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Developing spatial management options for the protection of vulnerable marine ecosystems in the South Pacific Ocean region

New Zealand Aquatic Environment and Biodiversity Report No. 155.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

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Vulnerable marine ecosystems (VMEs) are any ecosystem that are highly vulnerable to one or more kinds of fishing activity or other disturbance, and are identified by the vulnerability of their components (e.g. habitats, communities or species). The South Pacific Regional Fisheries Management Organisation (SPRFMO) Convention includes specific provisions to protect VMEs.

The SPRFMO Commission has determined that the interim measures put in place to protect VMEs would be replaced by an improved system of fishable and closed areas. These closures would effectively represent a preliminary spatial management plan, whereby conservation and management measures are implemented that will result in sustainable fisheries and benthic protection.

The Ministry for Primary Industries (MPI), the fishery management agency for New Zealand domestic and high seas fisheries, including in SPRFMO, asked the National Institute of Water & Atmospheric Research (NIWA) to assist them in meeting the immediate need to develop spatial management options for the protection of VMEs in the South Pacific Ocean region under project ZBD2013/01.

The main outcome of the present study is a demonstration of the practical utility of using habitat suitability models, historical fishing data, and the Zonation conservation planning software tool to develop options for the spatial management of the SPRFMO area.

The illustration exercise generated apparently useful habitat suitability maps for VME indicator taxa at bathyal depths across the entire SPRFMO area. However, it is also clear that uncertainities inherent in background-presence models of the deep sea need to be addressed in the future in order to make more reliable predictive maps for the area.

Data from the New Zealand orange roughy fishery was considered to be a proxy for the trawl footprint of all other nations in the SPRFMO area. The trawl footprint of the entire history of the fishery (1980–2012) is notably larger than the reference trawl footprint (2002–2006) currently used by SPRFMO to identify closed and open areas under the interim measures. Use of the 2002–2006 period for the trawl footprint affected spatial management modelling results, and areas may be identified as high priority for protection when they may no longer provide habitat for extant populations of VME indicator taxa.

The incorporation of bioregional representation in the prioritisation of areas for protection was possible using an existing global biogeography. However, this recently published physical environment-based scheme is currently untested and is for a restricted part of the ocean domain, and it may be more appropriate for future spatial planning efforts to use alternative biogeographic schemes. Further consideration should also be given to weighting or not weighting the representation of bioregions for the protection of VMEs in the SPRFMO area.

Running various scenario models for spatial planning allowed for the cost to fishing to be determined, in terms of the amount of the trawl footprint lost if high priority areas for VME indicator taxa are protected. Generally, the cost to fishing was low given the relatively high proportion of suitable habitat for VME indicator taxa protected.

Despite the perceived need to improve the future application of Zonation and other similar software tools to develop spatial management options for VMEs in the SPRFMO area, outputs from the present

study provide a starting point for discussions about where and what size closed areas could be put in place to protect VMEs.

1. INTRODUCTION

Many commercial fisheries that operate on the 'high seas' (areas beyond national jurisdiction) target fish species that live near to the seafloor. Fishing with trawls on the bottom can cause significant impact to benthic habitat and organisms in the deep sea (e.g., Althuis et al. 2009, Clark & Rowden 2009). Some types of benthic habitat and organisms are particularly susceptible to the adverse effects of fishing (e.g. deep-water corals, Williams et al. 2010), and are known as 'vulnerable marine ecosystems' (VMEs).

In 2006 the United Nations General Assembly (UNGA) adopted a resolution which called upon parties to identify VMEs and avoid significant adverse impacts on these ecosystems (Resolution 61/105, UNGA 2006). Further UNGA resolutions emphasised the urgency for action and invited the Food and Agriculture Organization of the United Nations (FAO) to develop guidance on the application of criteria for identifying VMEs (Resolution 66/68, UNGA 2009). In 2009 the FAO published such guidelines (FAO 2009), and species or taxonomic groups that can be used as indicators of a VME were subsequently identified by regional fisheries management organisations/agreements (RFMO/As) (e.g., Parker et al. 2009, Parker & Bowden 2010).

The Convention and Final Act of the International Consultations for the South Pacific Regional Fisheries Management Organisation (SPRFMO) were finalised in November 2009, establishing SPRFMO as the international fisheries management organisation with the mandate and responsibility to manage all non-highly migratory marine resources within the high-seas areas of the South Pacific Ocean (www.sprfmo.int). SPRFMO became a ratified fisheries agency in 2012. The first SPRFMO Commission meeting in January 2013 discussed the "interim measures" of the Convention which had been designed to address UNGA resolutions, and had been applied by various countries to their national fleets fishing in the SPRFMO area. The interim measures included a 'move-on rule' to force vessels encountering a potential VME to move a set distance away to avoid further impact, coupled with a spatial management regime with closed and open areas based on the historical trawl footprint (Penney et al. 2009). The efficacy of move-on rules as an effective measure to prevent impacts on VMEs has been questioned because there is a risk that such measures will result in the spread of the impacts of trawling (Auster et al. 2011).

Over the past few years there has therefore been a rapid increase in emphasis on the importance of implementing adequate and representative spatial closures to protect areas known or likely to support VMEs (Auster et al. 2011, Morato et al. 2010). The SPRFMO Commission meeting in 2013 determined that the interim measures would be replaced by an improved system of fishable and closed areas. These closures would effectively represent a preliminary spatial management plan, whereby conservation and management measures are implemented that will result in sustainable fisheries and benthic protection.

There are relatively few data records available on the distribution of VME indicator taxa in the SPRFMO area to use for the objective planning of spatial protection measures to protect VMEs. The alternative is to use model predictions of where VMEs are likely to occur. Such models have been developed for certain VME indicator taxa on a global scale (e.g., Actinaria, Guinotte et al. 2006; Scleractinia, Tittensor et al. 2009; Octocorallia, Yesson et al. 2012). However, the spatial resolution of global models is often too coarse for fisheries management purposes (i.e. larger than the scale of the topographic features typically the target of bottom fishing on the high seas) and finer scale global models (e.g., Davies & Guinotte 2011) or regional models (e.g., Tracey et al. 2011) need to be developed and used instead.

By combining models of the likely distribution of VME indicator taxa with data on the distribution of fishing effort and catch (i.e., trawl footprint) it is possible to identify areas that can be closed to protect VMEs and areas where fishing can continue. Software tools have been developed to facilitate this aspect of spatial management planning, and have been used globally to identify areas for conservation in both terrestrial and marine environments (e.g., Mikkonec & Moilanen 2013, Tognelli et al. 2005). These tools use various computational methods to select representative sets of areas to conserve biodiversity over extensive geographic areas, while at the same time minimising the cost to existing users (e.g., Klein et al. 2008).

The Ministry for Primary Industries (MPI), the fishery management agency for New Zealand domestic and high seas fisheries, including SPRFMO, asked the National Institute of Water & Atmospheric Research (NIWA) to assist them in meeting the immediate need to develop spatial management options for the protection of VMEs in the South Pacific Ocean region under project ZBD2013/01. NIWA has already undertaken a pilot, or Stage 1, VME project for the New Zealand region (ZBD2010/40; Rowden et al. 2013), and currently leads the Ministry of Business, Innovation and Employment-funded South Pacific VME project, which aims to deliver a similar outcome to the present study, but not until the end of September 2015.

1.1 Specific Objective

To investigate fisheries and biological research data to inform on options for a system of open and closed areas for bottom trawling within the SPRFMO area that protects VMEs while maintaining a sustainable fishery.

The project is comprised of three key activities:

(i) Identify areas of likely VMEs based on habitat suitability models for VME indicator taxa.
(ii) Map the recent historical and current distribution of bottom fishing (trawling) to identify areas where substantial impacts may have already modified VMEs.
(iii) Combine the main elements of i) and ii) to guide the choice of spatial management options that will balance protection of VMEs with maintenance of productive fisheries.

2. METHODS

2.1 Identifying vulnerable marine ecosystems

A VME is any ecosystem that is highly vulnerable to one of more kinds of fishing activity, and it is identified by the vulnerability of its components (e.g. habitats, communities or species). Criteria for identifying VMEs include uniqueness or rarity of species or habitats, their functional significance, fragility, and structural complexity as well as life histories that limit the probability of recovery (FAO 2009). The Food and Agriculture Organisation of the United Nations (FAO) guidelines also provide examples of taxa indicative of a VME: (i) cold-water corals of various types (e.g. reef builders and coral forest species) likely to be found on the edges and slopes of oceanic islands, continental shelves, seamounts, canyons, and trenches; (ii) sponge-dominated communities and structural biogenic habitats (e.g. those composed of large protozoans, hydrozoans or bryozoans) with a distribution similar to cold-water corals; (iii) endemic or rare types of hydrothermal vent and cold seep communities; and (iv) fish species that are sustainable only at low exploitation rates (FAO 2009).

SPRFMO has defined ten benthic invertebrate taxa that are regarded as indicators of VMEs (Parker et al. 2009). They are: Porifera (sponges); Actiniaria (anemones); Alcyonacea (soft corals); Gorgonacea (sea fans); Pennatulacea (sea pens); Scleractinia (stony corals); Antipatharia (black corals); Stylasteridae (hydrocorals); Crinoidea (sea lilies); and Brisingida (armless stars).

2.1.1 VME indicator taxa data

For Stage 1 of the South Pacific VME project (ZBD2010/40), over 31 000 records of the ten VME indicator taxa in the western part of the SPRFMO area centred around New Zealand were obtained from various database sources. These data and up to 11 environmental variables were used to make habitat suitability models that predicted the likely distribution of the VME indicator taxa. These models were made using two methods, Maximum Entropy (Maxent) and Boosted Regression Trees (BRT). Because they were constructed for the purposes of assessing the suitability of available data and different methodological approaches (Rowden et al. 2013), these models should be considered as preliminary.

Data from the Stage 1 of the MBIE-funded South Pacific VME project were available for immediate use in the present project. However, the data records are mainly concentrated in the New Zealand EEZ, with very few records from the high seas, where the models are less likely to be robust. Furthermore, the modelled region does not include the entire extent of the current fishing area on the Louisville Seamount Chain.

Ideally for management purposes, likely VMEs should be identified using habitat suitability models for indicator taxa across the entire SPRFMO area (Figure 1). This is the aim of the South Pacific VME project. In lieu of the final results of this project, all records of VME indicator taxa already extracted (as of 5 July, 2013) for the SPRFMO area and the New Zealand EEZ from OBIS (Online Biogeographic Information System: www.iobis.org) together with other online data sources, and data from research institutes (e.g., NIWA, CSIRO) and fisheries agencies (e.g. MPI, AFMA) were used for the present project. These data were compiled and groomed prior to use in the habitat suitability modelling. Overall, there were more than 300 000 records, but the number of records for each taxon varied considerably (Table 1).

2.1.2 Environmental data

The environmental data layers used in the study represent a sub-set of data collated and processed by Davies & Guinotte (2011) from global data sources (e.g. World Ocean Atlas). Nine environmental variables were used: depth, dissolved oxygen concentration, bottom water temperature, bottom water salinity, slope, particulate organic carbon flux to the seafloor, calcite saturation state, aragonite saturation state, and silicate (see Table 2 for full details of data sources). These variables were selected based on the knowledge or assumption that they directly or indirectly influence the distribution of VME indicator taxa across the study area.

Although depth is not a direct driver of species distributions, it was included as a surrogate for other variables that are known to influence species distributions in the deep sea, e.g., pressure and light (Carney 2005) and for which no appropriate data layers were available. Dissolved oxygen levels have been shown to have an influence on the distribution of deep-sea fauna, particularly once levels go below particular thresholds (Levin & Gage 1998). Temperature is known to influence the physiology and thus the distribution of deep-sea species (Thistle 2003). Salinity in the deep sea is relatively constant. However, where salinity changes due to coastal proximity, riverine inputs, or water circulation patterns, it is possible for this variable to influence the distribution of deep-sea fauna (e.g., Nielsen et al. 2010). Seabed slope is a proxy for a range of potentially relevant environmental conditions for fauna that inhabit steep or gently sloping seafloor. For example, substratum type, which is one of the most important variables controlling the distribution of seafloor organisms (Snelgrove & Butman 1994), is likely to be fine mud or sand where the slope is flat or gentle and sediment can remain deposited. Where the slope is steep, bottom current speeds can be accelerated, sediment is less likely to settle, and the seafloor is more often bare rock or composed of coarser substrates. Accelerated bottom currents along or up steep slopes also act as a delivery mechanism for food material (Genin et al. 1989, Thiem et al. 2006). The passive downward flux of particulate carbon to the seafloor has been shown to explain the distribution, diversity, abundance and biomass of deep-sea fauna (e.g., Johnson et al. 2007). This is because organic detritus, derived from surface water productivity, can provide a food source for VME indicator taxa such as corals and sponges (Duineveld et al. 2004, Duineveld et al. 2007). In addition to these six variables, carbonate chemistry variables (aragonite and calcite) were used for deep-sea coral taxa predictions as they exert a strong control on their distribution (e.g., Tittensor et al. 2009), while silicate was used in the sponge prediction model for the equivalent reason (e.g., Leys et al. 2002).

2.1.3 Habitat suitability modelling

A number of studies have recently modelled the distribution of a variety of marine taxa in environmental space (i.e., to determine habitat suitability). Examples for coldwater corals alone include; Bryan & Metaxas (2006), Bryan & Metaxas (2007), Davies et al. (2008), Tittensor et al. (2009), Woodby et al. (2009), , Davies & Guinotte (2011), Tracey et al. (2011), Yesson et al. (2012). These studies have used a number of different methods to model habitat suitability.

One of the most popular habitat suitability (or species distribution) modelling methods is maximum entropy modelling (Maxent) wherein models are designed to be maximally noncommittal with regard to missing information (Jaynes 1957). Maxent is a 'presence-background' modelling approach that has been shown to out-perform some other techniques that rely on presence data, including Ecological Niche Factor Analysis (ENFA) (e.g., Tittensor et al. 2009). The underlying assumption of Maxent is that the best approach to determining an unknown probability distribution is to maximise entropy based on constraints derived from environmental variables (Phillips et al. 2006). The algorithm is supplied within a Java software package (Maxent version 3.2.1), and the default model parameters of Maxent have been found to perform well in other studies (Phillips & Dudik 2008). Covariation between environmental data is a complication that must be addressed in many predictive modelling efforts. Environmental data used in Maxent analysis can be assessed for covariation in a correlation matrix. Strong correlations between variables (more than 0.7) can be addressed by omitting one of the correlated variables. The importance of a given variable in the model is assessed using a jack-knifing procedure that compares the performance of the model with and without that variable included. The final habitat suitability maps are produced by applying the calculated models to all cells in the study area, using a logistic link function to yield a probability of occurrence between zero and one (Phillips & Dudik 2008).

Maxent version 3.2.1 was used to predict the potential distribution for VME indicator taxa using the biological and environmental data for the SPRFMO area and New Zealand EEZ described above. However, the habitat suitability modelling, and hence the spatial management planning (see Section 2.3) and biological data was limited to data from 200–3000 m water depth. There are both ecological/conservation and practical/modelling reasons for this choice of depth range:

(1) If modelling of VME indicator taxa is restricted to target fishing depths (e.g., 600–1500 m) it will not be possible to know the relative importance of suitable habitat for VMEs within these depths, compared to shallower or deeper depths. It could be that almost all the VME suitable habitat is within fishing depths and thus this habitat is of high ecological value and it would be critical, from a conservation point of view, to protect as much of this habitat as possible. On the other hand, the amount of suitable habitat for VMEs at fishing depths could be relatively small compared to other depths, and potentially of less ecological value and the level of protection required could be argued to be less. In order to understand which of the above two scenarios is the case, VME habitat suitability models need to be made for as large an environmental space as possible - depending upon practical considerations.

(2) The performance of models is limited by the quality (e.g. taxonomic resolution), quantity and spatial distribution of available data. The VME indicator taxa are at relatively coarse taxonomic level (family to phylum) and therefore the environmental niches of these taxa are relatively large and the area of predicted habitat suitability is also likely to be very large, and thus not at a spatial resolution particularly useful for identifying closed areas. One way to constrain the model to be more useful, when using higher taxonomic levels, is to restrict the environmental space to the extent that it is possible to understand what will limit the distribution of suitable habitat for those species within a higher taxon occurring in the primary area of interest (e.g. the area around the fishing depths, in the high seas). Because depth indirectly influences the distribution of marine taxa, depth limits can be used to effectively exclude from the model those species that are adapted for environmental conditions at much shallower or deeper depths (e.g. hermatypic scleractinian corals versus ahermatypic scleractinian corals), and thus improve the model performance for

those species within a higher taxon in the area of primary interest. So what depth limits to apply –taking into account point (1)? The upper limit was set at 200 m – this depth marks the approximate shallow limit of the deep sea, where the fauna (including the VME indicator taxa) are different from those at continental shelf depths. The lower limit was set at 3000 m, for below this depth is where abyssal plains and a distinct abyssal fauna exist (and coincidently less data for the VME indicator taxa – which is partly a result of lower sampling effort here, but also known limits for some of the VME indicator taxa). Between these depths is the bathyal zone. The bathyal fauna is distinct, yet within the zone there is a gradient in faunal distribution that relates to a sometimes steep gradient in environmental conditions. This level of variability is useful for habitat suitability modelling.

For the modelling, default Maxent model parameters were used as they have performed well in other studies (a convergent threshold of 10^{-5}, maximum iteration value of 500 and a regularization multiplier of 1 (Phillips & Dudik 2008, Davies & Guinotte 2011)). Background data used for each model analysis were 10 000 randomly selected points throughout the maximum extent of the study area. The number of randomly selected points is a user-driven process and n=10 000 has performed well in other modelling efforts at similar spatial scales (Davies & Guinotte 2011, Guinotte & Davies 2012, Yesson et al. 2012). Duplicate taxa records (multiple records occurring in the same geographic cell) were removed prior to modelling to prevent model results being skewed towards environmental conditions found in heavily sampled areas. To calculate validation metrics, the presence data for each VME indicator taxon were randomly partitioned to create 75% training and 25% test datasets, with test data used to calculate performance metrics. Model accuracy between the test data and the predicted suitability models was assessed by three criteria: (1) the threshold-independent Area Under the Curve (AUC) procedure, (2) the threshold-dependent Omission Rate, and (3) test gain.

With presence-only data, Phillips et al. (2006) define the AUC statistic as the probability that a known presence site is ranked above a random background site; AUC scores of 0.5 indicate that the discrimination of the model is no better than random, and the maximum AUC value is 1, indicating highest probability that the model is accurately predicting suitable habitat (Hanley & McNeil 1982). The threshold-dependent omission rate (omission rate at fixed value of 10) (Pearson et al. 2007), evaluates model success by assessing the proportion of test locations that fall into cells that were not predicted as suitable. Test gain can be interpreted as the average log probability of the test presences being correctly predicted by the model. For example, if the test gain is 2, the average likelihood of a test presence locality is exp(2) (about 7.4) times greater than that of a random background pixel (Riordan & Rundel 2009).

Maxent model results (predicted habitat suitability from 0–100%) for each taxon were mapped using ArcMap 10 GIS software (www.esri.com).

2.2 Trawl footprint

Bottom trawling is the fishing method that has the greatest impact on VMEs within the SPRFMO area, and the project therefore focused on bottom trawling (not longlining or midwater trawling which occasionally contacts the seabed), and on benthic habitat (not pelagic habitat). The principal bottom trawl fishery, both historically and currently, is for orange roughy (*Hoplostethus atlanticus*) in the western South Pacific, in particular the Tasman Sea (Lord Howe Rise, Challenger Plateau, West Norfolk Ridge) and Louisville Seamount Chain (e.g., Clark et al. 2010). Hence the fishery analysis is based on data from the orange roughy fishery only.

2.2.1 Fisheries catch and effort data

Catch data were compiled for the entire SPRFMO area from three main sources:

(1) New Zealand high seas catch and effort data, from the MPI database (warehou). These data were obtained by combining a set of groomed data maintained by NIWA for the period 1981–2005, and a new data extract from MPI for the period 2006–2012. The dataset comprises tow by tow records for New Zealand-registered vessels fishing outside the EEZ, where the target species was declared as orange roughy, or where orange roughy were caught.

(2) FAO global catch statistics. Annual summaries of orange roughy catch (but not effort) by nation were obtained from the FAO website (http://www.fao.org/fishery/statistics/en) for the large FAO regions, a subset of which can be broadly aligned with the SPRFMO region. These data cover the years 1977 to 2011, but include domestic (within EEZ) catch as well as high seas catch.

(3) SPRFMO catch records, by nation, by year. Annual summaries of orange roughy catch in the SPRFMO area (without effort) have been provided by member nations for 1977–2011. Apart from New Zealand and Australia, these data were supplied at a coarse scale (either FAO or SPRFMO area) and for all nations are publically available only at the SPRFMO area scale. However, they exclude domestic catch.

All data were summarised into 0.1° latitude/longitude gridded squares, and catch statistics refer to the calendar year (not national fishing years, which can differ).

2.3 Spatial management planning

The practical challenges of selecting a representative set of areas to conserve biodiversity over extensive geographic areas have led to the development of a number of computer-based numerical tools, based on a variety of strategies including iterative selection, linear programming and simulated annealing. Zonation (Moilanen et al. 2012) and Marxan (Ball & Possingham 2000) are two such systematic conservation planning tools and are designed to prioritise areas for biodiversity protection based on combined analyses of the distributions of species and resource use. Both have been used widely in terrestrial and marine systems around the world, and comparisons between them result in similar spatial management for biodiversity protection (Delavenne et al. 2012).

2.3.1 Choice of software tool

Marxan is designed to solve the ‘minimum set problem’ where the goal is to achieve some minimum representation of biodiversity features for the least possible cost. It uses simulated annealing to calculate alternative sets of priority areas for achieving conservation targets; i.e., both a ‘best’ solution and a range of potential solutions that achieve similar biodiversity targets (Ball & Possingham 2000). Marxan variations include the ability to weight species or habitat types; the ability to pre-select or pre-exclude areas from protection; and aggregation options that allow for clumping of protected cells that are more suitable for management. Marxan outputs include maps of multiple solutions that provide similar levels of biodiversity protection. These are well-suited to stakeholder meetings, facilitating discussion of different options and how they interact with existing uses within a region.

Zonation uses a reverse stepwise heuristic algorithm to identify solutions that have both high value for conservation, and low cost in terms of resource use, but also are balanced with respect to representation of different species or habitats, and connectivity between protected areas (Moilanen 2007). Zonation produces a hierarchical prioritisation of the landscape based on the conservation value of the site (cells), iteratively removing the least valuable cell from the landscape until no cells remain. Zonation includes four options for cell removal rules; Core Area Zonation is the most commonly-used option, where highest values are given to the most important locations within each species’ distribution. Zonation does not require the specification of target representation levels, minimum site sizes or minimum number of areas or replicates, and model variations also include the ability to weight species, the ability to pre-exclude or pre-include particular areas, and the ability to aggregate cells.

While both Zonation and Marxan are suitable for the analyses presented here, Zonation was selected because it directly uses the kind of raster datasets which were available for the SPRFMO region, and because it has been used extensively in New Zealand contexts (e.g., Leathwick et al. 2008a, Leathwick et al. 2008b, Smith et al. 2008, Leathwick et al. 2012).

2.3.2 How Zonation works

In outline, Zonation starts with a full set of grid cells (e.g., of a particular area or degrees of latitude/longitude) that encompass the entire area of interest, and sequentially removes cells of the lowest 'value'. Cell value is calculated based on a combination of the value of the cell with respect to all taxa distributions, and cells are allocated higher value if they represent high habitat suitability for multiple taxa. However, representativeness of all taxa is also included in the solution; i.e., when taxa have disjunct or non-overlapping distributions, the solution will include cells that may be of value to only one or a few taxa. For example, if a taxon is only found in a small number of cells, these cells are more likely to be chosen as high priority to ensure protection for that particular taxon. Ideally, those cells are also of value to other taxa, but if not, the Zonation algorithm strives to make sure all taxa receive similar proportional levels of protection. Various options are available to differentially weight taxa so that particular taxa are given higher (or lower) levels of protection. For example, endemic species or particular endangered or threatened species can be given a higher weighting to make their level of protection higher than non-endemic species. Or, as in the earlier example, taxa with particularly disjunct distributions could be down-weighted, so that the solution is less dependent on one or a few taxa.

Zonation can be run with or without cost layers, i.e., trade-offs that conflict with biodiversity protection. When cost trade-offs are included, Zonation attempts to optimise biodiversity but avoid high cost areas. For example, cost areas can be those that are of value to a fishery (i.e., where fishing takes place and high catches have been historically returned). Generally, Zonation will attempt to find cells with similar biodiversity values, but that have low cost (i.e. relatively lower fish catch). Often, alternative cells can be found, although the solution may require a larger number of total cells to achieve the same value for biodiversity when optimising for both biodiversity and a cost layer.

Zonation outputs include maps of biodiversity prioritisation, where areas are identified from the highest to lowest priority in terms of biodiversity prioritisation for a particular model scenario with additional options (e.g., trade-offs). Typically, solutions are presented as maps that identify the top 10% of the area for biodiversity; next highest priority areas with ranks of 10–25%; area with ranks of 25–50%; and the 50–100% lowest priority areas for biodiversity protection. Outputs include the proportion of each taxon range protected across the full range (i.e., 0–100% of total area protected) of area put into biodiversity protection, such that solutions can identify combined metrics such as average, minimum and maximum levels of protection.

2.3.3 Use of Zonation in the present study

In the present study Zonation is used to integrate the VME indicator taxa habitat suitability distribution data and fishing catch/effort datasets derived above (Sections 2.1 and 2.2) to illustrate how priority sites for VME protection that minimise cost to existing users of the SPRFMO area can be determined, and thus inform the development of management options for the SPRFMO area.

Data for all VME indicator taxa were available at a 1 km^2 grid cell scale, but for use in Zonation were re-gridded to a 0.1° latitude/longitude grid to be at the same scale of the metrics that represent fishing cost. The re-gridding method used selected the 1 km^2 cell with the highest value of habitat suitability, rather than the mean value or the value of the cell nearest the centroid of the larger cell. While the Maxent models for VME indicator taxa were created using data from the New Zealand EEZ as well as from the SPRFMO area, all data layers for the Zonation prioritisation analyses were limited ('clipped') to the SPRFMO area only. Layers and analyses were also limited to a depth range of 200–3000 m to match the depth range over which the habitat suitability maps were created (see Section 2.1.3).

A range of model scenarios were developed to show how the Zonation tool works, and how different options within the software can be used to modify solutions to better suit the existing datasets.

2.3.4 Model scenarios

VME indicator taxa datasets

Model scenarios were performed using two datasets to represent VME indicator taxa distributions. Both VME indicator taxa datasets were based on the Maxent model output for each of the 10 VME indicator taxa (Section 2.1). For the first dataset, the full range of probability of occurrence values (ranging from 0 to 1) from the Maxent models were used. Higher values represent a higher likelihood of occurrence, suggesting higher habitat suitability for the VME indicator taxa. In the second dataset, a presence/absence map for each VME indicator taxon was used based on a threshold of 50% habitat suitability (i.e. greater than 0.5 probability of occurrence, or a taxon is more likely to be present than not). The use of higher suitability thresholds (70% and 90%) was also assessed; however, the total number of cells with these high values was not sufficient to perform the biodiversity optimisation modelling (Table 3).

Because reefs formed by scleractinian (stony) corals are considered to be significant VME habitats (UNGA 2006, FAO 2009), additional model runs were performed in the first set of scenarios to evaluate the Zonation output if the Scleractinia VME indicator taxon was weighted higher than the other nine VME indicator taxa. A weighting of 5:1 for Scleractinia versus other taxa was applied; this increased relative weighting means that Zonation gives a five times higher weighting to this taxa when calculating the relative priority ranking of cells in the Zonation algorithm.

Incorporating aggregation

The second set of scenarios investigated options for creating more aggregated solutions, such that larger numbers of cells are grouped together in solutions more practical for management than a suite of smaller, more fragmented groups of cells (Moilanen & Wintle 2007). There are a number of options within the Zonation software that create more aggregated solutions, which vary in the mechanism driving this increase in aggregation. Three of these methods were considered: edge removal; Boundary Length Modifier (BLM); and Boundary Quality Penalty (BQM).

The default 'edge removal' rule (where cells with fewer neighbours, i.e. on the edge, are given lesser priority for biodiversity) was used and compared with a run without this edge removal rule (i.e., edge rules or cells with few neighbouring cells within the model region, are not preferentially removed from solutions as lower priority). BLM is not taxa-specific, and uses algorithms that reduce the length of the perimeter of the combined cells, thus reducing fragmentation and increasing aggregation. BQP uses algorithms that allow for taxa-specific connectivity requirements. Solutions using BQP aggregation rules give higher priority to cells within a defined neighbourhood of other occupied cells. For example, the neighbourhood of a VME indicator taxon might be defined as being a maximum distance of 10 model cells. In this case, a cell with fewer cells occupied with a VME indicator taxon within that 10 cell neighbourhood is given lower priority than a cell with more occupied cells in its neighbourhood. This additional connectivity value is calculated for each taxon for each model cell, resulting in solutions where connected patches of cells are given higher priority than in scenarios without these rules.

Edge removal and BLM models was performed to illustrate the similarities in solutions with and without aggregation. BQP runs were not performed because these would require additional expert assessment to estimate connectivity neighbourhoods of each VME indicator taxon, but would be expected to show similar solutions to BLM scenarios.

Incorporating cost

The third set of model scenarios were run with cost trade-offs, comparing between different versions of fishing cost metrics over different time periods to see how biodiversity prioritisation changed when optimised to minimise fishing cost. Scenarios were run for four cost metrics, using either catch (metric tonnes) or effort (number of trawl tows), each of which was summarised over two periods: either the current SPRFMO reference trawl footprint based on fishing records from 2002–2006, or the complete historical trawl footprint based on fishing records from 1980–2012 (Section 2.2).

Bioregional representation

Finally, the last set of model scenarios used an existing 'bioregion' designation to aid in the identification of representative, high priority areas for VME indicator taxa throughout the SPRFMO area. These model runs used the lower bathyal benthic biogeographic provinces of Watling et al. (2013) (Figure 2). To incorporate biogeographic province representation, the lower bathyal provinces of Watling et al. (2013) were treated as 'taxa' datasets, and incorporated as additional taxa within the Zonation runs. As such, Zonation sees each province as a taxon, and attempts to provide solutions with similar protection to each province, as it does for each of the actual VME indicator taxa. Two sets of runs were performed: (1) including 10 VME indicator taxa and 8 lower bathyal provinces, with equal weighting given to VME indicator taxa and provinces; and (2) including 10 VME indicator taxa and 8 lower bathyal provinces, but giving 5 times higher weighting to VME indicator taxa than to provinces. Here, down-weighting is included as an option to allow a bioregional approach, but still let the VME indicator taxa suitability maps drive the resulting output.

Table 4 summarises the different model scenarios used in the Zonation analysis.

2.3.5 Assessing scenario performance

To analyse the performance of the Zonation scenarios, assuming that identified high priority areas (top 10% of VME indicator taxa priority ranking) would be closed to fishing, ArcMap was used to calculate the proportion of suitable habitat cells for each VME indicator taxon that were identified as high priority across each model run. Suitable habitat cells were defined as those with more than 50% habitat suitability for each VME indicator taxon.

A similar statistical comparison was carried out to determine the proportion of high priority cells (based on all VME indicator taxa) in each of the biogeographic provinces across each model scenario in order to assess the performance of the bioregionalisation approaches.

To assess the performance of the cost model scenarios in terms of the impact on fishing activity, ArcMap was also used to calculate the proportion of trawl footprint lost to fishing if high priority areas for VME indicator taxa were to be closed.

3. RESULTS

3.1 Modelled distributions of VME indicator taxa

Figures A1–A11 (Appendix 1) show distributions of habitat suitability for all VME indicator taxa within the study area between 200 and 3000 m water depth, as predicted by the Maxent models. Table A1 (Appendix 2) lists the environmental variables that contribute the most to the models that explain the distribution of the habitat suitability for the VME indicator taxa.

Selected figures from Appendix 1 are used here to illustrate the results of the modelling. No further reference is made to the variables that explain the different models, as these results are irrelevant to the objectives of the present study.

3.1.1 Model performance

Individual models for all VME indicator taxa had AUC scores of more than 0.7, which indicates that they are "useful" for predicting the distribution of habitat suitability across the study area (Guisan et al. 2007). The model for all taxa combined did not quite meet this criterion (Table 5). The best performing models (i.e., relatively low omission rate, and high test gain and AUC scores) were for Brisingida, Pennatulcea and Antipatharia, while the worst performing models (i.e., the converse of the above metrics) were for Porifera, Actinaria, and Scleractinia. The performance of the models for the remaining four VME indicator taxa fell between these extremes.

3.1.2 The distribution of habitat suitability for VME indicator taxa

The Maxent models predict that habitat suitability for the VME indicator taxa is generally low (less than 40% habitat suitability) over much of the SPRFMO area between 200 and 3000 m (e.g., Gorgonacea, Figure 3). Areas of relatively high habitat suitability (60–80% habitat suitability) are generally limited to the New Zealand EEZ, and the Kermadec and Colville Ridge, Lord Howe Rise, West Norfolk Ridge, Three Kings Ridge, Tasman Plateau, and Louisville Seamount Chain in the High Seas region of the study area (e.g., Alcyonocea, Figure 4). Within the Louisville Seamount Chain, predicted areas of relatively high habitat suitability (60–80%) are small and occur on the summit or flanks of individual seamounts along the chain (e.g., Scleractinia, Figure 5). Areas where habitat suitability is predicted to be particularly high (over 80%) in the study area are generally very limited, and only occur for some VME indicator taxa (e.g., Crinoidea, Figure 6).

3.2 Trawl footprint

3.2.1 New Zealand catch data

Orange roughy fishing by New Zealand vessels in the SPRFMO area began in 1981 (Table 6). Estimated catches initially fluctuated very widely, from nearly 11 000 t in 1983 to 20 t only two years later, with a maximum catch of 12 244 t reported in 1995. Annual catches were subsequently more stable, but have generally declined and since 2007 have been mostly less than 1000 t. For the current SPRFMO trawl footprint reference period (2002–2006) (see below), there were 12 445 trawl tows and the estimated catch totalled 11 661 t. This catch compares with 82 336 t from 46 419 tows for the period of entire fishing history (1981–2012).

3.2.2 New Zealand effort data

The annual geographical extent of the New Zealand fishing effort was estimated by gridding the effort data into 0.1° latitude/longitude rectangles. The number of non-empty cells were calculated for various time periods; the current SPRFMO trawl footprint reference period (2002–2006), then sequentially longer time periods going forward (2002–2007, 2002–2008, etc., as far as 2002–2012) and backward (2001–2006, 2000–2006, etc., to 1980–2006) for comparison (Table 7).

The total trawl footprint of the New Zealand fishery in the SPRFMO area in the reference period (2002–2006) covered 578 grid cells. By lengthening the reference period to include additional years prior to 2002 the footprint becomes progressively larger; rapidly at first, so that for the period 1993–2006 the footprint is about 70% larger than that for the reference period, covering 993 cells. Extending the reference period further back in time continues to grow the footprint, but at a much slower rate–approximately half that of the 1993–2006 period. In a similar fashion the footprint grows relatively slowly as extra years are added to the reference period subsequent to 2006 (Table 7).

The spatial distribution of the trawl footprint has changed over time (Figure 7). The total footprint from 1980 through to 2006 has a strong concentration of fished cells around the margins of the Challenger Plateau, Lord Howe Rise, and West Norfolk Ridge to the west of New Zealand. On the Louisville Seamount Chain to the east, effort has occurred over a considerable length of the Chain, but with several areas of concentrated effort on some of the major seamounts. Each panel in Figure 7 drops a year of effort, and shows how the distribution of effort contracts, especially on the Lord Howe Rise and the Louisville Seamount Chain. The final panel in the figure shows the footprint for the SPRFMO reference period 2002–2006.

3.2.3 FAO catch data

FAO areas 57, 71, 77, 81, and 87 encompass all the known SPRFMO orange roughy fisheries without including any other high seas fisheries (Figure 8). These data are only available for combined domestic and high-seas catches, and to ascertain high-seas catches separately domestic catches of orange roughy would need to be obtained for each nation and subtracted from the totals.

Orange roughy catch in the region (including domestic catch) has been dominated by vessels from New Zealand and, to a lesser extent, Australia. Lower catches by USSR/Russia were limited mainly to the 1980s, and by Norway to the 1990s (Table 8). Catches mostly came from the Pacific Southwest (area 81), with smaller contributions from the Eastern Indian Ocean (area 57) and the Pacific Southeast (area 87) (Table 9).

3.2.4 SPRFMO catch data

Data from the SPRFMO database, as supplied by member nations, are variable in that it has not been made clear in each case whether or not the catch totals include domestic (within EEZ) catches. Despite this uncertainty, the figures supplied provide a reasonable indication of the relative level of catch over time by each fishing nation (Table 10). As shown also in the FAO data, catches were mostly by New Zealand and Australian vessels. However there were also substantial catches by Russian Federation vessels in the 1980s as well as smaller amounts of catch recorded against Belize, the Republic of Korea, and China. Unlike for the FAO data, there is no Norwegian catch information.

The landings totals in the FAO data closely match those in the SPRFMO data for Belize, China, and the Russian Federation/USSR, whereas Chile and Norway have reported no high-seas catch to SPRFMO. However, there are domestic landings recorded for Chile and Norway to FAO for FAO areas 87 and 81, respectively. Other differences between the two data sets are in the Ukraine FAO catch which includes some domestic catch between 2000 and 2006, and the Republic of Korea which records some domestic catches between 1999 and 2002.

3.3 Spatial management planning

3.3.1 VME indicator taxa datasets

The first set of model scenarios compared the two VME indicator taxa datasets. The goal was to demonstrate whether results differed if the full range of habitat suitability values was used to run the prioritisation simulation, versus using only the subset of cells corresponding to at least 50% habitat suitability for each VME indicator taxa. These first runs were undertaken with the default 'edge removal rule' (see Section 3.3.2). A comparison of Figures 9 and 10 shows that the outputs from simulations are similar overall between the two VME indicator taxa datasets. For example, both simulations using the edge removal rule show nearly identical prioritisations within the Tasman Sea region (including here parts of the Lord Howe Rise, Challenger Plateau and West Norfolk Ridge) and Louisville Seamount Chain regions. While there is little difference in the selection of the highest priority cells (i.e., top 10% in terms of value for biodiversity alone), there is more variation in the 10–25% and 25–50% priority cells between simulations with the two underlying VME indicator taxa datasets. For example, differences in the distribution of the 10–25% priority cells are noticeable at the eastern end of the Chatham Rise and along the South East Pacific Rise.

This difference is primarily explained by differences in the amount of data for the full range of habitat suitability values dataset compared to the subset threshold-based dataset. The threshold dataset has non-zero values only for a limited number of cells (about 10%) in the SPRFMO area that have more than 50% habitat suitability as defined by the MaxEnt models for each taxon. As such, cells below the threshold suitability level are given zero values and they cannot be selected as priority areas (other than by model scenarios that use aggregation algorithms, see below), whereas cells with values less than 50% habitat suitability can be prioritised when using the full range of values dataset. For example, using the full range of values dataset would allow a cell with a 25% habitat suitability to be valued higher than a cell with a 1% habitat suitability, and priority would be assessed based on their proximity to higher priority cells.

The similarity in the selection of high priority cells between the full range and threshold datasets provides confidence that any full range dataset-based scenarios are prioritising the high habitat suitability areas that would be identified by threshold-based scenarios, but are also able to better resolve the relative priority of cells with values below the 50% threshold. As such, the full range of habitat suitability values dataset allows better representation of relative habitat suitability across the SPRFMO area, and is considered more useful than a prioritisation based simply upon a minimum model output threshold.

The scenario run based on the full range of habitat suitability values with equal weighting given to all VME indicator taxa, was generally similar to the run where the taxon Scleractinia was given a higher weighting for biodiversity value (compare Figures 10 and 11). This result suggests that the selection of high priority areas based on equally weighted taxa data provide adequate representation of areas of relatively high habitat suitability for scleractinian corals. Thus, all subsequent Zonation scenarios were run using the full range of habitat suitability values, using equal weighting for all 10 VME indicator taxa.

3.3.2 Incorporating aggregation

The second set of scenarios investigated whether options to create more aggregated solutions might be more amenable to management. Using Zonation's default option which promotes selection of non-edge cells, the run 'with the edge removal' rule results in a solution that shows highest priority along the centre of many of the ridges and rises (see above, Figure 10) compared with selections made 'without the edge removal' rule (Figure 12). The selection of cells along the centre of ridges and rises using the edge removal rule is primarily a result of the long and narrow form of some of the dataset boundaries which are aligned with elevated seafloor topography. The solution from the run 'without the edge removal' rule removes the focus from the centres of ridges and rise, and effectively reduces the topographic feature-related data bias from the results.

The output of the model using one of the other aggregation rules in Zonation, i.e., BLM, suggests a bias to prioritising areas where most of the high habitat suitability values occur for the VME indicator taxa (e.g., the Kermadec Ridge region), and low prioritisation to more fragmented areas of high biodiversity value (e.g., the Louisville Seamount Chain, Figure 13). Because the use of either aggregation results in a topographic-related bias (either towards or against), neither the edge removal rule nor BLM were included in any further model scenarios.

3.3.3 Incorporating cost

The third set of scenarios that used the 'basic' model (i.e., full range of habitat suitability values for all VME indicator taxa, no aggregation rule, Figure 12) with four different cost layers resulted in the selection of generally similar priority protection areas for VMEs (Figures 14, 15, 16, 17). Some differences do exist between the outputs for catch and effort for the period 2002–2006; for example in the Tasman Sea region cells in the southern part of the New Caledonia Trough have a lower priority when using catch versus effort as a cost metric (more than 50% versus 20–50%) (compare Figures 14 and 15). In general, there is a larger proportion of the main fishing areas deemed to be high priority for protection when using cost metrics for the period 2002–2006 versus those for 1980–2012, which relates to differences in the trawl footprint for these two periods. For example in the Tasman Sea region this difference is noticeable on the Challenger Plateau and the southern end of the Lord Howe Rise (e.g. compare Figures 14 and 17). Despite these variations between the cost metric and the time frames there is consistency across all trade-off models in the selection of the major high priority areas; i.e., the central parts of the Lord Howe Rise and west Norfolk Ridge, the northwest Challenger Plateau, the tops of seamounts on the Louisville Seamount Chain, the northern ends of the Colville and Kermadec Ridges, and the southern end of the South Tasman Rise.

3.3.4 Bioregional representation

The last set of model scenarios were designed to demonstrate how high priority areas for VME indicator taxa, without and with a trade-off for fishing cost, may be selected throughout the SPRFMO area while taking account of bioregional representation. The results for the no-cost run that included down-weighted lower bathyal provinces as a layer is generally similar to the basic model output without any inclusion of biogeographic provinces (compare Figure 18 with Figure 12). However, Figure 19 which represents the use of un-weighted biogeographic provinces illustrates how the Zonation algorithm distributes the high priority cells among all eight provinces, which noticeably reduces the amount of high priority area in the Tasman Sea region and Louisville Seamount Chain. The inclusion of a cost layer (e.g., catch for 1980–2012) in model runs for both weighted and un-weighted biogeographic province layers further reduces the amount, and alters the distribution of high priority areas in each biogeographic province (Figures 20 and 21). For example, the use of the un-weighted biogeographic provinces to achieve bioregional representation with a fishing cost trade off results in very few cells of the highest priority ranking (top 10%) being identified along the Louisville Seamount Chain (compare Figure 21 with Figure 17).

3.3.5 Scenario performance

Assuming that areas identified as high priority (top 10%) for VME indicator taxa would be protected by fishing closures, the basic model runs resulted in high protection of all VME indicator taxa, both without and with an aggregation rule (e.g. edge removal) (Table 11). This result is expected as these scenarios are designed to prioritise locations where habitat is most suitable for VME indicator taxa. Incorporating cost layers (both catch and effort, and both the current reference trawl footprint of 2002–2006, and the historical footprint of 1980–2012) resulted in reduced total protection for all VME indicator taxa (Table 11). Again this result is expected as these scenarios represent an attempt to trade off the selection of high priority areas for VME indicator taxa against those areas of importance for fishing. However, cost scenarios still resulted in relatively high protection of the high priority areas for each VME indicator taxon (i.e., under these scenarios the proportion of high priority area that was predicted to be suitable habitat for VME indicator taxa ranged from 67% to 95%). Assuming that VME indicator taxa are present in suitable habitat that was previously fished, protection was higher when using the current reference trawl footprint (2002–2006; 79 – 95 %) compared to the footprint based on all years (1980–2012; 67 – 92 %), with effort-based cost scenarios resulting in slightly higher protection (1 – 6 %) than catch based cost scenarios (Table 11). Across the four cost model scenarios, protection varied consistently between VME indicator taxa; with highest protection given to the Pennatulacea (85–95%) and Actinaria (82–94%) and the lowest to the Porifera (67–83%) (Table 11).

The model scenario using the un-weighted biogeographic provinces provided relatively little protection for 6 out of the 10 VME indicator taxa (less than 32%: Alyconacea, Antipatharia, Crinoidea, Gorgonacea, Scleractinia, Stylastridae) and highly variable levels of protection among taxa. Highest values of relative protection were achieved for Pennatulacea and Actinaria under the un-weighted biogeographic province scenarios (Table 11). The scenario where bioregional representation of high priority areas were identified using down-weighted biogeographic provinces, provided for greater levels of protection for all VME indicator taxa (more than 71%).

There were large differences in the distribution of high priority areas in each lower bathyal province across the SPRFMO area (Table 12). Provinces 5, 6 and 10 (Southeast Pacific Rise, New Zealand/Kermadec, and Subantarctic) had the highest percentage of high priority areas (22–35%), while the remainder of the provinces had relatively small proportions of high priority areas (about 1–7%). Relative protection for the high priority areas was highest for Province 6 in the basic and cost Zonation model scenarios (25–31%) (Table 12). Protection of high priority areas in the remaining provinces was generally low (2–7%) or very low (less than 2%) for the basic and cost scenarios (Table 12). Including un-weighted biogeographic provinces in scenarios for bioregional representation generally resulted in much higher proportional representation of high priority areas across all provinces; the exceptions being Province 5 and 10 (no change or slight decrease, respectively) and Province 6 (fourfold decrease). The down-weighted province scenario resulted in a more equitable increase in bioregional representation from the basic and cost model runs, less of a decrease for Province 6, and a small reduction in the amount of protection for high priority areas for Provinces 5 and 10 (Table 12).

The proportion of the trawl footprint lost to fishing if high priority areas for VME indicator taxa are protected (i.e., the cost to fishing) differed between model scenarios with different cost metrics, and with different cost years (Table 13). The larger area of the footprint for the historical (1980–2012) versus the current reference (2002–2006) trawl footprint resulted in generally lower costs to the fishing industry when cost was calculated based on the historical footprint. While apparently counter-intuitive, this calculation results because the historical footprint has a larger total area, but with a greater proportion of total catch and effort within the current reference footprint. When calculating relative cost of areas allocated to protection, the proportion of high priority cells outside the current reference footprint is low, such that when these cells are allocated to protection, the relative cost to fishing is lower for the historical footprint than for the current reference footprint where fishing is concentrated in fewer high fishing value cells, and the relative cost of allocating any of these cells to protection is thus higher. Using the catch metric (both 2002–2006, and 1980–2012) with an aggregated solution (‘with edge removal’) was more costly than a non-aggregated model solution; as individual cells of high fishing value within areas of generally high biodiversity value would be included as high priority for protection in an aggregated solution. Without aggregation, costs to the fishing industry based on catch metrics were all less than 1% of the trawl footprint when high priority areas (top 5–20%) for VME indicator taxa are protected. With aggregation, costs were higher, with 1.54% and 7.56% of the footprint lost to the fishing industry when the top 10% high priority area is protected based on the historical (1980–2012) and the current (2002–2006) fishing footprint, respectively. The cost to fishing increased non-linearly with increasing area protected for the catch metric scenarios, such that when protection levels were between 10 and 15%, there were no further alternative areas of high value for VME indicator taxa that could be selected that did not also have high value for fishing. Costs to fishing determined using effort were higher than costs calculated using catch, as the data range for the catch metric is much larger (up to 65 535 t for both 2002–06 and 1980–2012 datasets) than for the effort metric (up to 315 trawls for 2002–06, and 2608 for 1980–2012 datasets respectively). In the effort scenarios, the relative cost to fishing of allocating low effort cells to protection is larger than in the catch scenarios, as the low effort cell values are generally a larger percentage of the total number of tows compared to the low catch cell values relative to the total catch. Also the effort-based trawl footprint included a larger area so that fewer cells were available that did not have value for both biodiversity and fishing. Costs to fishing using the effort scenarios showed similar patterns between aggregated and non-aggregated scenarios, with lower costs to fishing for non-aggregated solutions which allowed for individual cells to be unprotected while surrounded by protected cells.

For model scenarios that include bioregional representation (e.g., unweighted provinces) as well as a cost (e.g., catch 1980–2012) layer, the proportion of the priority area for VME indicator taxa lost to fishing is very small (up to 1.4% for the top 20% priority areas for VME indicator taxa) (Table 13). This result is because the bioregionalisation distributes the priority areas among some bioregions that currently have no fishing in them.

4. DISCUSSION

The aim of the present study was to investigate fisheries and biological research data to inform possible options for a system of open and closed areas for bottom trawling within the SPRFMO area that protects VMEs while maintaining an economically sustainable fishery. Data for 10 VME indicator taxa were used in Maxent models to predict habitat suitability for these taxa across the study area, while effort and catch data for the New Zealand orange roughy fishery were used to determine the trawl footprint. These two data streams were then used in the software tool Zonation to explore different options for the spatial management of the SPRFMO area that would provide bioregional representative protection of VMEs in closed areas, while allowing bottom trawling to continue in areas that had previously been fished.

The aim of this project was to illustrate *how* closed and open areas can be identified in an objective and transparent manner, not to identify *which* particular areas SPRFMO should protect or leave accessible to fishing activity. The latter is for the members of the SPRFMO Commission to consider when they decide on the future of the interim measures put in place to protect VMEs. However, the results of this project can aid SPRFMO in their decision making process by first supplying information to MPI about how spatial management options can be developed for the protection of VMEs. This information was originally presented to MPI prior to the 2nd SPRFMO Scientific Committee meeting in La Jolla, USA in October 2013.

Before outlining the main outcome of the present study in the context of future efforts to designate open and closed areas in the SPRFMO area, it is important to discuss first how well each of the component parts performed in the context of the general approach adopted for this illustration of how to develop spatial management options for the SPRFMO area.

4.1 How useful are the Maxent predictive models for identifying VMEs in the SPRFMO area?

In a recent review of the use of presence-background models for predicting the distribution of VMEs in the deep sea, Vierod et al. (2013) identified the issues that face the use of models such as Maxent. Vierod et al. (2013) considered that despite improvements in model algorithms, the availability and spatial resolution of environmental data, and the accessibility of verified species record data, there are still limitations to the reliability of these modelling techniques, particularly in poorly studied areas such as the deep sea. The review focuses on the issues of sampling bias, spatial autocorrelation, spatial scale, model validation and evaluation, all of which influence the reliability of model outputs and their acceptance for use in ocean management (Vierod et al. 2013). The authors of this review also provided best practice information on how to aid the adoption of presence-background models for VMEs, and the incorporation of these predictions into spatial management initiatives designed to address the obligations of RFMOs to protect VMEs.

The models of VME indicator taxa for the bathyal region of the SPRFMO area (and the New Zealand EEZ) include measures to account for spatial autocorrelation (covariation between environmental data was checked), sampling bias (removal of duplicate records in a cell), and the model was internally validated (training and test data partitioning) and performance was evaluated using three independent measures. These evaluation metrics (omission rate, test gain, AUC score) indicated that the models for each VME indicator taxon were ‘useful’ for predicting the distribution of habitat suitability across the SPRFMO area.

Notwithstanding the limitations that are still attached to the use of presence-background models, their utility for identifying areas that might support VMEs, particularly in data poor areas, has been recognised and they are beginning to be incorporated into fishery management processes. For example, Maxent models of deepwater corals have been used in the Pacific Fishery Management Council’s review of its protection plan for Essential Fish Habitat and Habitat Areas of Particular Concern (Guinotte & Davies 2012), and to support discussions of management and conservation measures by the South Atlantic Fishery Management Council (Kinlan et al. 2012).

While models such as Maxent have been put to practical fishery management use by predicting the location of VMEs, the wider acceptance of, and confidence in, habitat suitability models is dependent upon field validation. Efforts to identify false positives, false negatives, and determine overall model accuracy for resource management and conservation are now seen as a priority (Vierod et al. 2013). To date, the results of any field validation surveys of large-scale models for VME indicator taxa that may have been carried out are yet to be published, so it was not possible at the time of this study to assess general reliability of models used here.

While the Maxent habitat suitability models presented here are considered useful for the purpose of illustrating how such models can be incorporated into a method for developing management options for open and closed areas in the SPRFMO area, they will need to be improved in the future. The South Pacific VME Project is seeking to produce more reliable models based on a greater amount of biological data and using improved and additional environmental data layers (e.g., improved layers for carbonate variables and new substrate type data layers), as well as field validation through a survey in February 2014. This project will use more than one modelling approach (e.g., Maxent and Boosted Regression Trees) and will attempt to make more refined models for VMEs across the entire SPRFMO area (e.g. by combining data for particular VME indicator taxa at a lower taxonomic resolution) and smaller-scale models for particular seamount features (e.g. using bathymetric data from research and fishing industry multibeam echosounder surveys) (see Rowden et al. 2013 for details).

4.2 How representative is the trawl footprint of the New Zealand orange roughy fishery of all bottom trawling in the SPRFMO area, and which footprint time period is the most appropriate to use for spatial planning?

Only tow by tow New Zealand data for the orange roughy fishery were used to determine the trawl footprint. There are two questions that arise with using a sub-set of the full fishery from only one nation to use as a footprint for the development of management options for closed and open areas in the SPRFMO area. Firstly, is the total catch from that nation large enough to be indicative of catch trends in the entire fishery? Secondly, is the distribution of the footprint from that nation representative of the areas fished by others?

The summary information of data reported to SPRFMO from each nation enables a comparison of the relative importance of various nations in the overall orange roughy fishery. Major commercial fisheries in the High Seas around New Zealand are known from 1988 (Clark 2008), and hence the Russian Federation catches prior to that date are likely to have been from inside the New Zealand EEZ (where it is known that Russian vessels were fishing orange roughy). Taking the period from 1990 onwards, New Zealand reported catches of about 55 000 t, which is 75% of the total reported to SPRFMO by all countries (even including the Korean catch history, some of which is inside an EEZ).

Detailed spatial data are not available for the distribution of the total fishery. However, at least in the western part of the South Pacific Ocean, extending into the Tasman Sea west of New Zealand, the New Zealand fleet has fished most of the likely orange roughy habitat. The footprint of the New Zealand and Australian fleets is known to be very similar, and focussed on the grounds of the northwest Challenger Plateau, Lord Howe Rise, West Norfolk Ridge, and Louisville Seamount Chain (Clark 2008). Hence there is no reason to suspect that the distribution of New Zealand fishing is markedly different from other nations.

The New Zealand data also give an insight into the differences of patterns in catch and effort over time. The 2002–06 period had 12 445 tows with a catch of 11 661 t. These figures represent about 14% of the New Zealand catch of orange roughy over the total period 1981–2012, and almost 27% of the number of tows. However, the summary data for footprint size show that fishing since 2002 has consistently occurred in about 500 0.1° latitude/longitude cells. This footprint area compares with earlier years where over 1100 cells were fished. The marked reduction in the footprint area is reflected in a contraction of the geographical extent of trawling for orange roughy in the SPRFMO area, which can be appreciated by examination of the sequence of panels presented earlier in Figure 7. The scale of Figure 7 is such that the distribution of cells in any one area is difficult to see in detail, but a comparison of the very first and very last panels demonstrates that in the earlier years more of the Louisville Seamount Chain, the northwest Challenger Plateau, and Lord Howe Rise were fished. Hence, using only the 2002–06 period for the fishing footprint will affect the spatial management modelling results in that it suggests that the fishing footprint, and therefore the distribution of fishing impact, is more restricted than it has been.

4.3 How useful is Zonation as a tool for developing spatial management options for the SPRFMO area?

Zonation and other conservation planning software tools have been used extensively to inform management decisions to determine high priority and representative networks of protected areas (e.g., Leathwick et al. 2008a, Leathwick et al. 2010, Sharp & Watters 2011, Mikkonen & Moilanen 2013).

In the present use of Zonation to illustrate the application of these tools for the SPRFMO area, the maps of priority areas that were produced showed consistency between model scenarios in the identification of high value areas for VME indicator taxa. Much of this consistency in identification of priority areas is due to the nature of the VME indicator taxa datasets. Habitat suitability models for the 10 VME indicator taxa showed high overlap, within the 200–3000 m depth range, such that the combined area with suitable habitat (over 50% habitat suitability) for one or more VME indicator taxa was a restricted portion (less than 15%) of the total SPRFMO area. A variation in the underlying habitat suitability models within one of the scenarios, to demonstrate how the selection of priority areas can be weighted towards relatively important taxa (Scleractinia in this case) also identified similar areas. This result (for the Scleractinia-weighted scenario) implies that the combined un-weighted data for the 10 VME indicator taxa can provide suitable representation for stony corals that can form reef structures; habitats that are considered as significant VMEs.

Consistency was also observed in model solutions that incorporated different cost metrics and periods of fishing history in trade-off scenarios to minimise the cost to the fishing industry. While the smaller, current reference (2002–2006) trawl footprint resulted in a smaller trade-off for biodiversity protection than the larger footprint for the entire history of the fishery (1980–2012), the resulting mapped solutions showed high spatial overlap. This consistency in area selected in trade-off analyses gives confidence that Zonation is consistently representing the fishing footprint, as well as suitable habitat for VME indicator taxa.

Other Zonation exercises have also used modelled species distribution layers to provide continuous information to inform biodiversity prioritisation (Leathwick et al. 2008a, 2008b, Duffy & Lundquist 2013). Modelled datasets for demersal fish (both modelled catch/abundance and presence/absence) have been used as proxies for biodiversity to identify high priority areas for protection in New Zealand's EEZ, inshore areas, and individual bioregions (Leathwick et al. 2008a, Leathwick et al. 2008b, Duffy & Lundquist 2013). Modelled distribution data for rocky reef fish in New Zealand's inshore waters have also been used successfully in Zonation for identifying high priority areas of an inherently fragmented habitat (Smith 2008).

The fragmented nature of the seafloor habitat (between 200 and 3000 m) in the SPRFMO area (ridges and seamounts where typically orange roughy and VME indicator taxa are located), did cause a potential issue for the identification of areas for protection outside of the Tasman Sea region with its contiguous rises and plateaus. The Zonation algorithm is designed to maximise selection of contiguous cells, and includes a number of aggregation options to further minimise fragmentation of priority cells. The Zonation scenarios that investigated two of these options (edge removal, BLM) showed that the use of aggregation rules did indeed reduce fragmentation in some areas (e.g., Lord Howe Rise) but in other areas (e.g., Louisville Seamount Chain) the result of the model's attempt to improve connectivity was a down-weighting of the prioritisation of cells for biodiversity protection.

Additional scenarios, performed to spread cells allocated to protection across the different biogeographic provinces recognised within the SPRFMO region, showed generally lower overall protection relative to scenarios without incorporating bioregions. Much of this difference is because the majority of the predicted suitable habitat for VME indicator taxa is located within Province 6 (New Zealand/Kermadec), probably a reflection of fact that the majority of the data records available to drive the MaxEnt models were located within this province (see Rowden et al. 2013 for this issue with Maxent models). As such, scenarios that spread protection across bioregions result in moving cells away from Province 6, and thus replacing highest priority cells with lower value cells found across the other bioregions in the SPRFMO area. By applying a down-weighting to Province 6, the bioregional representation of high priority became more equitable. If more equivalent bioregional protection is preferred, another method to achieve this result would be to run individual scenarios within each bioregion to identify the highest priority cells within each bioregion independently.

The results of applying Zonation to the SPRFMO area were similar to other Zonation exercises for New Zealand marine habitats that have also incorporated cost to fishing (Leathwick et al. 2008b). In the present analysis, substantial benefits to conservation were demonstrated with low cost to fishing, with protection for high priority areas (top 10%) resulting in protection of about 70–90% of suitable habitat across all 10 VME indicator taxa in all four cost scenarios. This relatively high level of protection, given only 10% of the SPRFMO area allocated to protection, comes at a low cost to the fishing industry; with estimates of 0–9.55% of the trawl footprint lost to fishing depending on the cost metric, bioregionalisation, and the degree of aggregation included in the model. Incorporating aggregation in the model scenarios resulted in a larger cost to fishing, as individual cells of high value to the fishing industry were included (connected) in larger high priority areas for protection.

4.4 What was the basic outcome of the study, and what can be done next to further the development of management options for the protection of VMEs in the SPRFMO area?

The main outcome of the present study is a demonstration of the practical utility of using habitat suitability models, historical fishing data, and a conservation planning software tool to develop options for the spatial management of the SPRFMO area.

The illustration exercise generated apparently useful habitat suitability maps for VME indicator taxa at bathyal depths across the entire SPRFMO area. However, it is also clear that uncertainties inherent in background-presence models of the deep sea need to be addressed in the future in order to make more reliable predictive maps for the area.

Data from the New Zealand orange roughy fishery is considered a useful proxy for the trawl footprint of all other nations in the SPRFMO area. The trawl footprint of the entire history of the fishery (1980–2012) is notably larger than the reference trawl footprint (2002–2006) currently used by SPRFMO to identify closed and open areas under the interim measures. Hence, using the 2002–06 period for the trawl footprint will affect spatial management modelling results in that it suggests that the footprint, and therefore the distribution of fishing impact, is more restricted than it has been - and areas may be identified as high priority for protection when they may no longer provide habitat for extant populations of VME indicator taxa. There is also a difference in the trawl footprint defined using effort versus catch data which could have similar consequences.

The incorporation of bioregional representation in the prioritisation of areas for protection is possible using an existing global biogeography. However, this recently published physical environment-based scheme is currently untested and is for a restricted part of the ocean domain (lower bathyal zone), and it may be more appropriate for future spatial planning efforts to use alternative biogeographic schemes (e.g. for seamounts). Considering the impact that using un-weighted versus down-weighted representation of bioregions had on the Zonation model results, it will also be worth investigating further the implications of different forms of bioregionalisation for the protection of VMEs in the SPRFMO area.

Running various scenario models allowed for the cost to fishing, in terms of the amount of the trawl footprint lost if high priority areas for VME indicator taxa are protected, to be determined. Generally, the cost to fishing was low given the relatively high proportion of suitable habitat for VME indicator taxa protected. The minimum levels of protection to be afforded VMEs and the maximum sustainable level of cost to fishing should ideally be established before future spatial planning scenario models are run.

Despite the recommendations above for improving the future application of Zonation type and other similar software tools to develop spatial management options for VMEs in the SPRFMO area, the outputs from the present study provide a starting point for discussions about where and what size closed areas could be put in place to protect VMEs.

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Table 1: Number of data records for each VME indicator taxon (listed alphabetically) from within the SPRFMO area and New Zealand EEZ that were available for potential use in Maxent models.

Taxon	Number of records for potential use in models
Actinaria	13 984
Alcyonacea	18 657
Antipatharia	2 875
Brisingida	703
Crinoidea	1 808
Gorgonacea	5 504
Pennatulacea	1 342
Porifera	29 291
Scleractinia	119 961
Stylasteridae	3 942
All taxa	323 927

Table 2: Description of the environmental variables used in the model analysis, where the variable name, description, units and original source of the data are shown (see Davies & Guinotte (2011) for further detail and references).

Variable	Description	Unit	Original data source
Temperature	Annual mean temperature at the seafloor	°C	Boyer et al. (2005)
Depth	Water depth from SRTM30 bathymetry	m	Becker et al. (2009)
Dissolved oxygen	Annual mean dissolved oxygen at the seafloor	ml l^{-1}	Garcia et al. (2006a)
Slope	Mean slope of SRTM30 bathymetry	m m^{-1}	derived from Becker et al. (2009)
Salinity	Annual mean salinity at the seafloor	PSU	Boyer et al. (2005)
POC flux	Particulate organic carbon flux to the seafloor	g C_{org} m^{-2} yr^{-1}	Lutz et al. (2007)
Calcite	Annual mean calcite saturation state at the seafloor	Ω_{calc}	Steinacher et al. (2009)
Aragonite	Annual mean aragonite saturation state at the seafloor	Ω_{arag}	Orr et al. (2005)
Silicate	Annual mean silicate at the seafloor	µmol l^{-1}	Garcia et al. (2006b)

Table 3: Number of cells with non-zero values for each VME indicator taxon in the SPRFMO area (of 31 569 total 0.1° latitude/longitude cells).

Taxon	# of cells ≥50% habitat suitability	# of cells ≥70% habitat suitability	# of cells ≥90% habitat suitability
Actiniaria	81	6	1
Alcyonacea	1 510	328	7
Antipatharia	2 140	382	4
Brisingida	313	26	0
Crinoidea	1 946	395	8
Gorgonacea	1 610	39	1
Pennatulacea	61	14	0
Porifera	582	0	0
Scleractinia	2 262	58	1
Stylasteridae	1 371	169	0
All taxa	1 319	3	0

Table 4: Summary of model scenario runs included in spatial management planning analysis using Zonation. (≥50% means at least 50% habitat suitability threshold for all VME indicator taxa; full = full range of habitat suitability values for all VME indicator taxa)

Model name	VME indicator taxa dataset	Aggregation rule	Cost layer	Bioregional layer
Basic and Aggregation (≥50% VME and edge removal)	≥50%	edge removal	none	none
Basic and Aggregation (full VME and edge removal)	full	edge removal	none	none
Basic weighted and Aggregation (full VME with weighted Scleractinia and edge removal)	full, with weighting for Scleractinia	edge removal	none	none
Basic (full VME)	full	none	none	none
Basic and Aggregation (full VME and BLM)	full	BLM	none	none
Cost (catch 2002–2006)	full	none	catch (2002–2006)	none
Cost (effort 2002–2006)	full	none	effort (2002–2006)	none
Cost (catch 1980–2012)	full	none	catch (1980–2012)	none
Cost (effort 1980–2012)	full	none	effort (1980–2012)	none
Bioregion (un-weighted provinces)	full	none	None	biogeographic provinces (un-weighted)
Bioregion (down-weighted provinces)	full	none	None	biogeographic provinces (down-weighted)
Cost and Bioregion (catch 1980–2012 and down-weighted provinces)	full	none	catch (1980–2012)	biogeographic provinces (down-weighted)
Cost and Bioregion (catch 1980–2012 and un-weighted provinces)	full	none	catch (1980–2012)	biogeographic provinces (un-weighted)

Table 5: Table showing the performance estimates for the Maxent models of VME indicator taxa (n= number of presence records between 200–3000 m in the SPRFMO area and New Zealand EEZ used for each model; see main text for explanation of Omission Rate, Test Gain and AUC).

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Taxon	n	Omission Rate (%)	Test Gain	AUC
Actinaria	5 774	10.5	0.755	0.80
Alcyonacea	671	7.6	1.322	0.90
Antipatharia	764	5.1	1.574	0.93
Brisingida	441	8.2	2.106	0.95
Crinoidea	345	7.9	1.396	0.91
Gorgonacea	1 465	5.1	1.311	0.90
Pennatulacea	566	6.4	2.027	0.94
Porifera	5 896	9.7	0.657	0.79
Scleractinia	3 329	6.9	0.756	0.82
Stylasteridae	792	8.7	1.336	0.90
All taxa	13 686	10.1	0.322	0.69

Table 6: Estimated orange roughy catches (t) and effort (number of trawls) for New Zealand vessels in the SPRFMO area by individual year and for the SPRFMO reference period (2002–2006), and the period 1981–2012.

Year	Catch	Effort	Year	Catch	Effort
1981	105	93	1998	2 331	1 366
1982	631	84	1999	5 707	2 670
1983	10 760	636	2000	1 901	1 882
1984	36	30	2001	2 943	2 030
1985	20	4	2002	3 073	3 381
1986	147	58	2003	2 417	3 008
1987	918	220	2004	2 004	2 339
1988	2 309	728	2005	2 485	2 305
1989	2 017	752	2006	1 682	1 412
1990	538	251	2007	908	624
1991	71	33	2008	837	238
1992	713	137	2009	920	645
1993	4 813	2 815	2010	1 474	1 171
1994	3 085	3 565	2011	976	1 152
1995	12 244	5 532	2012	721	713
1996	9 406	4 134			
1997	4 144	2 411			

Period	Catch	Effort
2002–2006	11 661	12 445
1981–2012	82 336	46 419

Table 7: Trawl footprint size (number of non-empty cells in a 0.1° latitude/longitude grid) calculated for a range of time-periods. (*, SPRFMO reference period).

Time period	Number of non-empty cells
2002–2012	625
2002–2011	619
2002–2010	604
2002–2009	593
2002–2008	587
2002–2007	585
2002–2006*	578
2001–2006	603
2000–2006	672
1999–2006	718
1998–2006	749
1997–2006	786
1996–2006	860
1995–2006	922
1994–2006	963
1993–2006	993
1992–2006	996
1991–2006	998
1990–2006	1 024
1989–2006	1 049
1988–2006	1 070
1987–2006	1 077
1986–2006	1 078
1985–2006	1 078
1984–2006	1 086
1983–2006	1 101
1982–2006	1 112
1981–2006	1 114
1980–2006	1 114

Table 8: Orange roughy catch (t) by nation, FAO major fishing area, and year. Comprises domestic (EEZ) and high-seas catch.

Year	Australia: Indian Ocean, Eastern (57)	Chile: Pacific, Southeast (87)	Belize: Pacific, Southeast (87)	China: Pacific, Southwest (81)	Australia: Pacific, Southwest (81)	Russian Federation: Pacific, Southwest (81)	Ukraine: Pacific, Southwest (81)	USSR: Pacific, Southwest (81)	Korea, Republic of: Pacific, Southwest (81)	New Zealand: Pacific, Southwest (81)	Norway: Pacific, Southwest (81)	Total
1977								319				319
1978												0
1979								1 251		5 000		6 251
1980								17 300		26 027		43 327
1981								14 076		24 060		38 136
1982								8 860		29 592		38 452
1983								7 229		41 759		48 988
1984								4 028		37 271		41 299
1985								4 306		39 999		44 305
1986					2 600			2 475		44 609		49 684
1987					5 400			130		49 014		54 544
1988					6 900	991				55 361		63 252
1989	1 966				13 542	1 132				51 538	1 153	69 331
1990	1 712				37 901	36				48 379	3 450	91 478
1991	959				33 111	506				35 819	82	70 477
1992	627				18 187					36 568	2	55 384
1993	432				12 050					29 681	1 602	43 765
1994	668				9 977					31 718	665	43 028
1995	227				7 070					33 077	1	40 375
1996	357				4 526					28 639	5	33 527
1997	350				3 129					20 545	12	24 036
1998	4 857				3 207					21 485	3	29 552
1999	7 553	779			28				234	23 780		32 374
2000	4 974	1 482			26		102			17 879		24 463
2001	5 197	1 868		520	17		195		93	14 044		21 934
2002	3 961	1 514		597	14				208	17 954		24 248
2003	4 455	1 249	9	562	54		176		243	17 778		24 526
2004	2 558	1 262	914	592	56		272		138	17 829		23 621
2005	3 250	783	506	710	144					18 451		23 844
2006	2 373	259	200	570	8		249		77	15 920		19 656
2007	1 120	5	332		9				44	14 276		15 786
2008	288	1			0					13 310		13 599
2009	659				2					12 446		13 107
2010	652				1					10 843		11 496
2011	278				2					6 958		7 238

Table 9: Orange roughy catch (t) by FAO major fishing area and year. Comprises domestic (EEZ) and high-seas catch.

Year	Area 57 (Indian Ocean, Eastern)	Area 87 (Pacific, Southeast)	Area 81 (Pacific, Southwest)	Total
1977	0	0	319	319
1978	0	0	0	0
1979	0	0	6 251	6 251
1980	0	0	43 327	43 327
1981	0	0	38 136	38 136
1982	0	0	38 452	38 452
1983	0	0	48 988	48 988
1984	0	0	41 299	41 299
1985	0	0	44 305	44 305
1986	0	0	49 684	49 684
1987	0	0	54 544	54 544
1988	0	0	63 252	63 252
1989	1 966	0	67 365	69 331
1990	1 712	0	89 766	91 478
1991	959	0	69 518	70 477
1992	627	0	54 757	55 384
1993	432	0	43 333	43 765
1994	668	0	42 360	43 028
1995	227	0	40 148	40 375
1996	357	0	33 170	33 527
1997	350	0	23 686	24 036
1998	4 857	0	24 695	29 552
1999	7 553	779	24 042	32 374
2000	4 974	1 482	18 007	24 463
2001	5 197	1 868	14 869	21 934
2002	3 961	1 514	18 773	24 248
2003	4 455	1 258	18 813	24 526
2004	2 558	2 176	18 887	23 621
2005	3 250	1 289	19 305	23 844
2006	2 373	459	16 824	19 656
2007	1 120	337	14 329	15 786
2008	288	1	13 310	13 599
2009	659	0	12 448	13 107
2010	652	0	10 844	11 496
2011	278	0	6 960	7 238

Table 10: Orange roughy catches (t) in the SPRFMO area by nation and FAO area (from SPRFMO database). See also table 5.1 in http://www.southpacificrfmo.org/assets/Commission-Meeting-1st/COMM-01-INF-07-Data-Submitted-to-the-Interim-Secreteriat.pdf

Participant	Australia[1]	Belize		China	Korea		NZ	Russian Federation		Ukraine	Total
FAO Area	Unknown	81	71	81	81	81	81	81	87	81	
High seas/EEZ	HS	HS	HS	Unknown	HS	HS + EEZ	HS	Unknown	Unknown	HS	
1977								319	0		319
1978								0	0		0
1979								1 251	0		1 251
1980								17 300	0		17 300
1981								14 076	0		14 076
1982								8 860	0		8 860
1983								7 229	0		7 229
1984								4 028	0		4 028
1985								4 306	0		4 306
1986								2 475	0		2 475
1987	2							130	0		132
1988	2							***	0		2
1989	2							1 132	0		1 134
1990	2						559	36	0		597
1991	122						141	506	0		769
1992	122						758	0	0		880
1993	122						2 566	0	0		2 688
1994	192						2 195	0	0		2 387
1995	11						11 195	0	0		11 206
1996	11						8 002	0	0		8 013
1997	1 458						3 862	0	0		5 320
1998	3 098						2 329	0	0		5 427
1999	2 514					7	4 948	0	0		7 469
2000	948					288	1 574	0	0	53	2 863
2001	751			520		94	2 499	0	0		3 864
2002	376			597		208	2 578	0	0		3 759
2003	166	9		562		[3]	1 973	0	0	164	2 874
2004	369	913	1	592	138		1 697	0	0	49	3 759
2005	207	506		710	0		1 597	0	0		3 020
2006	166	200		570	77		1 415	0	0		2 428
2007	148	[2]332		[2]336	44		866	0			1 390
2008	0				0		837				837
2009	0						928				928
2010	0	0	0				1 474				1 474
2011	2						1 079				1 081

1. Australia has reported grouped catch figures for some years. Those catches have been equally split between the affected years. The years which are affected are 1995–1996, 1991–1993, and 1987–1990.
2. In 2007, both Belize and China reported an annual total from the same vessel fishing in the same period. Therefore this catch amount (332 and 336 t) is represented twice in this table. (but 336 removed from total column)
3. Figure withheld as data is from less than 3 vessels, and has not yet been made public.

Table 11: Summary statistics for relative protection given to each VME indicator taxon in the SPRFMO area, where the number of suitable habitat cells (>50% habitat suitability) for each VME indicator taxon is calculated as a percentage of the total number of high priority cells (top 10%) selected for each Zonation scenario (see Table 4 for scenario details).

VME indicator taxon	No. of cells of >50% habitat suitability (percentage of SPRFMO area)	Basic (full VME)	Cost (catch 2002–2006)	Cost (effort 2002–2006)	Cost (catch 1980–2012)	Cost (effort 1980–2012)	Bioregion (un-weighted provinces)	Bioregion (down-weighted provinces)
Actinaria	81 (0.26)	100	92.59	93.83	82.72	86.42	98.77	100
Alcyonacea	1 510 (4.78)	100	87.28	89.60	80.07	83.25	30.20	80.79
Antipatharia	2 140 (6.78)	100	82.48	85.61	73.32	76.54	20.98	71.12
Brisingida	313 (0.99)	100	82.11	87.54	66.77	72.20	82.75	100.00
Crinoidea	1 946 (6.16)	100	85.56	88.34	78.78	82.07	24.56	73.59
Gorgonacea	1 610 (5.10)	100	80.93	84.04	71.43	74.16	24.97	79.57
Pennatulacea	61 (0.19)	100	91.80	95.08	85.25	91.80	100	100
Porifera	582 (1.84)	100	78.87	82.82	67.35	71.13	58.08	99.83
Scleractinia	2 262 (7.17)	100	84.39	87.00	76.53	79.49	20.91	71.84
Stylastridae	1 371 (4.34)	100	85.12	87.02	77.61	80.31	31.51	83.73

Table 12: Summary statistics for relative protection given to each biogeographic province in the SPRFMO area, where the number of cells in each province is calculated as a percentage of the total number of high priority cells (top 10%) selected for each Zonation scenario (see Table 4for scenario details).

Biogeographic province	No. of cells in each province (percentage of SPRFMO area)	Basic (full VME)	Bioregion (un-weighted provinces)	Bioregion (down-weighted provinces)	Cost (catch 2002–2006)	Cost (effort 2002–2006)	Cost (catch 1980–2012)	Cost (effort 1980–2012)
Province 5	11 192 (35.45)	3.21	4.23	2.76	4.00	4.07	4.22	4.24
Province 6	7 099 (22.49)	28.55	6.21	14.41	26.05	26.14	25.71	25.29
Province 7	815 (2.58)	0.37	54.48	38.40	0.37	0.37	0.37	0.37
Province 8	1 337 (4.24)	2.99	35.30	23.93	4.34	3.74	4.56	4.26
Province 9	1 097 (3.47)	2.46	40.02	27.99	2.83	2.92	3.01	2.92
Province 10	8 754 (27.73)	5.43	5.40	3.50	6.31	6.10	6.53	6.42
Province 12	2 180 (6.91)	0.23	21.65	13.94	0.23	0.23	0.23	0.23
Province 14	207 (0.66)	0.48	100.00	100.00	0.97	0.48	1.93	0.97

Table 13: Proportion of trawl footprint lost to fishing in the SPRFMO area, if high priority areas (top 5–20%) for VME indicator taxa are closed under different cost model scenarios.

	Top high priority areas for VME indicator taxa			
Model Scenario	5%	10%	15%	20%
Catch (2002–2006) with aggregation rule	1.66	7.56	10.77	10.80
Catch (2002–2006) without aggregation rule	0.03	0.06	0.10	0.13
Effort (2002–2006) with aggregation rule	4.20	9.55	13.58	17.46
Effort (2002–2006) without aggregation rule	3.85	7.71	11.60	15.49
Catch (1980–2012) with aggregation rule	1.30	1.54	18.23	18.37
Catch (1980–2012) without aggregation rule	0.01	0.03	0.04	0.05
Effort (1980–2012) with aggregation rule	3.30	5.72	13.04	17.35
Effort (1980–2012) without aggregation rule	2.39	4.81	7.25	9.66
Bioregion (un-weighted provinces) and Catch (1980–2012) with aggregation rule	0.09	0.15	0.56	1.38
Bioregion (un-weighted provinces) and Catch (1980–2012) without aggregation rule	0.01	0.03	0.04	0.05

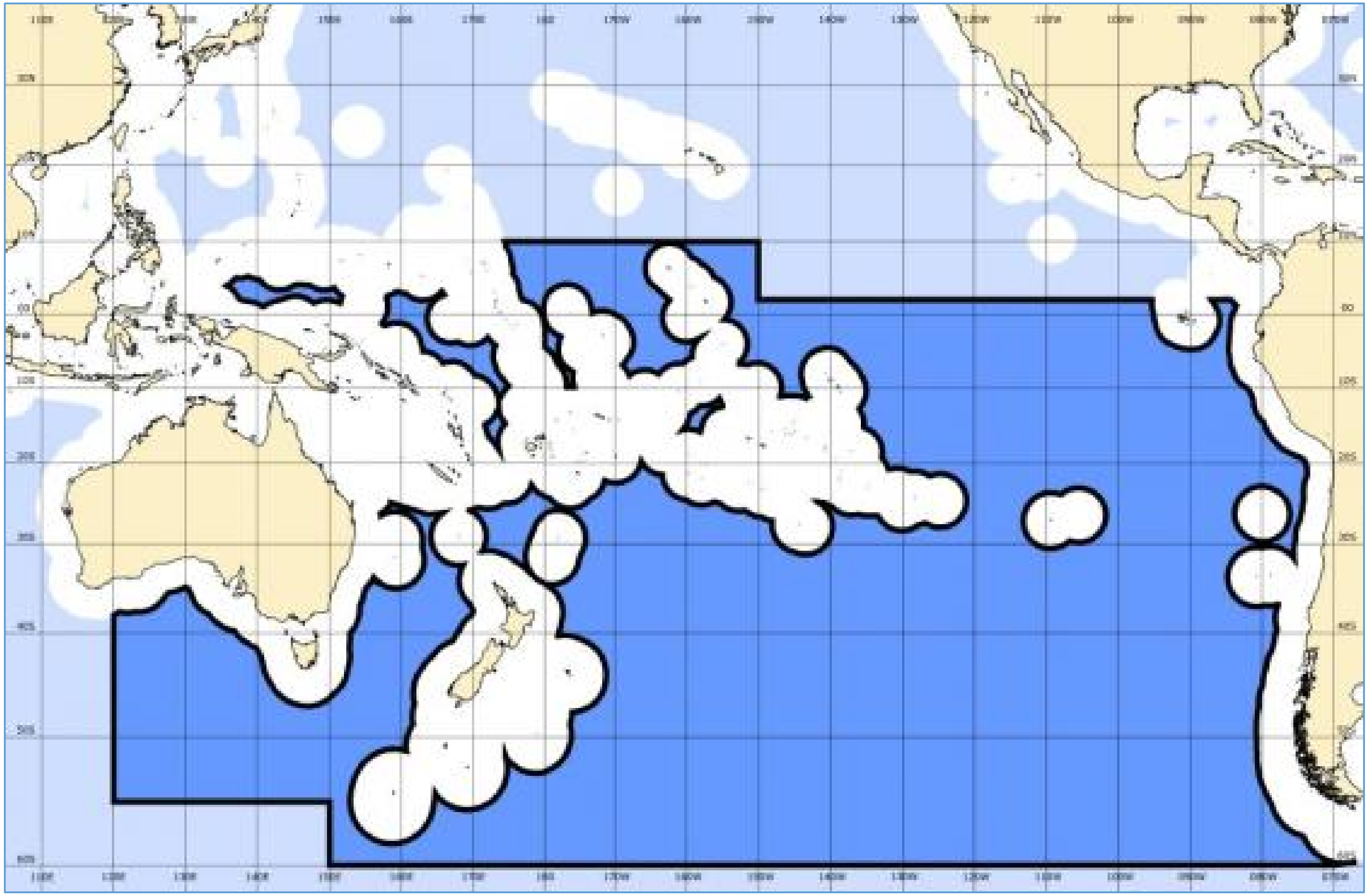


Figure 1: Map of the SPRFMO area. This map is a pictorial illustration of the area that is properly described in legal terms in Article 5 of the SPRFMO Convention. The map is not part of the Convention text and has no legal status. It is not intended to reflect exactly the maritime spaces of adjoining coastal states and cannot be considered to constitute recognition of the claims or positions of any of the participants in the negotiations leading to the adoption of the Convention concerning the legal status and extent of waters and zones claimed by such participants (source: http://www.southpacificrfmo.org/).

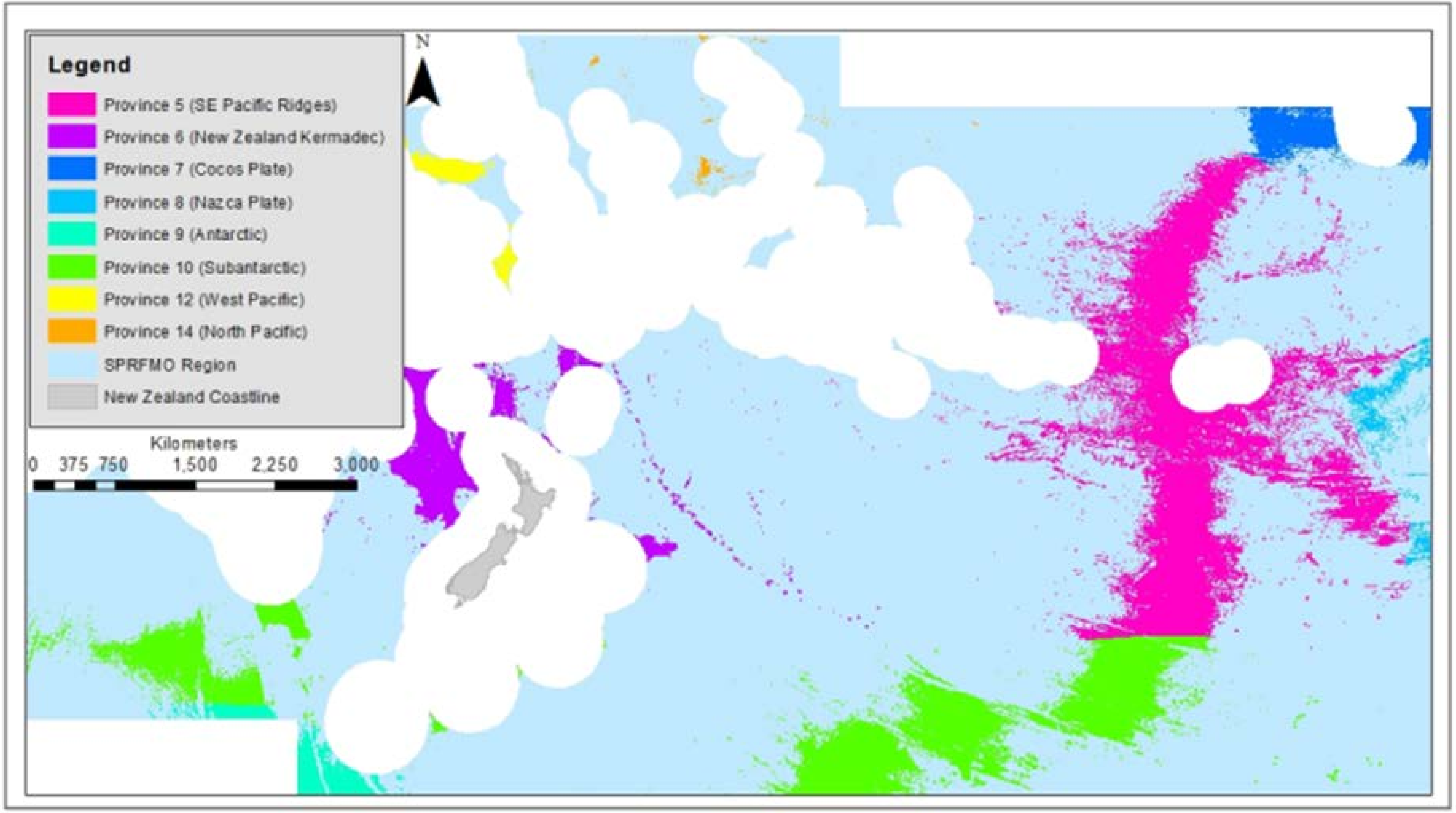


Figure 2: Map of SPRFMO area showing the distribution of biogeographic provinces (after Watling et al. 2013).

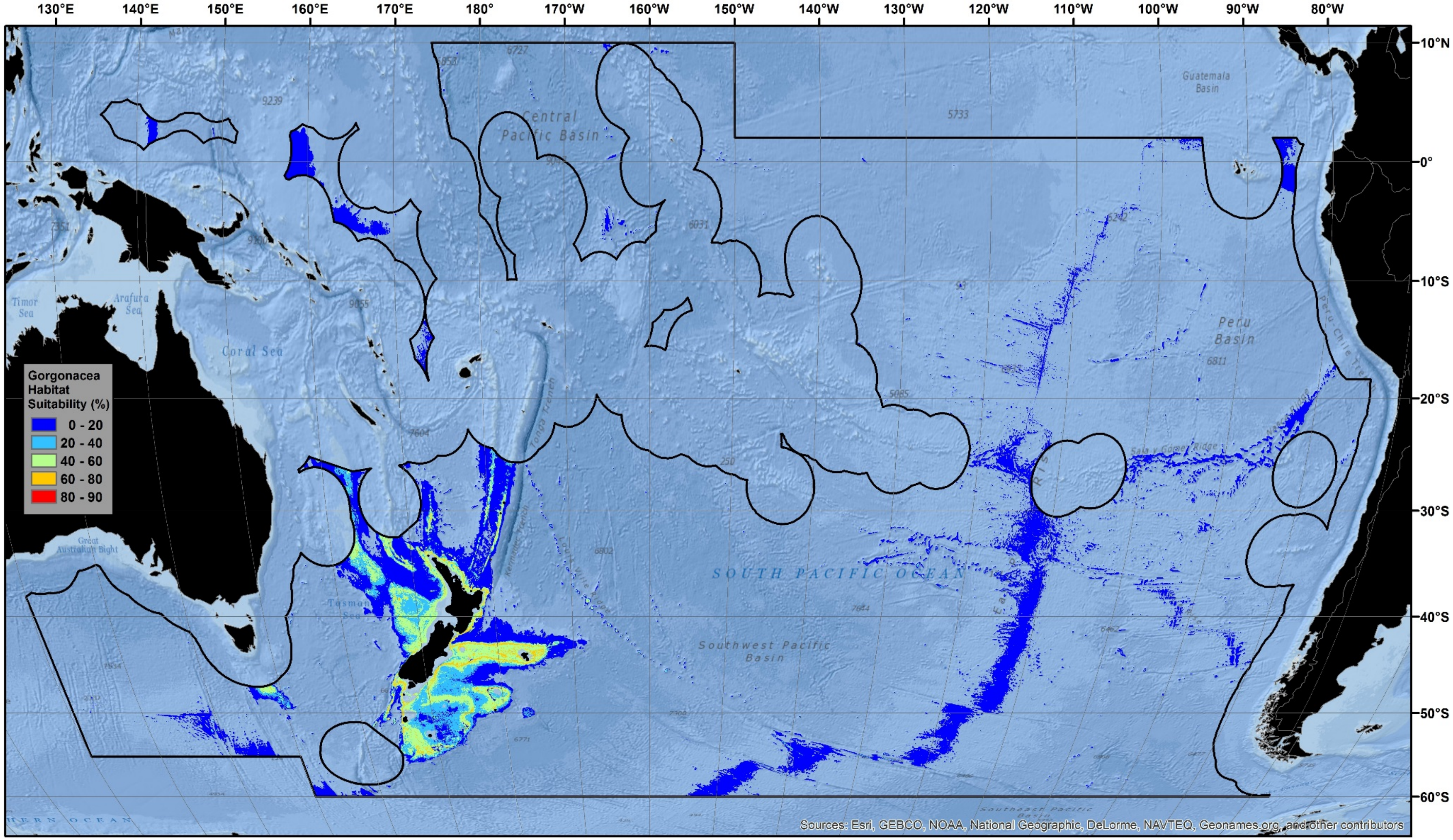


Figure 3: Map showing the predicted habitat suitability for Gorgonacea in the SPRFMO area and the New Zealand EEZ.

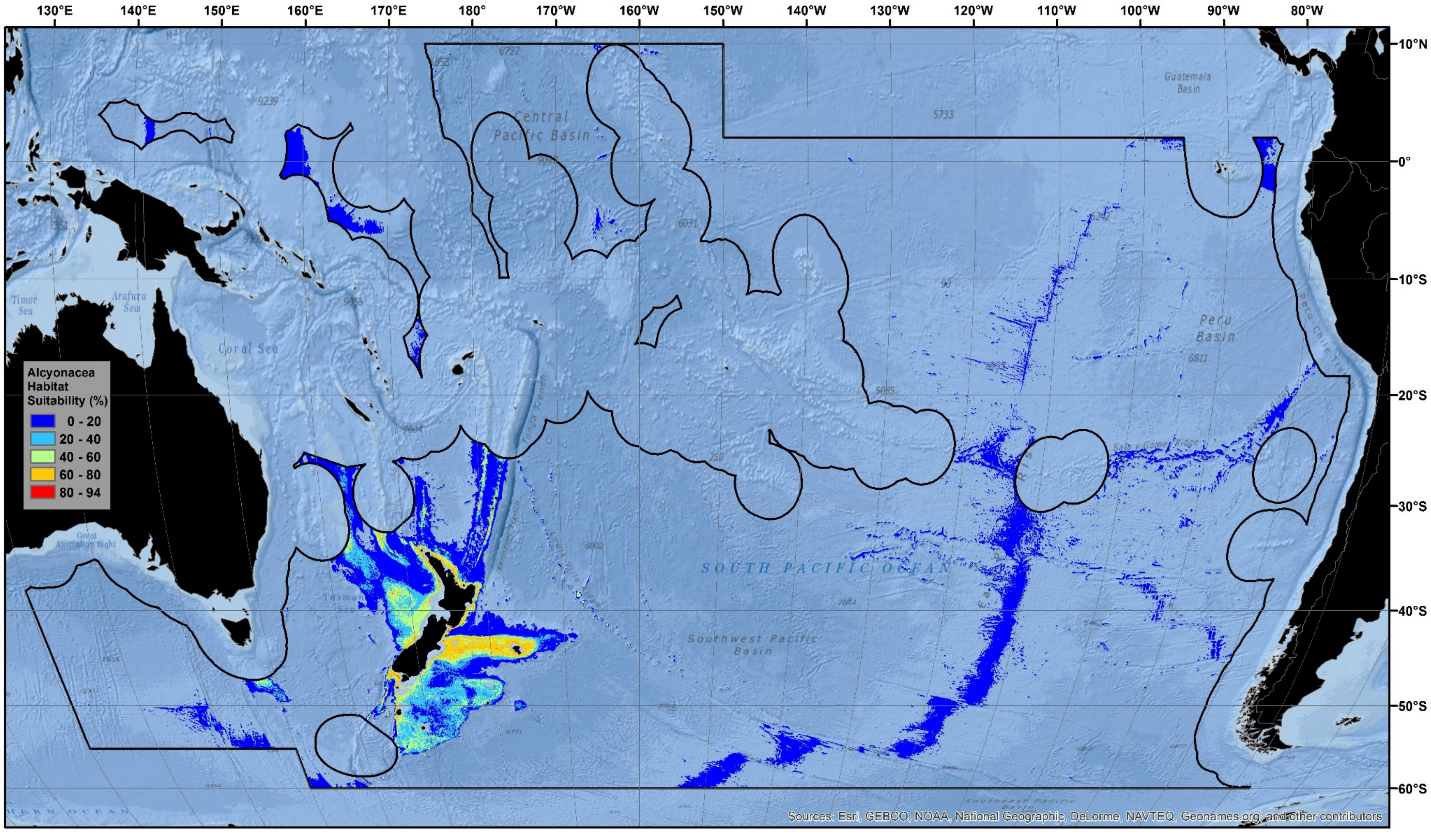


Figure 4: Map showing the predicted habitat suitability for Alyconacea in the SPRFMO area and the New Zealand EEZ.

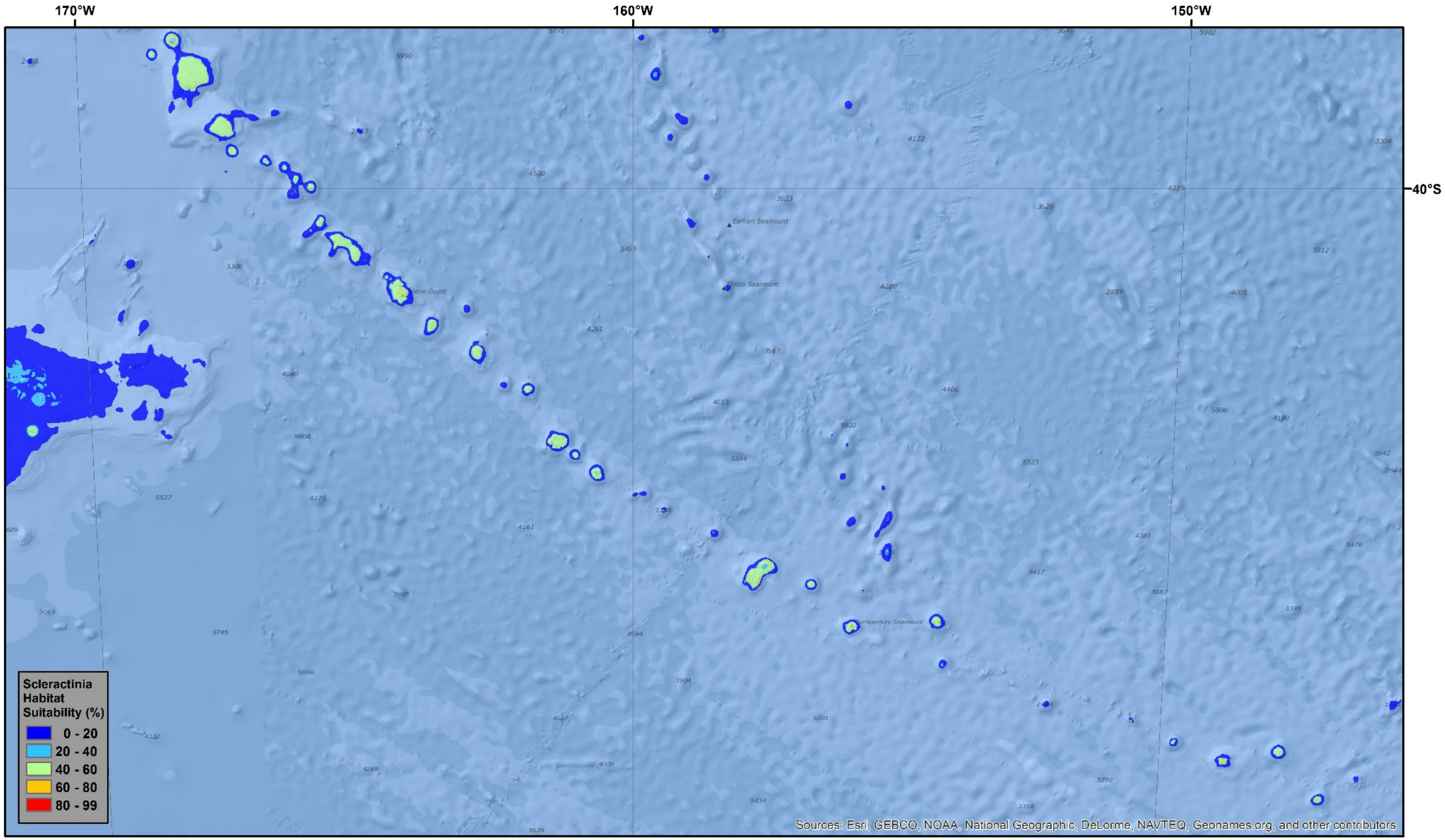


Figure 5: Map showing the predicted habitat suitability for Scleractinia on the southern part of the Louisville Seamount Chain.

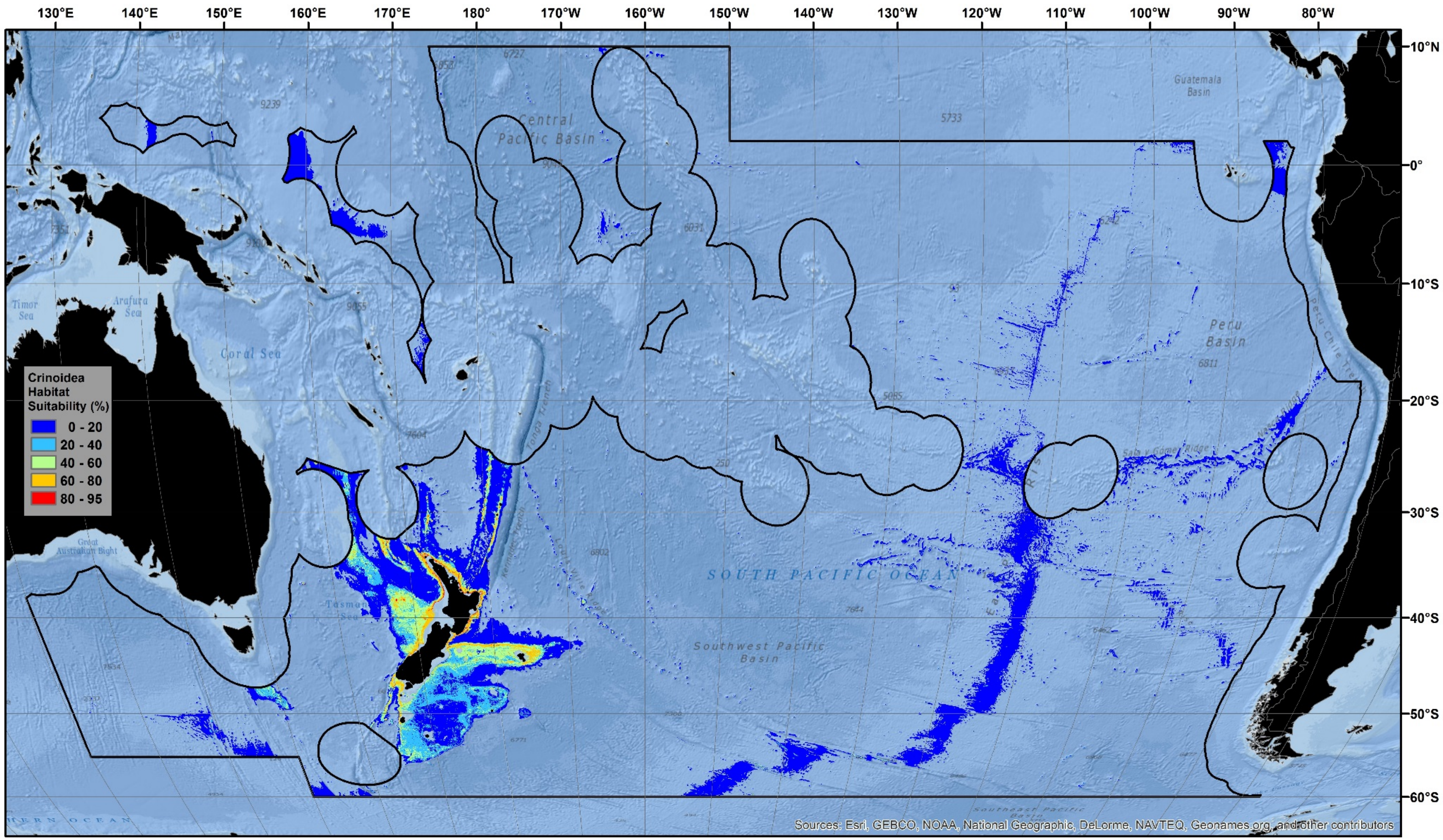


Figure 6: Map showing the predicted habitat suitability for Crinoidea in the SPRFMO area and the New Zealand EEZ.

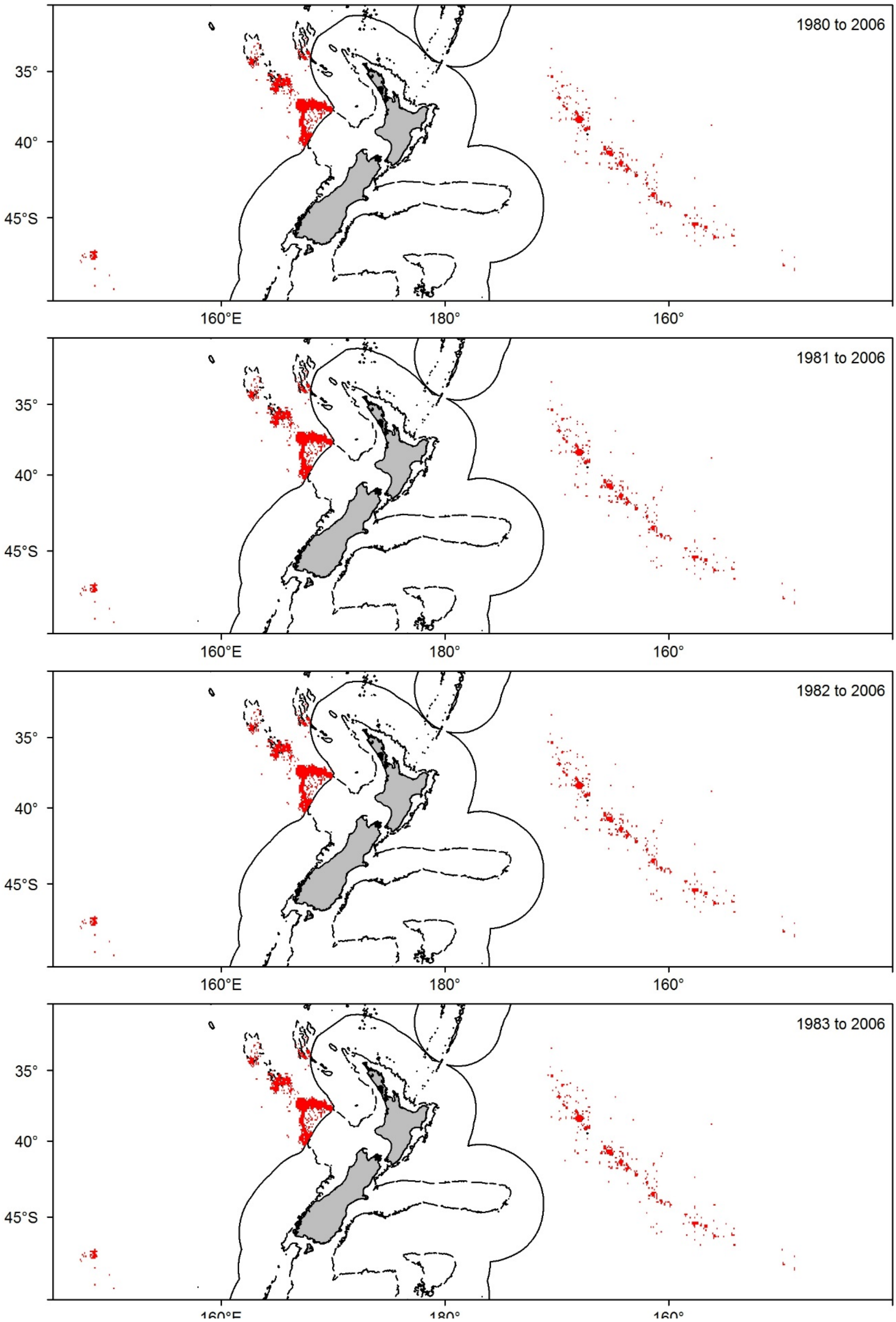


Figure 7: The total trawl footprint of the New Zealand orange roughy fishery (based on 0.1° latitude/longitude cells occupied annually).

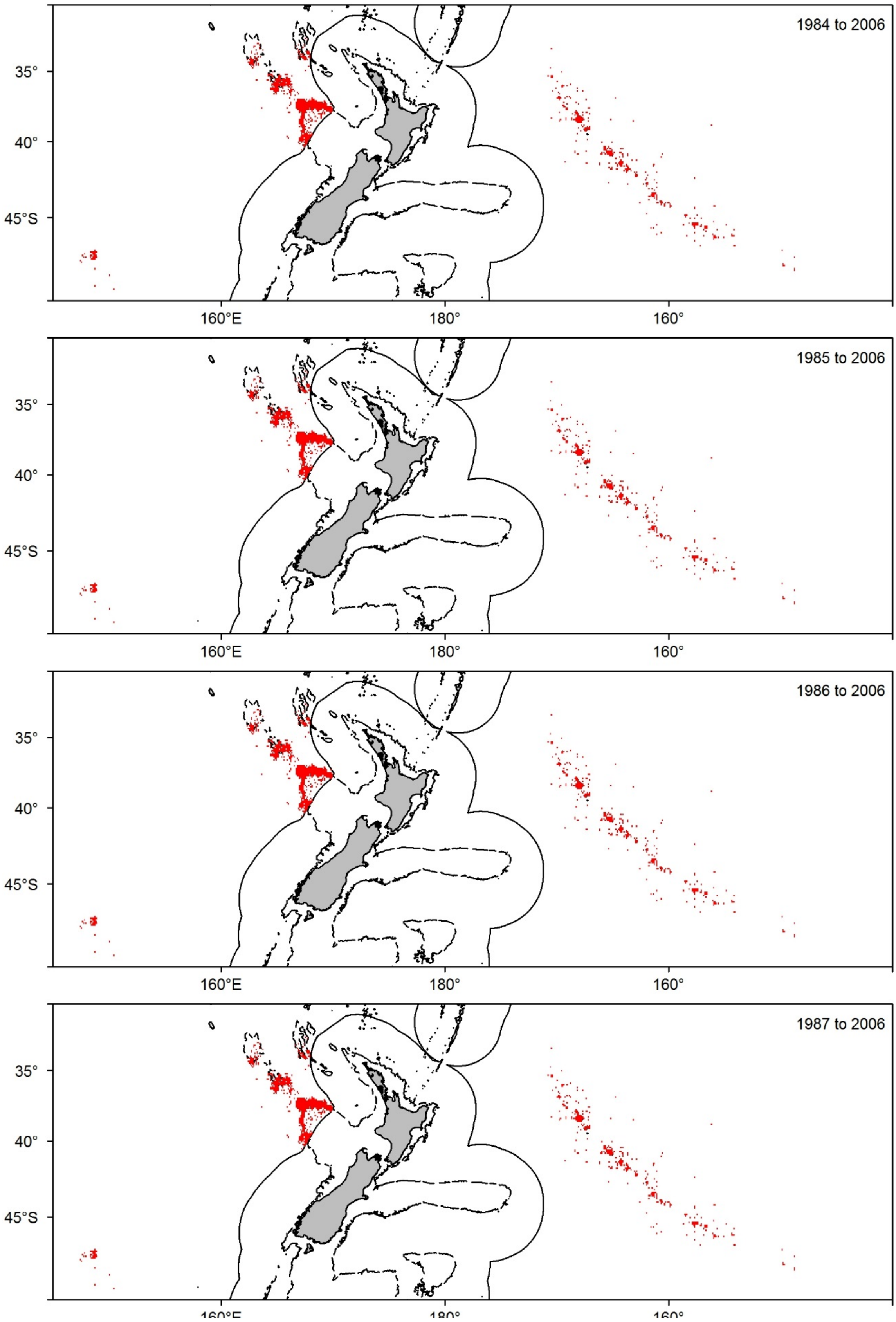


Figure 7: Continued

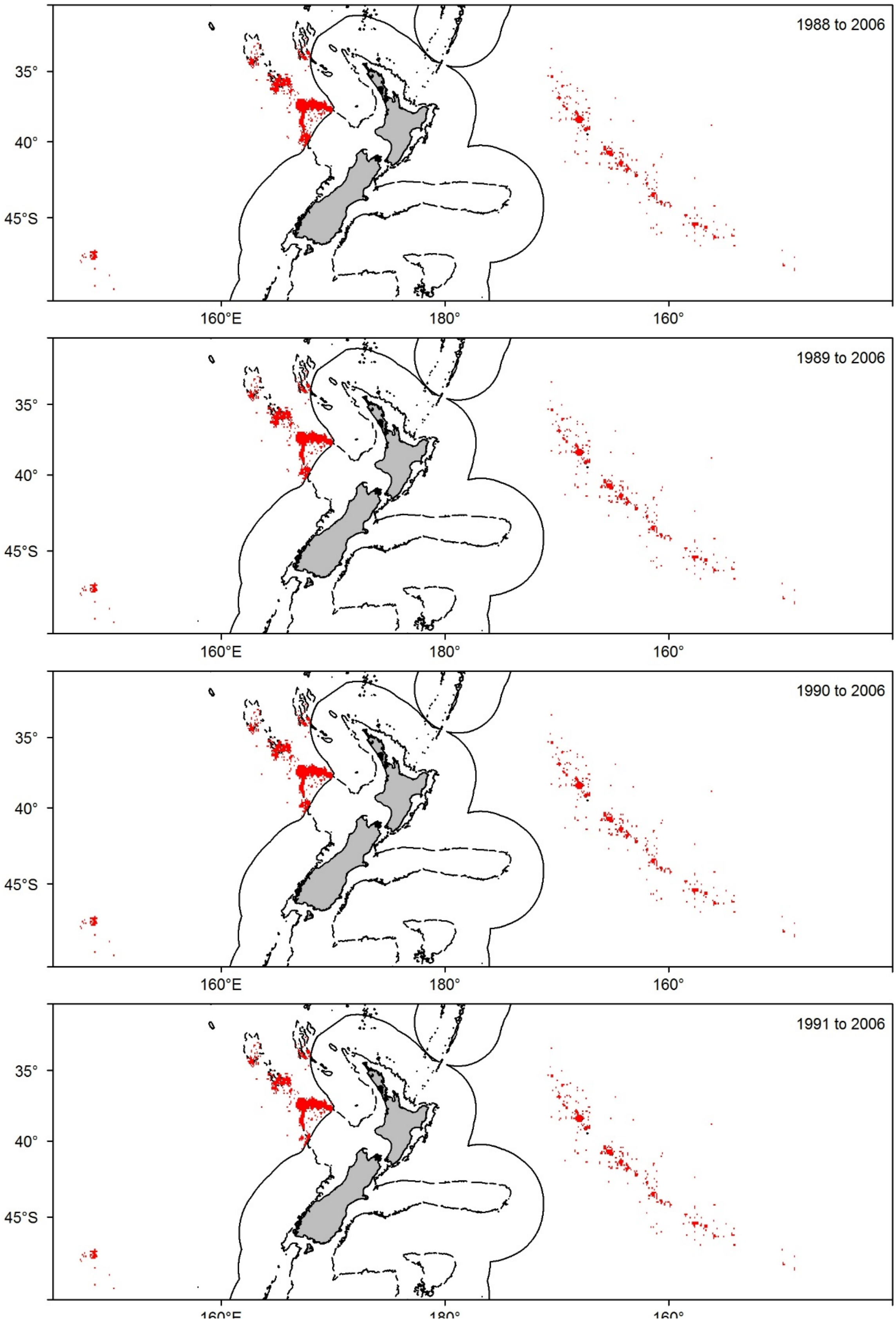
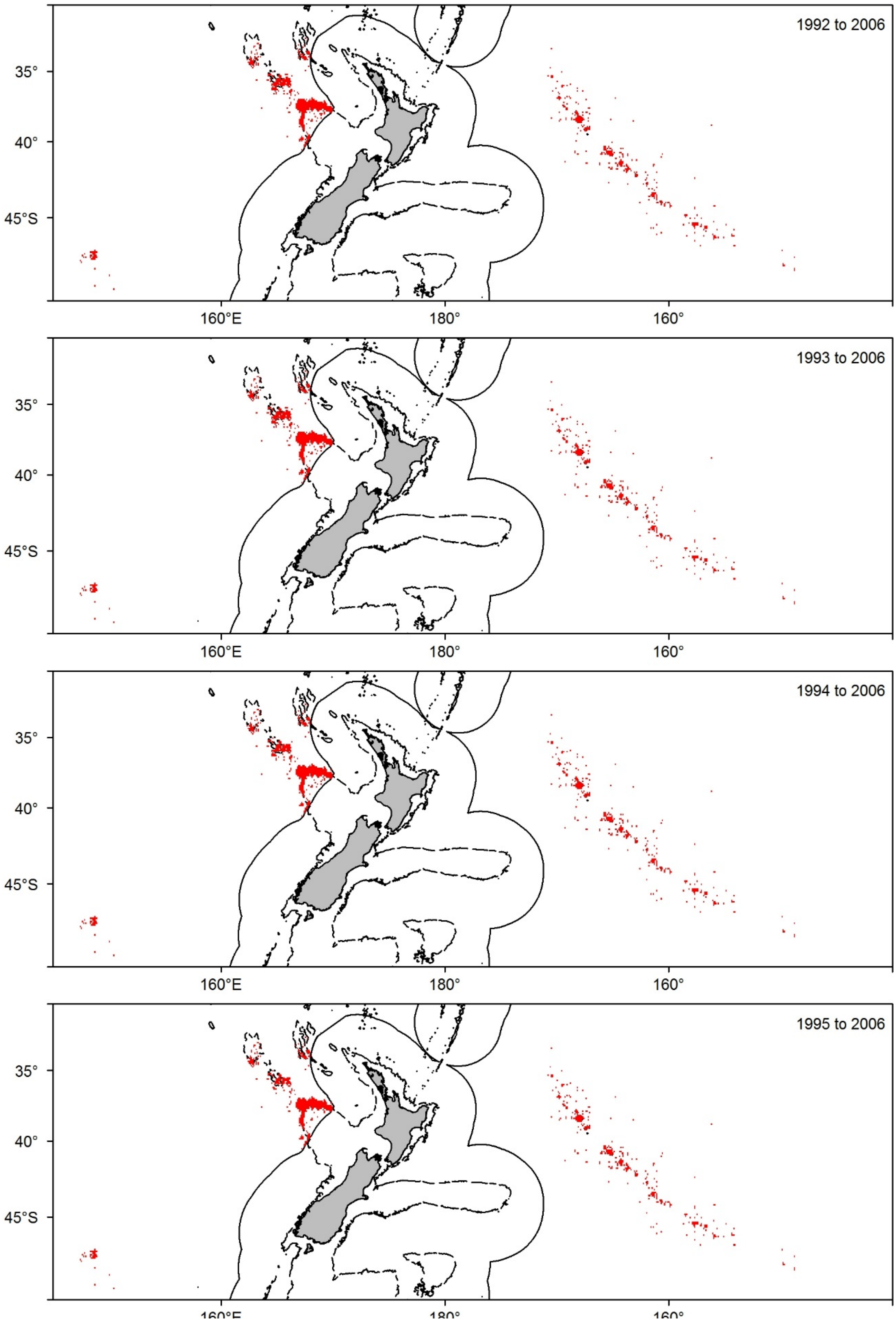


Figure 7: Continued



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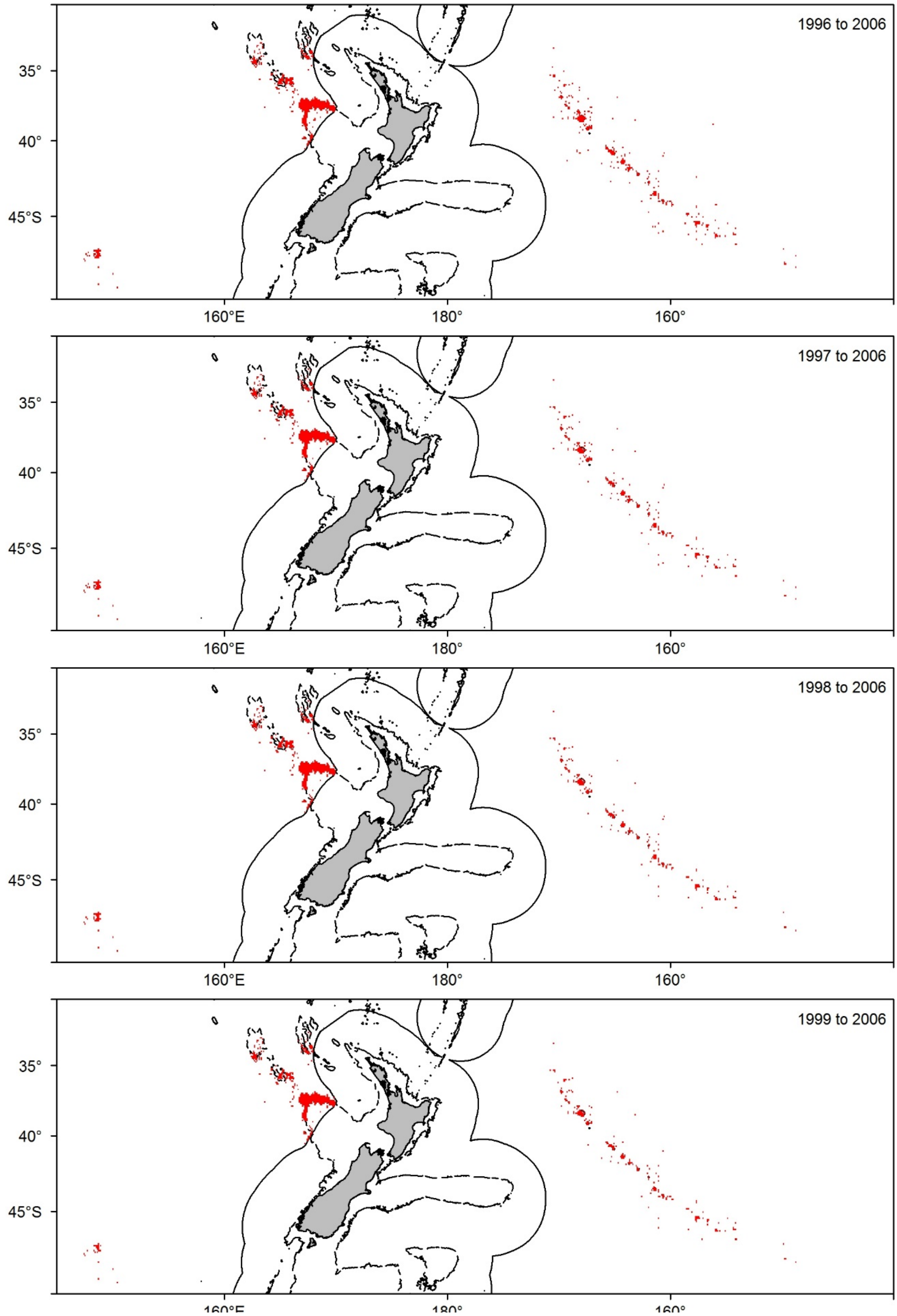

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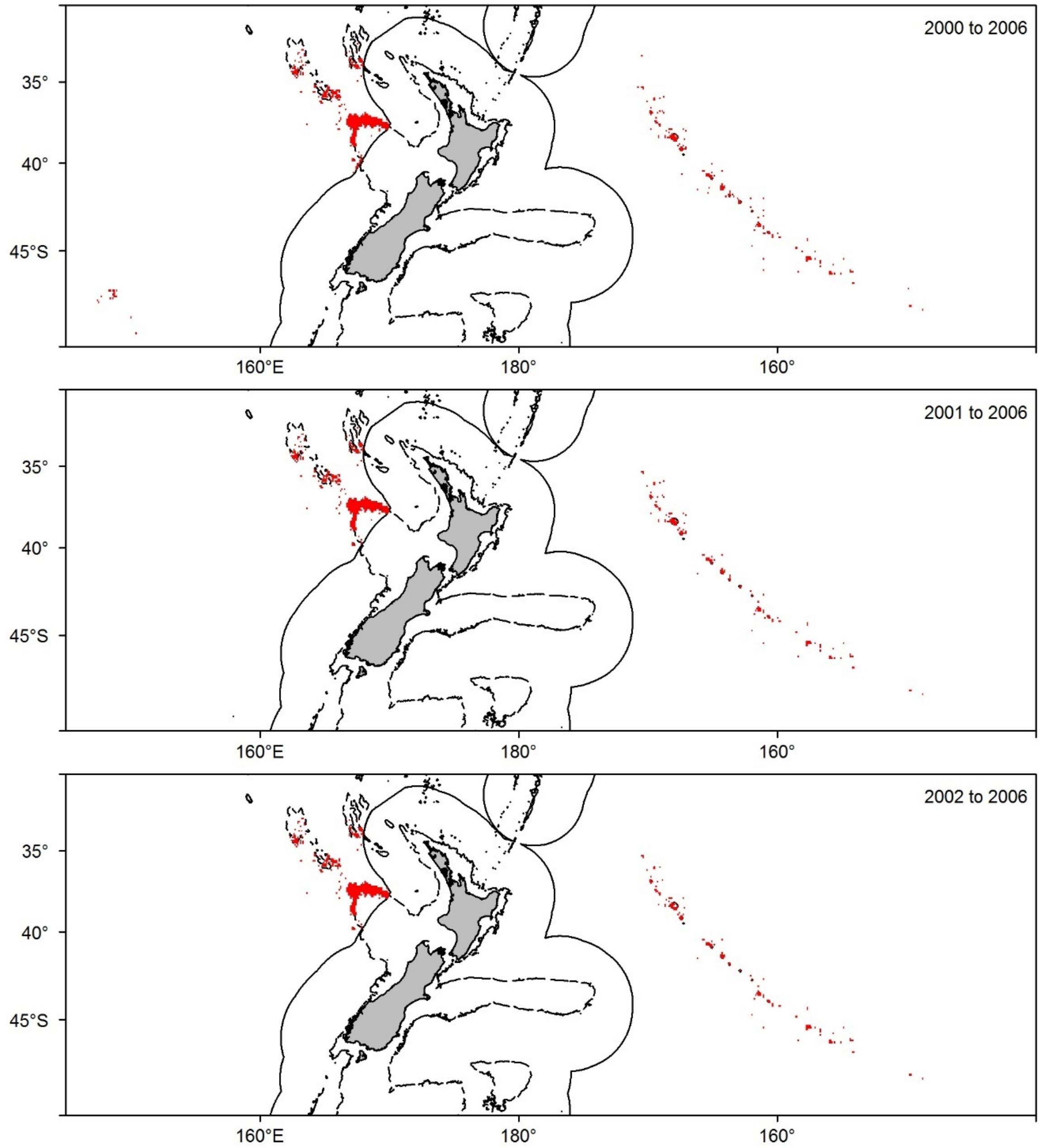

Figure 7: continued

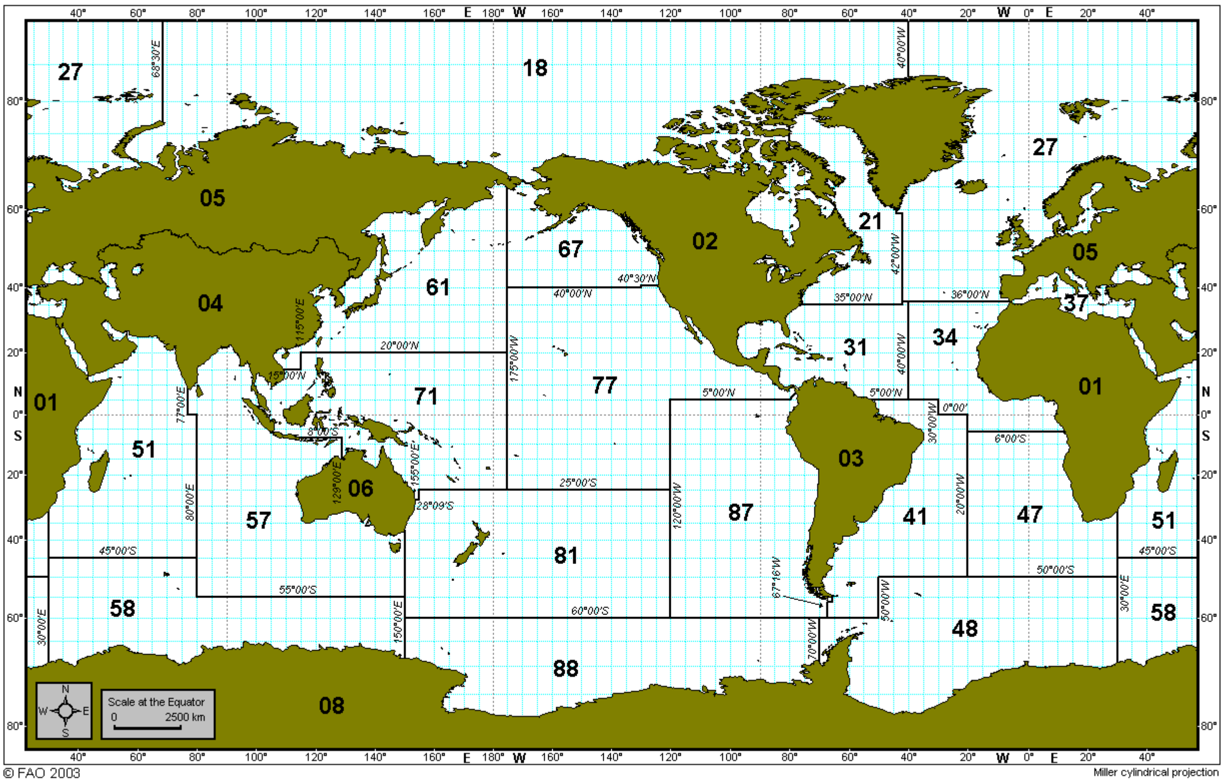

Figure 8: FAO Major Fishing Areas (from http://www.fao.org/fishery/statistics/en).

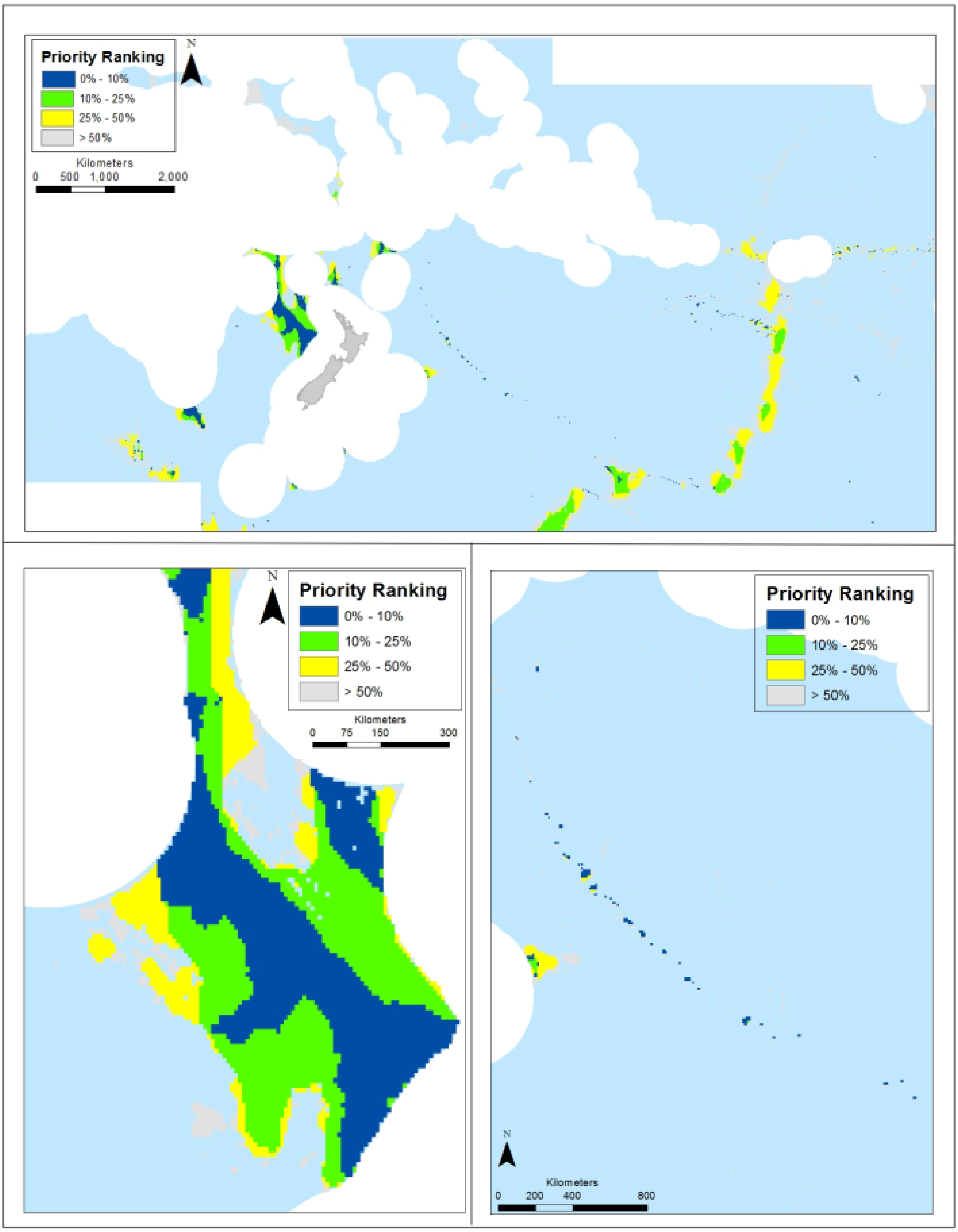

Figure 9: Zonation output for model scenario with 50% habitat suitability threshold for all VME indicator taxa, with aggregation rule (edge removal), no fishing cost layer, and no bioregional layer.

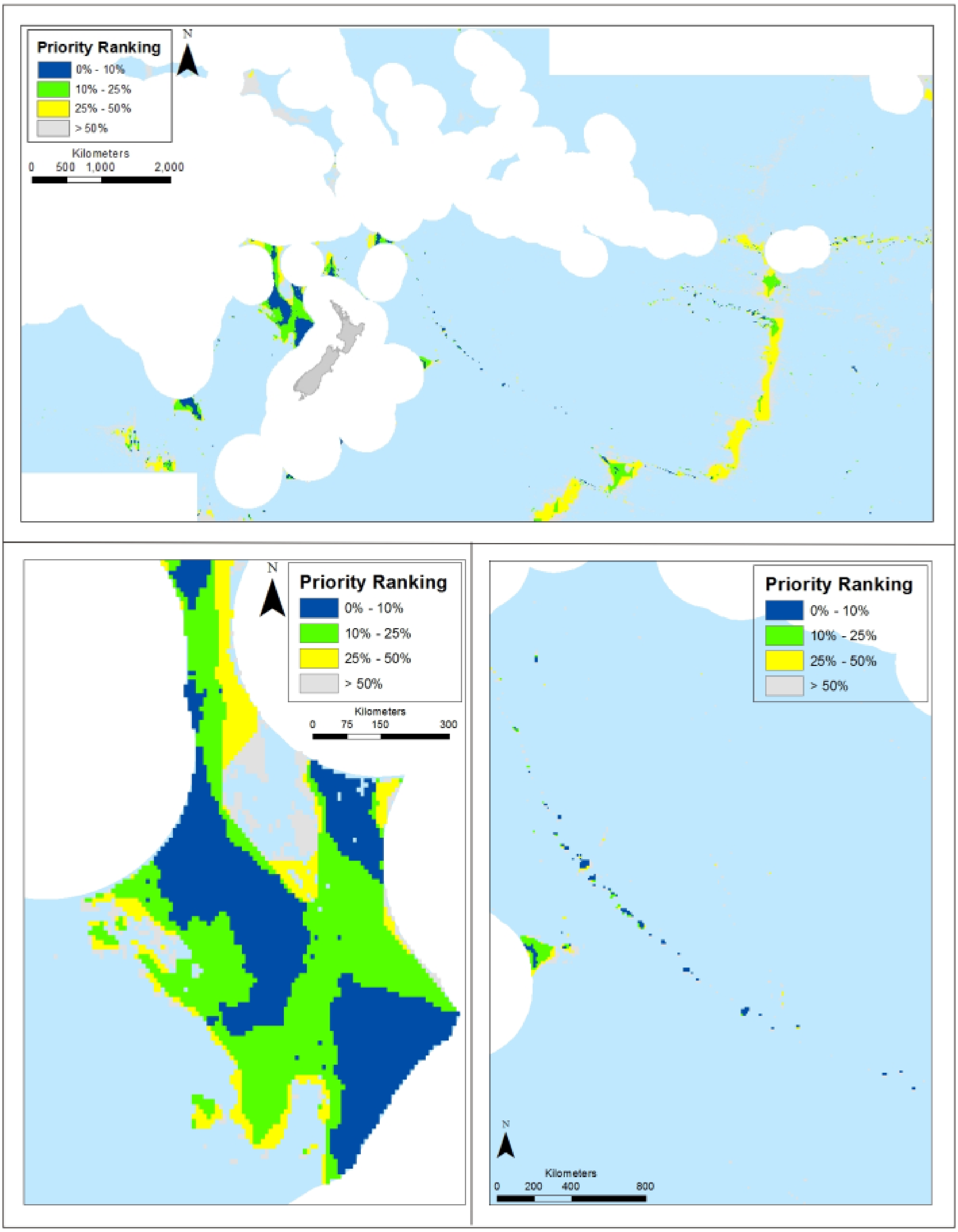

Figure 10: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, with aggregation rule (edge removal), no fishing cost layer, and no bioregional layer.

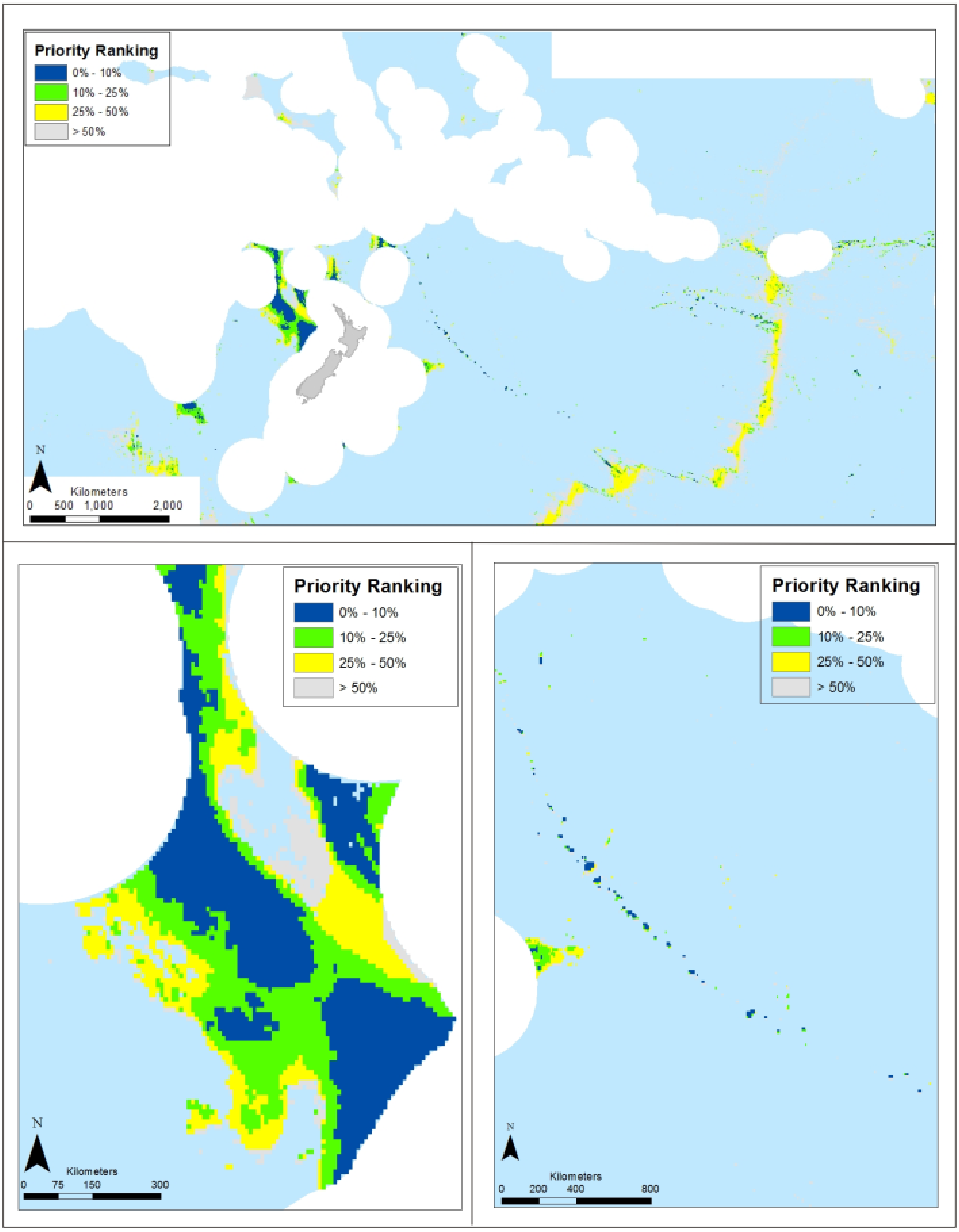

Figure 11: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, weighted for Scleractinia, with aggregation rule (edge removal), no fishing cost layer, and no bioregional layer.

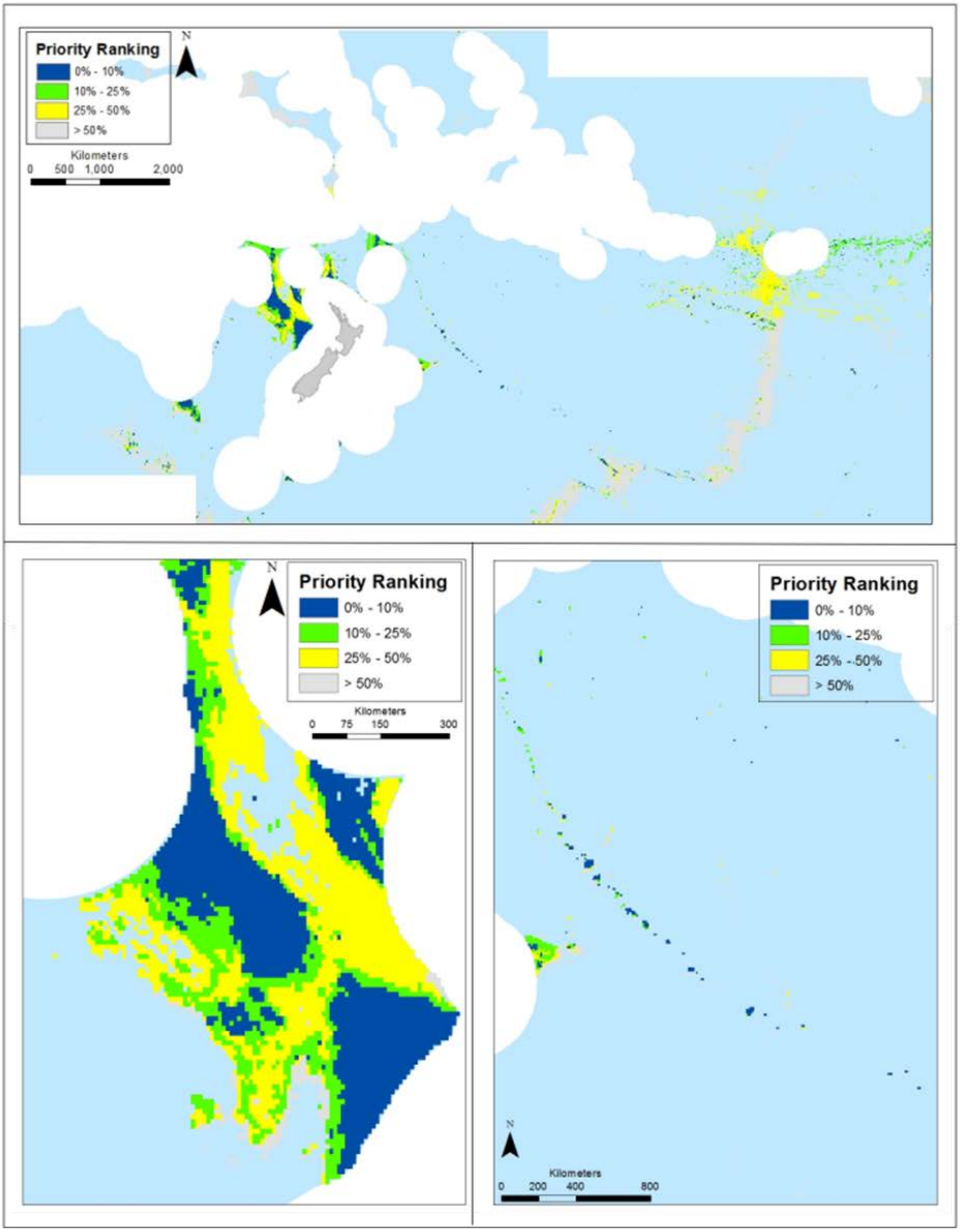

Figure 12: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, no fishing cost layer, and no bioregional layer.

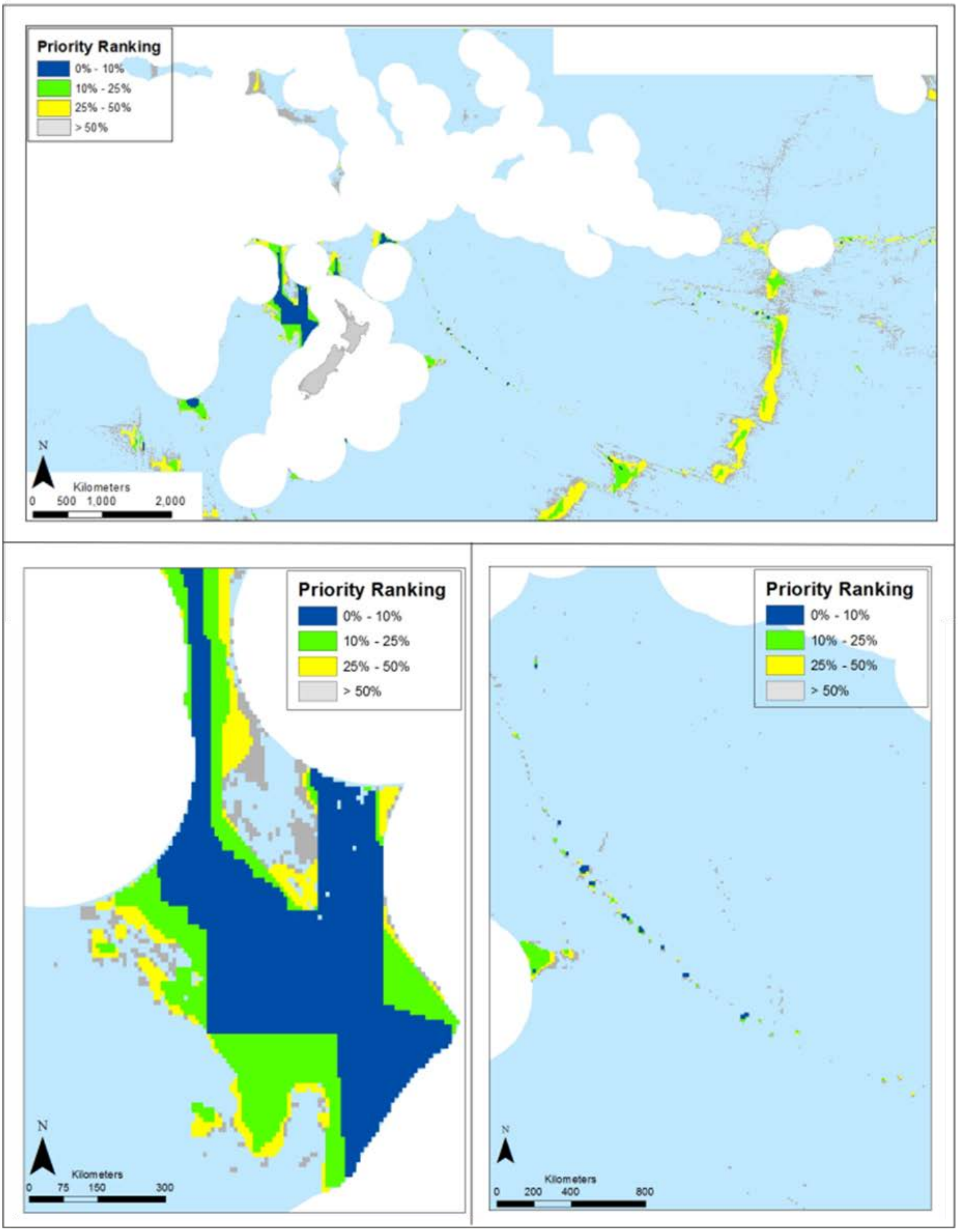

Figure 13: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, with aggregation rule (BLM), no fishing cost layer, and no bioregional layer.

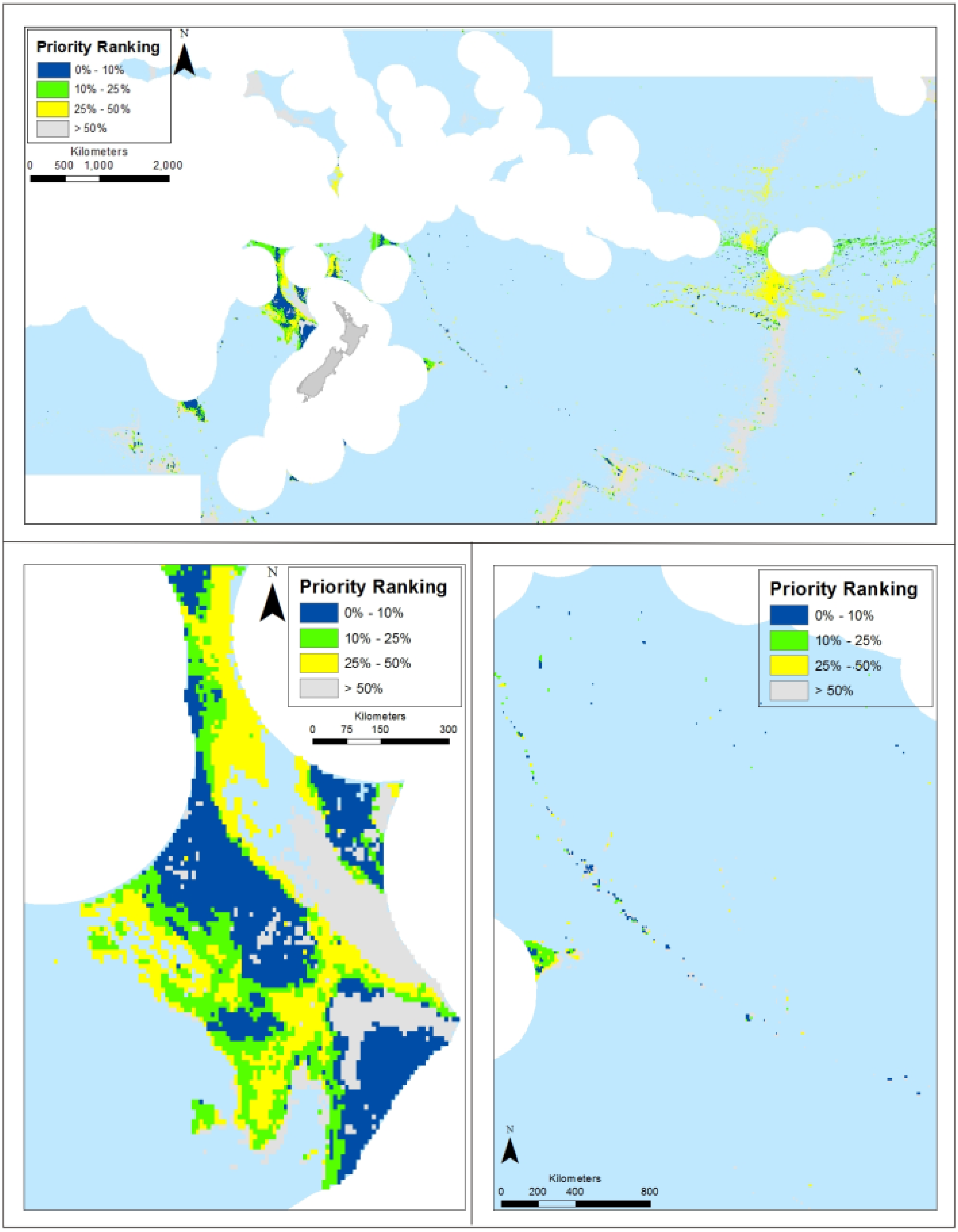

Figure 14: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, fishing cost layer (catch, 2002–2006), and no bioregional layer.

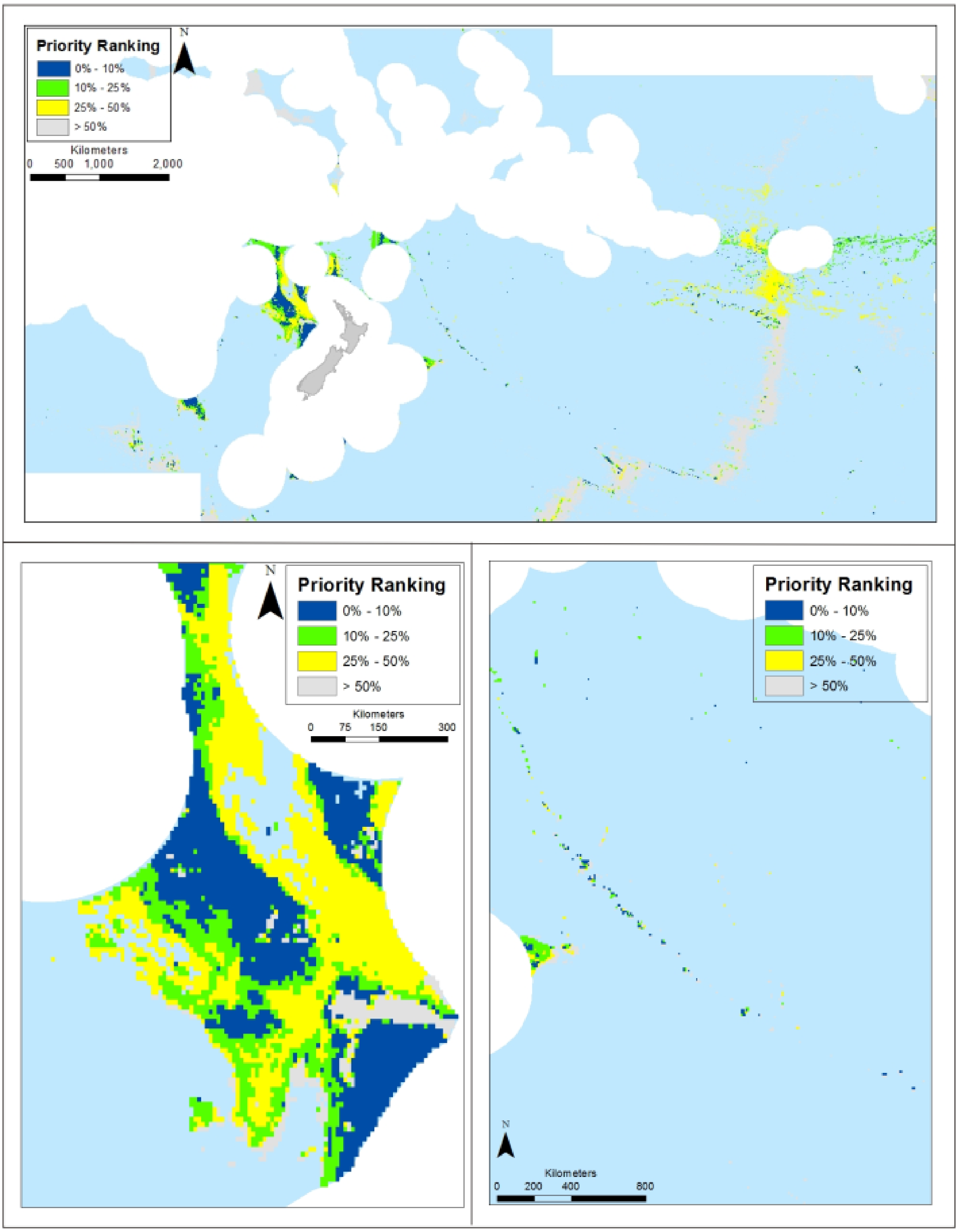

Figure 15: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, fishing cost layer (effort, 2002–2006), and no bioregional layer.

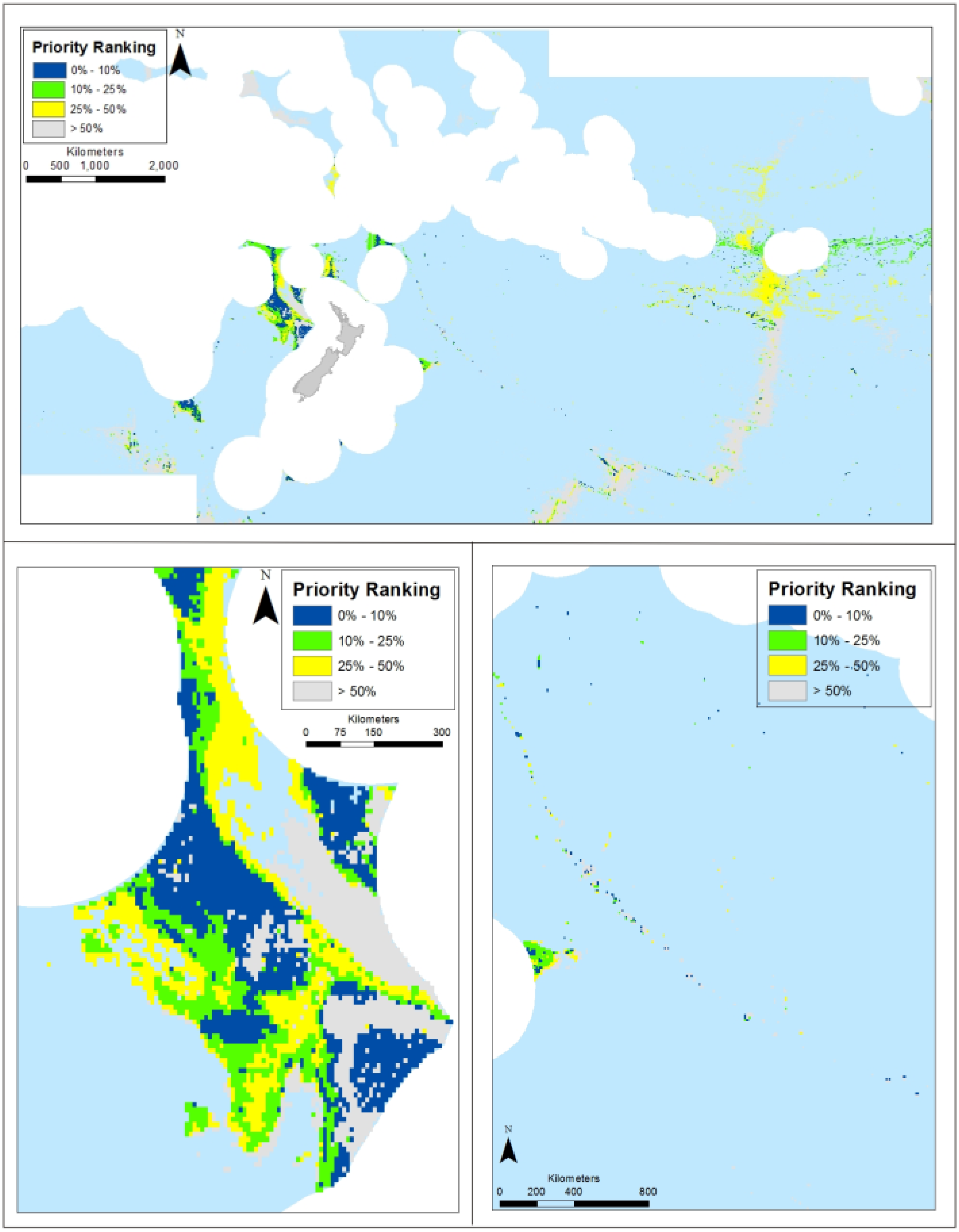

Figure 16: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, fishing cost layer (catch, 1980–2012), and no bioregional layer.

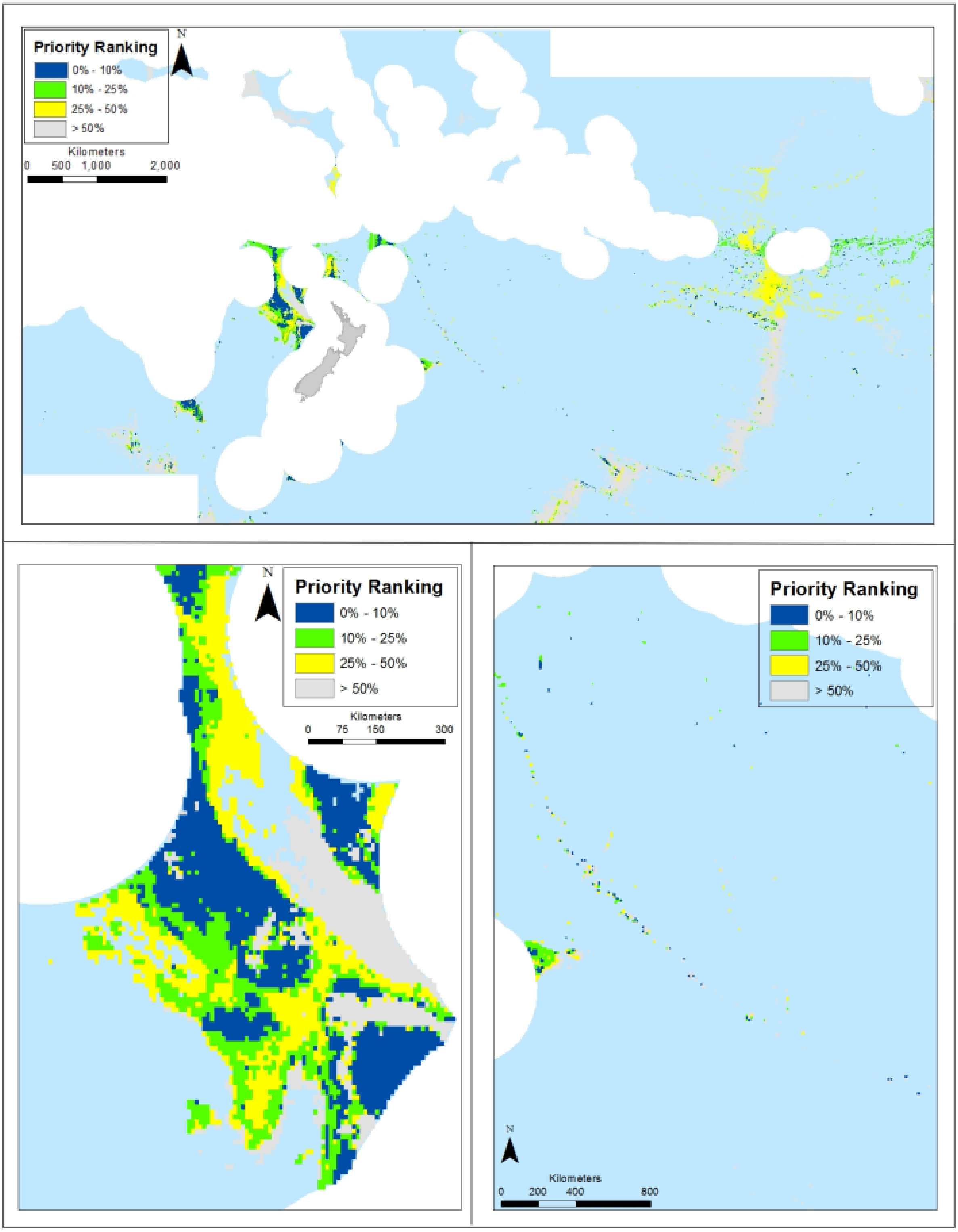

Figure 17: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, fishing cost layer (effort, 1980–2012), and no bioregional layer.

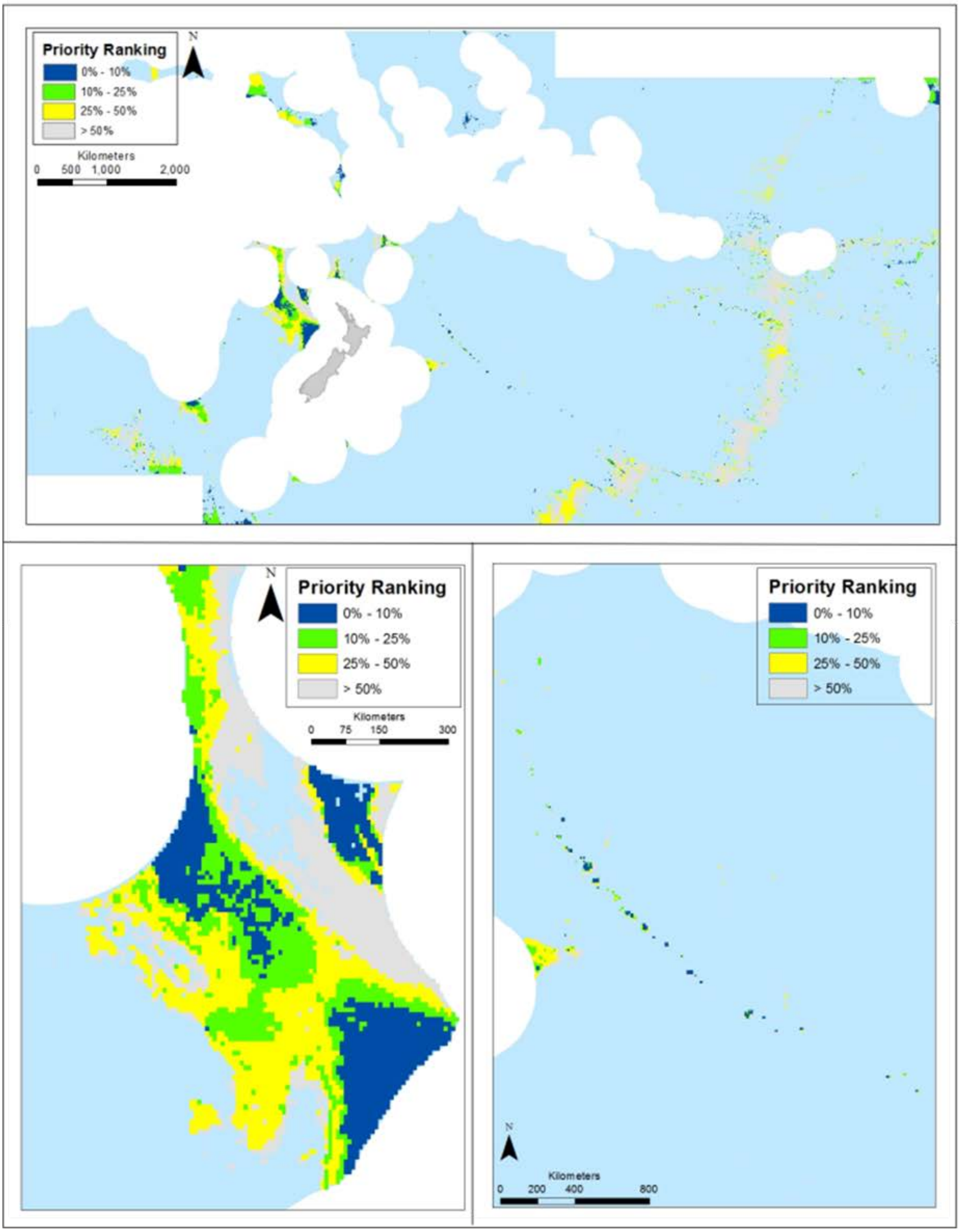

Figure 18: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, no fishing cost layer, and bioregional layer (down-weighted biogeographic provinces).

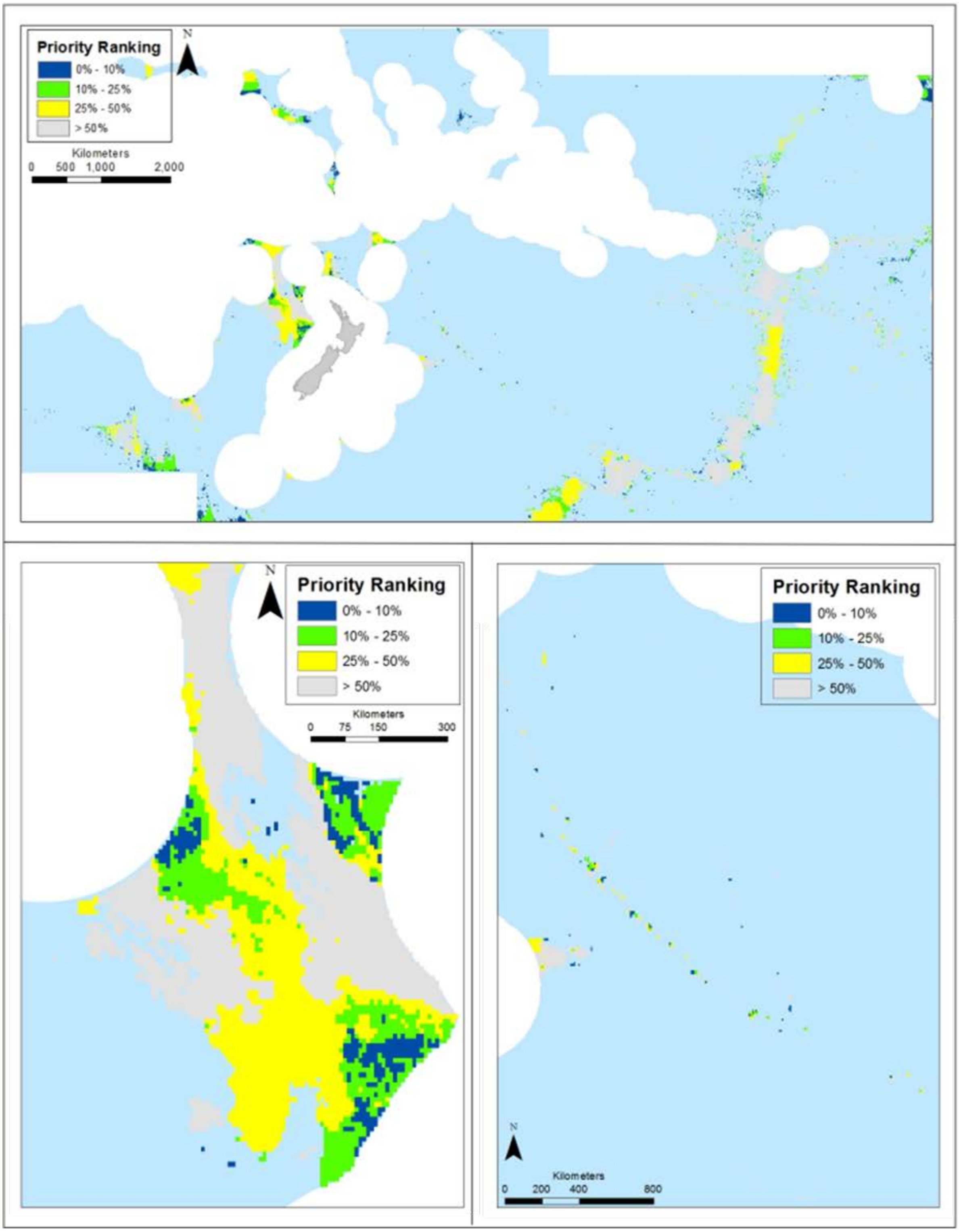

Figure 19: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, no fishing cost layer, and bioregional layer (un-weighted biogeographic provinces).

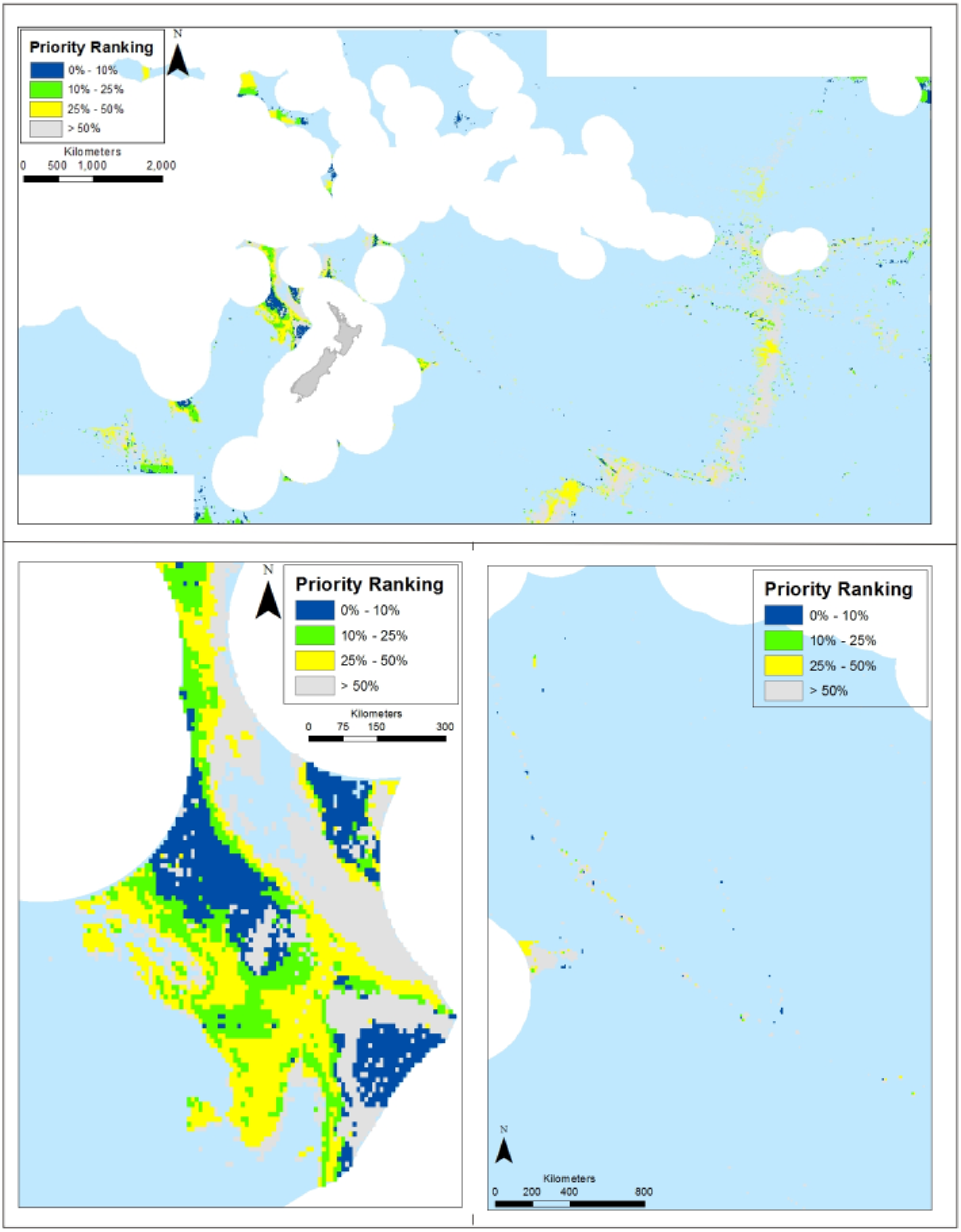

Figure 20: Zonation output for model scenario with full range of habitats suitability values for all VME indicator taxa, no aggregation rule, fishing cost layer (catch, 1980–2012), and bioregional layer (down-weighted biogeographic provinces).

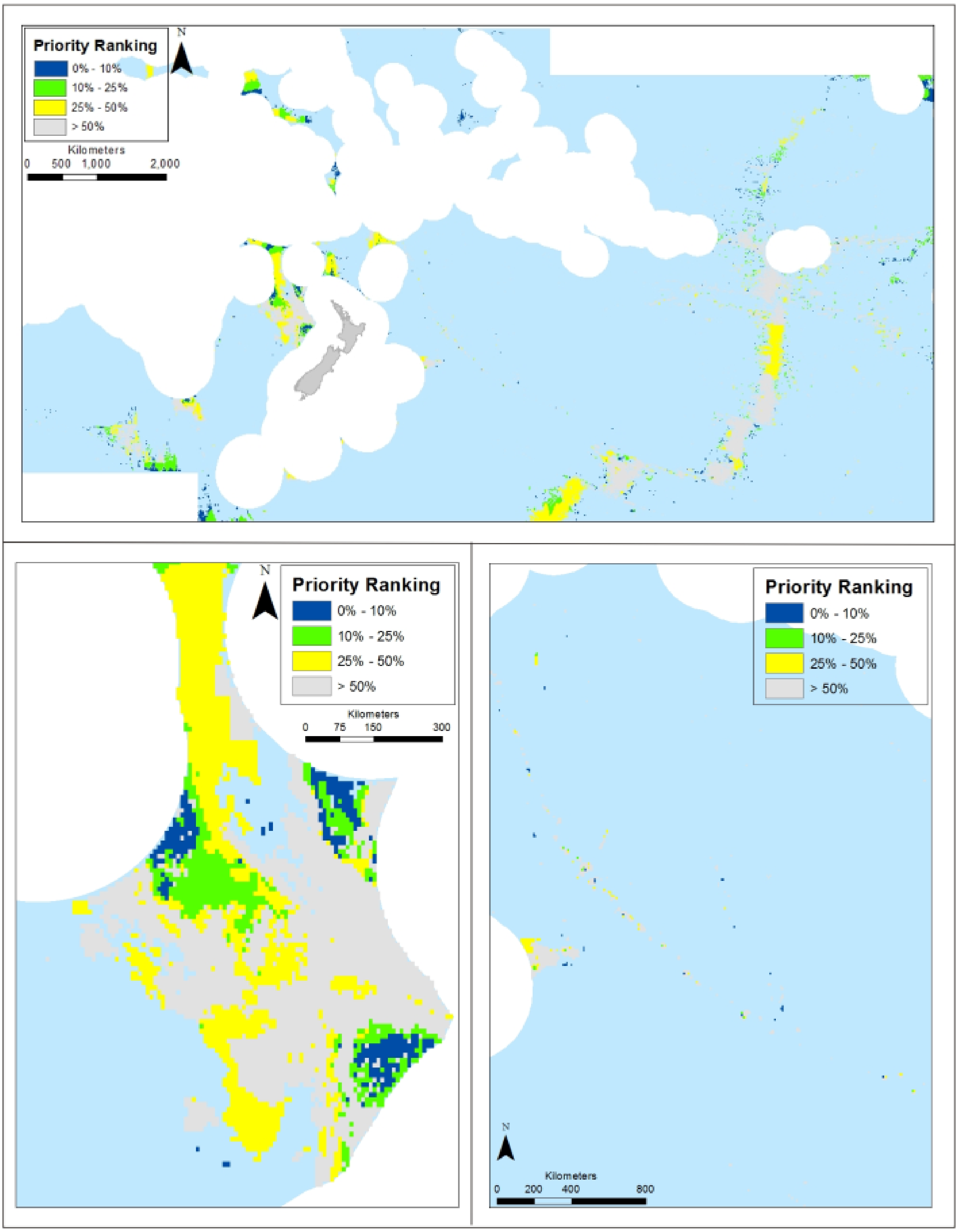

Figure 21: Zonation output for model scenario with full range of habitat suitability values for all VME indicator taxa, no aggregation rule, fishing cost layer (catch, 1980–2012), and bioregional layer (un-weighted biogeographic provinces).

APPENDIX 1

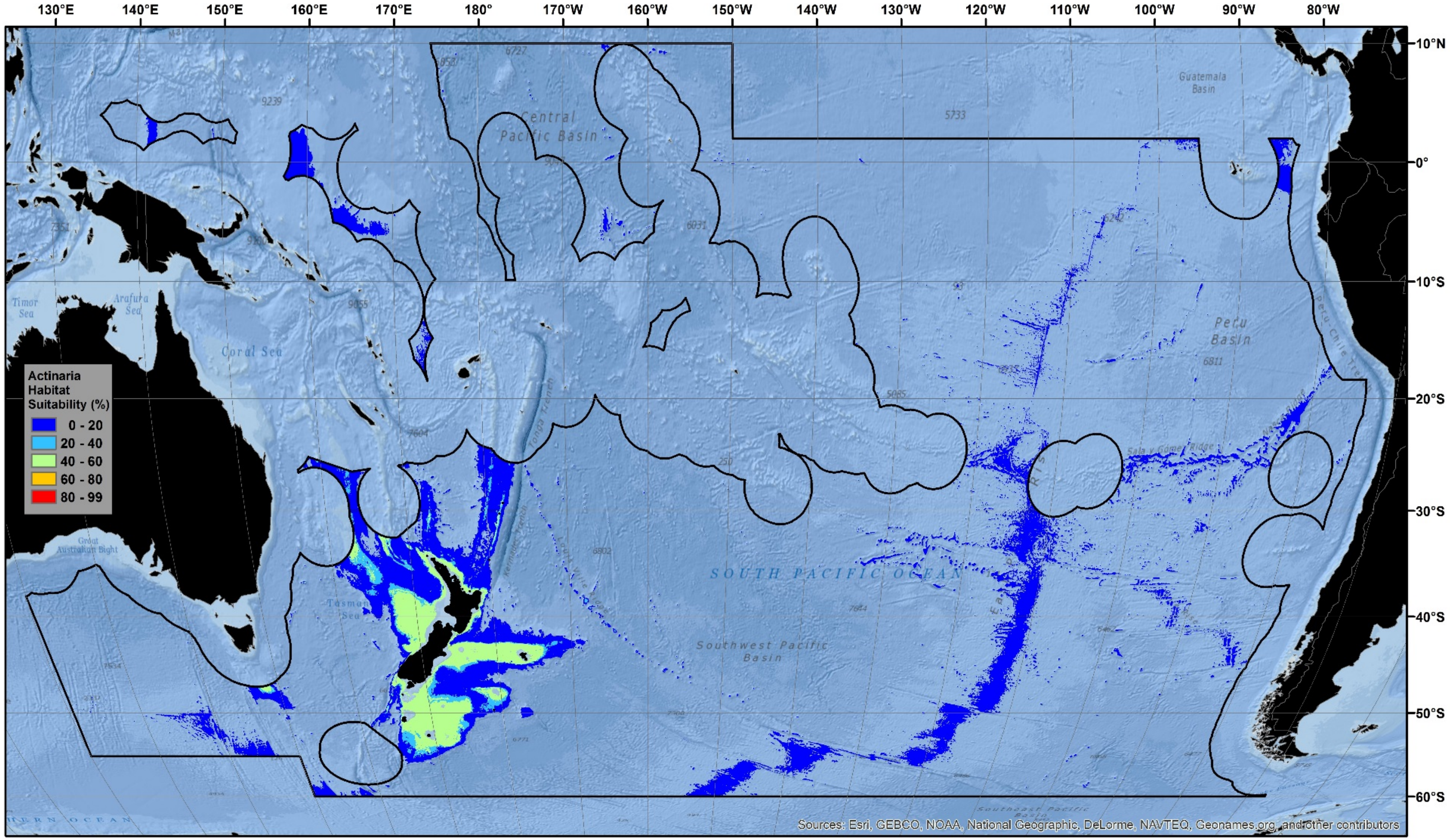

Figure A1: Map showing the predicted habitat suitability for Actinaria in the SPRFMO area and the New Zealand EEZ.

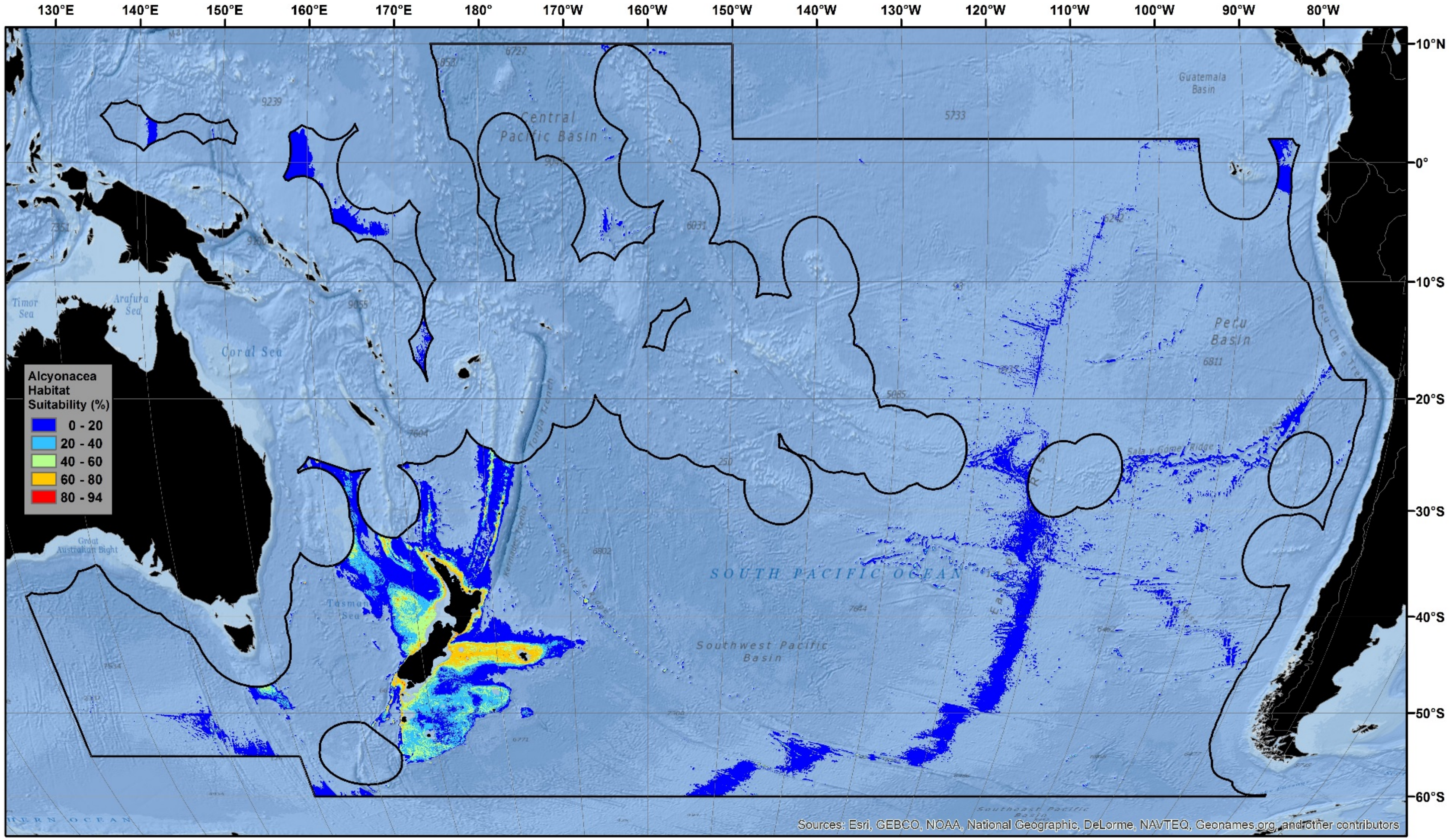

Figure A2: Map showing the predicted habitat suitability for Alcyonacea in the SPRFMO area and the New Zealand EEZ.

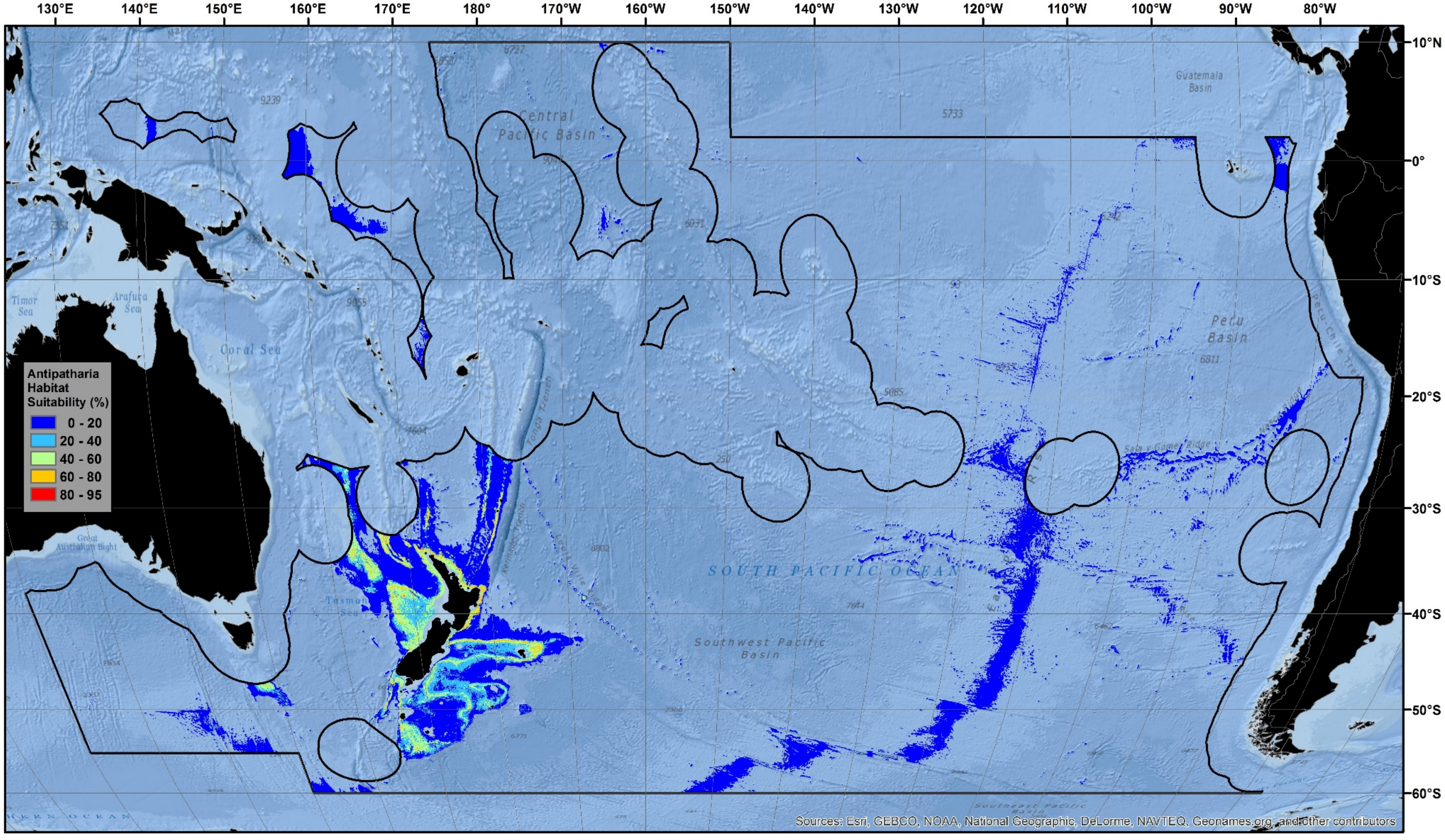

Figure A3: Map showing the predicted habitat suitability for Antipatharia in the SPRFMO area and the New Zealand EEZ.

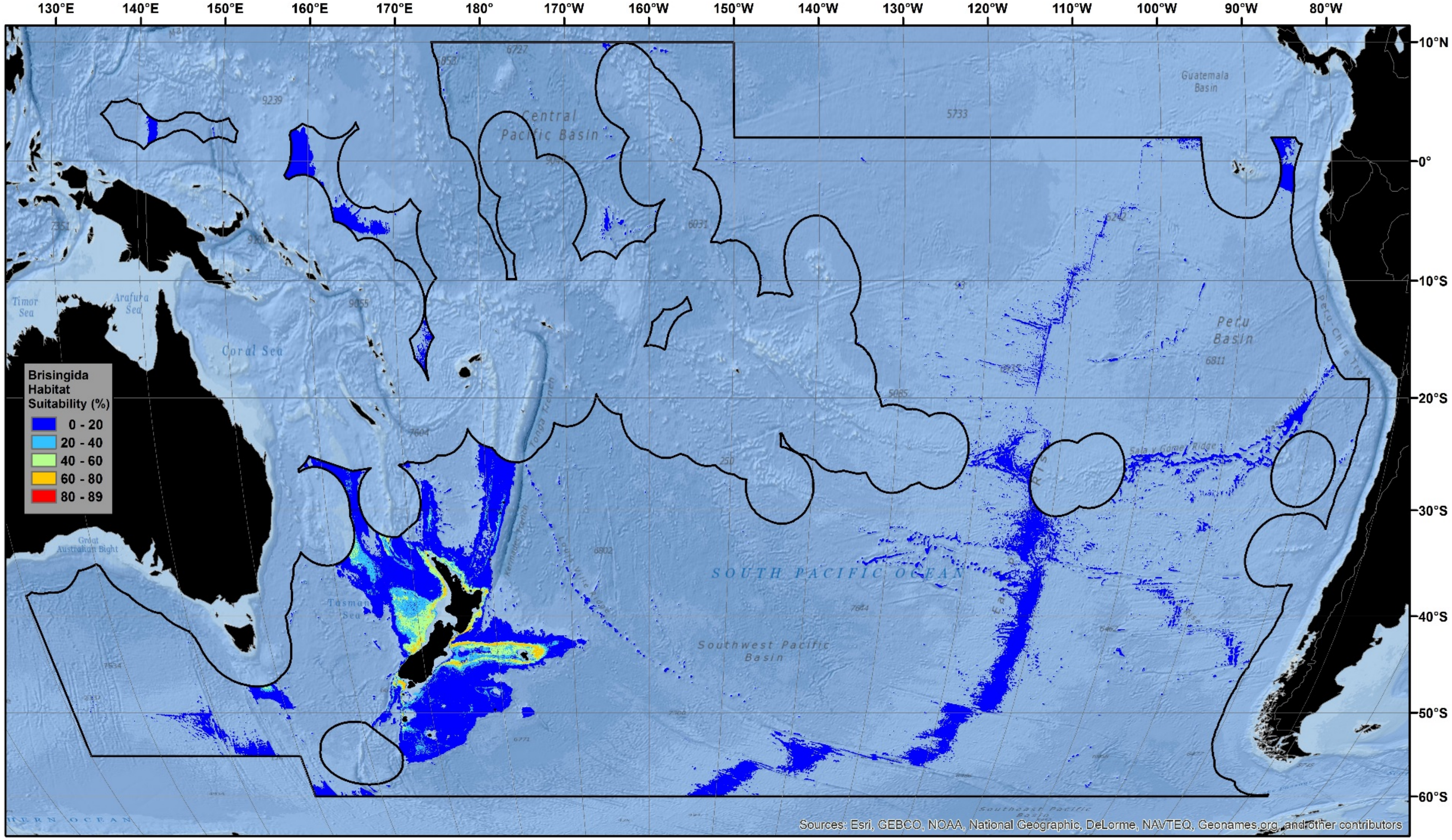

Figure A4: Map showing the predicted habitat suitability for Brisingida in the SPRFMO area and the New Zealand EEZ.

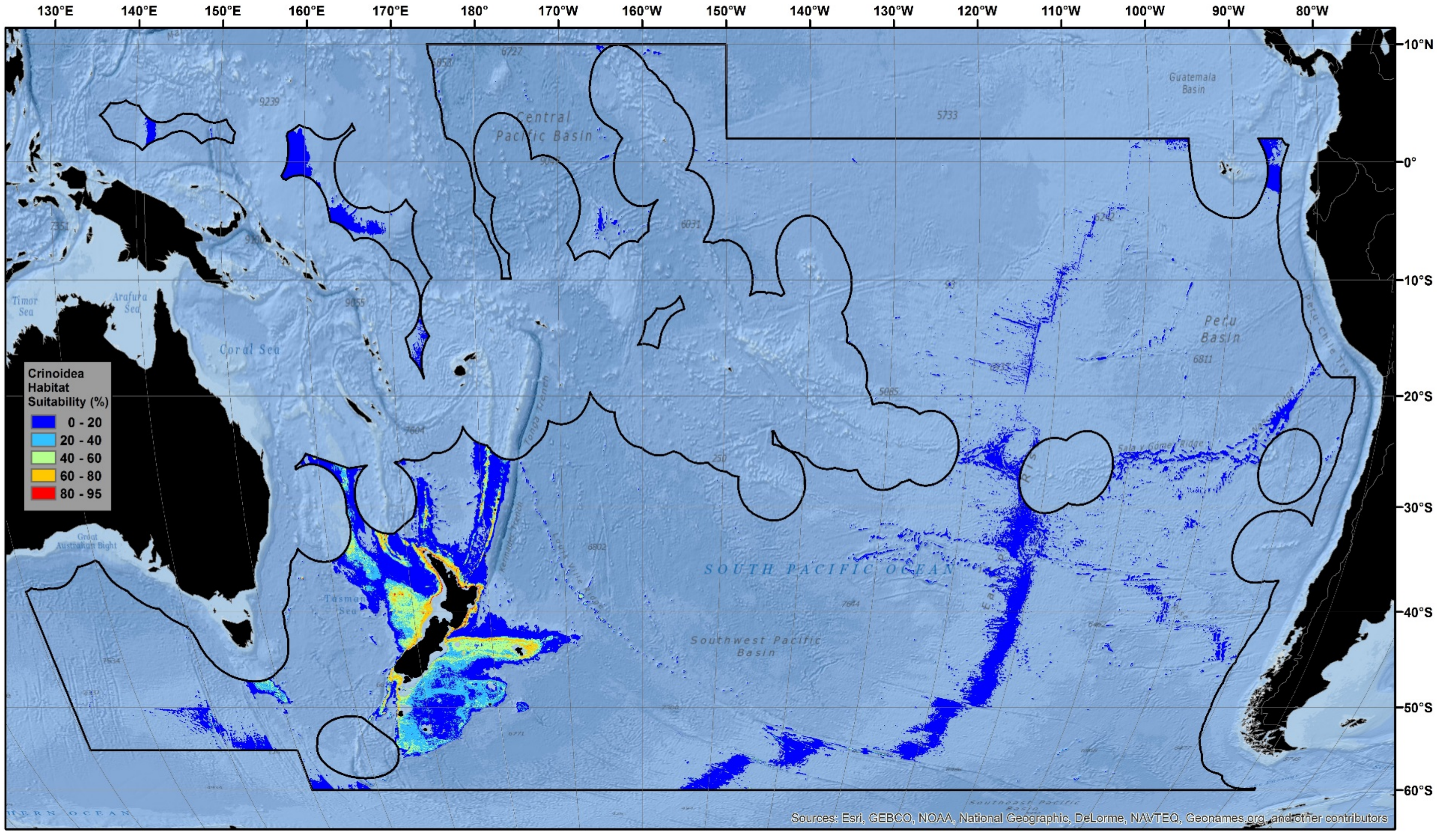

Figure A5: Map showing the predicted habitat suitability for Crinoidea in the SPRFMO area and the New Zealand EEZ.

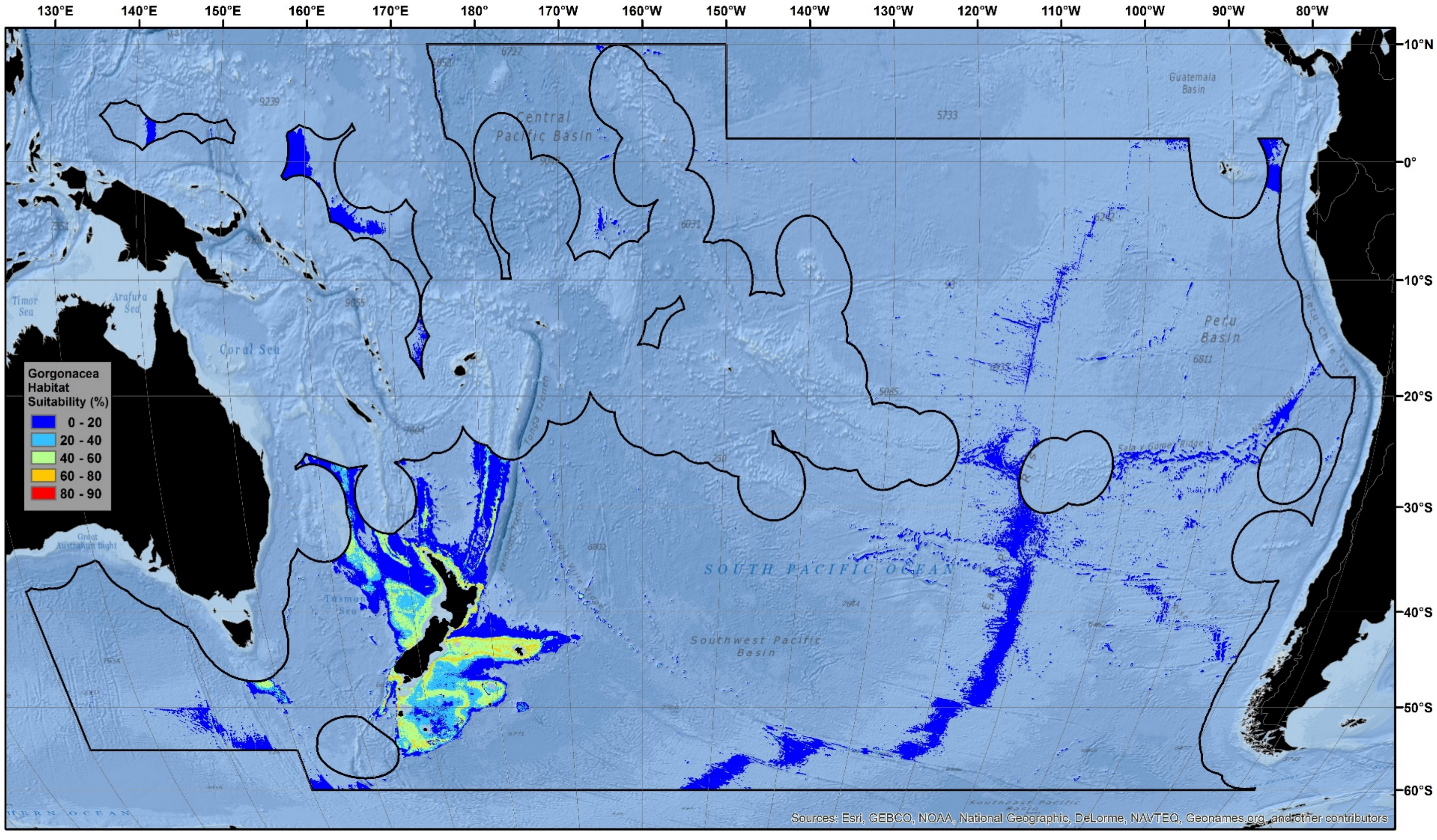

Figure A6: Map showing the predicted habitat suitability for Gorgonacea in the SPRFMO area and the New Zealand EEZ.

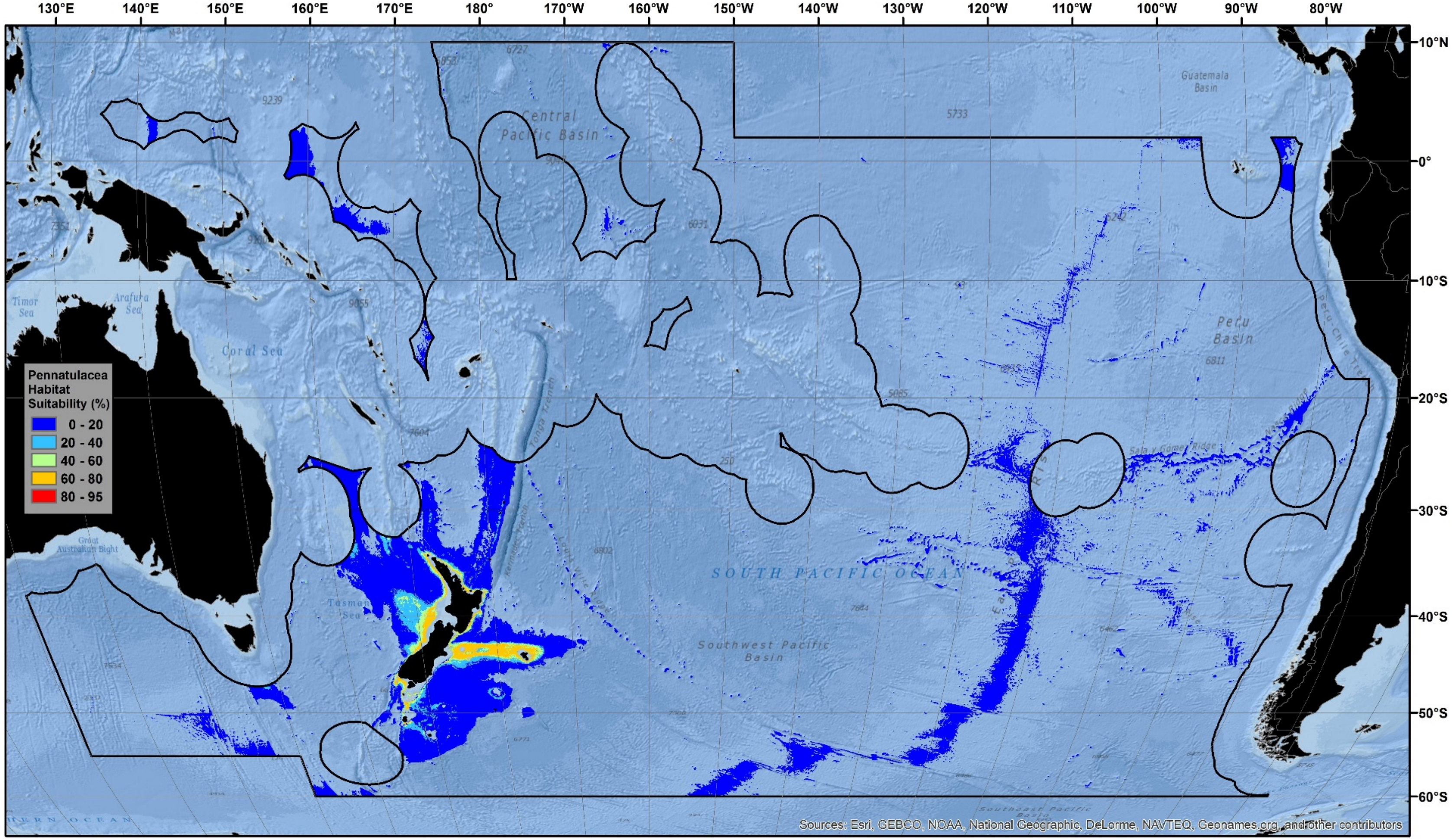

Figure A7: Map showing the predicted habitat suitability for Pennatulcea in the SPRFMO area and the New Zealand EEZ.

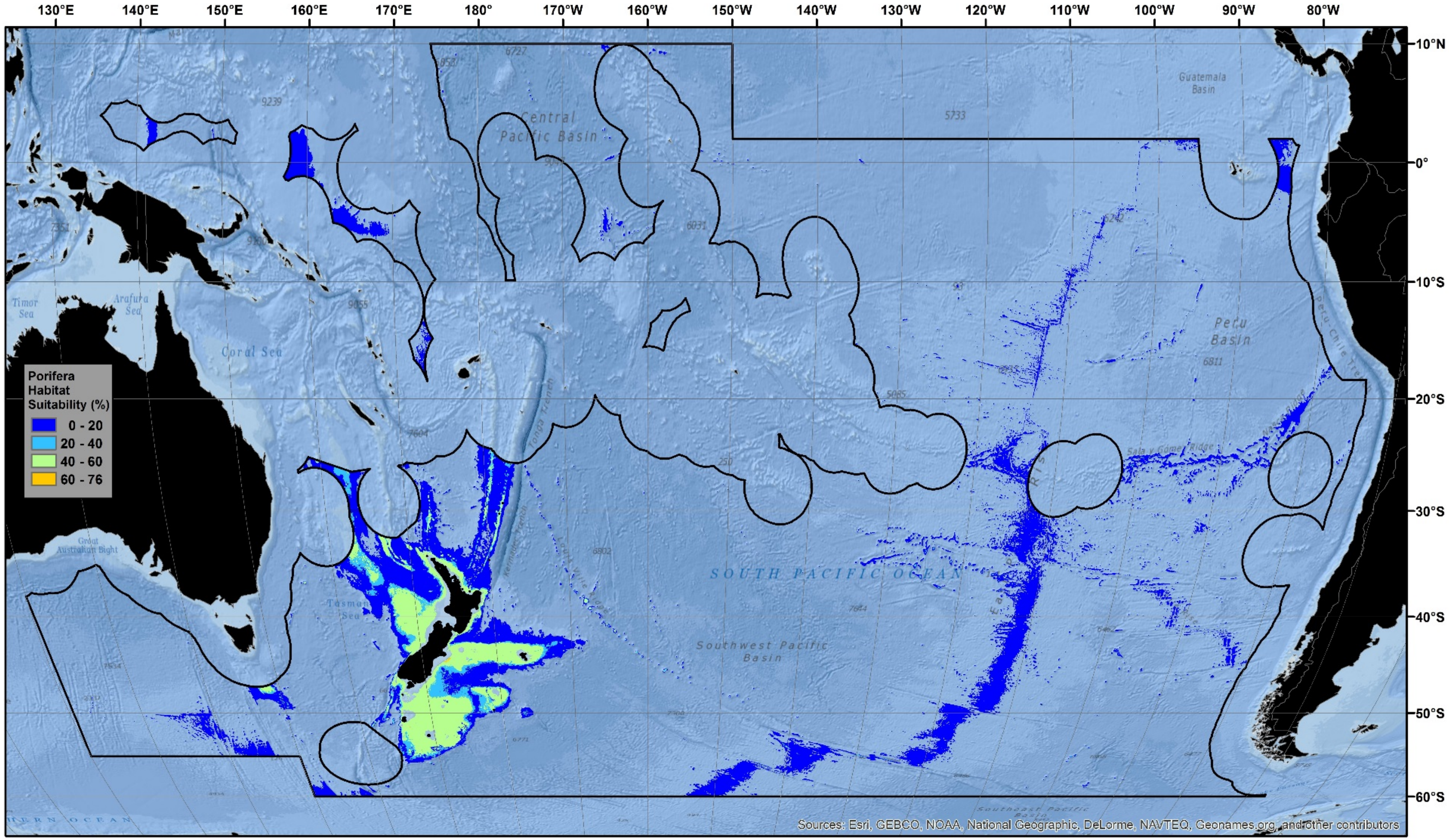

Figure A8: Map showing the predicted habitat suitability for Porifera in the SPRFMO area and the New Zealand EEZ.

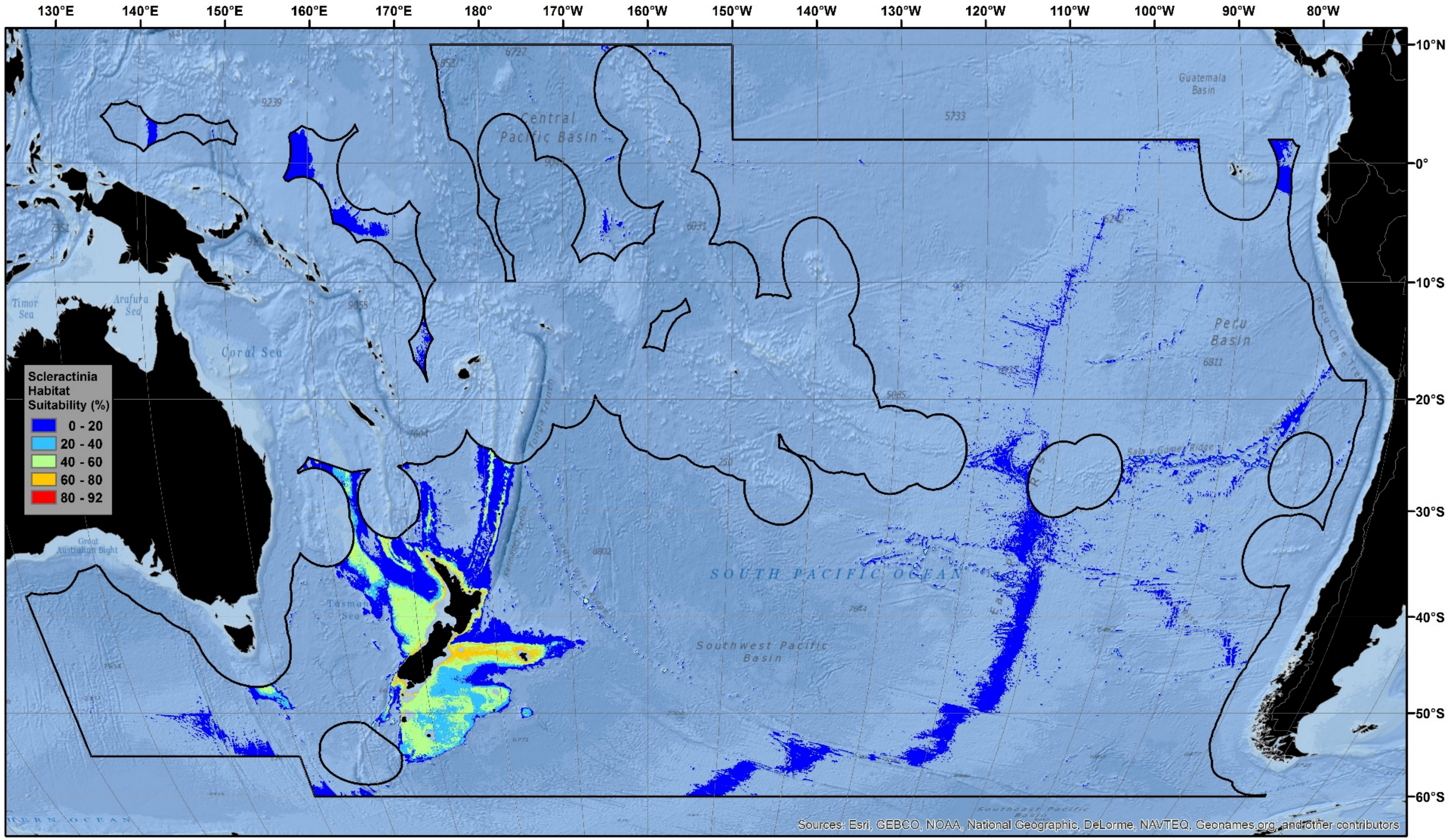

Figure A9: Map showing the predicted habitat suitability for Scleractinia in the SPRFMO area and the New Zealand EEZ.

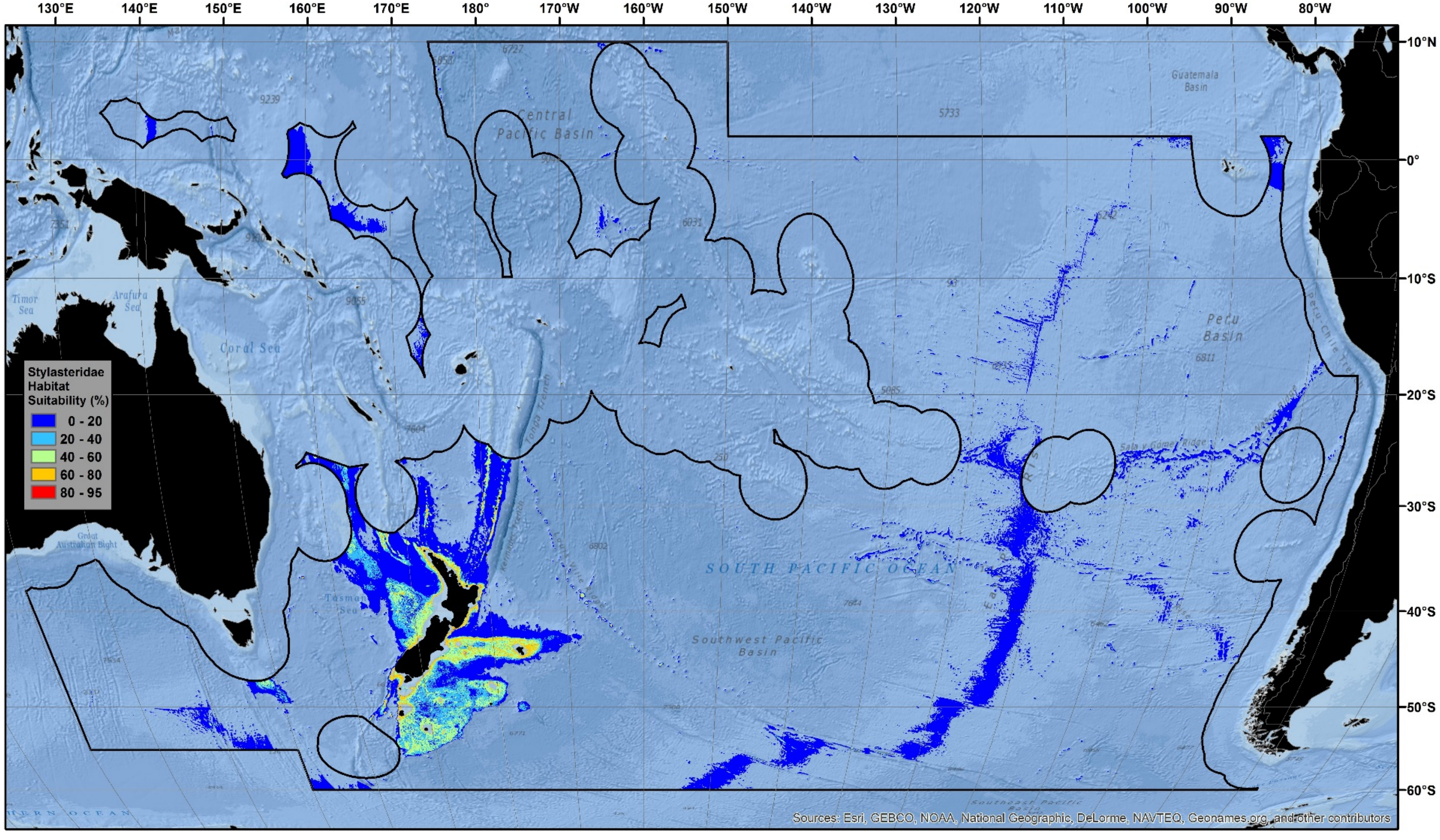

Figure A10: Map showing the predicted habitat suitability for Stylasteridae in the SPRFMO area and the New Zealand EEZ.

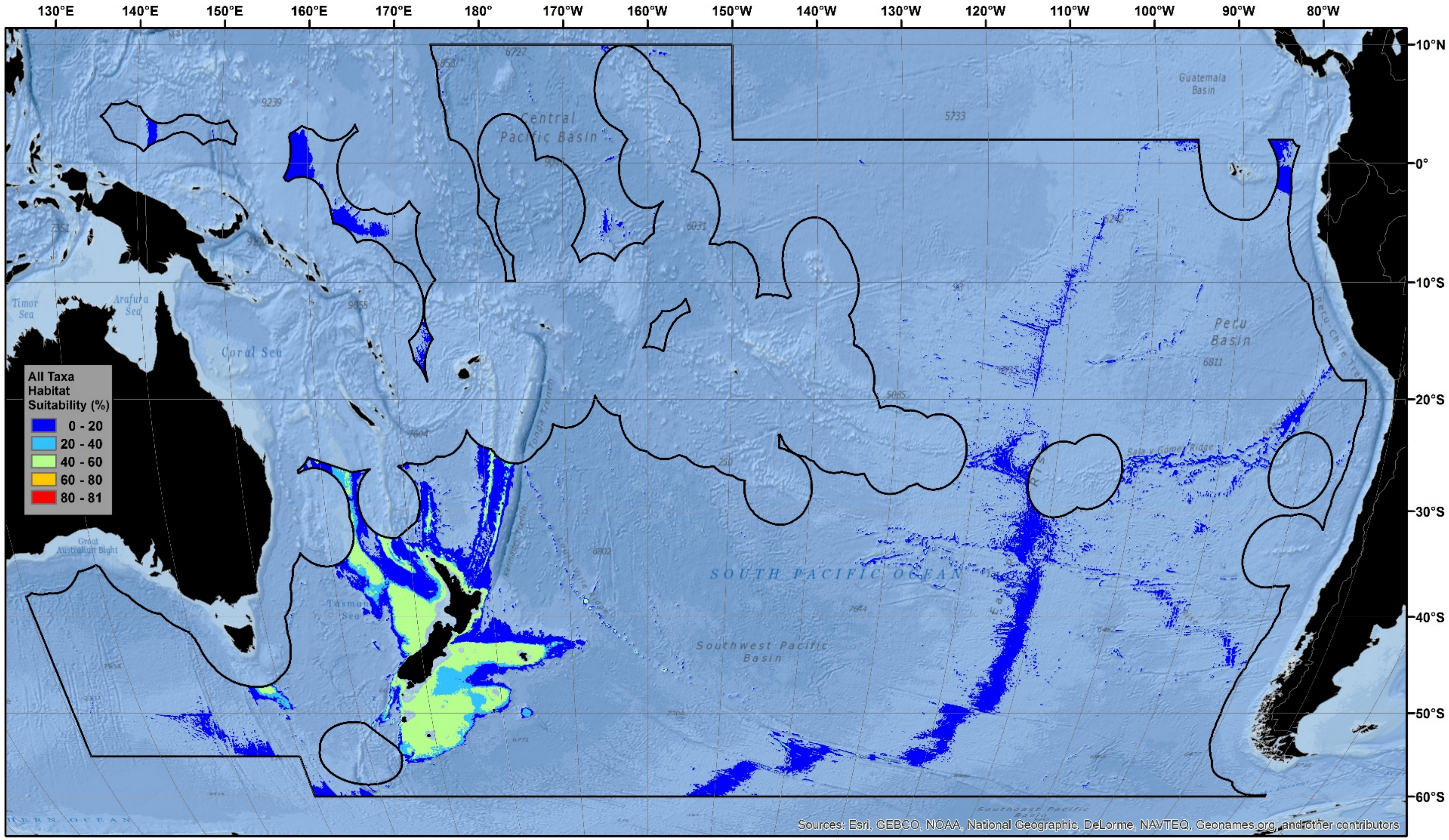

Figure A11: Map showing the predicted habitat suitability for all VME indicator taxa combined in the SPRFMO area and the New Zealand EEZ.

APPENDIX 2

Table A1: The mean percentage contribution of each environmental variable to explaining the habitat suitability of each VME indicator taxon for Maxent models of the SPRFMO area and New Zealand EEZ.

Variable	Actinaria	Alcyonacea	Antipatharia	Brisingida	Crinoidea	Gorgonacea	Pennatulacea	Porifera	Scleractinia	Stylasteridae	All taxa
Depth	9.2	6.4	34.4	3.5	34.5	5.5	9.8	2.1	15.3	7.3	61.3
POC	37.0	7.1	6.2	50.8	15.4	10.8	57.4	5.9	2.6	2.7	3.7
Slope	0.1	6.8	6.7	2.3	6.5	3.5	0.8	0.5	1.4	7.0	0.6
Temperature	26.5	2.6	11.7	10.0	21.9	1.7	7.5	4.2	12.3	1.9	15.7
Dissolved Oxygen	26.7	24.6	39.2	28.5	18.7	41.8	20.3	16.3	11.8	34.0	17.4
Salinity	0.5	4.1	1.8	4.9	3.0	2.1	3.3	1.6	1.2	1.2	1.3
Calcite	-	48.5	-	-	-	34.6	-	-	-	-	-
Aragonite	-	-	-	-	-	-	0.8	-	55.3	45.8	-
Silicate	-	-	-	-	-	-	-	69.3	-	-	-