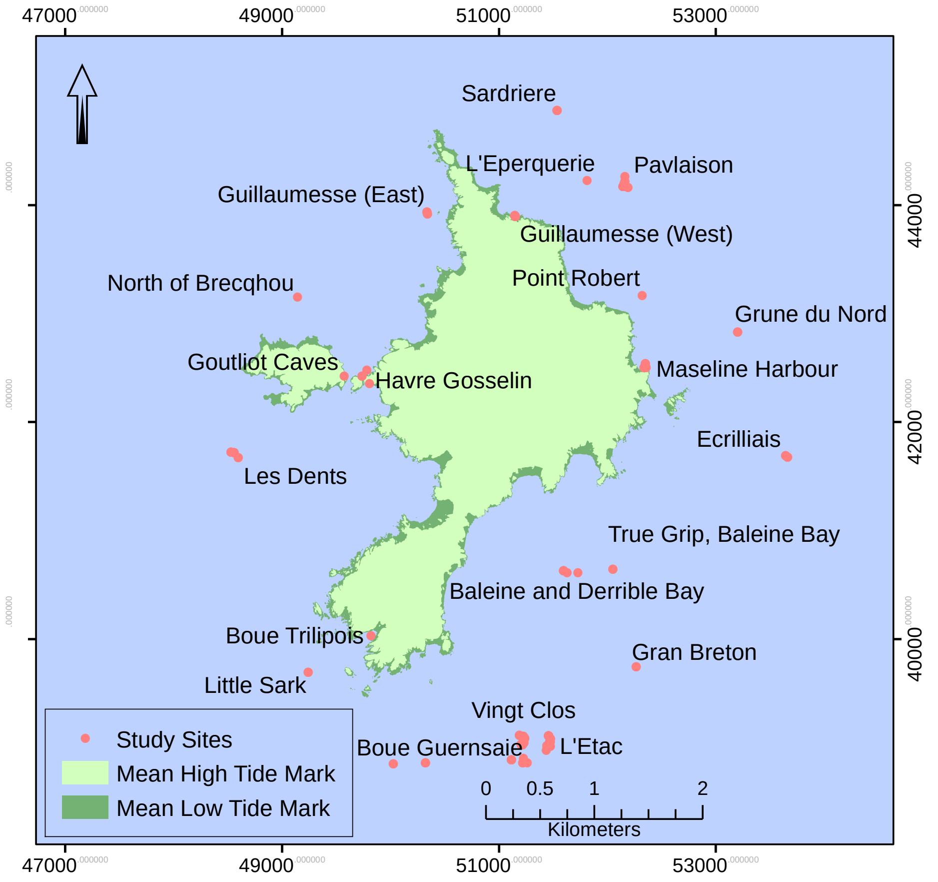


Fig. A.4.5 A labelled map of the Seasearch study sites that surround the island of Sark.



5.3. Appendix 5

Table A.5 A brief summary behind the relationships between certain key environmental parameters and species richness.

Environmental Variable	**Summary of Relationship with Species Richness**
Cloud fraction	This result may be anomalous, due to error from irregular temporal sampling (Tyberghein *et al*, 2012), particularly in conjunction to the lack of correlation between species richness and light.
Dissolved oxygen	Oxygen content is higher at the ocean surface, and within coastal locations, leading to increased aerobic performance and species richness (Dambach & Rödder, 2010; Speight & Henderson, 2010).
Minimum sea surface temperature	High temperature increases primary productivity and metabolic rate, particularly in filter feeders, and therefore equate to high species richness (Speight & Henderson, 2010).
pH	A lower pH means that the sea is more acidic which has multiple negative impacts on marine life; hence areas of higher pH have higher species richness (Kerr, 2010).
Wind power density and wind speed	Increased wind power density and speed cause oxygen to enter the euphotic zone, increasing nutrient enrichment and consequentially increasing species richness (MacIsaac et al, 1985).
Chlorophyll-α concentration	Although the presence of chlorophyll-α indicates high primary production and phytoplankton species density (Kaiser *et al*, 2011), such organisms were not the focus of this report, and therefore a positive species richness correlation was not observed throughout the higher levels of the marine food web.
Maximum sea surface temperature	When temperatures become very warm, the cover of primary producers decreases due to increased grazing by herbivores, potentially equating to a lower total species richness (Speight & Henderson, 2010).
Ocean depth	Topography and hydrology have a strong influence over biodiversity (Henry *et al*, 2013); ocean depth was one of the most defining variables within the construction of the SDMs. The lack of correlation observed was thought to be due to the low resolution of the data.

Salinity	Coastal waters normally exhibit a lower salinity than offshore areas, as do more shallow depths, lower salinity water being less dense (Speight & Henderson, 2010). The lack of correlation may be due to the small range of the data (34.43 – 34.85 PSS).