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Estimating orange roughy stock size on seamounts: a meta-analysis of physical seamount characteristics

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Indices of catch per unit effort have proven poor indices of abundance for several orange roughy fisheries in the New Zealand region outside the EEZ. A different approach is attempted in this project, building on previous studies of seamount fisheries, whereby regression modelling was undertaken that related virgin biomass (estimated from the catch history for orange roughy) to physical characteristics of each seamount. A total of 120 seamounts (the term “seamount” includes knolls and hills with an elevation of 100 m) throughout the New Zealand region were analysed, after selection by location and depth, as being suitable for orange roughy. A set of 23 physical characteristics for each seamount was used in the regression modelling.

A Generalised Additive Modelling approach was used, and for the final model the physical variables selected were latitude, summit depth, SST anomaly (an indication of frontal zones) and the level of spawning activity. Together these explained 83% of the deviance for the logarithm of virgin biomass. The physical variables were biologically sensible, and are readily available for new seamounts from either the exploratory fishing activities, or widespread oceanographic data. Spawning level may initially be unknown, but this was the least important of the model variables, and explained only 5% of the deviance.

Model fits were generally well aligned with actual catch values. Orange roughy biomass is estimated to be concentrated on seamount features of the Chatham Rise, with other major sites along the east coast of the North Island, Challenger Plateau, and Louisville Seamount Chain. Predicted abundance decreases rapidly in northern areas. In general it matches the known distribution of orange roughy relatively well. It indicates that low levels of biomass are expected on the West Norfolk Ridge. The model substantially underestimated biomass on several seamounts on the Chatham Rise, where it is likely that migration of fish from other seamounts in the cluster, and the adjacent slope, may result in higher historical catch levels than the model is able to predict for a single seamount.

Overall the study suggests that the physical characteristics of a seamount can be informative as a general guide to the likely level of orange roughy biomass.

1. INTRODUCTION

Orange roughy fisheries in the New Zealand region outside the EEZ developed in the mid-1980s on the southwest Challenger Plateau, and increased further in the late 1980s and early-1990s on the Lord Howe Rise, Northwest Challenger Plateau and the Louisville Ridge. In the late 1990s, areas on the South Tasman Rise and West Norfolk Ridge were fished. Further afield, New Zealand vessels have also been involved in fishing for orange roughy in the mid-Pacific, southern Atlantic, and southern Indian Oceans (Clark 2008).

Many of these fishing grounds are in an area which is covered by the South Pacific Regional Fisheries Management Organisation (SPRFMO). New Zealand has an ongoing obligation to monitor the status of its fisheries in international waters, and under the SPRFMO Measures for Bottom Fisheries (http://www.sprfmo.int/meetings/international-consultations-and-preparatory-conference/interim-measures/) and the FAO International Guidelines for the Management of Deep-Sea Fisheries in the High Seas (FAO 2009), New Zealand also has an obligation to implement measures to ensure the sustainability of deep-sea fish stocks. Such measures require some understanding of the likely abundance of these stocks in deep-sea areas.

Fishing for deepwater commercial species outside the New Zealand EEZ is to a large extent focused on seamounts, knolls and hills (all these seafloor features are combined under the term "seamount" in this report (after Pitcher et al. 2007)), where orange roughy (*Hoplostethus atlanticus*) and oreos (black oreo, *Allocyttus niger*, and smooth oreo, *Pseudocyttus maculatus*) often aggregate. In the general New Zealand region it has been estimated that over 60% of orange roughy catch, and 50% of oreo catch, was taken off seamounts (O'Driscoll & Clark 2005). However, in many areas the populations were rapidly depleted and most orange roughy fisheries on seamounts declined (e.g., Clark 2009, Clark et al. 2010a, Pitcher et al. 2010). Seamounts are widely regarded as being fragile habitat (Althaus et al. 2009, Clark et al. 2010b), and susceptible to both overfishing and benthic habitat damage, requiring careful management of bottom trawl fisheries to reduce the risks of uncontrolled spread of effort, and possible overexploitation of low productivity resources. Designing and carrying out appropriate abundance surveys on seamounts can be lengthy, expensive, and complicated. In addition, fish stocks on seamounts may be small and localised and dedicated research surveys are typically not cost-effective. Catch-per-unit effort analyses can be useful, but have proven problematic because of the variable nature of the fisheries outside the EEZ (Clark et al. 2010a). Spatially disaggregated approaches are showing more promise (Roux et al. 2016), although are not applicable in all areas. Hence there is value in considering alternative approaches to CPUE for estimating fish biomass.

Meta-analysis and associated predictive modelling, which examine trends in existing and historical seamount fisheries around New Zealand, together with information on their physical characteristics, have shown promise as a method for estimating original (unfished) orange roughy biomass on seamounts and underwater topographic features (Clark et al. 2001). Clark et al. (2001) compiled physical attributes and catch data of deepwater fisheries for 77 seamounts in the New Zealand region. Characteristics of location, depth, size, elevation above the seafloor, age, continental association, geological origin, distance offshore, distance from surrounding seamounts, and degree of spawning were defined for each seamount. These data were then regressed as independent variables against the minimum orange roughy population size estimated from the historical catch to investigate whether they could be useful predictors of likely long-term catch from newly found seamounts.

Multiple regression procedures were used to model the relationship between the physical variables and orange roughy biomass. There were two stages in the analysis. First, biomass was modelled for individual seamounts grouped into regions (as a categorical variable), including predictors specific to individual seamounts. This analysis showed region, depth of the peak, and slope of the seamount to be significant predictors of biomass. A second analysis was carried out where the region effects derived from the initial regression were modelled, using predictors related to entire regions. This analysis showed latitude and association (continental/oceanic) to be important predictors of biomass. The predictive power of the models was tested by cross validation, and compared with simpler models to assess their informative value. The method was applied to a section of the Louisville Ridge in Ministry of Fisheries project ORH2002/03 (Clark 2003), and more broadly to seamounts on the Lord Howe Rise, Northwest Challenger Plateau, West Norfolk Ridge, and Louisville Ridge under project IFA2008-05 (Clark et al. 2010a).

The original project had an overall objective, with two specific objectives. During the development of this work, the Deepwater Fishery Assessment Working Group considered that with resources available the project should focus solely on Objective 1, and not carry out Objective 2.

Overall objective:

1. To monitor orange roughy (*Hoplostethus atlanticus*) fisheries in the New Zealand region outside the EEZ.

Specific objectives:

1. To update the seamounts meta-analysis model produced in 2001 to estimate the potential abundance of orange roughy in an area based on data on historical catches and the physical and oceanographic characteristics of the seamounts in that area.

2. To develop estimates of biomass for orange roughy fisheries outside the EEZ based on the application of the meta-analysis to seamount features occurring within the area of the South Pacific RFMO.

2. METHODS

The project compiled and updated datasets on the physical characteristics of seamounts, and fisheries catch and effort data.

(a) Seamount physical data

The original analysis was carried out with 77 seamounts for which there were basic physical data (location, depth, physical shape) and associated orange roughy catch details. The number of seamounts in the NIWA database has roughly doubled since then (to over 1500 features in the New Zealand region), and the number with some fishing activity has increased to almost 300. The range of environmental variables has also increased. Twelve physical variables were included in the 2001 analysis, but in the NIWA "SEAMOUNT database" there are now 72 data fields for each seamount (Figure 1) (Rowden et al. 2008).

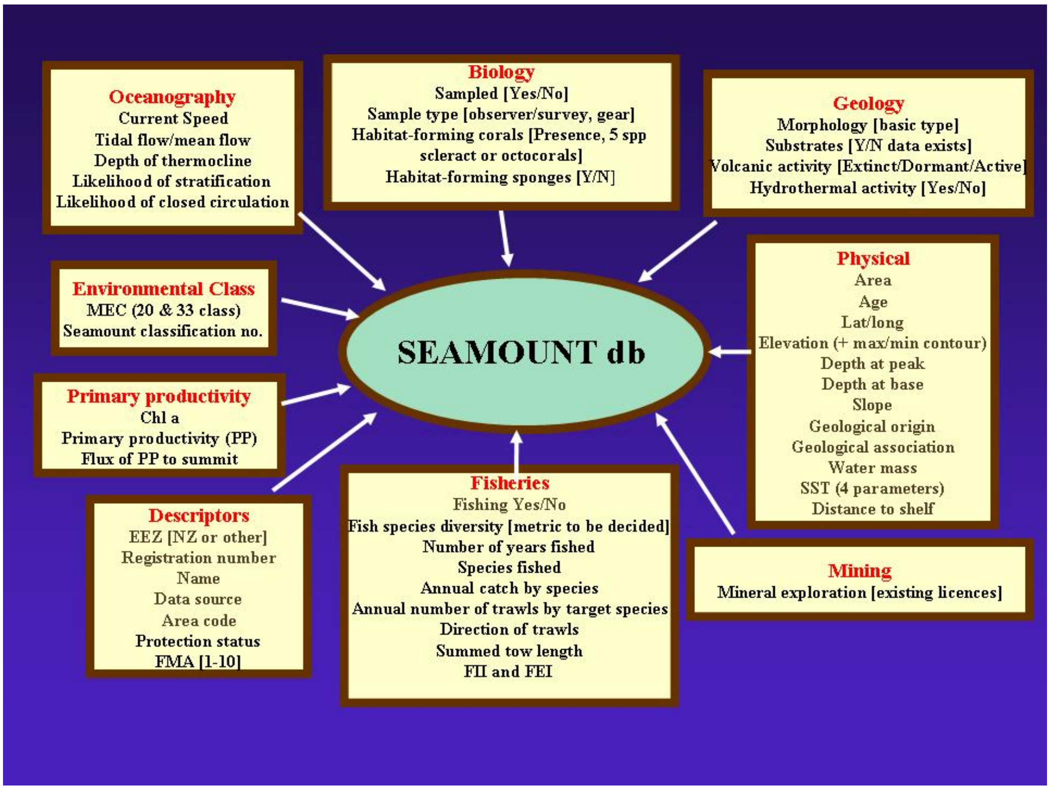

Figure 1: Schematic of the environmental variables in the NIWA "SEAMOUNT database".

Additional bathymetric data have become available from industry in recent years (Deepwater Group and The ORH1 Exploratory Fishing Company), and a 30 arc-second version of global bathymetry was analysed by Yesson et al. (2011) to estimate the location and depths of seamounts and knolls. These data sources were used where appropriate to revise estimates of seamount height and areal extent. Seamounts selected for inclusion satisfied 4 key physical criteria:

- Depth of peak shallower than 1500 m (deeper than this, seamounts are not fished, and orange roughy is getting towards its maximum depth in the New Zealand region)
- Depth of peak deeper than 500 m (most orange roughy are fished near the summit or upper flanks of a seamount, and their depth is typically deeper than 600 m)
- Elevation greater than 100 m (this excludes very small hills or mounds, and restricts the analysis to the commonly accepted hill, knoll and seamount features (after Pitcher et al. 2007)).
- Latitude ranged from 30° S to 60° S (outside this range orange roughy don't occur in the region).

(b) Fishing catch and effort data

Commercial catch and effort data were combined from several sources:

- An extract was made of Trawl Catch Effort Processing Returns (TCEPR) and High Seas Trawl Catch Effort Returns (HS-TCER)) from the Ministry for Primary Industries (fisheries) database *Warehou*. Tow by tow data covered the period from 1989–90 to 2010–11.
- Groomed data from MFish projects for New Zealand orange roughy fisheries outside the EEZ were maintained by NIWA (M Clark) for use in project IFA2008-05, which extended through to 2006–07.
- Groomed data obtained from the Australian Fisheries Management Authority for Australian vessels operating in orange roughy fisheries in the Tasman Sea. This was to 2006–07.

- Data from New Zealand vessels up to 1988–89 from the Fisheries Statistics Unit (FSU) of the Ministry of Agriculture and Fisheries (held by NIWA in the database *dw_cdb*).

Error checks were performed for the following data fields:

- Bottom depth (more than 1300 m or less than 500 m)
- Fishing effort depth (in comparison with bottom depth and bathymetry)
- Position (for large differences between start and finish position, and for estimated steaming speed between tow locations)
- Trawl speed (more than 5 kt or less than 1.5 kt)
- Tow duration (more than 10 hour)
- Tow distance (more than 30 nautical miles)
- Target species (not a deepwater bottom trawl target species)
- Vessel nationality (NZ vessels only. If none recorded then assumed to be domestic)

An important issue with orange roughy catch-effort data is incorrect east-west assignment of longitude for tows on the Louisville Seamount Chain. Many were recorded as an east longitude, which places them in the Tasman Sea. In most instances these are easy to identify, but where they transpose onto the Challenger Plateau it is more difficult, and examination of depth and other tow positions during that trip was required (Figure 2). Suspicious tows were corrected if necessary by checking whether the vessel had recorded tows in both the Challenger Plateau and on the Louisville Seamounts within the same week.

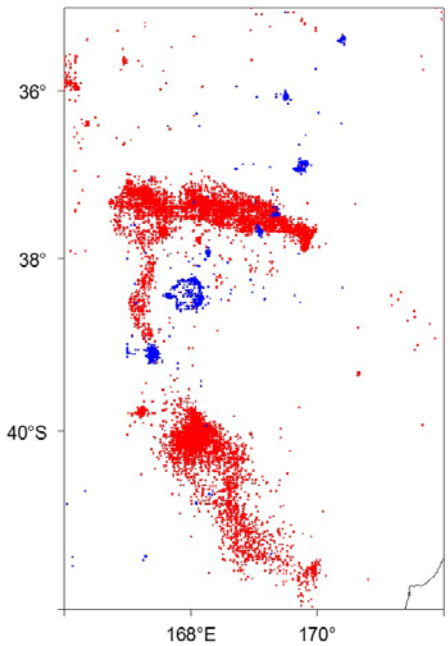

Figure 2: An example of an area of the Tasman Sea where tows on Louisville seamounts mistakenly recorded with an east longitude transpose directly onto known orange roughy fisheries on the Challenger Plateau (red dots). The blue dots show Louisville tows intentionally transposed onto the western hemisphere to illustrate the issue.

The above are generic deepwater fishery data checks. For seamount-assignment, the start position of tows were compared with the summit position of the seamounts, and assigned to the nearest seamount. Tows had to be within 5 km of the summit position, and less than 30 minutes in duration, which was less than the 10 km used by O'Driscoll & Clark (2005).

An issue with seamount assignment is that the recorded tow position is that of the vessel, and rounded to the nearest 1 n.mile. In an area where there are clusters of small knolls, automatic assignment is difficult because the nearest seamount to the recorded vessel position may not be the one being fished. Manual checks were carried out on tows within three seamount complexes on the Chatham Rise ("Graveyard", "Andes", "Chief") where it was known that the distribution and spacing of hills was problematic for accurate automatic assignment (see Figure 3). Seamount summit depth was checked against recorded tow depth, which identified tows that were shallower than the summit, or as deep as the base of the seamount, and hence incorrect. Tow direction and sequence of tows by the same vessel were also checked to re-assign them correctly.

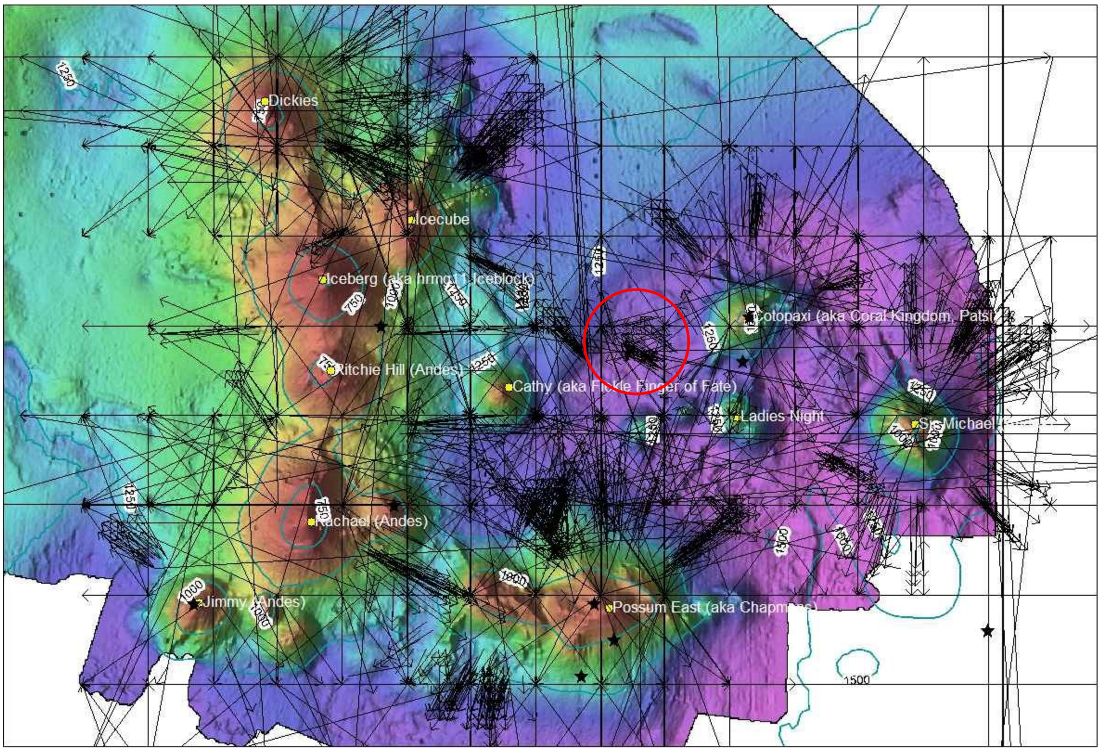

Figure 3: Plot of recorded tow lines (vessel position) from TCEPR data for the Andes Seamount complex. Many tows can correctly be assigned to the appropriate seamount, but some features like Ladies Night would have their fishing effort automatically assigned to Cotopaxi which is closer (tows inside the red circle).

The catch history based solely on New Zealand or Australian data may be an underestimate for some seamounts outside the EEZ where vessels from other flag states have fished in the past. In most cases foreign vessel tow by tow data, or specific seamount catch information, are unavailable. Where seamounts were known to have been fished, this was noted, but no account taken in the analysis.

The total catch of orange roughy from a seamount was used as the estimate of SSB_0 for model runs. In the 2001 analysis, the catch history by year was used in a deterministic orange roughy model to estimate B_{min}, the minimum biomass consistent with the catch history and productivity parameters assumed for orange roughy. Initial model runs in the present study investigated the sensitivity of summing catches to runs with assumptions about r and M. However, the Deepwater Fishery Assessment Working Group recommended using total catch, without making any population model assumptions.

(c) Seamount fishery selection

During the course of the project, several iterations of data selection occurred, based on aspects of the fishing history.

<u>"Fished out" dataset</u>
Initially, seamounts were excluded if the catch did not show a strong decline to low levels. Rules were imposed to exclude closed hills (the 2001 Seamount closures), if the current catch was still a substantial proportion of the initial catch, orif there were fewer than 10 tows per year. This resulted in 55 seamounts selected.

Additional "boundary" seamounts were included, especially in the north and south, where it is known that orange roughy are near the limit of their distribution. This was based on several research survey results that covered seamounts in the mid-Tasman Sea (e.g., "Halipro2" Clark et al. 2010, "NORFANZ, Clark & Roberts 2008), and commercial data from slope and plateau regions with low catch rates of orange roughy (e,g., northern regions of New Zealand, Clark 2006; southern regions, Clark 1998). These were included to prevent the modelling extrapolating high abundance into areas where there were few seamount catch data.

<u>Shorter time series dataset</u>
The first iteration constrained the seamount selection largely to features on the Chatham Rise, where fishing took place for long enough to establish a trend in catch. This was considered to be too restrictive, and so a second analysis examined seamounts with 3 years or more of fishing, where there were 10 tows or more per year. Catch rates (as a sign of depletion) were also considered, with requirements that the average catch-per-tow in at least one of the first three years of fishing exceeded 1 t/tow, and catch rate could not exceed 1 t/tow in either of the last two fished years. Closed seamounts were again excluded, but seamounts within closed or semi-closed fisheries (Puysegur and Mercury-Colville Box) were retained. Together with 21 "boundary" features, this resulted in 90 seamounts for analysis.

The results from this analysis were presented to the joint 2013 conference of the New Zealand Marine Sciences Society, and the Australian Marine Sciences Association. Several problems were identified with this dataset, which excluded seamounts that had only recently been fished, or had an intermittent catch history. An example of this effect was that all the seamounts included on the West Norfolk Ridge were boundary features because the actual fished hills failed the criteria.

<u>Final dataset</u>
As a compromise between criteria being too restrictive and hence excluding young fishery data and limiting seamount numbers, and being too free and allowing many uninformative non-fishery seamounts, or seamounts not substantially fished down to be included, a final set of criteria were agreed:

- Closed seamounts were excluded
- A seamount had to be fished for 3 or more years, with 10 or more tows per year
- The total catch history had to have at least 200 tows (signifying a serious fishery)
- Boundary seamounts (21) were included in some areas

The final dataset comprised 121 features.

(d) Regression modelling

The original analysis of Clark et al. (2001) was carried out in two stages - the first to model biomass of seamounts using region as a categorical effect and including predictors specific to individual seamounts; and then secondly the region effects were modelled using predictors relating to entire regions. This approach was taken to deliberately emphasise that orange roughy biomass differs by region around New

Zealand, and it was felt that individual variables may not capture this very well. However, a single regression approach was taken in this project, described below.

Regression methodology

The theory behind the approach is that biomass (effectively virgin Spawning Stock Biomass, SSB) on hill *i*, SSB_{0i}, can be predicted based on a set of predictor variables, x_{ij}, (see below) using parameter values estimated in a regression on data from seamounts that have an estimate of SSB_0. Yield will subsequently be a small percentage of SSB_{0i}. It was assumed that fish available to fishing on a seamount are mature and that each seamount population is independent within a region and category.

Physical variables were selected from NIWAs "Seamount database", where they were felt to be biologically meaningful, and also reasonably independent of one another. After some initial runs, and checks of whether too many variables were being fitted, a final set of 23 predictor variables were considered, 16 continuous and 7 categorical (Table 1).

Table 1: The predictor variables used in the final regression modelling (for further details of seamount variables see Rowden et al. 2008).

Predictor variable	Variable type	Explanation
Latitude	Continuous	Latitude of the summit position of the seamount, to 0.01°.
Longitude	Continuous	Longitude of the summit position of the seamount, to 0.01°.
Summit depth	Continuous	Minimum depth of the seamount from the surface (m).
Base depth	Continuous	The deepest depth contour which completely encircles the seamount.
Elevation	Continuous	The depth range between the summit and base.
Area	Continuous	The area of the seamount base calculated in the horizontal plane within the base depth contour.
Distance to continental shelf	Continuous	Distance from the continental shelf edge may reflect the degree to which the feature is influenced by near-shore processes. Calculated using ArcGIS, from the 250 m depth contour, based on an azimuthal equidistant projection (Central Meridian 171°E, Latitude of Origin 41°S, Datum WGS84).
SST amplitude	Continuous	Variations in the annual amplitude of SST reflect differences in stratification and wind mixing that together produce the mixed layer across the region. Calculated from NIWA's archived SST climatology data set.
SST winter	Continuous	Patterns in wintertime SST are a proxy for water mass (which is related to nutrient availability). Calculated from NIWA's archived SST climatology data set.
SST anomaly	Continuous	Summertime SST anomaly is expected to recognise anomalies in temperature that are owing to hydrodynamic forcing, such as upwelling and vigorous mixing from eddies. Calculated from NIWA's archived SST climatology data set.

Predictor variable	Variable type	Explanation
SST gradient	Continuous	SST gradient recognises fronts in oceanic water masses (and is expected to correlate with variation in primary productivity). Calculated from NIWA's archived SST climatology data set.
Slope	Continuous	Approximated as $\text{Elevation}/\sqrt{\text{Area}}$. This represents the average steepness of the flanks of the seamount.
Nearest neighbour	Continuous	The distance to the nearest adjacent seamount, to reflect connectivity patterns of the seamount.
Number neighbours 100 km	Continuous	The number of seamounts within a 100 km radius of the summit location. This reflects the degree of seamount topographic complexity near the individual seamount, and its colonization potential based on a maximum average dispersal distance of benthic invertebrates of 100 km.
Chl a level	Continuous	Estimates of "chlorophyll *a*" were derived from the mean of SeaWiFS data. Is a proxy for phytoplankton biomass in the ocean above the seamount.
Primary production model	Continuous	Primary production estimates based on a Vertically Generalised Production Model.
Association	Categorical	Either continental or oceanic. Continental classification indicates that the seamounts are close to the continental shelf around New Zealand or its associated rises and plateau; an oceanic association means a seamount is more isolated from continental margins.
Shape	Categorical	Either a conical seamount, or elongated and flat-topped guyot.
Connectivity	Categorical	A binary variable indicating whether a seamount is part of a cluster, or isolated.
Spawning	Categorical	Classified as none (<0.1), low (0.1–0.4), medium (0.4–0.7), and high (>0.7) based on the proportion of female fish in spawning condition recorded in observer and research survey databases. An estimate of how important the seamount is for spawning and hence the likelihood of aggregations.
Surface water mass	Categorical	The surface water mass overlying the seamount-whether a frontal mass, or tropical, subtropical, subantarctic water etc.
Fishery region	Categorical	A set of 11 regions were defined to reflect the distribution of the main orange roughy fishing grounds in the NZ region (see Figure 4).

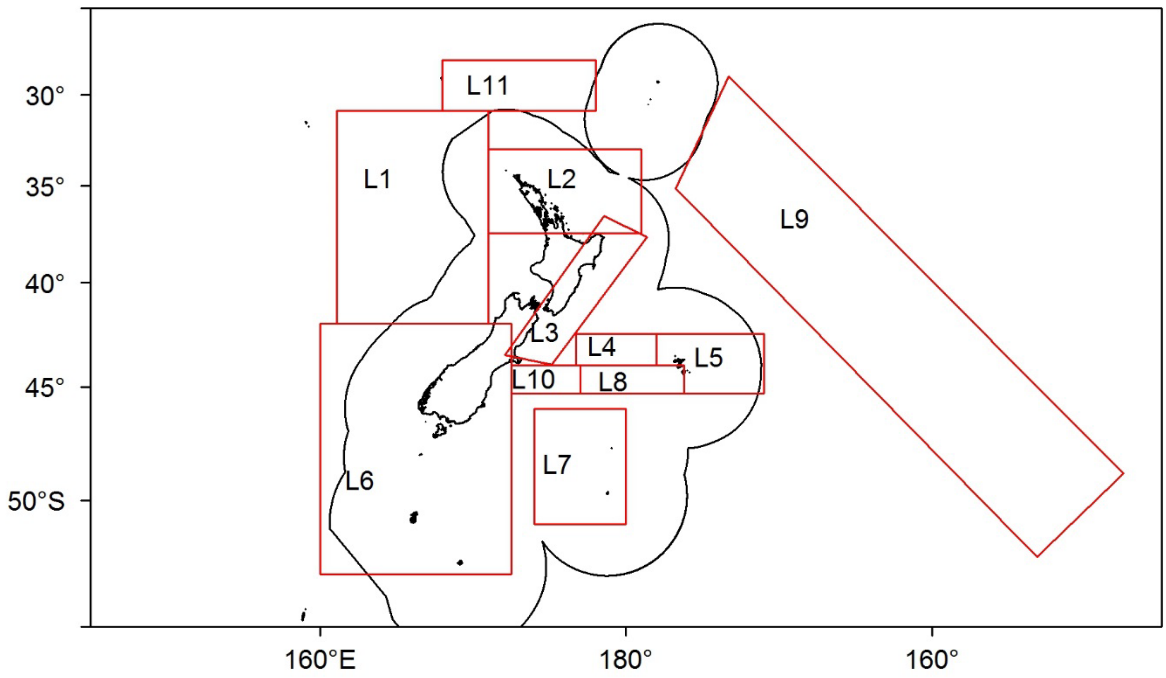

Figure 4: The distribution of 11 deepwater fishery regions used in this study.

A Generalised Additive Model (GAM) approach was taken, where $\log(B_0)$ was modelled as a function of predictor variables $x_1, x_2, \ldots, x_n$ (e.g. longitude, latitude):

$$\log(B_0) = \alpha + f_1(x_1) + f_2(x_2) + \cdots f_n(x_n) + \varepsilon_i$$

where $\varepsilon_i \sim N(0, \sigma^2)$ and f_i are smoothing spline curves (Wood 2006).

Splines are a flexible way of allowing for a non-linear relationship between $\log(B_0)$ and the predictor variables. The GAM modelling was implemented in the R package *mgcv* (version 1.7-22).

To select predictor variables p-values were calculated for their associated estimated smoothing splines under the fitting method Restricted Maximum Likelihood (REML) for the *mgcv* package (Wood 2011). Predictor variables with a p-value less than 1% dropped. The calculated p-values are approximate, so a conservative dropping criterion of 1% was used, instead of a more typical 5% criterion.

As the GAM algorithm was unable to fit all the continuous and categorical predictor variables in one step, fitting was broken up into three steps as follows:

- Using the full set of continuous predictor variables, and p-values were used to drop some of them
- Using the full set of categorical predictor variables, and p-values were used to drop some of them
- Using the remaining continuous and categorical predictor variables, and p-values were used to drop variables

In a previous iteration of the fitting procedure for the GAM it was not possible to fit all the continuous variables at once, hence a reduced set of continuous variables was used for the fitting. This reduced set was selected by dropping variables that were correlated with others. The final set of continuous variables offered to the fitting procedure were:
-latitude
-longitude

-depth_top (= summit depth)
-elevation
-area
-SST anomaly
-SST gradient
-slope
-primary production (model)

Catch was re-assigned a nominal value of 1 t (so the log value was 0) for boundary seamounts where recorded catch was 0 t.

3. RESULTS

3.1 Seamount distribution

The distribution of the final selected seamounts covered a wide range throughout the New Zealand region (Figure 5).

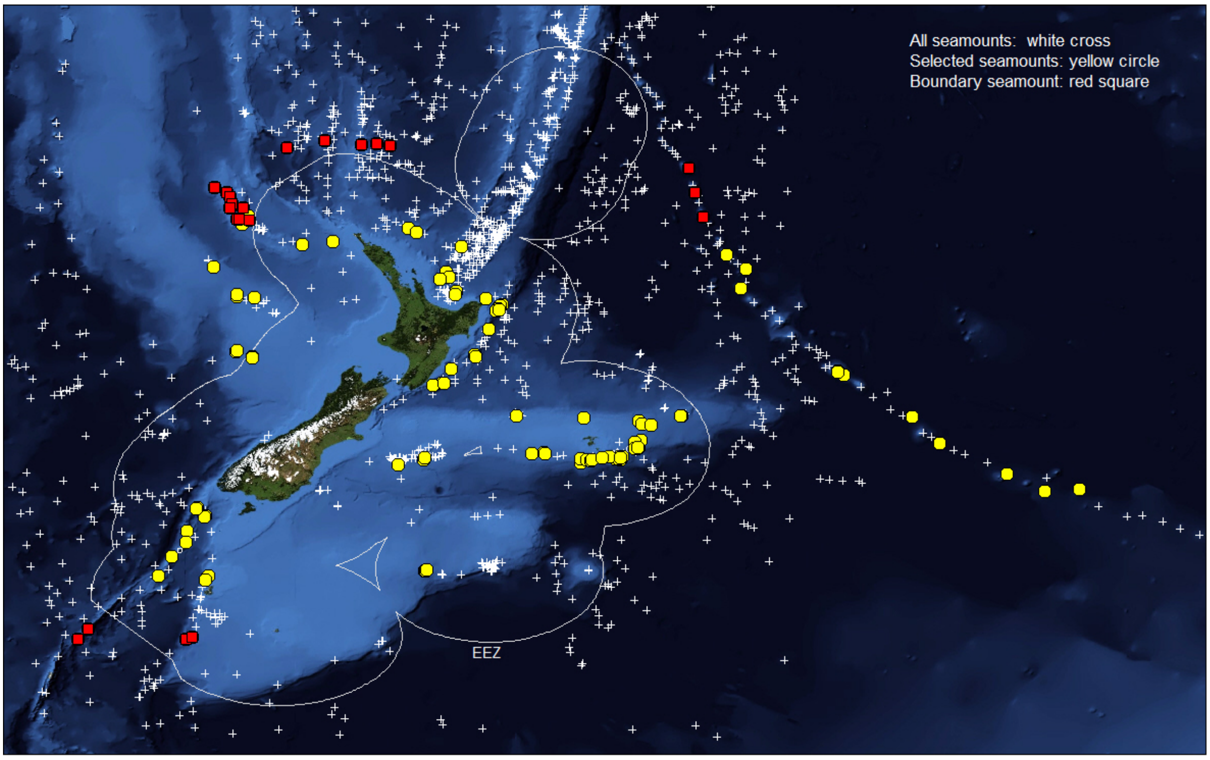

Figure 5: The distribution of seamounts in the New Zealand region (white crosses), showing the subset selected for this study (yellow circles) and the boundary seamounts (red squares).

3.2 The final regression model

The final model included four variables:

Latitude
Summit depth
SST anomaly
Spawning level

Together these explained 83% of the deviance for $\log(B_0)$. The estimated degrees of freedom (edf) are a measure of how non-linear the final estimated smoothing splines are. For latitude, summit depth, and SST anomaly the edf values are 5.4, 3.1, and 2.8 respectively, and the p-values are less than 1×10^{-05} for all predictor variables (Table 2).

Table 2: Summary statistics for predictor variables included in the final model.

Variable	edf	F	p-value
Latitude	5.4	15.6	4.93E-25
Summit depth	3.1	3.2	1.51E-06
SST anomaly	2.8	2.8	6.22E-06
Spawning level	3	11.2	2.09E-06

As a sensitivity test, boundary seamounts were dropped from the data set. The final model explained 50% of the deviance for $\log(B_0)$, down from 83%, and the summit depth predictor variable was no longer significant (p-value of 0.401). The latter was because the boundary seamounts (with zero virgin biomass) have summit depths that are shallower or deeper than most of the rest of the seamounts (with non-zero virgin biomass) (Figure 6).

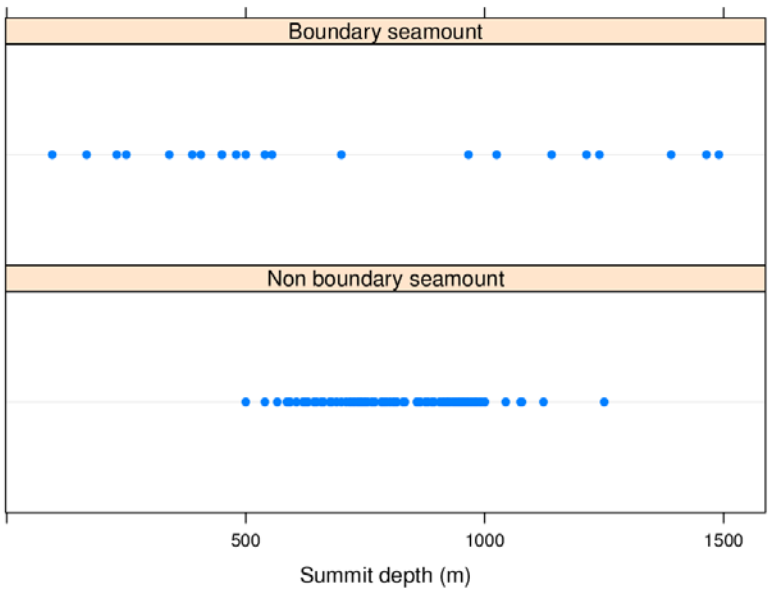

Figure 6: Summit depth distribution for boundary seamounts, and non-boundary seamounts.

With the full dataset, the form of relationship between the continuous variables and biomass is shown in Figure 7a. The effect of latitude was highest in a band between 36° S and 46° S, with biomass dropping away rapidly outside this. The maximum effect of summit depth was 600 m to 1000 m, which probably matches the depth of Antarctic Intermediate Water which is affected by localised shoaling over seamounts. The relationship between biomass and Sea Surface Temperature anomaly values varied between -0.3 and +0.3, indicating that orange roughy occur mainly in areas where the water column profiles are likely to be fairly consistent, rather than being highly variable. The biomass increased with spawning level, although the relationship is highly uncertain (Figure 7b).

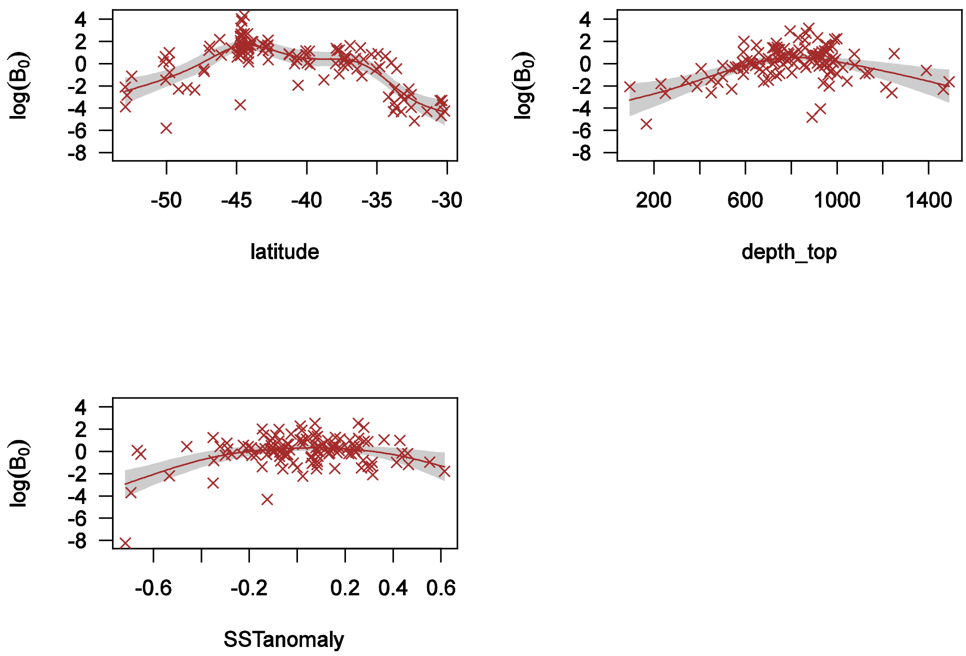

Figure 7a: Relationship between estimated biomass and the main environmental drivers of latitude, summit depth, and SST anomaly. On the y-axes log(B_0) is scaled to have a mean value of zero for all graphs.

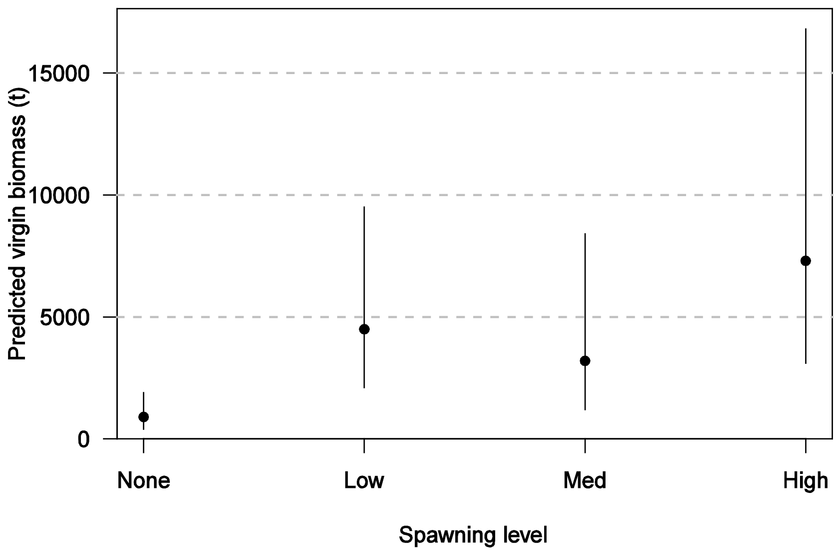

Figure 7b: Plot of the relationship between estimated biomass and the categorical variable spawning level. Predicted values are at the median values for the continuous predictor variables latitude, summit depth, and SST anomaly. Predicted values are shown as dots with vertical lines showing approximate 95% confidence intervals.

The model fit diagnostics were generally good with the residuals following the assumed normal distribution, although there are signs that the variance decreases for higher biomass (Figure 8). Note that the points forming straight lines within the two right-hand plots come from the boundary seamounts (which all have zero B_0), and hence don't reflect the overall model fit.

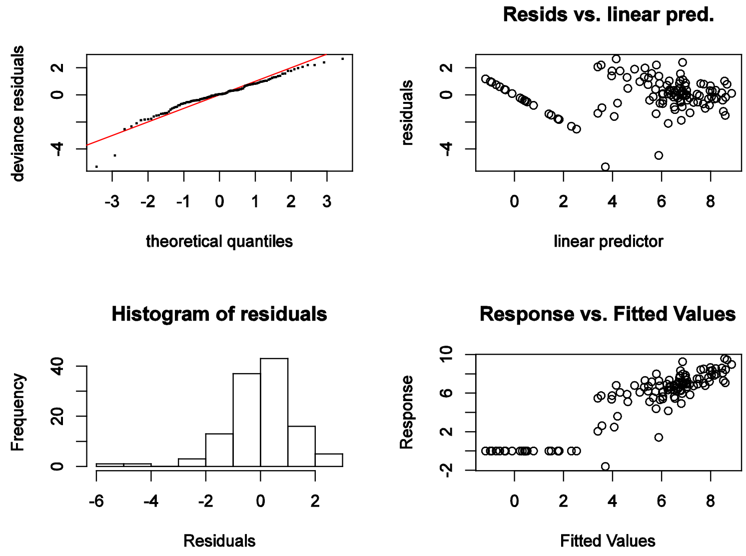

Figure 8: Diagnostic plots for the final model.

3.3 Orange roughy biomass

The overall relationship between the estimated virgin biomass from the catch history, and that predicted by the final model, is shown in Figure 9. In general there is a good relationship, although for the three most productive seamounts the model fails to predict biomass levels near the actual catch of over 10 000 t. The three seamounts are part of hill complexes on the Chatham Rise: Possum East (predicted 5300 t, actual catch 14 600 t), Graveyard (predicted 5800 t, actual catch 12 700 t), and Big Chief (predicted 1000 t, actual catch 10 500 t).

As a further sensitivity test for the effect of boundary seamounts, if they are removed from the data then predicted virgin biomass (B_0) from the model tends to be higher when the virgin biomass is less than 750 t, and lower otherwise (Figure 10).

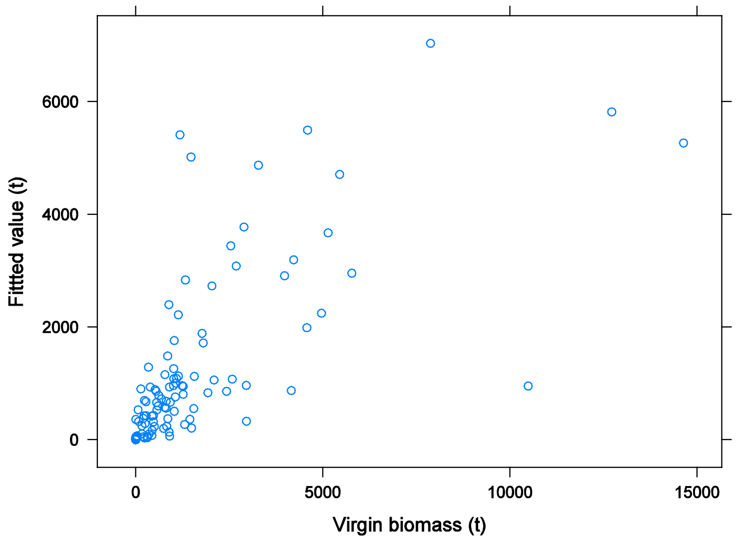

Figure 9: Comparison of the estimated and predicted orange roughy biomass values on seamounts.

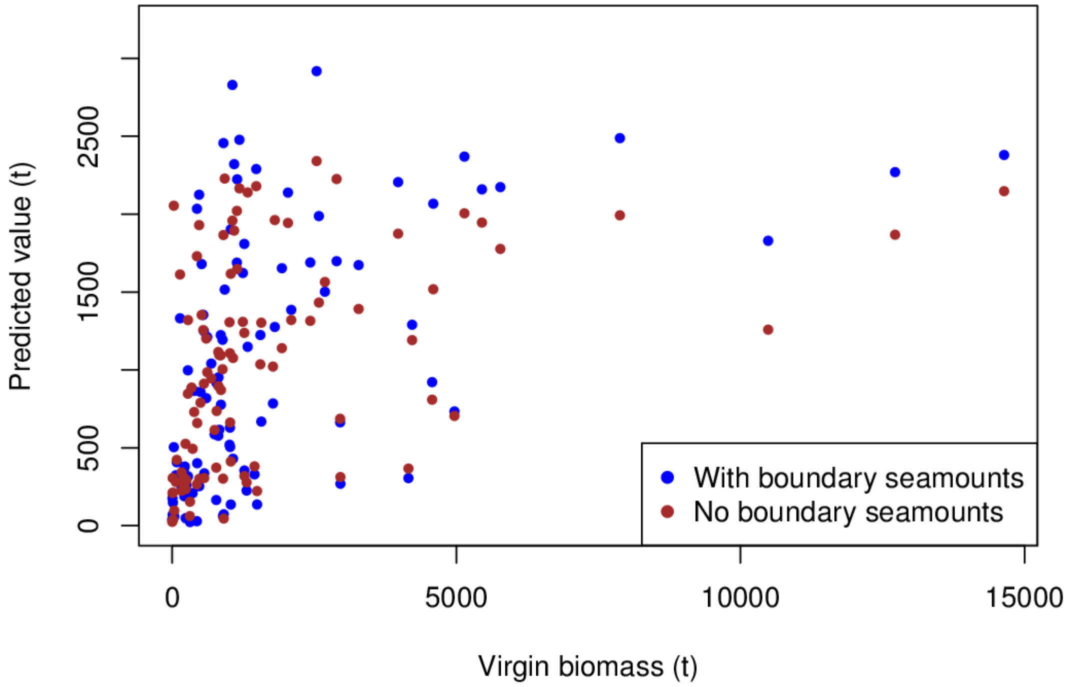

Figure 10: Comparison of the estimated and predicted orange roughy biomass values on New Zealand seamounts: with and without boundary seamounts.

The spatial distribution of estimated versus predicted biomass generally matches well (Figure 11), with highest values on the Chatham Rise, and lower, but substantial biomass on seamounts scattered along the east coast of the North Island, Challenger Plateau, Puysegur, and the Louisville Seamount Chain.

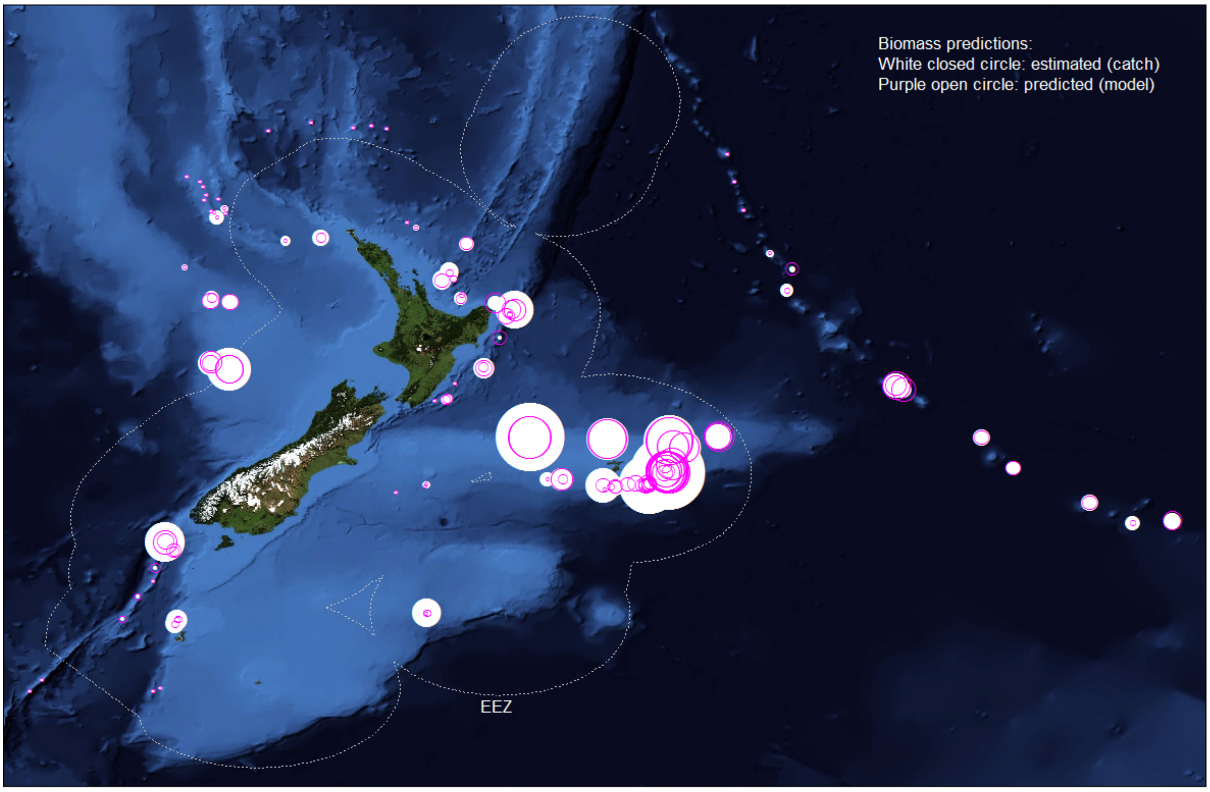

Figure 11: Comparison of estimated biomass (closed white circle) and predicted biomass (open purple circle) of orange roughy on seamounts. Expanding circles are standardised by area, maximum 15 000 t.

In order to see if the pattern of predicted biomass matched the expectations of the authors in the wider New Zealand region, the regression model was then applied to other seamounts with the necessary variable data. This excluded spawning level, as this was only assessed for the final selected subset, and was unknown for many of the seamounts in the full dataset. It also gives an indication of how the model might work given solely the physical characteristics of the seamounts.

The bulk of seamount biomass was estimated to be concentrated on the Chatham Rise, with other major sites along the east coast of the North Island, Challenger Plateau, and Louisville Seamount Chain (Figure 12). Predicted biomass decreased rapidly in northern areas. Results matched the known distribution of orange roughy relatively well. It indicates that low levels of biomass are expected on the West Norfolk Ridge.

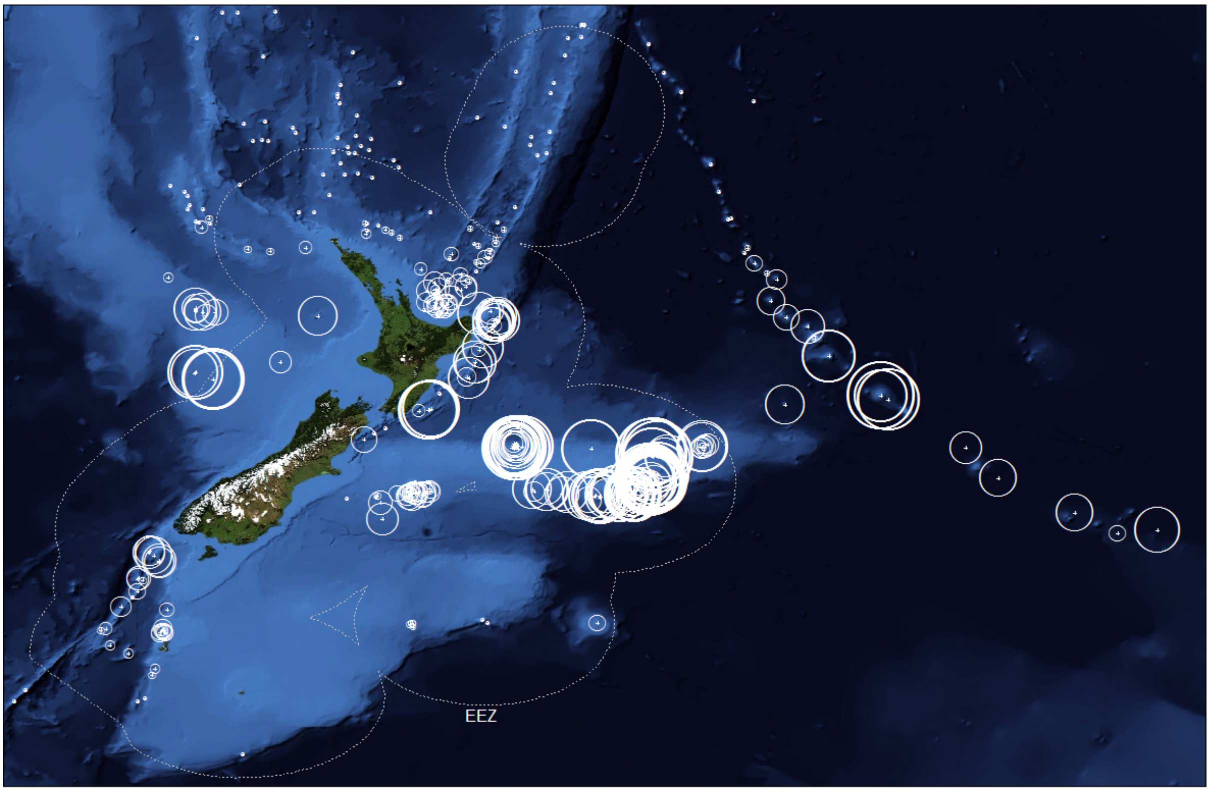

Figure 12: Predicted biomass (white circle) of orange roughy for the full seamount dataset. Expanding circles are standardised by area, maximum is 3100 t. The model was run without spawning level.

4. DISCUSSION

The data compilation, selection, and modelling approach used in this work built on previous studies, and developed further the general linkages found between physical characteristics and orange roughy biomass suggested in the earlier studies. There are clearly many uncertainties still, but the overall model fits here were relatively good, and suggest that results can be used to provide plausible guidance to likely orange roughy biomass in newly discovered fishing grounds.

The physical variables used in the final model (latitude, summit depth, and SSTanomaly) are biologically sensible, and are readily available for new seamounts from either the exploratory fishing activities, or widespread oceanographic data. The latter may give general indications of physical characteristics, although care is needed with offshore features where depth may be inaccurate (e.g., Anderson et al. 2016). Spawning level may initially be unknown, but this was the least important of the model variables, and contributed only 5% of the deviance.

The model performed well, in that it explained a high level of variability within the data. The modelled distribution of predicted biomass also appeared reasonable for the seamounts on the Chatham Rise, along the east coast of the North Island, on the Challenger Plateau, and the Louisville Seamount Chain. The model appeared to do well in areas where there were already data to give it an idea of what was there. It indicated that there was a likelihood of low biomass levels on seamounts of the West Norfolk Ridge. This was a result of early model runs as well, and so in the final data selection the restrictions on seamount inclusion criteria were relaxed. However, this didn't make much difference to the result for most of the seamounts, except on the Northwest Challenger where the biomass increased (relative to the authors' expectations) substantially. The West Norfolk seamounts are on the northern limit of known orange roughy aggregations, and so it is probable that the model can't deal well with this edge effect. Boundary seamounts with 0 catch were added to constrain extrapolation. While this is arguably a realistic constraint, it did not have a large effect on the model estimates or general biomass patterns, despite a lower explanatory power. Their inclusion, however, was useful for capturing the importance of summit depth, which is typically a major driver of orange roughy abundance and commercial catch rates (e.g., Clark et al. 2001, Dunn 2006).

The variables included in the model, especially latitude and depth, can alias many biological processes, and care is needed interpreting the relative effects of these variables. For example, adult orange roughy typically occur in Antarctic Intermediate Water in the New Zealand region, and this has its core (defined by a salinity minimum) at depths around 800–1000 m (e.g., Koslow et al. 1994, Clark et al. 2010c). The modelled peak includes this range, but the strong effect at 600 m may be too shallow.

The interpretation of catch history as a measure of seamount biomass needs to consider the degree of independence of fish populations on seamounts. The extent of residency of orange roughy on seamounts is not well known. There appear to be several uses of seamount habitat, including for feeding and spawning, at various time of the year (Clark et al. 2010a). Migration onto and off seamounts occurs, and this does not necessarily follow a consistent pattern between areas or years (e.g., Dunn & Devine 2010). Using total catch history could therefore give high biomass estimates for seamounts where aggregations for spawning occur, with fish migrating in from a wider area during the spawning months. Similarly recruitment over time could overestimate the biomass that is resident on the seamount.

Migration might not be a major problem for modelling biomass on isolated oceanic seamounts (e.g., Louisville Ridge, West Norfolk Ridge), but could be on the Chatham Rise and Challenger Plateau where smaller knolls are surrounded by continental slope. The difference between observed and predicted biomass on the Chatham Rise was often poor (see Figure 11), and stock "areas" are believed to cover large areas of the Rise (e.g., Dunn & Devine 2010). Early model runs used several time periods (e.g., 3 years, 6 years, total) of catch history, to examine the influence that fishing duration has on the model output, but this revealed no consistent pattern. But, it is likely that the overall catch taken on continental slope seamounts includes fish that are normally resident on the flat, and hence will be an overestimate of the seamount resident population. This hypothesis is supported by the three seamounts (Possum East, Graveyard, and Big Chief) where the model predictions were much less than the actual catch history. The three seamounts were all part of a seamount complex, and in areas where migrations of fish are known to occur for spawning or feeding.

5. MANAGEMENT IMPLICATIONS

The work confirms results of earlier seamount meta-analysis studies that indicated that there is predictive information in the physical characteristics of seamounts. The model fits are good, but there is still considerable uncertainty in any predictions of biomass outside, or towards the edges, of the known distribution of orange roughy. We expect that the analyses can provide general indications of biomass levels for orange roughy on seamounts, and hence give SPRFMO managers some guidance to help manage new and vulnerable resources in the absence of detailed information.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Althaus, F.; Williams, A.; Schlacher, T.A.; Kloser, R.K.; Green, M.A.; Barker, B.A.; Bax, N.J.; Brodie, P.; Schlacher-Hoenlinger, M.A. (2009). Impacts of bottom trawling on deep-coral ecosystems of seamounts are long-lasting. *Marine Ecology Progress Series 397*: 279–294.

Anderson, O.F.; Guinotte, J.M.; Rowden, A.A.; Clark, M.R.; Mormede, S.; Davies, A.J.; Bowden, D.A. (2016). Field validation of habitat suitability models for vulnerable marine ecosystems in the South Pacific Ocean: implications for the use of broad-scale models in fisheries management. *Ocean and Coastal management 120*: 110–126.

Clark, M.R. (1998). Orange roughy fisheries in southern areas of New Zealand: a summary of commercial catch and effort information from 1991–92 to 1996–97 fishing years. New Zealand Fisheries Assessment Research Document 98/14. 16 p (Unpublished report held by NIWA library, Wellington.)

Clark, M.R. (2003). Estimation of orange roughy biomass on the Louisville Ridge: application of “Seamount Meta-analysis” results. Final Research Report to the Ministry of Fisheries for Project ORH2002/03. 10 p. (Unpublished report held by the Ministry for Primary Industries, Wellington).

Clark, M.R. (2006). Descriptive analysis of orange roughy fisheries in the New Zealand region outside the EEZ: Lord Howe Rise, Northwest Challenger Plateau, West Norfolk Ridge, South Tasman Rise, and Louisville Ridge to the end of the 2004–05 fishing year. *New Zealand Fisheries Assessment Report No. 2006/56*. 38 p.

Clark, M.R. (2008). Descriptive analysis of orange roughy fisheries in the New Zealand region outside the EEZ: Lord Howe Rise, Northwest Challenger Plateau, West Norfolk Ridge, South Tasman Rise, and Louisville Ridge to the end of the 2005–06 fishing year. *New Zealand Fisheries Assessment Report 2008/12*. 46 p.

Clark, M.R. (2009). Deep-sea seamount fisheries: a review of global status and future prospects. *Latin American Journal of Aquatic Research 37(3)*. 501–512.

Clark, M.R.; Althaus, F.; Williams, A.; Niklitschek, E.; Menezes, G.; Hareide, N-R.; Sutton, P.; O’Donnell, C. (2010c). Are deep-sea fish assemblages globally homogenous? Insights from seamounts. *Marine Ecology 31(suppl. 1)*: 39–51.

Clark, M.R.; Bull, B.; Tracey, D.M. (2001). The estimation of catch levels for new orange roughy fisheries on seamounts: a meta-analysis of seamount data. *New Zealand Fisheries Assessment Report 2001/75*. 40 p.

Clark, M.R.; Dunn, M.R.; Anderson, O.F. (2010a). Development of estimates and sustainable catches for orange roughy fisheries in the New Zealand region outside the EEZ: CPUE analyses, and application of the “seamount meta-analysis” approach. *New Zealand Fisheries Assessment Report. 2010/19*. 47 p.

Clark, M.R.; Roberts, C.D. (2008). Fish and invertebrate biodiversity on the Norfolk Ridge and Lord Howe Rise, Tasman Sea (NORFANZ voyage, 2003). *Aquatic Environment and Biodiversity Report No. 28*. 131 p.

Clark, M.R.; Rowden, A.A.; Schlacher, T.; Williams, A.; Consalvey, M.; Stocks, K.I.; Rogers, A.D.; O'Hara, T.D.; White, M.; Shank, T.M.; Hall-Spencer, J. (2010b). The ecology of seamounts: structure, function, and human impacts. *Annual Review of Marine Science 2*: 253–278.

Dunn, M.R. (2006). CPUE analysis and assessment of the Northeast Chatham Rise orange roughy stock (part of ORH3B) to the end of the 2003–04 fishing year. *New Zealand Fisheries Assessment Report 2006/59.* 67 p.

Dunn, M.R.; Devine, J.A. (2010). An holistic approach to determining stock structure of orange roughy on the Chatham Rise. *New Zealand Fisheries Assessment Report 2010/17*. 65 p.

Food and Agricultural Organization of the United Nations (FAO). (2009). *International guidelines for the management of deep-sea fisheries in the High Seas*. 73 p. FAO, Rome.

Koslow J.A.; Bulman C.M.; Lyle J.M. (1994). The mid-slope demersal fish community off southeastern Australia. *Deep-Sea Research I, 41*: 113–141.

O'Driscoll, R.L.; Clark, M.R. (2005). Quantifying the relative intensity of fishing on New Zealand seamounts. *New Zealand Journal of Marine and Freshwater Research 39*: 839–850.

Pitcher, T.J.; Clark, M.R.; Morato, T.; Watson, R. (2010). Seamount fisheries: do they have a future? *Oceanography 23(1)*: 134–144.

Pitcher, T.J.; Morato, T.; Hart, P.J.B.; Clark, M.R.; Haggan, N.; Santos, R.S. (eds) (2007). *Seamounts: ecology, fisheries, and conservation*. Blackwell Fisheries and Aquatic Resources Series 12. Blackwell Publishing, Oxford. 527 p.

Roux, M-J.; Doonan, I.J.; Edwards, C.; Clark, M.R. (2016). Low information stock assessment of orange roughy *Hoplostethus atlanticus* in the SPRFMO Convention Area. Draft New Zealand Fisheries Assessment Report held by Ministry for Primary Industries.

Rowden, A.A.; Oliver, M.; Clark, M.R.; MacKay, K. (2008). New Zealand's "SEAMOUNT" database: recent updates and its potential use for ecological risk assessment. *New Zealand Aquatic Environment and Biodiversity Report No. 27*. 49 p.

Wood, S.N. (2006). Generalised Additive Models: An Introduction with R. Chapman and Hall/CRC.

Wood, S.N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (B) 73(1)*:3–36.

Yesson, C.; Clark, M.R.; Taylor, M.; Rogers, A.D. (2011). The global distribution of seamounts based on 30-second bathymetry data. *Deep Sea Research I. 58*: 442–453.