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**Preliminary stock assessments for stocks of orange roughy (*Hoplostethus atlanticus*) in the western SPRFMO Area using spatially disaggregated CPUE and Bayesian biomass dynamic models**

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## 1. Purpose of paper

This paper updates the Scientific Committee on New Zealand's preliminary stock assessments (based on New Zealand data alone) for orange roughy (*Hoplostethus atlanticus*) in the western part of the SPRFMO Area and, where relevant, straddling New Zealand's EEZ and the SPRFMO Area. This work is one component of progress toward a revised comprehensive CMM for bottom fisheries, the other components being prediction and mapping of VMEs, an update of New Zealand's bottom fishing impact assessment, and the development of software tools to develop candidate spatial management areas.

## 2. Historical summary

Orange roughy (*Hoplostethus atlanticus*) fisheries in the New Zealand region but outside New Zealand's EEZ developed in the mid-1980s on the southwest Challenger Plateau, and expanded in the late 1980s and early-1990s to 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. Many of these fishing grounds are in the SPRFMO Area.

Fishing for deepwater commercial species outside the New Zealand EEZ is to a large extent focused on seamounts<sup>1</sup> in this report (after Pitcher et al. 2007), where orange roughy (ORY, *Hoplostethus atlanticus*) and oreos (black oreo, BOE, *Allocyttus niger*, and smooth oreo, SSO, *Pseudocyttus maculatus*) often aggregate. In the general New Zealand region it is estimated that over 60% of orange roughy catch, and 50% of oreo catch has been 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 also widely regarded as supporting fragile habitats and benthic communities (Althaus et al. 2009, Clark et al. 2010b), susceptible to both overfishing and direct and indirect seabed impacts from trawlings. 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 of limited statistical value given the variable nature of the fisheries outside the EEZ (Clark et al. 2010a).

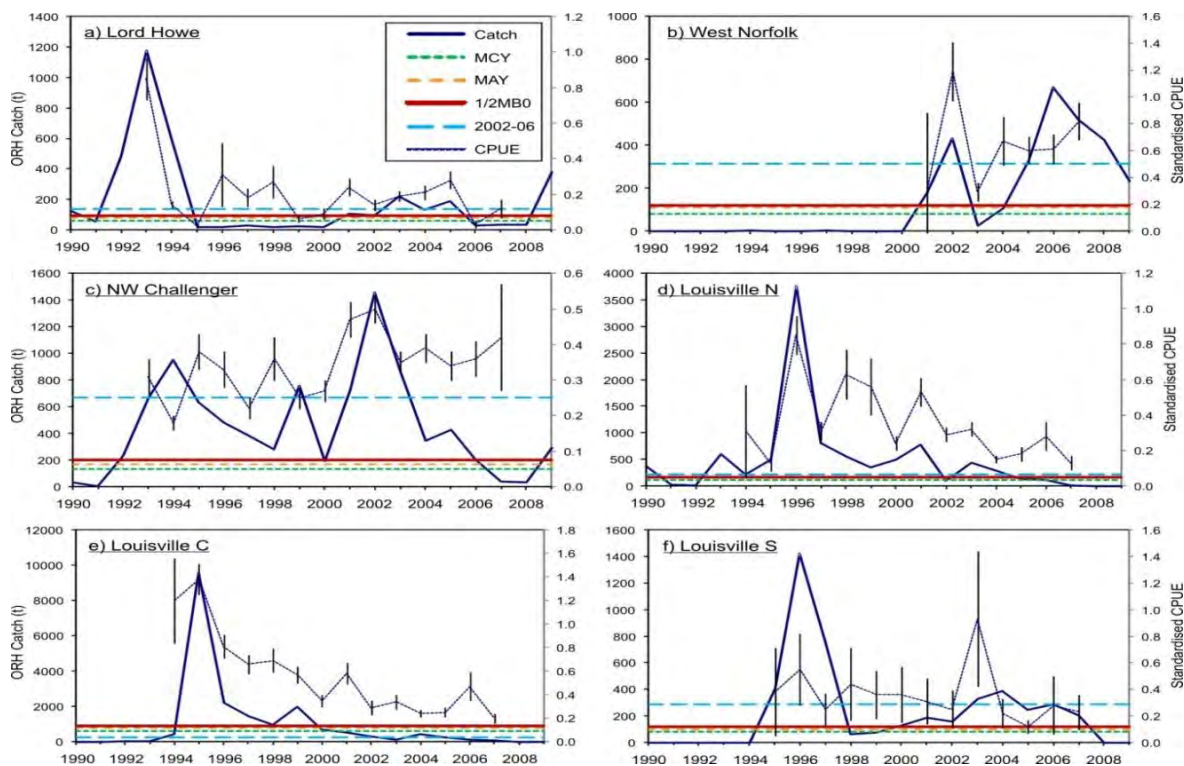
Meta-analysis and associated predictive modelling, which examine trends in existing and historical seamount fisheries around New Zealand, together with information on their physical characteristics, have shown promise as a method for estimating original (unfished) orange roughy biomass on seamounts (Clark 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.

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<sup>1</sup> The term "seamount" includes knolls and hills with an elevation of 100 m or more

Region (related to latitude and continental/oceanic association), summit depth, and slope of the seamount were significant predictors of biomass. The method was applied to a section of the Louisville Ridge (Clark 2003), and more broadly to seamounts on the Lord Howe Rise, Northwest Challenger Plateau, West Norfolk Ridge, and Louisville Ridge (Clark et al. 2010a, SWG-09-INF-01, Penney 2010, SWG-09-DW-02).

Catch per unit effort analyses were carried out for most of the New Zealand fisheries outside the EEZ (e.g., Clark & Anderson 2001, O'Driscoll (2003), Clark et al. (2010a) but with limited success. Figure 1 shows Penney's (2010) analysis of trends in orange roughy catch (t), CPUE (t/tow, with standard errors) and estimated Maximum Constant Yield (MCY, a static interpretation of MSY), Maximum Average Yield (MAY, a dynamic interpretation of MSY),  $\frac{1}{2}MB_0$ , and the 2002-2006 average catch reference levels from Clark et al. (2010a) for the main fishing areas (Table 1).



**Figure 1: Summary of trends in total orange roughy catch (t), CPUE (t/tow, with standard errors) and estimated MCY, MAY,  $\frac{1}{2}MB_0$  and 2002–2006 average catch reference levels for each fishing area (from Penney 2010).**

Penney (2010) concluded it was unlikely that fishery-independent surveys of low-productivity, high-seas bottom fishery resources would occur, and this remains true. This means that predictive, model-based approaches to estimating abundance are required (e.g., the seamounts meta-analyses of Clark et al. 2001, 2010). Penney considered that short-term (2–5 year) sustainable fishing levels for orange roughy could lie somewhere between the yield estimates (MCY / MAY / MSY) for each area and recent average catches at that time but noted that the 2002–2006 average catches exceed the estimated long-term sustainable yields (MCY, MAY or MSY) at that time for all SPRFMO areas except the Central Louisville Ridge. However, those estimates of sustainable yield are now dated and this paper provides

an update using more sophisticated methods applied to New Zealand catch and effort data in preliminary analyses aimed at methods development and testing.

It should be noted that, because fewer vessels have been fishing, the average catch of orange roughy by New Zealand flagged vessels for the 9 years since the reference period has been substantially lower than during the reference period, 1,039 t compared with 1,852 t.

**Table 1 (reproduced after Table 3 of Penney 2010a): Summary of predicted biomass (from the seamount meta-analysis), estimated MCY and MAY (from predicted biomass), estimated MSY (=0.5MB<sub>0</sub>) and average annual orange roughy catches over the 2002–2006 reference years.**

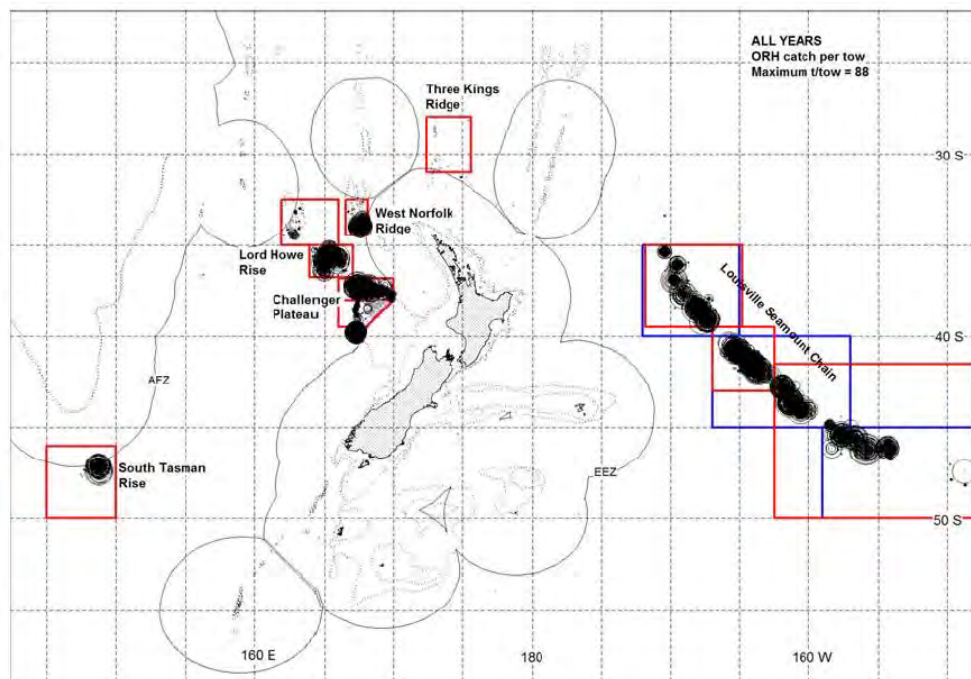
Fishing Area	Predicted Biomass (t)	MCY	MAY	½MB <sub>0</sub>	2002-06 Average
Lord Howe	4,130	60	80	93	134
West Norfolk	5,350	80	100	120	315
NW Challenger	8,800	130	170	198	666
North Louisville	7,510	110	150	169	214
Central Louisville	38,620	580	770	869	238
South Louisville	5,200	80	100	117	284
<b>Total</b>	<b>69,610</b>	<b>1,040</b>	<b>1,380</b>	<b>1,566</b>	<b>1,852</b>

### 3. Stock discrimination in the SPRFMO Area

Studies on stock discrimination were reported in detail to SC3 by [Clark et al. \(2015\)](#) and have since been published ([Clark et al. 2016a](#)) so are only summarised here.

Stock structure of orange roughy in the SPRFMO Area is uncertain and previous analyses and stock assessments have assumed stock boundaries based on the distribution of fishing effort. Clark et al. (2016a) described and updated the available information for fisheries in the western part of the SPRFMO Area and examined multiple data sets concurrently to infer stock structure (because no single data set provided unequivocal results). These data sets were: catch distribution; the location of spawning grounds; differences in life history characteristics including length frequencies; length or age at maturity; genetic studies using allozymes or mitochondrial DNA; otolith composition and shape; morphometric parameters; and parasite composition and load.

No single data set had complete coverage and there were inconsistencies between data sets on putative stock structure and boundaries. However, taken holistically, the available information is consistent with the existing assessment boundaries for orange roughy in the Tasman Sea (including Lord Howe Rise, Northwest Challenger Plateau, Southwest Challenger Plateau, West Norfolk Ridge, and South Tasman Rise). The Louisville Seamount Chain was previously divided into three sub-areas for catch description and analysis. Clark et al. (2016a) supported the retention of three sub-areas but suggested revising the boundaries based largely on a north-south gradient in the timing of orange roughy spawning.



**Figure 2 (after Fig. 11 of Clark et al. 2016a): Comparison of management areas considered for the purposes of CPUE analysis and stock assessment in this study (in red) and previous areas (in blue) overlaid on the total distribution of catch rates for orange roughy (black open circles, catch rate proportional to area, maximum 88 t per tow). Where they are coincident, red boxes overlay blue boxes**

These stock boundaries remain uncertain and Clark et al. (2016a) strongly recommended additional genetic analyses for the Louisville and West Norfolk Ridge fisheries and also the continuation of otolith collection for age-based analyses.

#### 4. Predicting initial stock size from seamount characteristics

Indices of catch per unit effort have hitherto not provided useful methods of estimating initial abundance for several orange roughy fisheries in the SPRFMO Area, prompting New Zealand to explore other approaches. Regression modelling (Clark et al. 2016b) was used to relate virgin biomass of orange roughy (estimated from the catch history) to 23 physical characteristics of each of 120 seamounts throughout the New Zealand region (New Zealand's EEZ plus parts of the SPRFMO Area to the west of approximately 150° W).

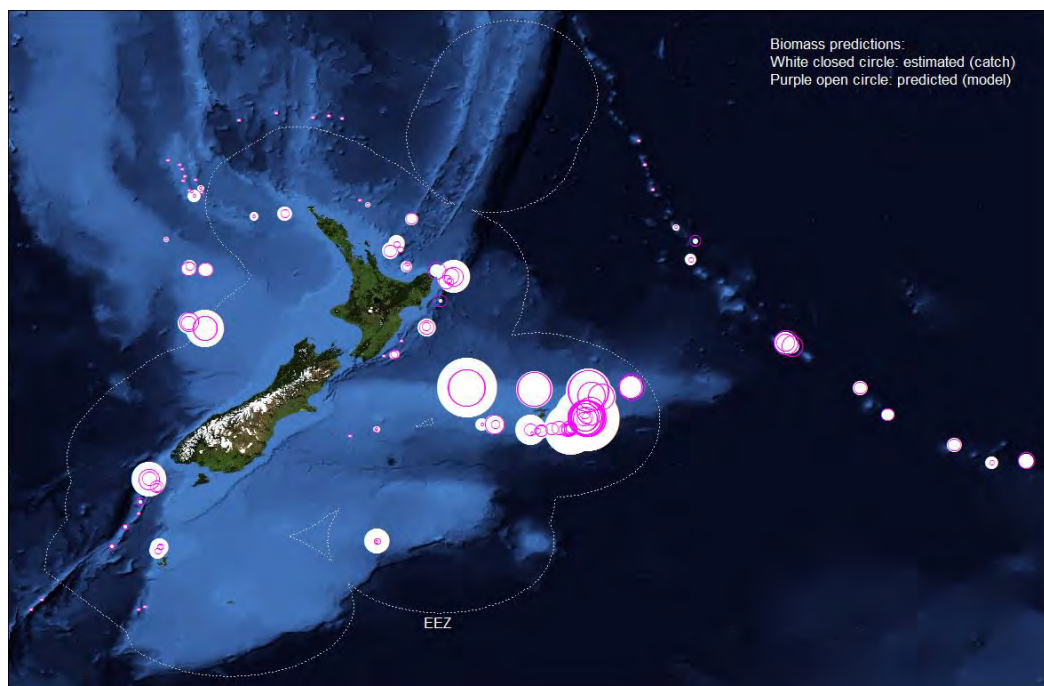
Clark et al. (2016b) fitted a generalised additive model (GAM) and their final model included latitude, summit depth, SST anomaly (an indication of frontal zones) and the level of spawning activity (a categorical index based on the proportion of female fish in spawning condition). Together these variables explained 83% of the deviance for the logarithm of unfished biomass. These physical variables seem biologically reasonable and are readily available for new seamounts from either exploratory fishing activities or widespread oceanographic data. Spawning level is likely to be unknown for newly-discovered seamounts, but this was the least important of the model variables, and contributed only 5% of the deviance (6% of the explained deviance, Table 2).



**Table 2: Summary statistics for predictor variables included in Clark et al.'s (2016b) final model.**

Variable	Type	Effective d.f.	F	p-value
Latitude	Continuous	5.4	15.6	4.93E-25
Summit depth	Continuous	3.1	3.2	1.51E-06
SST anomaly	Continuous	2.8	2.8	6.22E-06
Spawning level	Categorical (4)	3	11.2	2.09E-06

Model fits were broadly aligned with actual accumulated catch values for most seamounts (Figure 2). 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 and matches the known distribution of orange roughy relatively well. This model indicates that low levels of biomass are expected on the West Norfolk Ridge. The model substantially underestimated biomass on three seamounts on the Chatham Rise, where it is thought that migration of orange roughy from other seamounts in the cluster, and from the nearby slope, may result in higher historical catch levels than the model is able to predict for a single seamount.



**Figure 3 (after Fig. 11 of Clark et al. 2016b): Comparison of estimated unfished biomass of orange roughy based on catch history (closed white circles) and model-predicted biomass based on physical characteristics (open purple circles) on seamounts in New Zealand's EEZ and western SPRFMO Area. Circles standardised by area, maximum 15,000 t**

Overall, Clark et al. (2016b) concluded that the physical characteristics of seamounts can be broadly informative about the likely level of orange roughy biomass across relatively large areas, but predictions for individual seamounts can be inaccurate.

## 5. Progress on stock assessments in the SPRFMO Area.

### 5.1. Introduction

Early results of spatially-disaggregated CPUE analyses and their potential utility for stock assessment modelling were presented to SC3 by Clark et al. (2015) and are now being published (Roux et al. in press). The results from all preliminary analyses are summarised here in some detail as there have been some adjustments to the CPUE analyses and biomass dynamic models have since been developed and fitted.

CPUE models are important because CPUE data are the only available index of biomass / abundance for use in stock assessments of orange roughy in fisheries in the SPRFMO Area. Hybrid spatial CPUE analyses (after Carruthers et al. 2011) were chosen to cope with bias arising from non-random temporal changes in the spatial distribution of the fishing effort. Ignoring non-random spatial patterns in fishing can lead to severe hyperdepletion in abundance indices in fisheries that develop progressively over large regions (i.e., CPUE indices averaged over only those areas that were fished in a year can decline faster than abundance declines, Walters 2003).

Biomass dynamic models (BDMs) have been chosen because insufficient data exists to fit more complex age-structured models. A cohort-aggregated state-space BDM fitted using Bayesian methods (after Edwards & McAllister 2014, Edwards 2016) was chosen because it allows stochasticity in input data to be readily incorporated into future projections, improving estimates of risk (Harwood and Stokes 2003).

### 5.2. Spatial CPUE analysis

#### 5.2.1. Methods for spatial CPUE analysis (after Roux et al. in press)

Commercial catch and effort data from all fishing events that targeted or caught orange roughy within and outside the New Zealand EEZ boundaries between 1 October 1989 and 30 September 2014, were extracted from the fishery statistics database managed by the Ministry for Primary Industries (MPI, Replog no. 10009) and used for analyses. These data included all fishing effort from New Zealand vessels occurring within the SPRFMO Area in that time. The data consisted of tow-by-tow information on fishing location, fishing patterns (i.e. trawl depth, speed, tow duration, etc.), estimated catch and vessel specifications. Standard error-checking and grooming procedures were applied and missing values and outliers were corrected by median imputation on larger ranges of data. Fishing events with no target species and no catch were removed. The final dataset was restricted to bottom trawl effort (a small number (<1%) of tows that used midwater trawl gear were excluded). This analysis and report uses the New Zealand fishing year (1 October to 30 September of the following year), and the fishing year ending



on 30 September 2001 is referred to as the 2001 fishing year. Tows and catches were assigned to the six principal orange roughy management areas recommended by Clark et al. (2016a), including three areas in the Tasman Sea (Lord Howe Rise, Northwest Challenger Plateau and Lord Howe Rise) and the three Louisville fisheries (north, central and south) (see Figure 2). Catch and effort data in the upper Lord Howe Rise (700 tonnes over 25 years) and Three Kings Ridge area (no catch in 3 tows over 25 years) were insufficient to undertake an assessment. The Southern Challenger Plateau is managed as a straddling stock between NZ and SPRFMO and was assessed in 2014 (Cordue 2014). The South Tasman Rise area was not considered for preliminary assessment because the substantial Australian catch and effort information was not available.

The spatial CPUE approach assumes that overall population abundance is contained in several strata or subarea  $a$  within the fishing grounds, which can be weighted to reflect their respective contributions to total abundance (Walters 2003). Thus for a given stock in year  $y$ :

$$CPUE_y = \sum_a^{subareas} cr_{a,y} w_a$$

The annual abundance index  $CPUE_y$  is calculated as the weighted sum ( $w_a$ = subarea weight) of subarea catch rates in that year  $cr_{a,y}$ . Subarea weights  $w_a$  are assumed proportional to subarea-specific catchability  $q_a$ :

$$w_a \propto \frac{n_{a,y}}{N_y} \propto \frac{1}{q_a}$$

Where  $N$  is the total population abundance in year  $y$  and  $n$  is the sample (subarea  $a$ ) relative abundance in year  $y$ . The subareas need to be small enough for an assumption of random fishing within subarea boundaries to be reasonable (Walters 2003). For this assessment, the hybrid GLM-imputation method described by Carruthers et al. (2011) was used to calculate spatial CPUE indices of stock abundance, which combined a GLM standardisation (with year-subarea interactions) to predict CPUE in year-subarea strata in which fishing occurred, and Walters' (2003) imputation methods to estimate CPUE in year-subarea strata where fishing did not occur.

Fishing for orange roughy in the SPRFMO Area can be concentrated on underwater topographic features (UTFs) (e.g. Louisville Chain), on the continental slope (e.g. Lord Howe Rise), or both (e.g. Northwest Challenger Plateau and West Norfolk Ridge). Subarea strata were defined by first assigning individual tows to UTFs (where UTF fishing occurred) and/or by subsequently performing hierarchical distance clustering on non-UTF tows. Hierarchical cluster analyses consisted of calculating the average distance between non-UTF tows and applying an average linkage clustering algorithm to the distance matrix in order to group tows by subarea strata.

For each assumed stock, analyses were restricted to positive catch and effort data in subareas that had at least 50 tows in the time series. "Core vessels" were selected if they had at least 2 years with 5 or more tows. Spatial CPUE indices were calculated for fishing years in which total effort (following subarea and core vessels selection) was equivalent to at least 10 tows.

A lognormal, interaction GLM (Generalised Linear Model (Chambers & Hastie 1991)) was fitted to log-transformed, non-zero catch-effort data (tonnes per tow). A forward stepwise multiple regression procedure implemented in R code (R Development Core Team 2015) was used to select among the explanatory variables offered in the full (saturated) model (Table 3). Fishing year (*fyear*) was fixed as the first term and additional variables were included sequentially if there was at least a 1% improvement in explained residual deviance. Selected variables ("significant covariates") were included in the final model along with *fyear*, *subarea*, and the *fyear-subarea* interaction term. Year effects and *fyear-subarea* interaction effects were extracted from the final GLM model for each stock and used to predict standardised CPUE values in *fyear-subarea* strata in which fishing occurred.

**Table 3: Summary of explanatory variables offered in the saturated, interaction GLM model fitted to orange roughy CPUE data. Continuous variables were offered as third-order polynomials.**

Variable	Type	Description
<i>fyear</i>	Factor	Fishing year (Oct 1-Sep 30)
<i>subarea</i>	Factor	Subarea within the fishing ground/management area
<i>fyear:subarea</i>	Interaction term	year-subarea interaction
<i>vessel</i>	Factor	Unique vessel identifier
<i>target sp.</i>	Factor	Target species as reported on a tow by tow basis
<i>month</i>	Factor	Calendar month
<i>day of year</i>	Continuous	Day of calendar year
<i>fweek</i>	Factor	Fishing week (relative to <i>fyear</i> )
<i>trawl depth</i>	Continuous	Average trawl depth (m)
<i>trawl.speed</i>	Continuous	Average trawl speed (knots)
<i>tow duration</i>	Continuous	Average tow duration (in hours)

In *fyear-subarea* strata with no fishing, the default imputation method described by Roux & Doonan (2015) was used to populate strata with no data. Imputation criteria were as in Roux & Doonan except that forward imputation was averaged over the last 2 years of data (as opposed to the last 3 years) and standardised catch rates predicted for strata with fewer than five tows were considered potentially unreliable and treated as missing data subject to imputation:

- Backward imputation (before the start of fishing) was carried out by assigning the maximum standardised catch rate recorded during the first three years of fishing to earlier years.
- Forward imputation (following the cessation of fishing) was carried out by assigning the mean standardised catch rate from the last two years of fishing to subsequent years.
- Linear interpolation was used to populate any strata with no data between non-consecutive years when fishing did occur.

Sensitivity to the choice of these criteria was tested using two other runs:

- 1) Backward imputation using the mean standardised catch rate calculated for the first three years of fishing; forward imputation using the standardised catch rate recorded in the last year of fishing (Walters 2003).
- 2) Backward and forward imputation using the mean standardised catch rates calculated for the first and last two years of fishing, respectively.

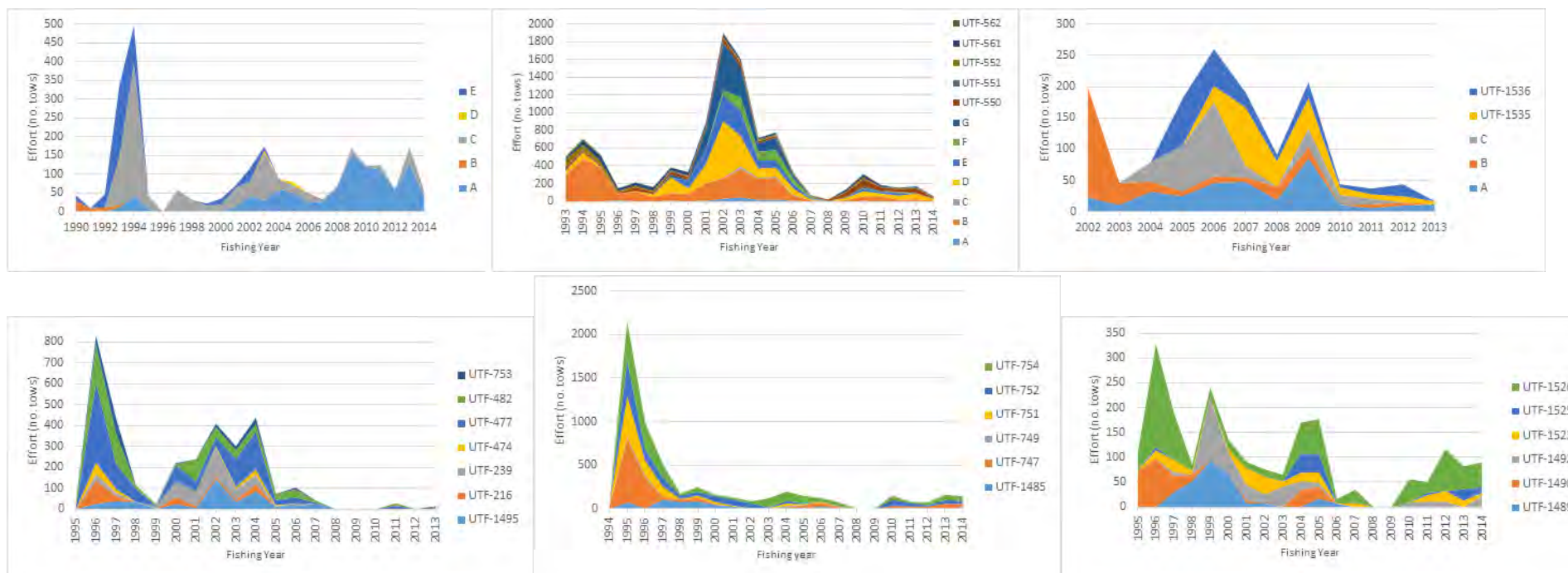
In each stock, subarea-specific time series of standardised and imputed CPUE were normalised to a geometric mean of 1 (canonical form (Francis 1999)) and weighted. Two different weighting schemes ( $w_a$ ) were applied and the results compared:

- 1)  $w_a=1$ : same catchability in all subarea.
- 2)  $w_a=cc$ : subarea catchability proportional to cumulative catch contribution.

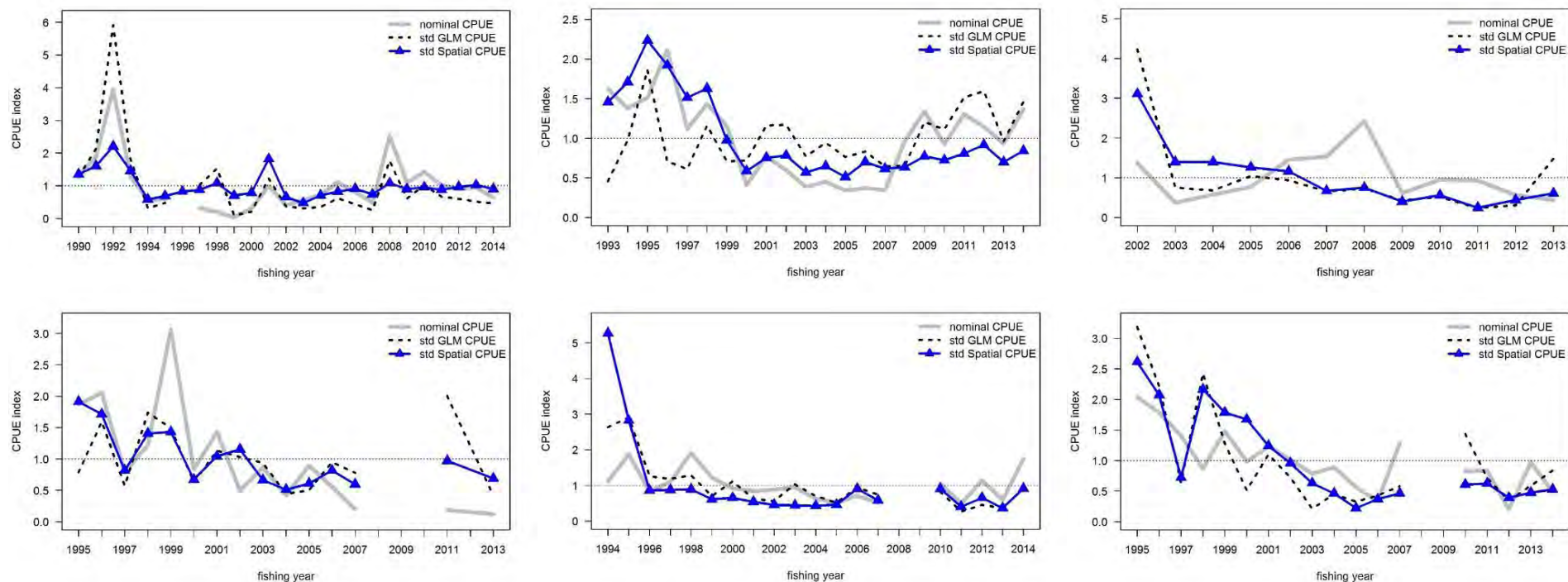
The weighted CPUE data were summed across subarea in each year to derive the annual indices. Uncertainty in the annual indices was estimated using a bootstrap re-sampling procedure (with replacement), resampling the catch-effort data and significant covariates and repeating the GLM standardisation, data imputation, subarea weighting and summation procedures within each of 500 bootstrap replicates.

### 5.2.2. Results of spatial CPUE analysis (after Roux et al. in press)

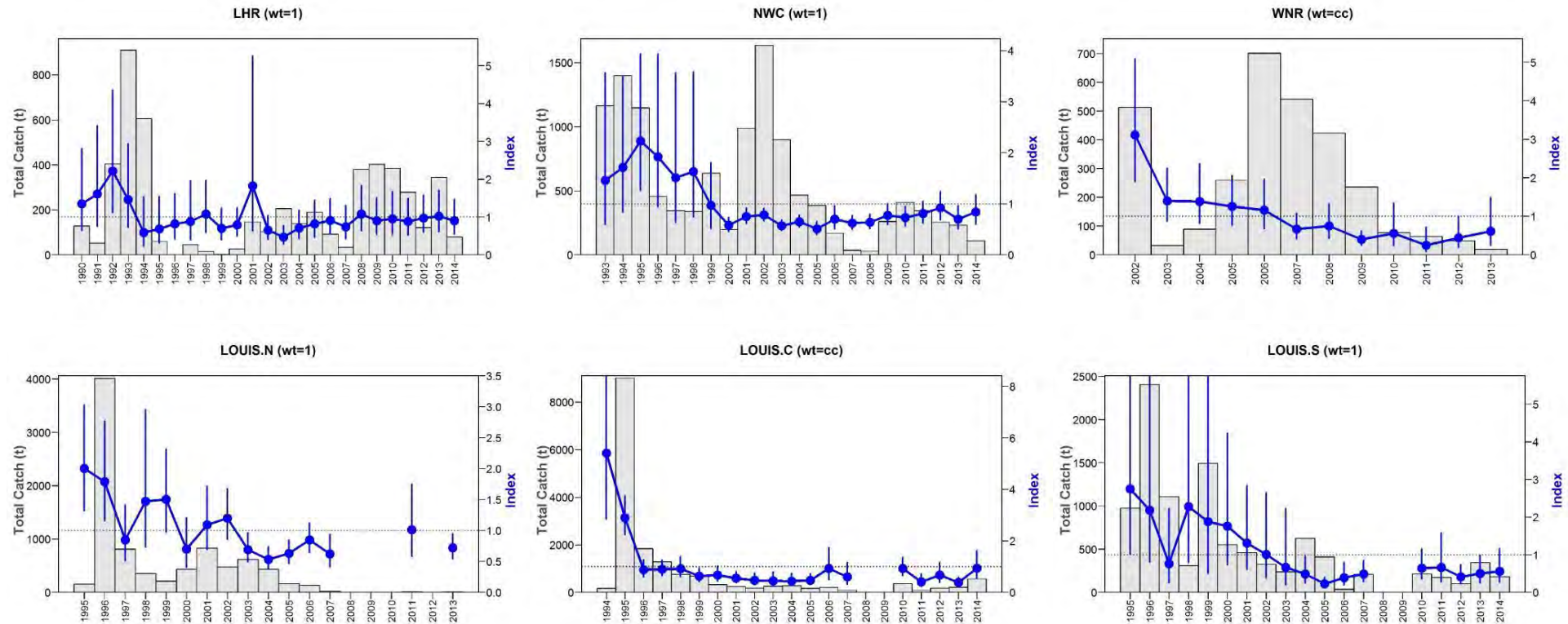
There were distinct trends over time in the number and proportion of tows among subareas in each of the six management areas considered for preliminary assessment (Figure 4). These patterns are likely to lead to the type of bias raised by Walters (2003). As expected, recognising this heterogeneity using the hybrid spatial approach substantially affects the estimated CPUE indices compared with unstandardized indices and standardised indices assuming spatially homogenous fishing (Figure 5). Indices generally show a decline since the start of New Zealand fishing in each area (Figure 6), but the declines estimated using the spatial approach were not always less steep than those using other approaches.



**Figure 4: Number of tows in each subarea each year for each fishery. Colours indicate subareas identified as individual UTFs or by hierarchical clustering. Tasman Sea fisheries are on the top row (left to right, Lord Howe Rise, Northwest Challenger, and West Norfolk Ridge), and Louisville Ridge fisheries are on the bottom row (left to right, North, Central, and South areas).**



**Figure 5: Comparisons of indices estimated as nominal CPUE (grey lines), using standardised CPUE (typical GLM procedure, black dotted lines), and standardised spatial CPUE (using the hybrid interaction GLM and data imputation, blue lines) Tasman Sea fisheries are on the top row (left to right, Lord Howe Rise, Northwest Challenger, West Norfolk Ridge) and Louisville Ridge fisheries are on the bottom row (left to right, North, Central, and South areas).**



**Figure 6: Catch series (grey bars, left axes) and normalised, standardised spatial CPUE indices of abundance (blue line/full circles, right axes) for orange roughy stocks in the Tasman Sea region (top row) and Louisville Ridge (bottom row) within the SPRFMO Area. Error bars are 95% bootstrap confidence intervals. Naming conventions above each plot as in Table xx. Area weightings:  $wt=1$ : equal catchability in all subareas,  $wt=cc$ : subarea catchability proportional to cumulative catch.**



### 5.3. Biomass dynamics modelling (BDM)

#### 5.3.1. Methods for biomass dynamic modelling (after Roux et al. in press)

A cohort-aggregated biomass dynamics model (implemented via the BDM R-package) was used to assess the status of orange roughy stocks. BDM describes changes in exploited biomass ( $B$ ) over time  $t$  in response to a particular harvest regime (catch  $C$ ) and according to the production function  $g()$ :

$$B_{t+1} = B_t + g(B_t) - C_t$$

The generalized production function described by McAllister et al. (2000) is assumed, which consists of a hybrid model that combines the logistic function (Shaefer 1954, 1957) with the Fletcher (1978) model:

$$g(B_t) = \begin{cases} rB_t \left(1 - \frac{B_t}{2B_{MSY}}\right) & B_t \leq B_{MSY} \\ \gamma m \left(\frac{B_t}{K} - \left(\frac{B_t}{K}\right)^n\right) & B_t > B_{MSY} \end{cases}$$

$$\gamma = \frac{n^{(n/(n-1))}}{n-1}$$

$$m = MSY$$

The function has three parameters: the maximum intrinsic growth rate  $r$  (corresponding to the maximum rate of population increase as the biomass approaches zero, ignoring any depensatory effects); the arithmetic mean biomass at unexploited equilibrium or carrying capacity  $K$ ; and a shape parameter  $n$  that defines the inflection point of the production function relative to  $K$ . In the deterministic case, useful reference points can be obtained from the parameter estimates:

$$MSY = \frac{rB_{MSY}}{2}$$

$$B_{MSY} = K \left(\frac{1}{n}\right)^{1/(n-1)}$$

The shape parameter  $n$  determines the value of  $B_{MSY}/K$  and is most intuitively understood via the parameter  $\varphi = B_{MSY}/K$ . A symmetric production function for example, has  $n = 2$  and  $\varphi = 0.5$ .

BDM models were fitted to the catch history and spatial CPUE index for each stock. Parameters were estimated within a Bayesian state-space framework. Such a framework re-formulates the process equation to include a time-dependent, multiplicative error term (the process error,  $\varepsilon_{[p]}$ ) and a parallel observation process that relates an abundance index  $I$  to the unobserved biomass state with some degree of error (the observation error,  $\varepsilon_{[o]}$ ), according to an estimated catchability scalar  $q$ :

$$B_{t+1} = (B_t + g(B_t) - C_t) \cdot \varepsilon_{[p]t}$$

$$I_{it} = (q_i B_t) \cdot \varepsilon_{[o]it}$$

Subscripts  $i$  refer to the abundance indices. The inclusion of process error allows the model to account for inter-annual variability in stock biomass caused by temporal changes in biological processes that are not explicitly modelled (e.g., variability in recruitment, natural mortality, etc.). The model therefore partitions the fishery variability in a way that includes stochastic components of the dynamics when the stock is projected forward in time.

The catchability scalar was calculated as a “nuisance” parameter, meaning that it was derived analytically as the maximum posterior density (MPD) estimate, assuming a uniform prior on the natural scale (Bull et al. 2012). A uniform prior was assumed for  $\ln(K)$ , which is proportional to  $1/K$  and therefore gives lower weight to higher  $K$  values. The upper and lower bounds were chosen subjectively so as to not impinge on the parameter space explored during estimation:

$$\ln(K) \sim U(3.0, 30.0)$$

Because for this class of model  $r$  and  $K$  are highly correlated, estimation is improved through the use of an informative prior for the intrinsic growth. An informative log-normal prior for  $r$  was constructed for orange roughy using available life-history data on the species:

$$r \sim LN(\mu_r, \sigma_r^2)$$

This was done using the method described by McAllister et al. (2001), which consists of estimating  $r$  numerically based on iterated solving of the Euler-Lotka equation (with 1000 iterations). Life history data used to construct an  $r$  prior for orange roughy are summarised in Table 4. The resulting (species-specific) prior was centred at 0.050 (median value) and had a mean of 0.055 and standard deviation (in log space) of 0.024.

**Table 4: Life history parameters used to construct an informative prior on the maximum intrinsic population growth rate  $r$  for orange roughy in BDMs.**

Life history trait	Parameter	Unit	Value	Reference(s)
Maximum age (yr)	$A_{max}$	Year	91	Andrews et al. 2009
Natural Mortality	$M$	Yr <sup>-1</sup>	0.045	Doonan et al. 2015, Doonan 1994
Age at maturity (yr)	$A_{mat}$	Year	38	Doonan et al. 2015
	$L_{inf}$	cm	37.63	
Growth (von Bertalanffy)	$k$		0.065	Doonan et al. 2015
	$t_0$	Year	-0.5	
	$a$		0.0921	
Length-weight	$b$		2.71	Doonan et al. 2015
Recruitment steepness (B-H)	$h$		0.75	Doonan et al. 2015, Francis 1992

The same prior on  $r$  and a similar set of model specifications were used to fit a BDM in each stock. Process error was fixed on input at 0.05 (5%) in all models. The ratio of  $B_{MSY}/K$  (shape parameter  $\phi$ ) was given a fixed value of 0.30 (i.e.,  $B_{MSY}$  was assumed to occur at 30% of the biomass at unexploited equilibrium  $K$  in all stocks (whereby  $K \approx B_0$ )). This is slightly higher than deterministic estimates derived from age-structured stock assessment models of four orange stocks within the New Zealand EEZ (range 21.5-24.5%  $B_{MSY}/B_0$ ) (MPI 2015). Observation error was defined for each stock/model as the annual coefficients of variation calculated for the spatial CPUE indices.

Bayesian fitting and estimation was conducted using Markov chain Monte Carlo chains in the rstan package in R (R Development Core Team 2015) (Stan Development Team 2014). Model convergence was assessed by comparing posterior distributions of the estimated parameters ( $r$  and  $K$ ) and plots of cumulative parameter values among four independent MCMC chains. The information content of abundance indices was assessed by conducting separate BDM runs with and without the index and comparing the posterior distributions for  $K$  and current status between the runs. Model sensitivity to the  $B_{MSY}/K$  input value was tested by conducting separate runs using  $B_{MSY}/K$  values of 0.25, 0.30, 0.40, 0.50 and 0.60 and comparing model outputs. Model performance was assessed through cross-validation checks after removal of the last five years of data.

### 5.3.2. Results of biomass dynamic modelling (after Roux et al. in press)

Two separate BDMs were fitted for each stock, one fitted to the catch series and spatial CPUE index assuming constant catchability among subareas ( $w_a=1$ ), the other fitted to the catch series and spatial CPUE index assuming subarea catchability proportional to cumulative catch ( $w_a=cc$ ). The run with the more precise estimate of  $K$  was selected as the base case for each subarea. In the West Norfolk Ridge and Central Louisville Ridge stocks,  $K$  was estimated more precisely using the  $w_a=cc$  abundance index. Conversely,  $K$  was estimated more precisely using the  $w_a=1$  abundance index for the North and South Louisville stocks. Diagnostic plots suggested successful model convergence was achieved for these four stocks and the spatial CPUE index of abundance was found to be informative in all four (Figure 7 & Figure 8).

The BDM models for the Lord Howe Rise and NW Challenger stocks yielded poorly constrained and/or implausible estimates of  $K$ , and diagnostic plots indicated model convergence problems, especially for the Lord Howe Rise stock (Figure 7 & Figure 8). These poor fits may be at least partly a result of the incomplete catch series (especially the lack of catch data from other nations, mostly Australia).

Preliminary estimates of  $K$ , using only New Zealand catch and effort information, are shown in Table 5. Those for the Lord Howe Rise and the Northwest Challenger stocks are very poorly constrained and the models had serious convergence problems, but those for the other four stocks are estimated reasonably well. Although the confidence intervals all overlapped, the preferred BDM models suggested a higher maximum intrinsic population growth rate  $r$  (median 0.075) in the Central Louisville stock than in other stocks where models converged (median estimates 0.052–0.054, very close to the midpoint of the prior) (Table 6).

**Table 5: Posterior distribution information for  $K$  (medians, 95% confidence intervals (CI) and the range between the 95% CI), as estimated from preliminary BDMs for orange roughy fitting to the New Zealand catch series and two different spatial CPUE indices of abundance for New Zealand vessels in each stock. Shaded cells indicate the final (selected) BDM model for each stock.**

Stock		Index 1, $w_a=1$	Index 2, $w_a=cc$
Louisville North	K median	13 520	21 694
	K 95% CI	9 682–24 551	1.1E+04–7.9E+11
	K 95% CI range	14 869	7.9E+11
Louisville–Central	K median	19 266	18 526
	K 95% CI	15 629–24 658	15 274–22 627
	K 95% CI range	9 029	7 353
Louisville–South	K median	13 854	14 662
	K 95% CI	10 715–21 095	11 014–22 826
	K 95% CI range	10 380	11 812
Lord Howe Rise	K median	1 400 880	2 409 019
	K 95% CI	8.3E+03–5.8E+12	1.3E+04–5.3E+12
	K 95% CI range	5.8E+12	5.3E+12
Northwest Challenger	K median	25 811	34 837
	K 95% CI	1.6E+04–8.6E+10	1.6E+04–2.0E+12
	K 95% CI range	8.6E+10	2.0E+12
West Norfolk Ridge	K median	4 362	4 050
	K 95% CI	3 073–6 839	2 913–6 015
	K 95% CI range	3 766	3 102

**Table 6: Summary of preliminary estimates from BDM models of orange roughy using catch and effort data from New Zealand vessels only, including posterior distributions of estimated model parameters ( $r$  and  $K$ ); estimates of current biomass ( $B_{\text{current}}$ ) and harvest rate ( $HR_{\text{current}}$ ); MSY-based reference points ( $MSY$ ,  $B_{\text{MSY}}$  and  $HR_{\text{MSY}}$ ) and current status relative to  $K$  (i.e.  $B_{\text{current}}/B_0$ ). All values are medians (95% CI). Models for the NW Challenger and Lord Howe Rise had serious convergence problems (see Figures 7 and 8) and are not shown.**

Stock	$r$	$K$	$MSY$	$B_{\text{msy}}$	$B_{\text{current}}$	$HR_{\text{MSY}}$	$HR_{\text{current}}$	Status
Louisville North	<b>0.052</b>	<b>13 520</b>	<b>110</b>	<b>4056</b>	<b>5937</b>	<b>0.03</b>	<b>8.0E–04</b>	<b>0.44</b>
	(0.023–0.116)	(9 682–24 551)	(49–253)	(2 905–7 366)	(3 625–13 602)	(0.01–0.06)	(0.0004–0.0015)	(0.32–0.63)
Louisville–Central	<b>0.075</b>	<b>18 526</b>	<b>210</b>	<b>5558</b>	<b>4004</b>	<b>0.04</b>	<b>0.14</b>	<b>0.22</b>
	(0.037–0.131)	(15 274–22 627)	(107–343)	(4 582–6 788)	(2 751–5 801)	(0.02–0.07)	(0.10–0.21)	(0.15–0.30)
Louisville–South	<b>0.054</b>	<b>13 854</b>	<b>116</b>	<b>4156</b>	<b>3004</b>	<b>0.03</b>	<b>0.06</b>	<b>0.22</b>
	(0.022–0.120)	(10 715–21 095)	(51–232)	(3 215–6 329)	(1 580–7 780)	(0.01–0.06)	(0.02–0.12)	(0.13–0.41)
West Norfolk Ridge	<b>0.054</b>	<b>4050</b>	<b>33</b>	<b>1215</b>	<b>930</b>	<b>0.03</b>	<b>0.02</b>	<b>0.23</b>
	(0.023–0.130)	(2 913–6 015)	(14–75)	(874–1 805)	(494–1 898)	(0.01–0.07)	(0.01–0.04)	(0.13–0.40)

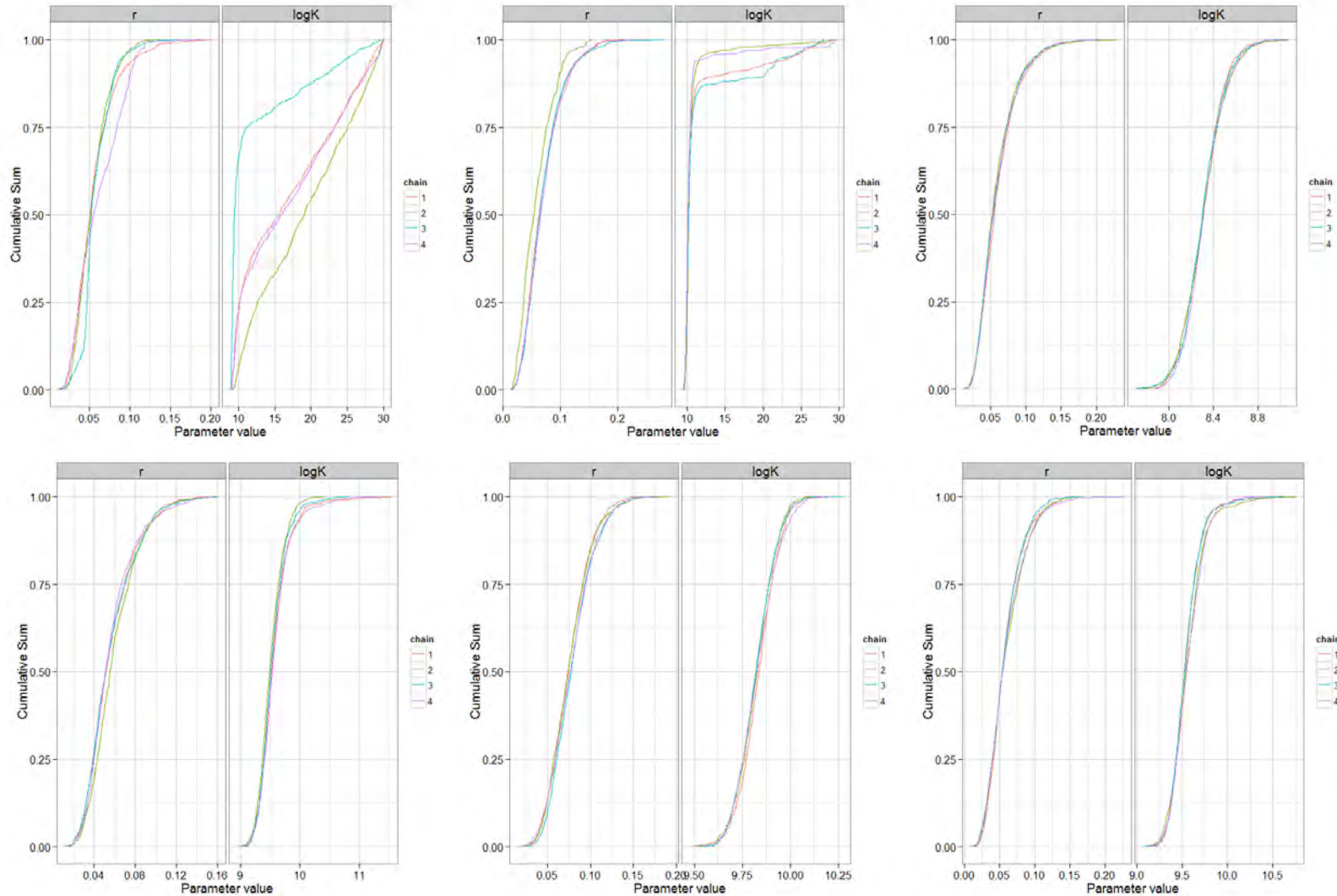
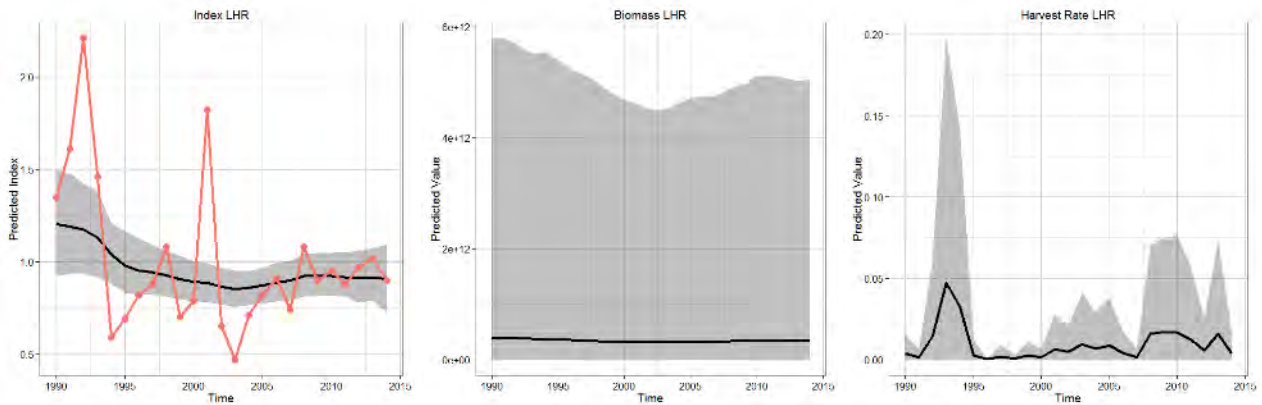
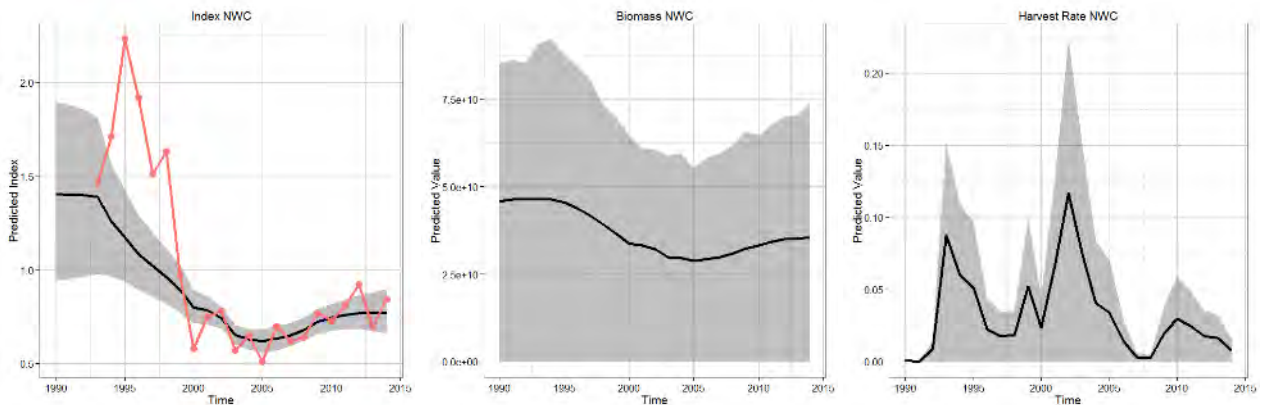


Figure 7: Cumulative plots of the estimated posterior distributions of  $r$  and  $K$ , estimated using four separate MCMC chains, from BDM models of orange roughy stocks in the Tasman Sea region (top row, Lord Howe Rise, Northwest Challenger, West Norfolk Ridge) and Louisville Ridge (bottom row, North, Central, and South) within the SPRFMO Area. Lines for individual MCMC chains for a given model not lying close together is an indicator of poor convergence (see Lord Howe Rise, Northwest Challenger).

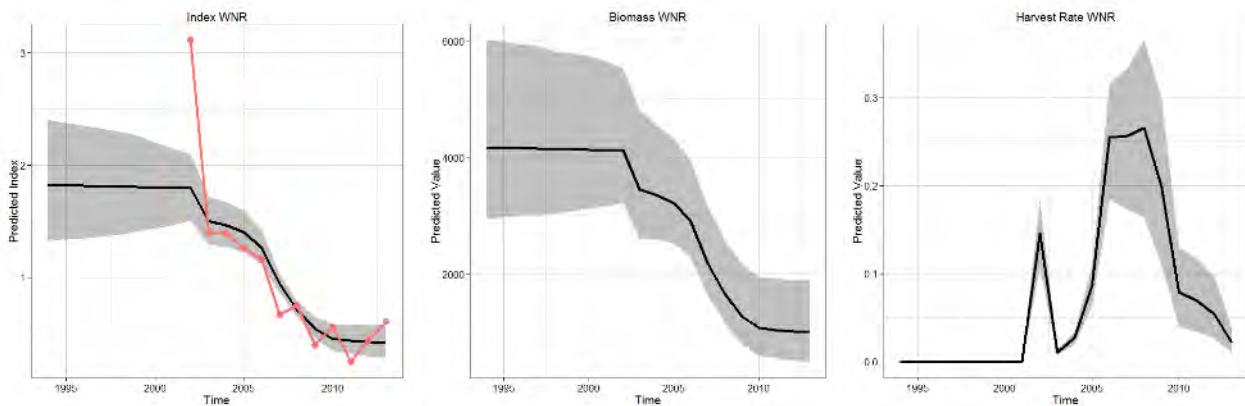
### A. Lord Howe Rise (poor convergence – incomplete catch series)



### B. Northwest Challenger (poor convergence – incomplete catch series)

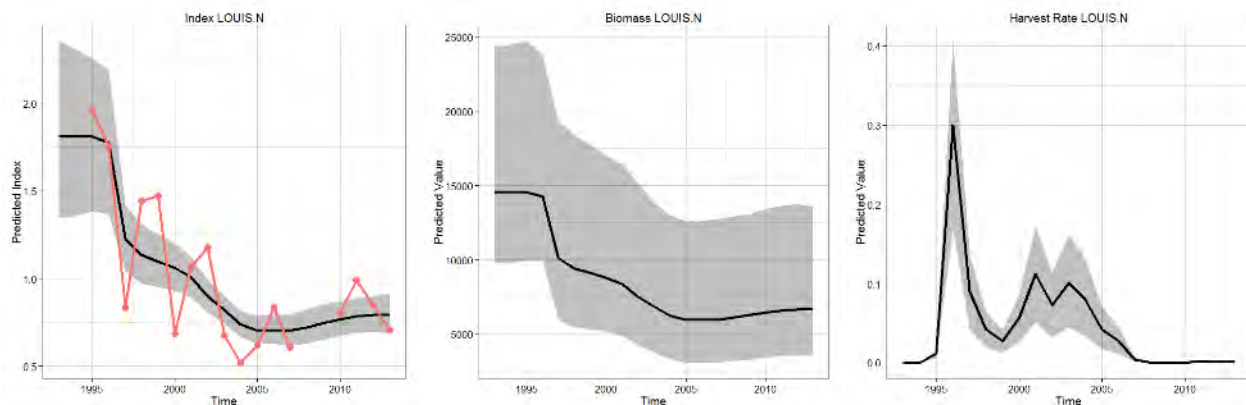
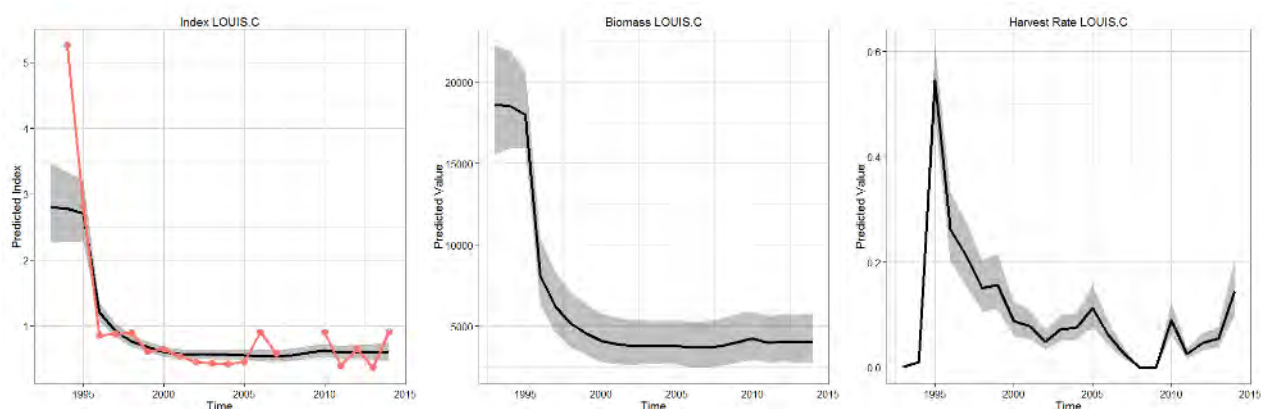
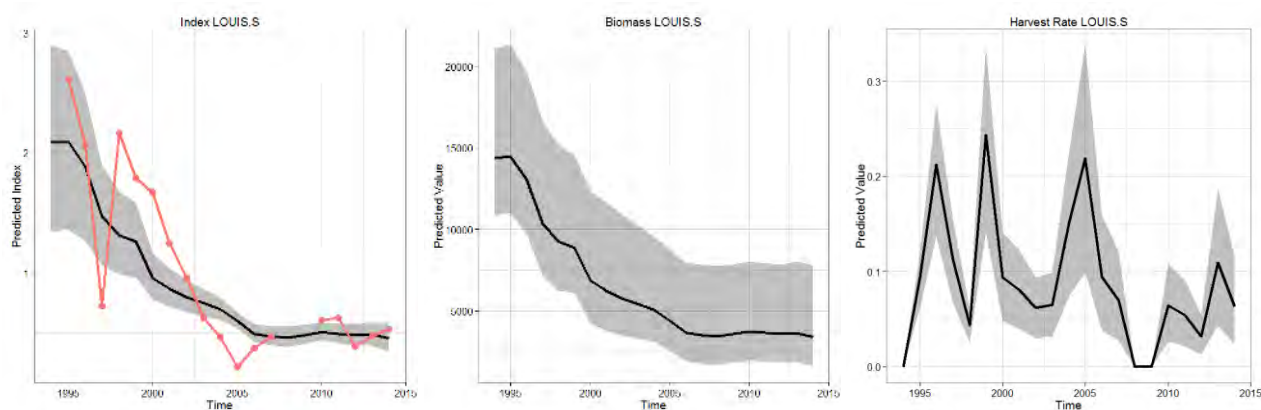


### C. West Norfolk Ridge



**Figure 8: Model estimates (black lines) with 95% confidence limits (grey shading) of the expected abundance index (left); biomass trajectory (centre); and estimated harvest rate (right) for orange roughy stocks in the Tasman Sea. The spatial hybrid CPUE index is shown as a red line in the left plots.**



**A. North-Louisville****B. Central Louisville****C. South Louisville**

**Figure 8 (continued):** Model estimates (black lines) with 95% confidence limits (grey shading) of the expected abundance index (left); biomass trajectory (centre); and estimated harvest rate (right) for orange roughy stocks on the Louisville Ridge. The spatial hybrid CPUE index is shown as a red line in the left plots.

#### 5.4. Discussion of preliminary stock assessment results

The lack of fisheries-independent abundance indices complicates stock assessment of orange roughy in the SPRFMO Area and means that commercial CPUE must be used. There is much evidence to suggest that such data can provide unreliable results (Clark 1999, Clark & Anderson 2001, O'Driscoll 2003, Clark et al. 2010, Penney 2010) because fishing is often highly aggregated and can show non-random fleet movements among subareas within fishing grounds. Failing to account for these non-random spatial patterns can cause bias<sup>2</sup> in the abundance index (Walters 2003, Campbell 2004, Carruthers et al. 2011). Ruled-based imputation of expected CPUE in year-subarea combinations where no fishing occurred (after Walters 2003, McKechnie et al. 2013), following GLM standardisation, is one way of addressing that bias. The hybrid GLM-imputation method used here seems especially appropriate for deepwater fish species and fisheries in which only limited dispersal or mixing and re-distribution of aggregations between subareas is believed to occur (Roux and Doonan 2015).

The sensitivity of CPUE and BDM models presented here was tested in relation to key modelling choices. The spatial CPUE indices for a subarea were found to have low sensitivity to the choice of imputation rules used for inferring expected CPUE in subarea-year cells where no fishing, or very little fishing, had occurred. However, the choice of weighting regime for combining CPUE indices across subareas did influence the CPUE trend in some cases (e.g., North Louisville), thereby affecting BDM estimates of  $K$  (although estimates of status relative to  $K$  were not very sensitive to this choice). BDM estimates of  $K$ , and current status relative to  $K$ , were not sensitive to the assumed point of inflection for the production curve, although status relative to the (assumed)  $B_{MSY}$  was obviously sensitive to this choice. The sensitivity to other modelling choices, for example the formulation of priors and the assumed or fitted level of process error within each model, have not yet been tested. Another area for testing and resolution is around the implicit assumption inherent in the imputation methods that CPUE (and hence biomass) remains constant at a location after fishing has ceased. This may cause a small negative bias in the CPUE index and the overall inferred biomass trajectory for a stock within a BDM, and this bias would be expected to increase as the time since last fishing increases. The inclusion of process error in the BDMs allows for rebuilding to occur in the overall biomass trajectory (i.e., deviation from the depletion trend inferred from the catch series and abundance index). Whether the level of process error specified in these preliminary models (5%) was sufficient to offset a potential bias in the spatial CPUE index remains to be tested and demonstrated. A useful next step will be to estimate an appropriate level of process error for these stocks.

The performance of BDM models has been simulation tested using data from well-understood fish stocks within New Zealand's EEZ (Edwards and McAllister 2014). This work demonstrated that BDM can provide similar estimates of stock status relative to  $K$  to those provided by more complex integrated age-structured population models implemented in CASAL (Bull et al 2012). BDM models may, however, have less power to estimating the absolute scale of current and initial biomass. Similar simulation testing of the hybrid GLM-imputation method for developing spatial CPUE indices of relative abundance in similar deepwater fisheries is currently underway.

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<sup>2</sup> For example, hyper-stability will occur if the fishery progressively moves to new subareas having higher fish densities than the currently-fished subarea over time. Hyper-depletion may occur if fishing activities spread across an increasing number of subareas having lower fish densities over time.

The key uncertainties in these assessments relate to the catch records used to drive the BDM models. Convergence problems in the Lord Howe Rise and NW Challenger BDM models probably related at least in part to the use of an incomplete catch series because only New Zealand catch was included. Australian and other nations' vessels accounted for > 50% of the annual catch from these stocks in some years between 1988 and the mid-2000s (Clark 2008). For stocks where models did converge, missing catch information will probably lead to negative bias in estimated stock productivity and K. Work is underway to acquire the necessary spatially-resolved catch records from Australia and, potentially, from other nations where the location of fishing can be reasonably inferred.

For orange roughy from the Louisville Ridge, the initial (unexploited equilibrium) biomass estimated using BDM (total 45 900 t across the three stocks) was slightly lower than predicted by the seamount meta-analysis (51 500 t after adjusting for seamounts located beyond the distribution range for orange roughy) (Clark et al. 2010). Results for individual Louisville stocks were not directly comparable since revised and adjusted stock boundaries were used in this study. Similarly, results for Tasman Sea fisheries were not comparable to the outputs of the seamount meta-analysis, as our study utilised catch and effort data from both UTF and slope areas in biomass dynamics modelling.

Several development and fine-tuning options exist for the BDM models presented here once a more complete series of catch records by stock have been assembled. These include:

- the development of stock-specific priors for  $r$  (for example using maximum length information available in the observer data to estimate stock-specific natural mortality  $M$ );
- the construction of informed priors on  $K$  for each area;
- estimation of process error within models; and
- development of stock projections.

## 5.5. Ongoing work

These preliminary analyses used only commercial catch and effort data from New Zealand fishing vessels outside New Zealand's EEZ. This restriction was necessary because catch and effort data for other bottom fishing nations was not available at the fine scale needed for these analyses. More reliable estimates of CPUE trends, unfished biomass, sustainable yield, and current status will be available once complete catch series are available including other nations' data.

Sensitivity testing and validation of the spatial CPUE analyses is underway on similar stocks and fisheries that have reliable biomass estimates based on fisheries-independent data. This work is showing promise but was not ready for discussion at SC4. It will be completed by the end of 2016 and should identify any consistent biases and/or suggest ways of increasing the performance of these methods.

At this stage, New Zealand researchers consider that the performance of these methods can be improved by developing more robust definitions of stock-specific subarea strata, sharing information on catchability across spatial strata, estimating process error within each BDM model, and using other

information to develop stock-specific priors on “r” and “K” (the latter using the predictive models using physical characteristics described in Section 4, perhaps).

It is expected that the results of BDM stock assessments including the catches of all nations and simulation testing of the approach will both be available before the SPRFMO Scientific Committee meets in late September 2017. These will feed into the development of a comprehensive measure for bottom fisheries.

## 6. Recommendations

It is recommended that the Scientific Committee:

- **notes** New Zealand’s continued work on stock assessment of demersal species, specifically provisional stock assessments for orange roughy in the western part of the SPRFMO Area
- **notes** that simulation testing of the CPUE approach is underway and the results should be available by the end of 2016. The BDM modelling approach has already been simulation tested
- **notes** that full catch histories for the assessed areas will be required to finalise these stock assessments
- **urges** other bottom fishing nations to consider providing full catch histories with sufficient precision to be used in the CPUE and BDM analyses
- **notes** that finalised estimates of initial biomass, productivity, and stock status for some orange roughy stocks should be available before the committee meets in 2017
- **agrees** that this work should contribute to the development of a revised CMM for bottom fisheries in the SPRFMO Area once the stock assessments are finalised

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