Ministry for Primary Industries
Manatū Ahu Matua

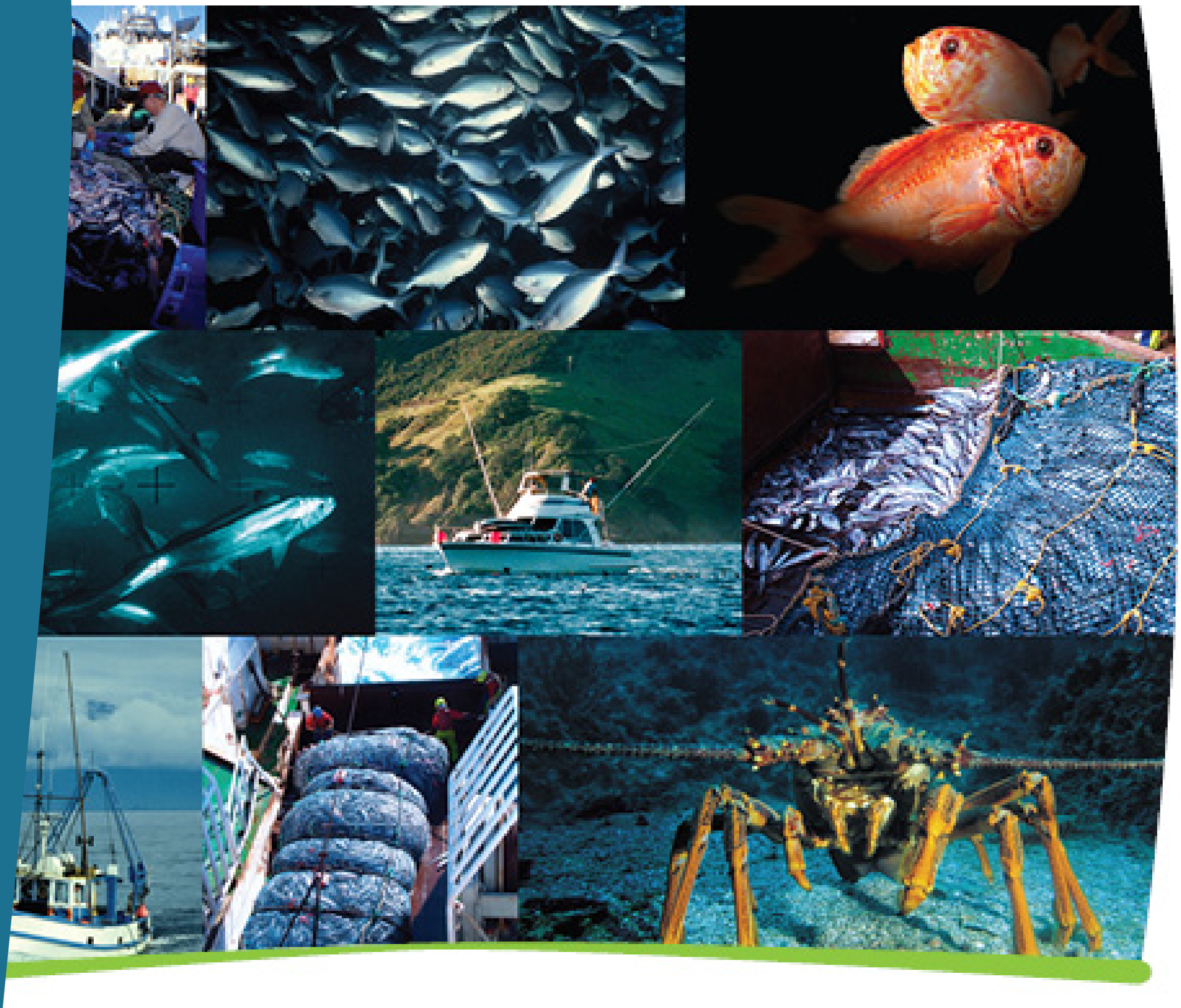
Low information stock assessment of orange roughy *Hoplostethus atlanticus* in the South Pacific Regional Fisheries Management Organisation Convention Area

New Zealand Fisheries Assessment Report 2017/01

M.-J. Roux;
I. Doonan;
C. T. T. Edwards;
M. R. Clark

ISSN 1179-5352 (online)
ISBN 978-1-77665-461-1 (online)

January 2017



New Zealand Government

Growing and Protecting New Zealand

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries websites at:
http://www.mpi.govt.nz/news-resources/publications.aspx
http://fs.fish.govt.nz go to Document library/Research reports

TABLE OF CONTENTS

EXECUTIVE SUMMARY 1

1. INTRODUCTION 2

2. METHODS 2

- 2.1 Dataset 2
- 2.2 Assessment areas 3
- 2.3 Spatial CPUE analyses 4
  - *2.3.1. Approach and assumptions* 4
  - *2.3.2. Subarea definition* 5
  - *2.3.3. Data selection* 5
  - *2.3.4. Interaction GLM* 6
  - *2.3.5. Data imputation* 6
  - *2.3.6. Subarea weighting, summation of annual indices and randomisation* 7
- 2.4 Biomass dynamics modelling (BDM) 7
  - *2.4.1. Model description* 7
  - *2.4.2. Estimation framework and model specifications* 8
  - *2.4.3. Performance evaluation and sensitivity testing* 10

3. RESULTS 10

- 3.1 Available catch and effort data 10
- 3.2 Spatial CPUE indices of stock abundance 10
  - *3.2.1. Lord Howe Rise spatial CPUE* 14
  - *3.2.2. Northwest Challenger Plateau spatial CPUE* 18
  - *3.2.3. West Norfolk Ridge spatial CPUE* 22
  - *3.2.4. North Louisville Ridge spatial CPUE* 25
  - *3.2.5. Central Louisville Ridge spatial CPUE* 29
  - *3.2.6. South Louisville Ridge spatial CPUE* 33
- 3.3 Stock status evaluation using BDM 37

4. DISCUSSION 49

5. ACKNOWLEDGMENTS 52

6. REFERENCES 53

APPENDIX 1 56

APPENDIX 2 62

EXECUTIVE SUMMARY

Roux, M.-J.; Doonan, I.; Edwards, C.; Clark, M.R. (2017). Low information stock assessment of orange roughy *Hoplostethus atlanticus* in the South Pacific Regional Fisheries Management Organisation Convention Area.

***New Zealand Fisheries Assessment Report 2017/01.* 62 p.**

Commercial catch per unit effort (CPUE) data are the principal information source available for stock assessment of orange roughy in high seas fisheries beyond the New Zealand EEZ. We developed and applied spatial CPUE analyses and a cohort-aggregated Bayesian state-space biomass dynamics model (BDM) to evaluate the status of six orange roughy stocks within the South Pacific Regional Fisheries Management Organisation (SPRFMO) Convention Area. Spatial CPUE analyses consisted of a GLM standardisation with year-spatial effects and rule-based imputation to account for missing year-subarea data. These provided indices of stock abundance that coped with bias arising from non-random temporal changes in the spatial distribution and extent of fishing. The BDM fitted to catch series and spatial CPUE indices provided new and relatively robust estimates of initial biomass, population growth rate, maximum sustainable yield (MSY) and current status (with uncertainty) in four of the six stocks. Used in conjunction, these methods can serve to infer stock status in such low-information fisheries. Preliminary analyses were restricted to commercial data from New Zealand fishing vessels and excluded data from within the New Zealand EEZ. Future iterations should include the use of complete catch series (with other nations' data) as well as stock projections. Development options that will assist with enhancing performance include a more robust definition of stock-specific subarea strata, catchability estimation or refined assumptions across spatial strata, the development of stock-specific *r* priors, the construction of an informed prior on *K* and process error estimation. Sensitivity testing and validation of the spatial CPUE analyses on similar stocks having reliable biomass estimates from fisheries independent data is also recommended.

1. INTRODUCTION

Deepwater trawl fisheries for orange roughy (*Hoplostethus atlanticus*) account for most of New Zealand's bottom trawl footprint within the South Pacific Regional Fisheries Management Organisation (SPRFMO) Convention Area. New Zealand fisheries for orange roughy on the high seas developed in the mid-1980s and expanded to different areas until the late 1990s (Clark et al. 2010).

Commercial catch and effort data are the only accepted information source available for stock assessment of orange roughy in the SPRFMO Area. Since 1998, a number of fisheries characterisations, catch per unit effort (CPUE) analyses and a predictive modelling approach (the seamount meta-analysis) have been applied to evaluate stock status and formulate science advice for the setting of catch limits, the most recent being Clark (2008), Clark et al. (2010) and Clark et al. (2016). Problems and limitations with these methods include: i) uncertainty in stock structure/discrimination; ii) high levels of uncertainty in predictive modelling outputs; and iii) unreliable indices of stock abundance. High seas commercial CPUE data tend to be spatially and temporally dispersed and are thus uninformative as raw indicators of stock abundance (Clark et al. 2010).

Research was undertaken under MPI project DEE2014-10 *Assessment of orange roughy stocks outside the EEZ*, with the aim of addressing ongoing challenges and limitations in stock status evaluation and developing reliable, low-information stock assessments for orange roughy. The objectives of this project were:

- Overall objective
  To develop stock assessments for orange roughy in the SPRFMO Convention Area

- Specific objectives

1. To evaluate options for assessing and managing orange roughy in the SPRFMO Convention Area, on the basis of stock structure or spatial criteria.
2. To apply a range of low-information stock assessments for each stock or management area for orange roughy in the SPRFMO Convention Area
3. To provide the tools developed in specific objective 2 to MPI for ongoing use.

Specific objective one is the subject of a separate report (Clark et al. 2016). The present document focuses on the analyses and results conducted under specific objectives two and three.

Hybrid spatial CPUE analyses (Carruthers et al. 2011) and cohort-aggregated state-space biomass dynamics models (BDM) (Edwards 2016, Edwards & McAllister 2014) have recently been developed that have potential in advancing attempts to undertake stock assessments for low information orange roughy fisheries, such as those outside the EEZ. In particular, spatial CPUE analyses can be used to estimate reliable indices of stock abundance using commercial fisheries data, whilst minimizing bias arising from non-random temporal changes in the spatial distribution of fishing effort (Walters 2003).

The purpose of this report is to evaluate the usefulness and validity of these methods for stock assessment of orange roughy and the provision of science advice for the setting of sustainable catch limits in the SPRFMO Area.

2. METHODS

2.1 Dataset

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 that occurred within the SPRFMO Area boundaries over that time period. 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 to the following data fields: positions (start and end latitude/longitude), bottom and trawl depths, trawl speed, tow duration, tow distance, time of day and vessel nationality. Missing values and outliers were corrected by median imputation on larger ranges of data (i.e. by assigning median values calculated from records with similar vessel-start date or vessel-year-week combinations). Fishing events with no target species and no catch were removed from the dataset. East-West longitudinal corrections were applied, which consisted of identifying records from vessels that reported start/end positions both east and west of 180 degrees longitude within the same week, and correcting for the outliers. Fishing events located within the New Zealand EEZ were deleted once East-West corrections were completed.

The final dataset was restricted to bottom trawl effort (a small number (less than 1%) of tows that used midwater trawl gear were excluded). The New Zealand fishing year runs from 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. The term ‘year’ is used in reference to the New Zealand fishing year in this report, and distinguished from calendar year (1 January to 31 December).

2.2 Assessment areas

The six orange roughy management areas considered for assessment are those defined by Clark (2008) and revised by Clark et al. (2016) (Figure 1). Each area is assumed to represent a potential biological stock of orange roughy. The final polygon boundaries (in decimal degrees) for each of the stocks are as follows:

Lord Howe Rise (LHR): 35.00–36.75 S; 164.00–167.00 E.

Northwest Challenger Plateau (NWC): 36.83–38.00 S; 166.00–170.00 E.

West Norfolk Ridge (WNR): 32.50–34.50 S; 166.50–168.17 E.

Louisville-North (LOUIS-N): 35.00–39.50 S; 172.00–165.00 W.

Louisville-Central (LOUIS-C): 39.40–43.00 S; 167.00–162.50 W.

Louisville-South (LOUIS-S): 41.50–50.00 S; 162.45–148.00 W.

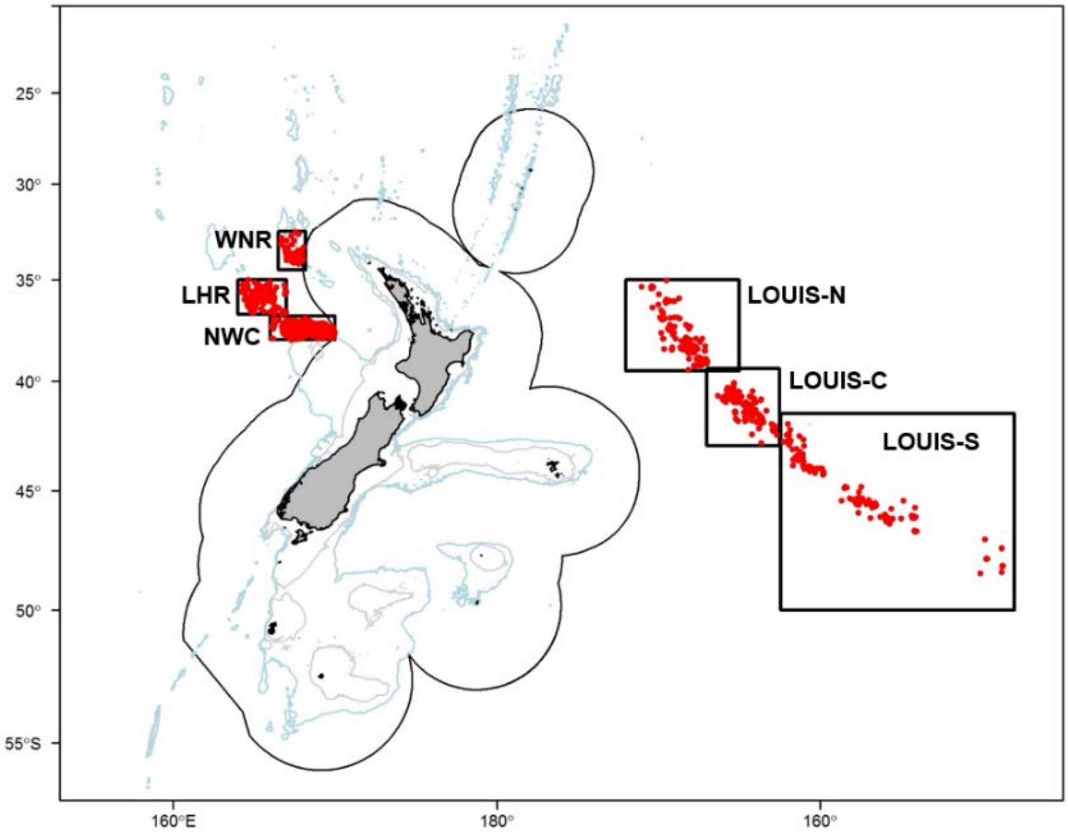


Figure 1: **Location of the six management areas/potential biological stocks of orange roughy considered for assessment (boxes), relative to the New Zealand EEZ. Red dots are bottom trawl tows (n=41 256, 1989–90 to 2013–14). Depth contours are for 1000 m (pale blue) and 500 m (light grey). Area abbreviations are explained in the text above.**

2.3 Spatial CPUE analyses

2.3.1. Approach and assumptions

Tows and catches were divided into the six principal orange roughy assessment management areas recommended by Clark et al. (2016), 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 represents a straddling stock between NZ and SPRFMO subject to a recent in-zone stock assessment (Cordue 2014). The South Tasman Rise area was not considered for preliminary assessment due to Australian catch and effort information being unavailable.

The spatial CPUE approach assumes that overall population abundance is contributed from several strata or subareas 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 inversely proportional to the fraction of the population (or total biomass) available in each subarea, and inversely 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 (or biomass, in weight) in year y and n is the sample (subarea a) relative abundance (or biomass) in year y.

This approach assumes limited dispersal and/or slow mixing/redistribution of fish among subarea, which appears to be a valid assumption in slow-growing, deepwater fish stocks (Roux & Doonan 2015). Subareas need to be small enough that an assumption of random fishing within subarea boundaries is reasonable (Walters 2003).

For this orange roughy assessment, the hybrid GLM-imputation method described by Carruthers et al. (2011) was used to calculate spatial CPUE indices of stock abundance. The hybrid method consists of fitting an interaction GLM (i.e., GLM with year-subarea interactions and significant covariates) to predict standardised CPUE in year-subarea strata where fishing occurred and applying Walters' (2003) imputation methods to estimate CPUE in year-subarea strata with no data (i.e., where fishing did not occur).

2.3.2. Subarea definition

Fishing activities for orange roughy outside the New Zealand EEZ can be concentrated on underwater topographic features (UTFs) (e.g. Louisville Seamount 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 firstly assigning individual tows to UTFs (where UTF fishing occurred) and/or by subsequently performing hierarchical distance clustering on non-UTF tows.

UTF data were extracted from the Seamounts database (SEAMOUNT V2) managed by NIWA (Rowden et al. 2008). Only UTFs within the orange roughy distribution range (summit depth between 500 and 1500 m) were retained for analyses. Three criteria were used to assign individual tows to UTFs: 1) tow start position (at the vessel) relative to UTF summit position; 2) UTF category as distinguished by UTF elevation (100–499 m = hill; 500–999 m = knoll; ≥ 1000 m= seamount); and 3) tow duration. Tows were assigned to UTFs if their duration was 30 minutes or less and their start position was within 3 NM of the summit position (hills); 5 NM (knolls) and 8 NM (seamounts). For the Louisville fisheries, the third criterion (tow duration) was ignored because long tows are possible on these large oceanic seamounts; all tows were assigned to the nearest seamount by measuring the distance between tow start positions and summit positions. A few tows located further than 50 NM from the nearest summit position were excluded from the analyses, as they were likely to be positional errors as the seafloor depth away from the seamounts is 3000–4000 m.

Hierarchical cluster analyses consisted of calculating the average distance between non-UTF tows and applying an average linkage clustering algorithm (Sokal & Sneath 1973) to the distance matrix in order to group tows by subarea strata.

2.3.3. Data selection

For each assumed stock, analyses were restricted to positive catch and effort data in subarea that had a minimum of 50 tows over the entire time series. A "core vessels" selection was performed that retained data from vessels that fished for a minimum of two years with at least five tows per year. The criteria used in core vessels selection were unrestrictive compared to most CPUE analyses, owing to the limited amount of data. Spatial CPUE indices were calculated for fishing years and subareas in which at least ten tows remained after core vessels selection.

2.3.4. Interaction GLM

A lognormal, interaction GLM (Generalised Linear Model (Chambers & Hastie 1991)) was fitted to log-transformed, non-zero catch-effort data (t 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 1). Fishing year (*fyear*) was fixed as the first term and the algorithm added variables based on changes in residual deviance. Variables were added to the model up to a 1% improvement in explained residual deviance. Selected variables (hereinafter referred to as "significant covariates") were included in the final model, along with *fyear*, *subarea*, and the *fyear-subarea* interaction term. The explanatory power of the final model was described by the reduction in residual deviance relative to the null deviance defined by a simple intercept model (R^2). Model fits were investigated using standard residuals diagnostics (plots of residuals against fitted values and quantiles of the standard normal distribution) to check for departures from the regression assumptions of homoscedasticity and normality of errors in log-space (i.e., log-normal errors).

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 1: 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
fyear	Factor	Fishing year (Oct 1–Sep 30)
subarea	Factor	Subarea within the fishing ground/management area
fyear:subarea	Interaction term	year-subarea interaction
vessel	Factor	Unique vessel identifier
target sp.	Factor	Target species as reported on a tow by tow basis
month	Factor	Calendar month
day of year	Continuous	Day of calendar year
fweek	Factor	Fishing week (relative to fyear)
trawl depth	Continuous	Reported trawl depth (m)
trawl.speed	Continuous	Reported trawl speed (kn)
tow duration	Continuous	Calculated tow duration (in hours) (based on reported start and finish times)

2.3.5. Data imputation

In *fyear-subarea* strata with no fishing activities, missing data were imputed using the method and criteria described by Roux & Doonan (2015), with the difference that forward imputation was here averaged over the last two years of data (as opposed to the last three years):

- Backward imputation (prior to 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 missing data in-between non-consecutive years.

These criteria are hereinafter referred to as the default imputation method.

A minimum effort threshold was applied prior to conducting imputation. Standardised catch rates predicted for *fyear-subarea* strata with fewer than five tows were not considered representative of local abundance and were replaced using imputed values.

Two other sets of backward/forward imputation criteria were applied and compared during sensitivity testing:

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.

2.3.6. Subarea weighting, summation of annual indices and randomisation

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 weight in all subareas.
2) w_a=cc: subarea weight proportional to cumulative catch contribution.

The weighted CPUE data were summed across subarea in each year to derive the annual indices. A bootstrap re-sampling procedure (with replacement) was applied to the catch-effort data (including significant covariates) to estimate uncertainty in the annual indices as coefficients of variation (CV). GLM standardisation, data imputation, subarea weighting and summation procedures were iterated 500 times for this purpose.

The most appropriate weighting regime for the index of abundance (and corresponding BDM) for each stock was selected by assessing the plausibility and variability of BDM estimates of the biomass at unexploited equilibrium (see also Section 3.3).We note that this approach was useful to select among equally plausible scenarios in preliminary analyses, but may not constitute a solid basis for selecting reliable and representative indices of abundance for each stock when finalising stock assessments

2.4 Biomass dynamics modelling (BDM)

2.4.1. Model description

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:

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

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

$$m = MSY$$

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 $\varphi = 0.5$.

2.4.2. Estimation framework and model specifications

BDM was 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:

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

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

The i subscript refers to the abundance index. 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 2. The resulting (species-specific) prior is shown in Figure 2. The prior was centred at 0.050 (median value) and had a mean and standard deviation of 0.055 and 0.024 respectively.

Table 2: Life history parameters used to construct an informative prior on the maximum intrinsic population growth rate *r* for orange roughy in the SPRFMO Convention Area. Values were selected based on available information as per the given references.

Life history trait	Parameter	Value	Reference(s)
Maximum age (yr)	A_{max}	91	Andrews et al. 2009
Natural Mortality	M	0.045	Doonan et al. 2015
Age at maturity (yr)	A_{mat}	38	Doonan et al. 2015
Growth (von Bertalanffy) (cm)	L_{inf}	37.63	Doonan et al. 2015
	k	0.065	
	t_0	-0.5	
Length-weight	a	0.0921	Doonan et al. 2015
	b	2.71	
Recruitment steepness (Beverton and Holt)	h	0.75	Doonan et al. 2015, Francis 1992

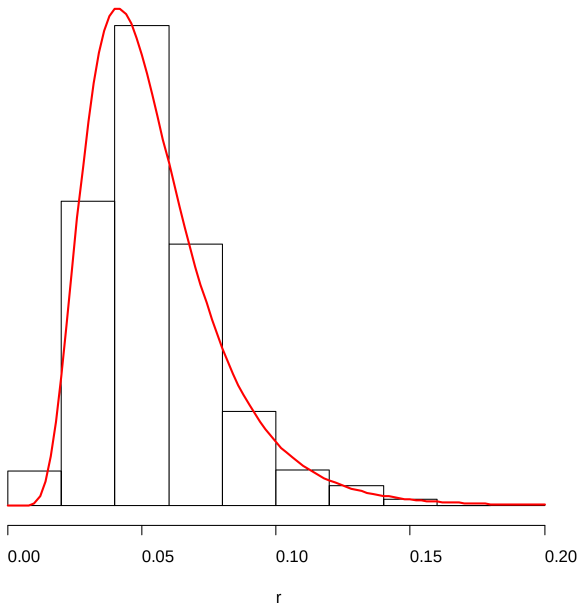


Figure 2: Constructed prior for the maximum intrinsic population growth rate *r* of orange roughy. The median value is 0.05.

A consistent prior on *r* (above) and a similar set of model specifications were used to fit a BDM in each stock. Process error standard deviation was fixed on input at 0.05 (5%) in all models. The ratio of B_{MSY}/K (shape parameter φ) 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 estimation of the parameters was achieved in R software (R Development Core Team 2015) using the rstan package (Stan Development Team 2014), which implements a Markov Chain Monte Carlo routine. Model convergence was assessed by comparing posterior distributions of the estimated parameters (r and K) and plots of cumulative parameter values among chains. The following model outputs were summarised for each stock: time series of predicted biomass, abundance index and harvest rate; and estimates of K and r, MSY and current status (relative to K), with uncertainty.

2.4.3. Performance evaluation and sensitivity testing

Whether or not the abundance indices were informative in the BDM process was assessed by conducting separate model 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.

3. RESULTS

3.1 Available catch and effort data

Catch and effort data from New Zealand vessels that targeted or caught orange roughy in bottom trawling activities within the SPRFMO Area, 1990–2014, are summarised for each stock in Appendix 1. Tows targeting orange roughy accounted for most of the annual effort (between 95% and 100% of tows) in all management areas. The occurrence of zero catch tows was variable over time and in some cases higher in earlier years, which is indicative of exploratory fishing. This supported the use of only positive catch data in the development of spatial CPUE indices of stock abundance (i.e., served to avoid confounding effects of changes in fishing efficiency over time).

Among stocks, effort was highest on the Northwest Challenger Plateau, where 64 different vessels performed a total of 14 600 tows between 1990 and 2014, for a total catch of 13 886 t of orange roughy. The Lord Howe Rise was fished from 1990 to 2014 by 59 different vessels. Total catch and effort over that period were 6181 t and 5061 tows, respectively. The West Norfolk Ridge had the shortest time series and lowest catch and effort, with 3130 t caught in 1892 tows performed by 23 different vessels between 1994 and 2013.

Fisheries on the Louisville Ridge developed in 1993–1995 but no fishing occurred there in 2008 and 2009. Between 43 (Louisville South) and 52 (Louisville Central) New Zealand vessels fished on the Louisville Ridge during the study period. Among stocks, the Central Louisville fishery had the highest catch of orange roughy (18 357 t) from 9649 tows. Total catch and effort in the North Louisville area were 8822 t and 5250 tows, respectively, compared with 12 368 t and 4804 tows in the South Louisville.

3.2 Spatial CPUE indices of stock abundance

Standardised, spatial CPUE indices of abundance are summarised for each stock in Table 3, and plotted together with catch series in Figure 3. These are the final indices calculated using the default imputation method and subarea weights of 1 (w_a =1) (in the North and South Louisville, Lord Howe Rise and Northwest Challenger stocks) or assumed proportional to cumulative catch (w_a=cc) (Central Louisville and West Norfolk Ridge stocks). Index selection was performed in conjunction with BDM applications and outputs and are discussed in Section 3.3 below.

Trends in relative abundance indices show initial declines and a high degree of uncertainty early in the time series for all stocks (Figure 3). Indices for the Northwest Challenger and Lord Howe Rise show relatively stable low abundance and a slight increase in the index over the last 4–5 years (relative to the early- and mid-2000s). A shorter time series was available for the West Norfolk Ridge, which shows declining abundance followed by stable low CPUE during the last three years in which fishing occurred (2011–2013) (Figure 3A). Louisville stocks (Figure 3B) exhibit sharp, initial declines and stable-low abundance since the mid-2000s. Lower than average CPUE was observed in all stocks on the Louisville Ridge in 2013.

The following sections provide stock-by-stock analytical information for the development and validation of spatial CPUE abundance indices, including detailed results and comparisons and outcomes of sensitivity analyses on subarea catchability and missing year-subarea data imputation assumptions.

Table 3: Lognormal, standardised annual spatial CPUE abundance indices and calculated coefficients of variation (CV) for orange roughy stocks in the SPRFMO Convention Area.

	Tasman Sea fisheries						**Louisville Ridge fisheries**					
Fishing year	**LHR**		**NWC**		**WNR**		**LOUIS-N**		**LOUIS-C**		**LOUIS-S**	
	index	CV	index	CV	index	CV	index	CV	index	CV	index	CV
1989–90	1.35	0.38										
1990–91	1.61	0.39										
1991–92	2.21	0.35										
1992–93	1.46	0.36	1.46	0.47								
1993–94	0.59	0.51	1.71	0.37					5.41	0.33		
1994–95	0.69	0.42	2.23	0.29			2.00	0.21	2.90	0.13	2.75	0.53
1995–96	0.82	0.35	1.92	0.37			1.79	0.22	0.88	0.19	2.18	0.53
1996–97	0.88	0.42	1.51	0.45			0.85	0.26	0.90	0.17	0.76	0.58
1997–98	1.08	0.31	1.63	0.41			1.47	0.36	0.92	0.21	2.28	0.57
1998–99	0.70	0.29	0.97	0.32			1.50	0.22	0.63	0.20	1.88	0.74
1999–00	0.79	0.23	0.58	0.12			0.70	0.28	0.67	0.22	1.76	0.46
2000–01	1.82	0.57	0.75	0.10			1.09	0.23	0.55	0.20	1.31	0.40
2001–02	0.65	0.24	0.78	0.08	3.11	0.25	1.20	0.17	0.47	0.24	1.01	0.51
2002–03	0.47	0.25	0.57	0.09	1.40	0.24	0.69	0.17	0.45	0.29	0.66	0.67
2003–04	0.71	0.26	0.65	0.09	1.39	0.27	0.53	0.17	0.44	0.27	0.49	0.35
2004–05	0.82	0.29	0.51	0.13	1.26	0.25	0.63	0.15	0.47	0.22	0.23	0.29
2005–06	0.91	0.25	0.70	0.16	1.16	0.27	0.85	0.14	0.93	0.32	0.39	0.37
2006–07	0.74	0.29	0.62	0.11	0.67	0.24	0.62	0.21	0.60	0.34	0.49	0.28
2007–08	1.08	0.27	0.64	0.11	0.75	0.29						
2008–09	0.90	0.26	0.77	0.13	0.40	0.22						
2009–10	0.95	0.29	0.73	0.13	0.56	0.46			0.93	0.19	0.64	0.30
2010–11	0.88	0.27	0.81	0.13	0.25	0.57	1.01	0.28	0.41	0.29	0.66	0.46
2011–12	0.97	0.25	0.92	0.15	0.44	0.43			0.67	0.28	0.41	0.30
2012–13	1.02	0.26	0.70	0.16	0.61	0.47	0.72	0.14	0.38	0.22	0.50	0.35
2013–14	0.90	0.25	0.84	0.17					0.94	0.28	0.56	0.38

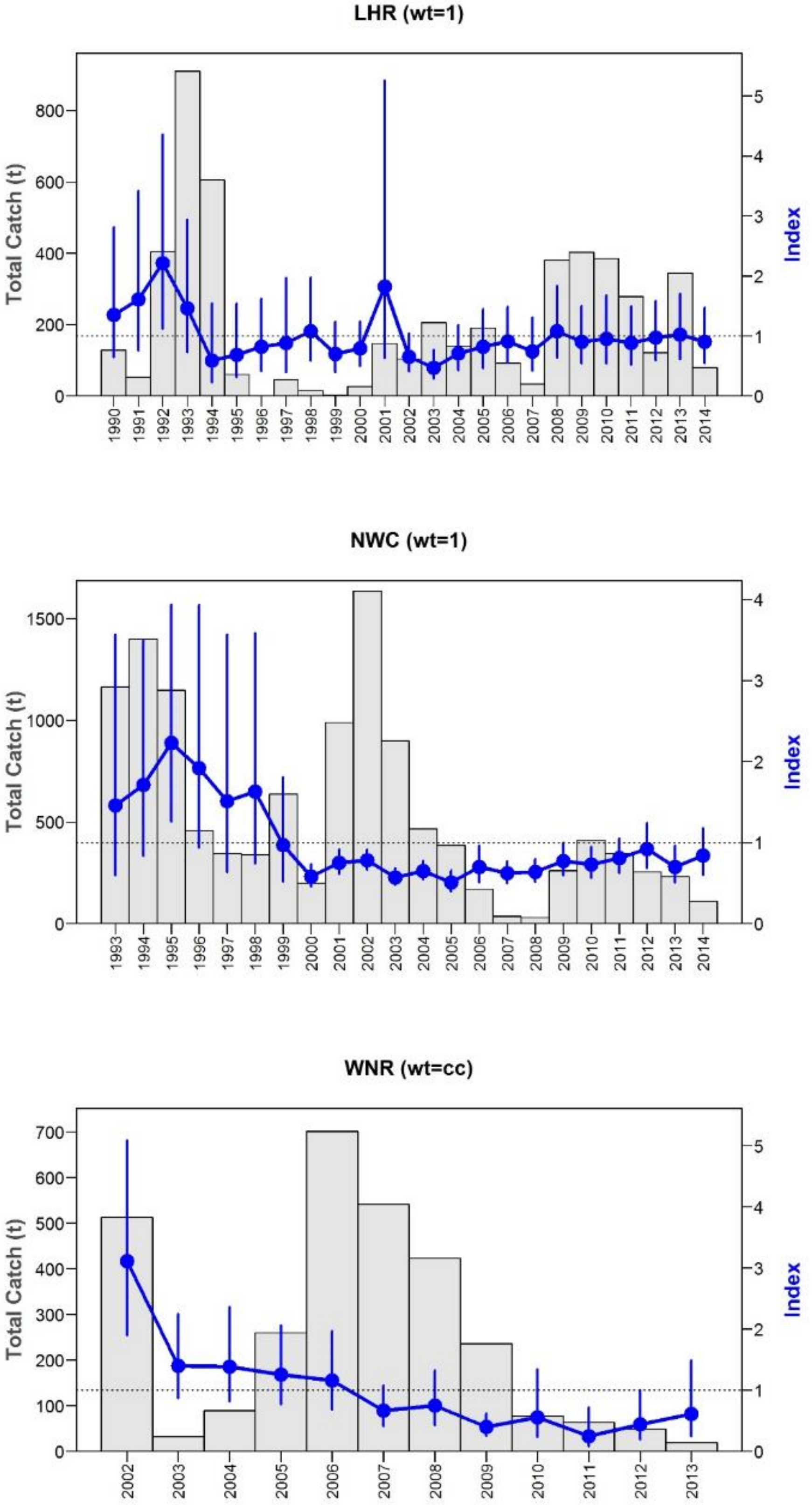


Figure 3A: Catch series (grey bars, left axes) and normalised, standardised spatial CPUE abundance indices (blue line/full circles, right axes) for orange roughy stocks in the Tasman Sea region of the SPRFMO Convention Area. Error bars are 95% confidence intervals.

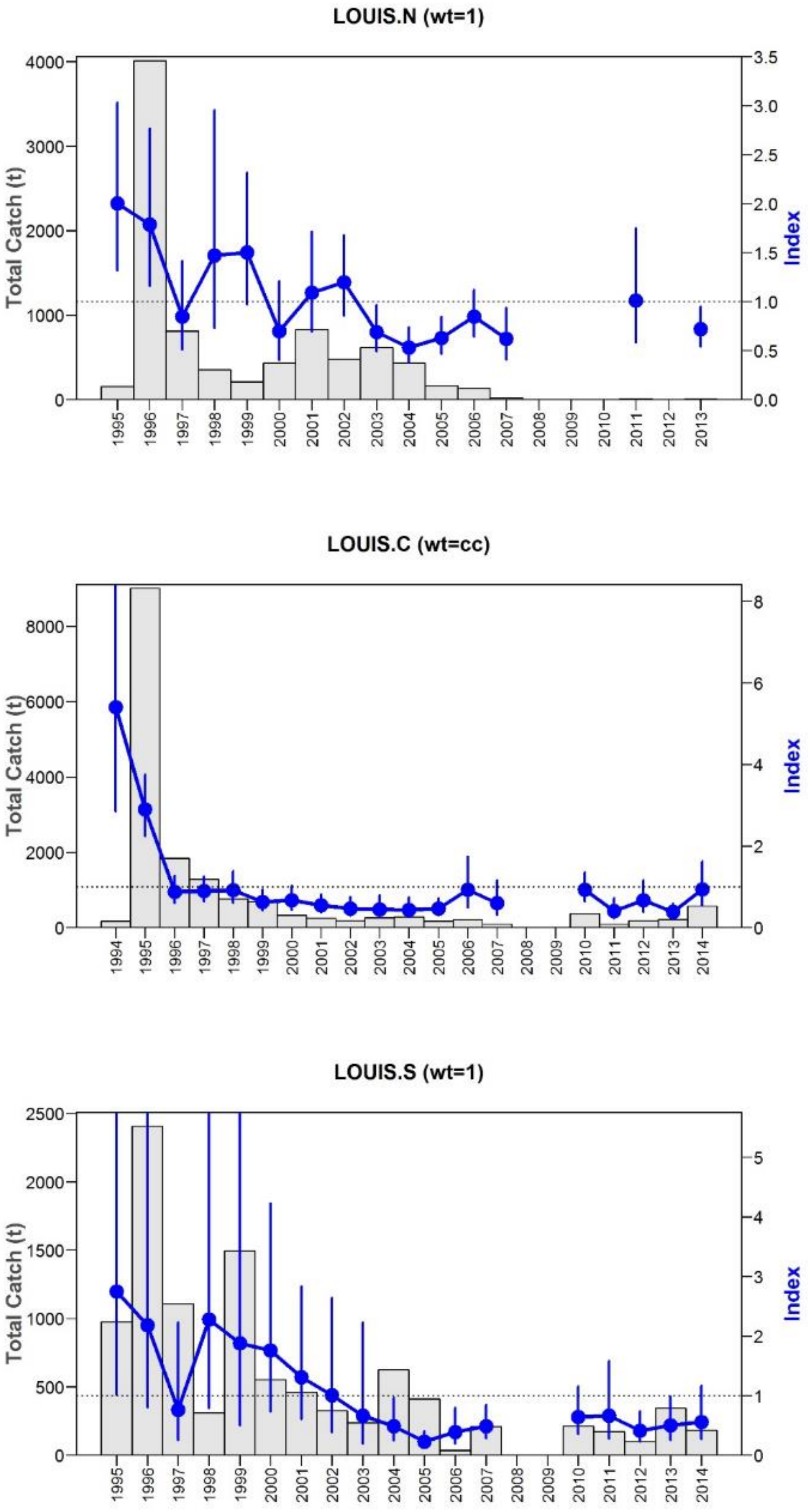


Figure 3B: Catch series (grey bars, left axes) and normalised, standardised spatial CPUE abundance indices (blue line/full circles, right axes) for orange roughy stocks from the Louisville Ridge region of the SPRFMO Convention Area. Error bars are 95% confidence intervals.

3.2.1. Lord Howe Rise spatial CPUE

Five subarea strata (A, B, C, D and E) were distinguished on the slope of the Lord Howe Rise and used to calculate spatial CPUE indices of relative abundance (Figure 4A). The final dataset for the stock comprised a total effort of 2578 tows over 25 years (from 1990 to 2014). Most of the catch (more than 2500 t) was taken from subarea A (Figure 4B). The fishery developed in subarea B and E (in 1990–1992) and subarea C (starting in 1993) (Figure 4C). Subarea B was not fished from 1994. Subarea E was fished until 1994 and again in 1999–2003. Subarea C was consistently fished from 1993 to 2007 and intermittently thereafter. Most of the effort from 1993 to 2003 took place in subarea C. From 2004 onwards, most tows took place in subarea A, which was fished from 2001 to 2014. Subarea D was only fished intermittently and generally accounted for a small fraction of the overall effort.

Core vessels selection retained 24 of the 59 vessels that fished in the Lord Howe Rise area over time and 85% of the catch. The interaction GLM fitted to the final catch-effort dataset for the stock identified *vessel* and *fishing week* as significant covariates (Table 4). Subarea effects and the *fyear:subarea* interaction term contributed to reduce the residual deviance (Table 4). The final model explained a 22% reduction in the residual deviance in CPUE.

Standardised and imputed catch rates by subarea strata are presented in Table 5. Different imputation methods had minimal effects on the abundance index, although the Walters (2003) imputation generated a higher initial (1992) peak in relative abundance (Figure 5). Indices calculated assuming subarea weights based on cumulative catch contributions (w_a=cc) were least sensitive to the choice of imputation method, but suggested a slightly more pronounced increase in relative abundance during years with limited observations (1996–2000) (Figure 5).

The index calculated using the default imputation method and assuming equal subarea catchability (w_a=1) was used as the final spatial CPUE index for the stock. This model suggested less rapid initial depletion and generated less inter-annual variation in abundance relative to the nominal CPUE data and the CPUE index calculated using GLM standardisation with no spatial effects (Figure 6).

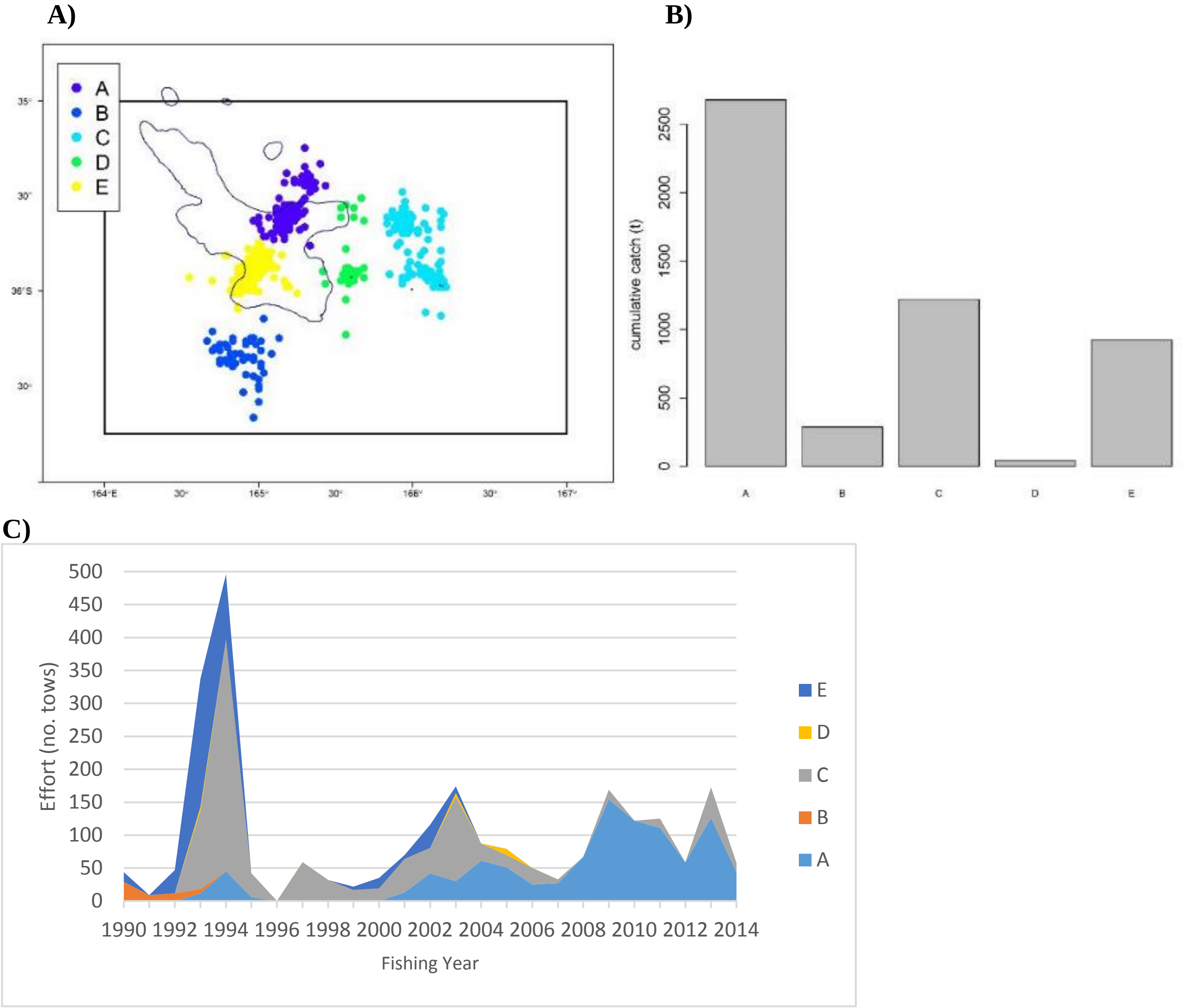


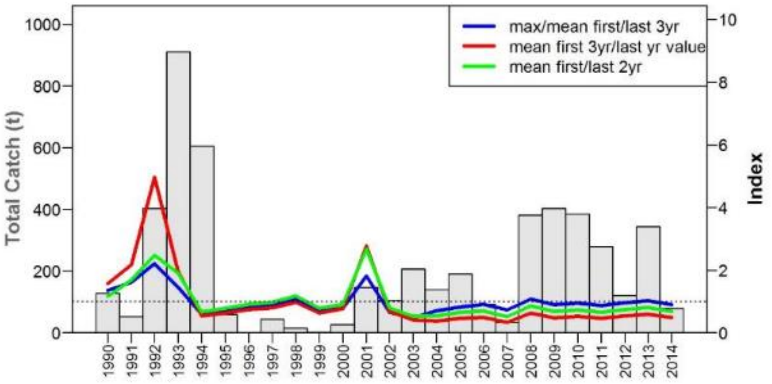
Figure 4: A) Subarea strata (n=5) identified by hierarchical distance clustering for spatial CPUE analyses in the Lord Howe Rise management area (black square); coloured dots are individual tows (n=2578); contour line is the 1000 m isobath. B) Cumulative catch of orange roughy by subarea, 1990–2014. C) Annual effort (no. tows) by subarea strata, 1990–2014 fishing years.

Table 4: Summary of the final log-normal, interaction-GLM model fitted to orange roughy CPUE data from the Lord Howe Rise management area. df = degrees of freedom; Resid = residual; Dev= deviance.

	df	**Deviance**	**Resid. df**	**Resid. Dev**	**R^2**
Null Model			2 577	14 020.19	
fyear	23	1008.01	2 554	13 012.18	7.19
subarea	4	307.97	2 550	12 704.21	9.39
vessel	23	711.53	2 527	11 992.68	14.46
fweek	50	663.87	2 477	11 328.82	19.20
fyear:subarea	56	341.94	2 421	10 986.87	21.64

Table 5: Populated and normalised space-time table of standardised orange roughy CPUE in the Lord Howe Rise management area, 1990-2014 fishing years. Missing year/subarea data (shown in italics) were populated using the default imputation method (backward/forward imputation using the max/mean of the first/last 3/2 years, respectively).

	Subarea strata				
Fishing year	**A**	**B**	**C**	**D**	**E**
1990	*1.56*	0.47	*3.39*	*1.59*	2.32
1991	*1.56*	0.49	*3.39*	*1.59*	5.63
1992	*1.56*	2.25	*3.39*	*1.59*	8.93
1993	1.56	0.08	3.39	1.59	4.74
1994	0.37	*1.16*	0.77	*1.13*	0.42
1995	1.12	*1.16*	0.94	*1.13*	*0.43*
1996	*1.61*	*1.16*	*1.17*	*1.13*	*0.43*
1997	*1.61*	*1.16*	1.40	*1.13*	*0.43*
1998	*1.61*	*1.16*	2.51	*1.13*	*0.43*
1999	*1.61*	*1.16*	0.18	*1.13*	0.44
2000	*1.61*	*1.16*	0.28	*1.13*	0.89
2001	2.10	*1.16*	1.77	*1.13*	8.99
2002	0.41	*1.16*	0.85	*1.13*	1.05
2003	0.43	*1.16*	0.64	0.67	0.52
2004	0.52	*1.16*	0.58	*0.78*	*0.78*
2005	0.82	*1.16*	1.23	0.90	*0.78*
2006	0.55	*1.16*	1.23	*0.78*	*0.78*
2007	0.41	*1.16*	0.25	*0.78*	*0.78*
2008	2.63	*1.16*	*0.44*	*0.78*	*0.78*
2009	0.94	*1.16*	0.63	*0.78*	*0.78*
2010	1.36	*1.16*	*0.67*	*0.78*	*0.78*
2011	0.90	*1.16*	0.71	*0.78*	*0.78*
2012	0.86	*1.16*	*1.20*	*0.78*	*0.78*
2013	0.62	*1.16*	1.69	*0.78*	*0.78*
2014	0.67	*1.16*	0.90	*0.78*	*0.78*



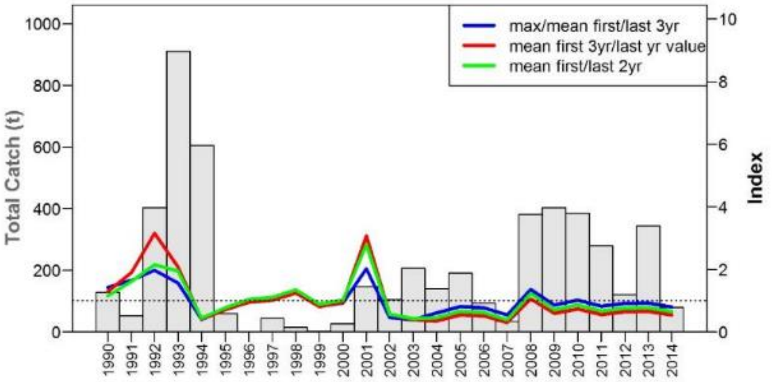


Figure 5: Spatial CPUE for Lord Howe Rise orange roughy: index sensitivity to different imputation methods (blue (default imputation based on Roux & Doonan 2015), red (Walters 2003) and green lines) and subarea weighting (top: all areas equally contribute to total abundance (w_a=1); bottom: subarea contribution to total abundance proportional to cumulative catch (w_a=subarea cumulative catch/total area catch). All indices are normalised. Grey bars = total annual catch in the final dataset.

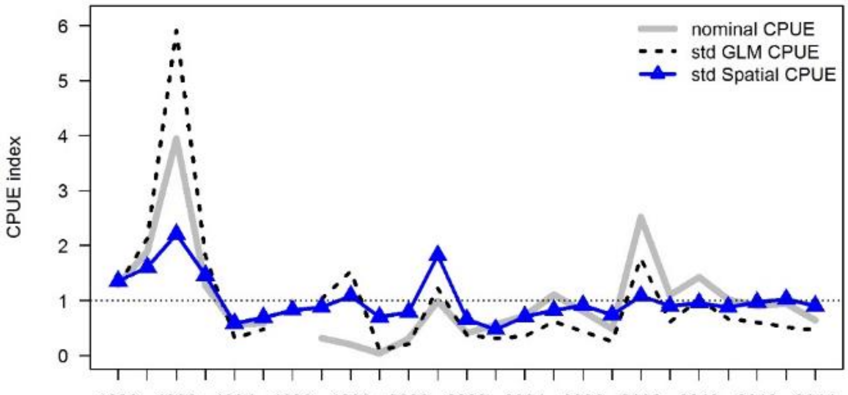


Figure 6: Index comparison for LHR orange roughy: time series of 1) nominal CPUE (grey line); 2) standardised CPUE (using standard GLM procedure) (black dotted line); and 3) standardised spatial CPUE (using the hybrid (interaction-GLM with data imputation) method).

3.2.2. Northwest Challenger Plateau spatial CPUE

Twelve subarea strata (seven on the slope (A–G) and five UTFs) were distinguished on the Northwest Challenger Plateau and used to calculate spatial CPUE indices of relative abundance (Figure 7A). Data from two adjacent UTFs (UTF-562 and UTF-563) were combined due to small sample sizes in each. The final dataset comprised a total effort of 10 302 tows over 22 years (1993 to 2014 fishing years). Subarea B and D contributed most of the catch over time, followed by UTF-550 (Figure 7B). Other subareas contributed less than 1000 t of orange roughy over the study period. The fishery was concentrated in subarea B during earlier years (1993–1996), expanded spatially to include all 12 subareas in the early 2000s, and contracted to five or six subareas in 2009–2014, with UTF-550 generally accounting for most tows during later years (Figure 7C).

Core vessels selection retained 34 of the 64 vessels that fished in the area and 88% of the orange roughy catch. The interaction GLM fitted to the CPUE data for the stock explained a 24% reduction in residual deviance and identified *vessel*, *fishing week* and tow *duration* as significant covariates (Table 6). *Subarea* effects and *year-subarea* interactions were significant (i.e., reduced the residual deviance by at least 2%).

Standardised and imputed catch rates by subarea strata are presented in Table 7. The index calculated using the default imputation method and equal subarea weights (w_a=1) was selected as the final, spatial CPUE index for the stock. This index suggested a higher relative abundance during earlier years (1993–1997) compared with other imputation methods, followed by a relatively stable period (Figure 8). Other indices (especially those calculated using subarea weights proportional to cumulative catch) distinguished two successive peaks in abundance during early years (in 1995 and 1998) and a more pronounced increase in CPUE in 2011–2014 relative to the mid-2000s (Figure 8).

The spatial index had less inter-annual variability in relative abundance relative to the nominal and GLM-standardised CPUE (Figure 9). Initial abundance estimated using the spatial CPUE method was on a similar scale as the nominal CPUE but higher than predicted using standard GLM procedure. The standard GLM procedure without spatial effects produced a relatively flat index that may have over-estimated the increase in relative abundance in recent years.

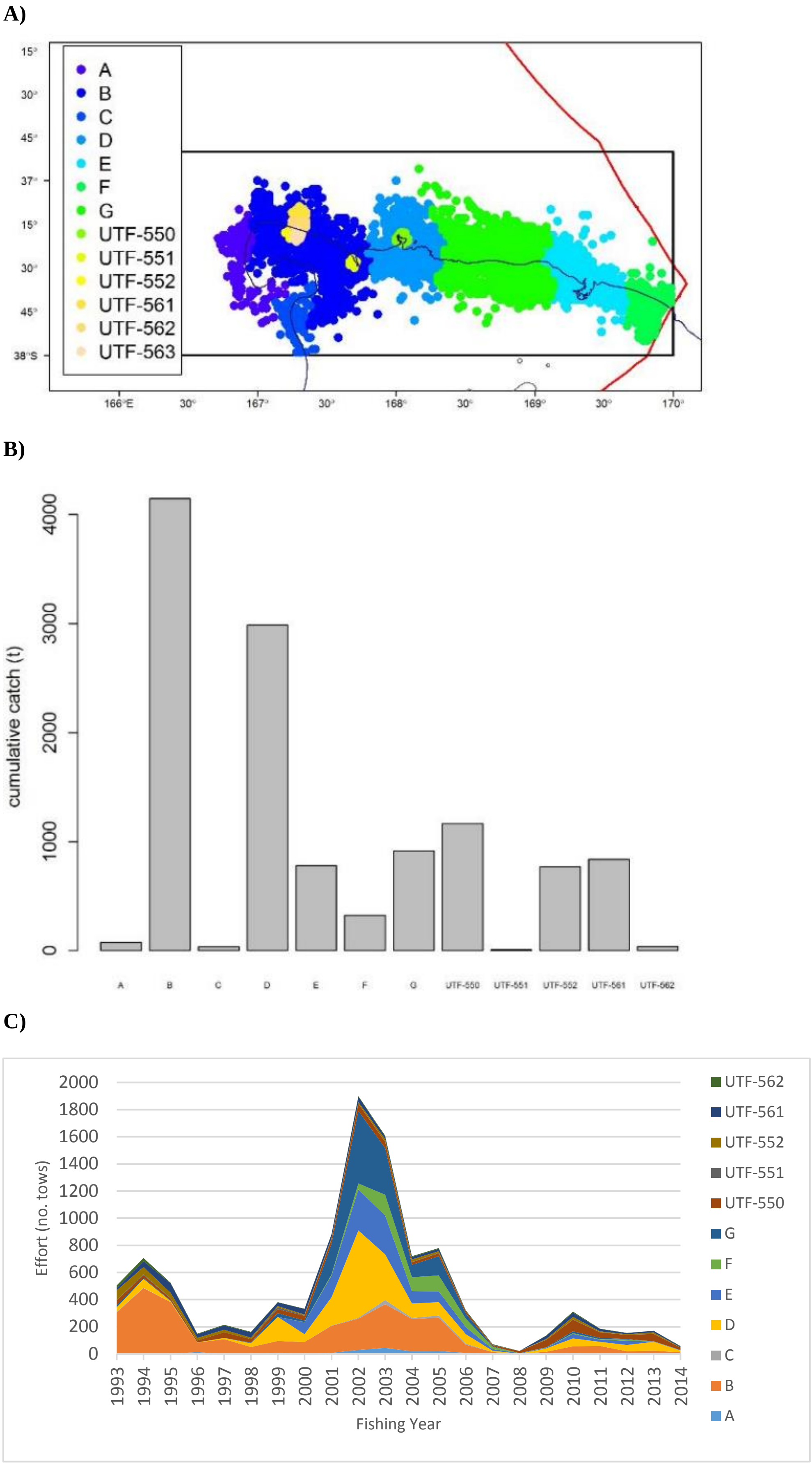


Figure 7: A) Subarea strata (n=12) identified for spatial CPUE analyses in the Northwest Challenger Plateau management area (black square), note UTF numbers relate to the NIWA "registration number" (as per Rowden et al. 2008); coloured dots are individual tows (n=10 302); contour lines are the 500 m (light grey) and 1000 m (dark blue) isobaths, respectively; the red line is the NZ EEZ boundary. B) Cumulative catch of orange roughy by subarea, 1993–2014. C) Annual effort (no. tows) by subarea strata.

Table 6: Summary of the final log-normal, interaction-GLM model fitted to orange roughy CPUE data from the Northwest Challenger management area. df = degrees of freedom; Resid = residual; Dev= deviance.

	df	Deviance	Resid. df	Resid. Dev	R^2
Null Model			10 252	27 864.83	
fyear	21	990.04	10 231	26 874.79	3.55
subarea	11	619.36	10 220	26 255.44	5.78
vessel	33	2287.18	10 187	23 968.26	13.98
fweek	52	883.79	10 135	23 084.47	17.16
poly(duration, 3)	3	592.50	10 132	22 491.97	19.28
fyear:subarea	183	1340.00	9 949	21 151.97	24.09

Table 7: Populated and normalised space-time table of standardised CPUE for orange roughy on the Northwest Challenger Plateau, 1993–2014 fishing years. Missing year/subarea data (shown in italics) were populated using the default imputation method (backward/forward using the max/mean of the first/last 3/2 years).

	Subarea strata											
Fishing year	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**UTF-550**	**UTF-551**	**UTF-552**	**UTF-561**	**UTF-562**
1993	*1.24*	0.58	*0.98*	0.20	*18.37*	*1.19*	0.30	0.45	*1.91*	0.95	0.22	0.38
1994	*1.24*	1.17	*0.98*	0.78	*18.37*	*1.19*	0.51	0.63	0.52	0.82	3.44	1.05
1995	*1.24*	2.04	*0.98*	2.89	18.37	*1.19*	*0.67*	3.37	*0.52*	5.17	3.41	0.26
1996	0.25	0.70	*0.98*	*1.59*	*18.37*	*1.19*	*0.67*	0.16	*0.52*	7.83	1.90	1.42
1997	*0.42*	0.58	*0.98*	0.29	*18.37*	*1.19*	*0.67*	0.90	*0.52*	0.51	2.14	*0.90*
1998	*0.42*	1.11	*0.98*	1.39	18.37	*1.19*	*0.67*	2.33	*0.52*	0.53	1.19	*0.90*
1999	0.59	0.59	*0.98*	1.03	*9.28*	*1.19*	0.84	0.54	0.51	0.43	0.54	*0.90*
2000	*0.92*	1.04	*0.98*	0.68	0.19	*1.19*	1.08	0.63	*1.21*	0.46	0.79	*0.90*
2001	1.24	2.31	*0.98*	1.19	0.21	0.70	1.60	0.81	1.91	0.22	1.03	*0.90*
2002	1.66	1.31	0.98	0.98	0.30	0.98	2.08	1.74	*1.21*	0.70	1.06	*0.90*
2003	1.09	0.95	0.83	0.61	0.20	1.19	1.31	1.36	*1.21*	0.80	0.22	0.37
2004	0.95	1.62	0.66	0.73	0.20	1.35	1.12	1.35	*1.21*	1.06	0.67	*0.31*
2005	0.69	1.24	0.94	0.50	0.18	1.17	1.20	0.67	*1.21*	0.17	0.47	0.25
2006	0.99	1.24	1.23	0.55	0.24	1.03	1.17	2.03	*1.21*	*1.17*	*1.03*	1.94
2007	*1.36*	0.62	*1.08*	0.74	0.27	1.53	*1.10*	0.41	*1.21*	*1.17*	*1.03*	*1.97*
2008	*1.36*	*0.62*	*1.08*	*1.25*	*0.20*	*0.92*	*1.10*	0.92	*1.21*	*1.17*	*1.03*	*1.97*
2009	*1.36*	0.62	*1.08*	1.76	0.13	*0.92*	*1.10*	1.41	*1.21*	2.16	1.58	*1.97*
2010	1.73	1.39	*1.08*	1.38	0.47	0.31	1.03	0.95	*1.21*	1.37	1.62	2.01
2011	*1.36*	1.61	*1.08*	2.70	0.29	*0.74*	1.62	2.04	*1.21*	0.60	0.99	*1.97*
2012	*1.36*	0.67	*1.08*	1.97	0.67	1.17	*1.32*	1.21	*1.21*	2.09	3.46	*1.97*
2013	*1.36*	1.33	*1.08*	1.26	*0.48*	*0.74*	*1.32*	0.65	*1.21*	2.16	0.45	*1.97*
2014	*1.36*	0.78	*1.08*	2.29	*0.48*	*0.74*	*1.32*	3.12	*1.21*	*2.13*	0.56	*1.97*

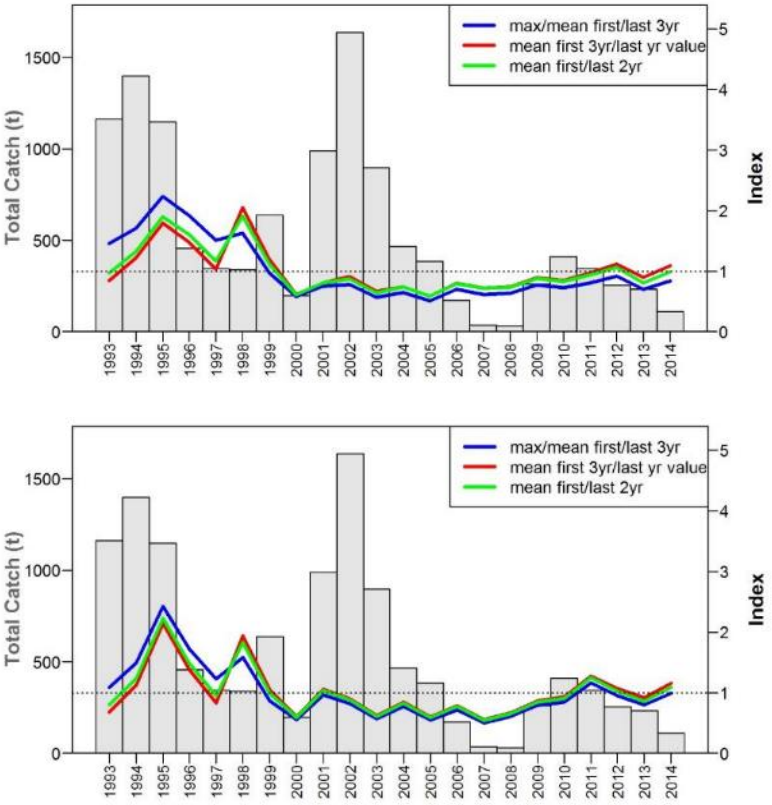


Figure 8. Spatial CPUE in Northwest Challenger orange roughy: index sensitivity to different imputation methods (blue (default, as per Roux & Doonan 2015), red (Walters 2003) and green lines) and subarea weighting (top: all areas equally contribute to total abundance (w_a=1); bottom: subarea contribution to total abundance proportional to cumulative catch (w_a=subarea cumulative catch/total area catch). All indices are normalised. Grey bars = total annual catch in the final dataset.

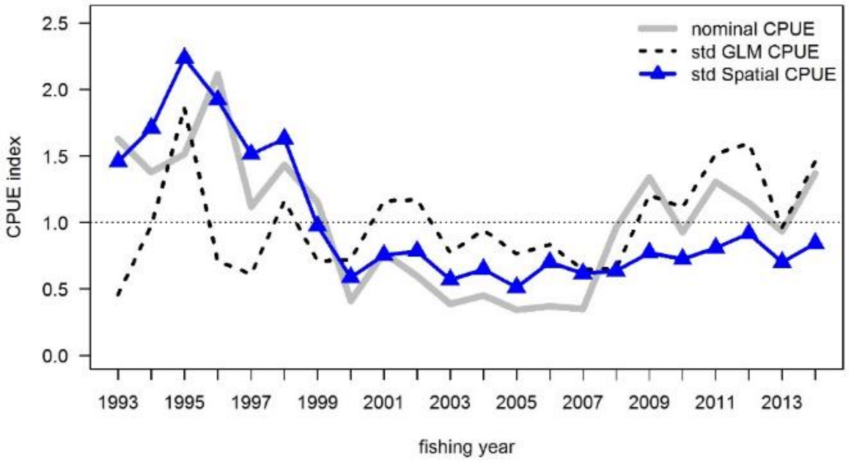


Figure 9: Index comparison for Northwest Challenger orange roughy: time series of 1) nominal CPUE (grey line); 2) standardised CPUE (using standard GLM procedure) (black dotted line); and 3) standardised spatial CPUE (using the hybrid (interaction GLM with data imputation) method).

3.2.3. West Norfolk Ridge spatial CPUE

Five subarea strata (three on the slope (A-C) and two UTFs) were identified and used for spatial CPUE analyses of orange roughy in the West Norfolk Ridge management area (Figure 10A). These included two pairs of UTF and surrounding slope subarea, each on a separate ridge (UTF-1535/subarea A and UTF-1536/subarea C). The fifth subarea (subarea B) was located near the boundary of the New Zealand EEZ along the 1000 m depth contour (Figure 10A). The final dataset was comprised of 1420 tows over 12 fishing years (2002–2013). UTF-1535 accounted for most of the catch over time, followed by subarea A and B on the slope (Figure 10B). During the first few years, the fishery developed on the slope in subarea A and B (in 2002–2003) and subarea C (as of 2004) (Figure 10C). Fishing on features began in 2005 on UTF-1536 and in 2006 on UTF-1535. Together, UTF-1536 and subarea C accounted for most of the effort in 2005–2006. Starting in 2007, effort was concentrated on UTF-1535 and subarea A, which were consistently fished until 2013. Subarea C was last fished in 2011 and UTF-1536, in 2012. Subarea B was fished only sporadically after 2009 (Figure 10C).

A core vessel selection retained 6 of the 23 vessels that fished in the area between 2002 and 2013 and 99% of the orange roughy catch. The interaction GLM explained 19% of the residual deviance in CPUE for the stock (Table 8). The model identified *fishing week* and fishing *depth* as significant covariates. *Subarea* effects were marginally significant. *Subarea-year* interactions explained a reduction in residual deviance of over 3%.

Standardised and imputed catch rates of orange roughy by subarea strata are given in Table 9. Different backward/forward imputation methods and subarea weights had minimal or no effects on the spatial CPUE index (Figure 11). The index calculated using the default imputation method and subarea weights proportional to cumulative catch (w_a=cc), was selected as the final spatial CPUE index of abundance for the stock. The nominal CPUE was consistent with the available catch series for the stock (Figure 3A). The spatial index suggested a more progressive decrease in initial abundance than did the GLM-index with no spatial effects (Figure 12). Both methods yielded similar (sometimes identical) indices between 2007 and 2011. The standard GLM procedure may have over-estimated relative abundance in 2013, when only two of the five subareas were fished.

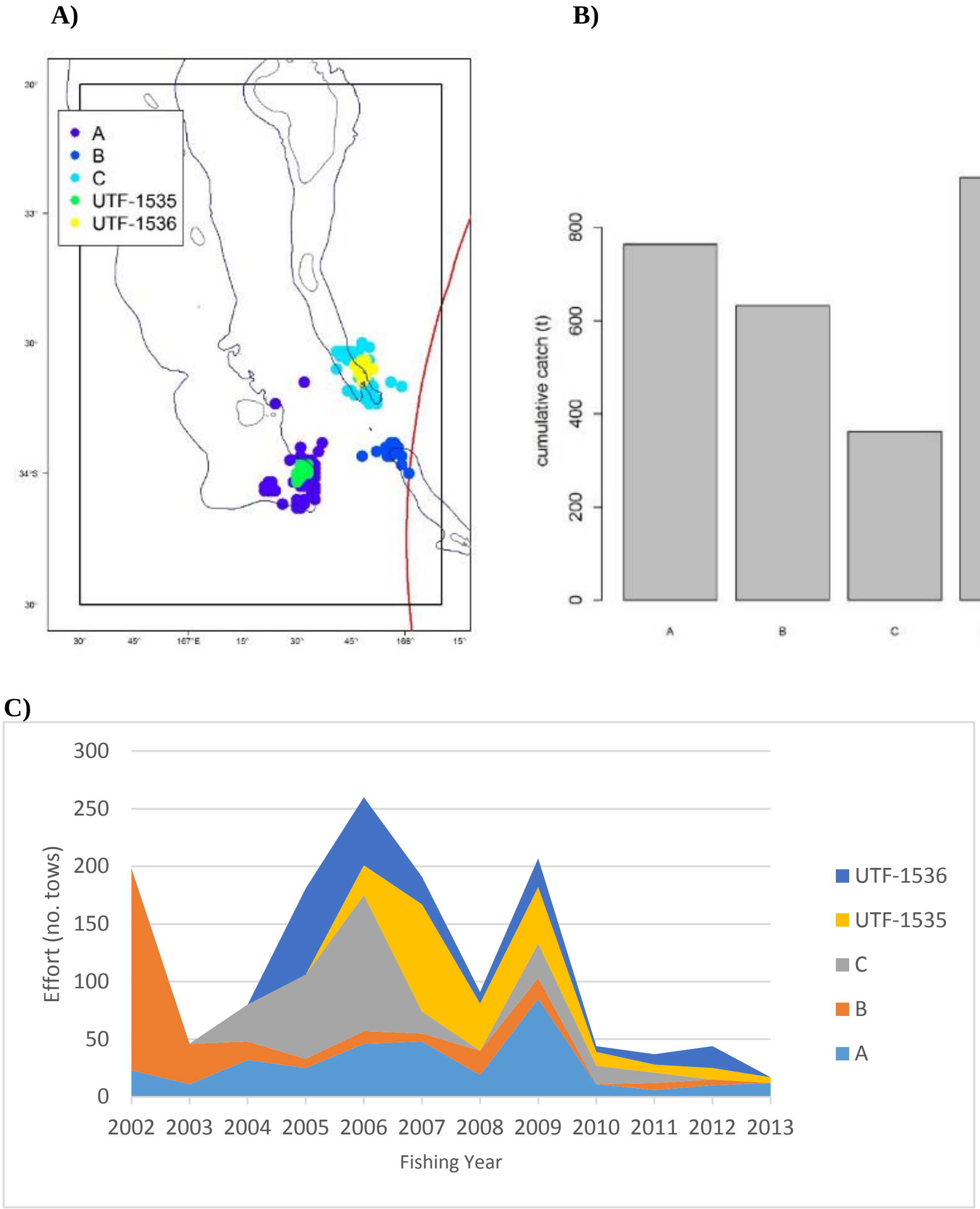


Figure 10: A) Subarea strata (n=5) identified for spatial CPUE analyses in the West Norfolk Ridge management area (black square); coloured dots are individual tows (n=1420); contour lines are the 500 m (light grey) and 1000 m (dark blue) isobaths, respectively; the red line is the NZ EEZ boundary. B) Cumulative catch of orange roughy by subarea, 2002–2013; C) Annual effort (no. tows) by subarea strata.

Table 8: Summary of the final log-normal, interaction-GLM model fitted to CPUE data for orange roughy in the West Norfolk Ridge management area. df = degrees of freedom; Resid = residual; Dev= deviance.

	df	Deviance	Resid. df	Resid. Dev	R^2
Null Model			1 419	6 895.92	
fyear	11	442.61	1 408	6 453.32	6.42
subarea	4	68.00	1 404	6 385.31	7.40
fweek	45	464.75	1 359	5 920.56	14.14
poly(trawl.depth, 3)	3	117.25	1 356	5 803.31	15.84
fyear:subarea	40	223.21	1 316	5 580.10	19.08

Table 9: Populated and normalised space-time table of standardised CPUE for orange roughy in the West Norfolk Ridge management area, 2002–2013 fishing years. Missing year/subarea data (shown in italics) were populated using the default imputation method (backward/forward using the max/mean of the first/last 3/2 years).

	Subarea strata				
Fishing year	**A**	**B**	**C**	**UTF-1535**	**UTF-1536**
2002	4.38	6.42	*2.41*	*3.11*	*2.65*
2003	0.70	2.28	*2.41*	*3.11*	*2.65*
2004	1.39	0.56	2.41	*3.11*	*2.65*
2005	0.88	0.67	1.00	*3.11*	2.65
2006	1.23	0.94	0.82	3.11	0.62
2007	0.97	1.33	1.18	0.81	1.04
2008	0.62	2.13	*1.78*	1.02	0.86
2009	0.53	0.57	2.37	0.18	0.43
2010	1.80	*0.40*	0.57	0.76	1.21
2011	0.68	0.23	0.20	0.12	0.49
2012	0.48	1.54	*0.39*	0.25	0.35
2013	1.15	*0.88*	*0.39*	1.06	*0.42*

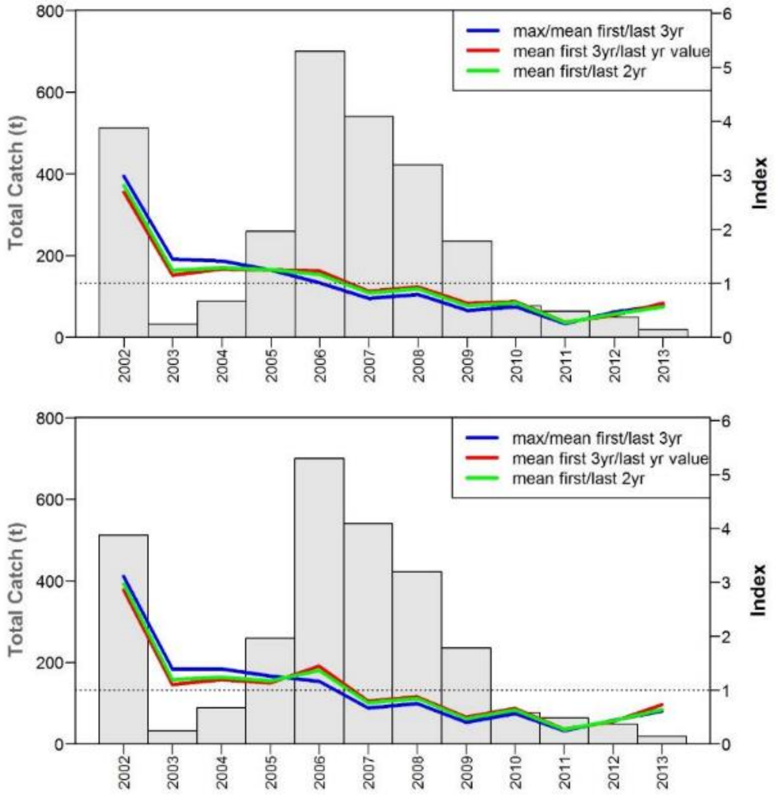


Figure 11. Spatial CPUE in West Norfolk Ridge orange roughy: index sensitivity to different imputation methods (blue (default – as per Roux & Doonan 2015), red (Walters 2003) and green lines) and subarea weighting (top: all areas equally contribute to total abundance (w_a=1); bottom: subarea contribution to total abundance proportional to cumulative catch (w_a=subarea cumulative catch/total area catch). All indices are normalised. Grey bars = total annual catch in the final dataset.

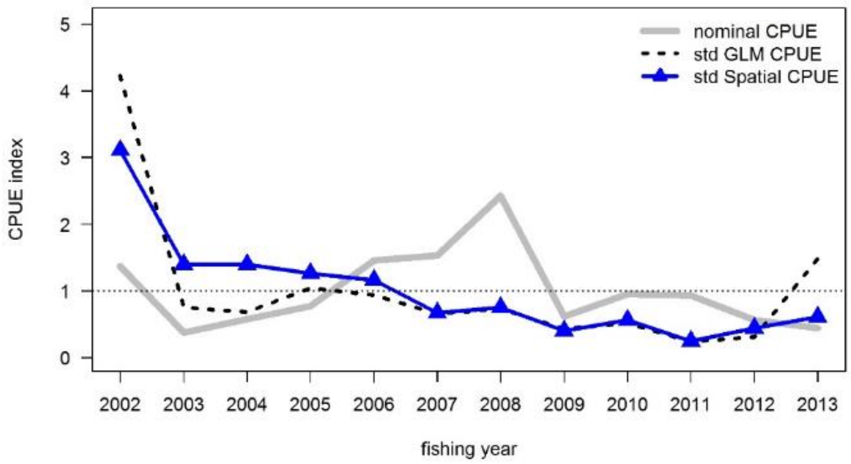


Figure 12: Index comparison for West Norfolk Ridge orange roughy: time series of 1) nominal CPUE (grey line); 2) standardised CPUE (using standard GLM procedure) (black dotted line); and 3) standardised spatial CPUE (using the hybrid (interaction GLM with data imputation) method).

3.2.4. North Louisville Ridge spatial CPUE

Seven UTF subarea were identified and used in spatial CPUE analyses of orange roughy in the North Louisville Ridge management area (Figure 13A). The final dataset consisted of 3343 tows over 19 fishing years (1995–2013), including two years (2008 and 2009) during which no fishing occurred. The two southern-most subareas (UTF-477 and UTF-482) accounted for most of the catch (Figure 13B) and were consistently fished between 1995 and 2007 and again in 2011 (Figure 13C). Only UTF-477 was fished in 2013. Other UTFs were fished sporadically from 1996 until 2004 (UTF-216), 2005 (UTF-474), 2006 (UTF-239 and UTF-753) and 2007 (UTF-1495). The spatial extent of the fishery was greatest in 1996–1997 and in 2002–2004, when all seven UTFs were fished (Figure 13C).

Core vessel selection retained 25 of the 45 vessels that fished in the area between 1995 and 2013 and 98% of the orange roughy catch. The interaction GLM fitted to final dataset explained 33% of the residual deviance in CPUE (Table 10). The model identified *vessel* and *fishing week* as significant covariates. *Subarea* effects were marginally significant. *Subarea-year* interactions explained a 3% reduction in residual deviance.

Standardised and imputed catch rates of orange roughy by subarea strata are given in Table 11. No fishing occurred in the North Louisville in 2008–2010 and 2012. Data imputation was restricted to years with observations when calculating the final index. During sensitivity analyses, imputation was allowed to proceed over years with missing data. Different backward/forward imputation methods produced a difference in the calculated CPUE index only in the first year (1995) of the time series (Figure 14). Indices calculated assuming subarea weights proportional to cumulative catch tended to have higher indices in years with limited observations (2008–2013) (Figure 14). The index calculated using the default imputation method and constant catchability among subareas (w_a=1) was selected as the final, spatial CPUE index of abundance for the stock.

The standard GLM index and spatial CPUE index showed similar trends of decreasing abundance from 1995 to 2007 (Figure 15). Initial abundance (1995) was similar in the spatial index and nominal CPUE data. The standard GLM index calculated with no spatial effects predicted a lower initial abundance in 1995 and highest abundance in 2011, which appears to be unrealistic given the harvest level.

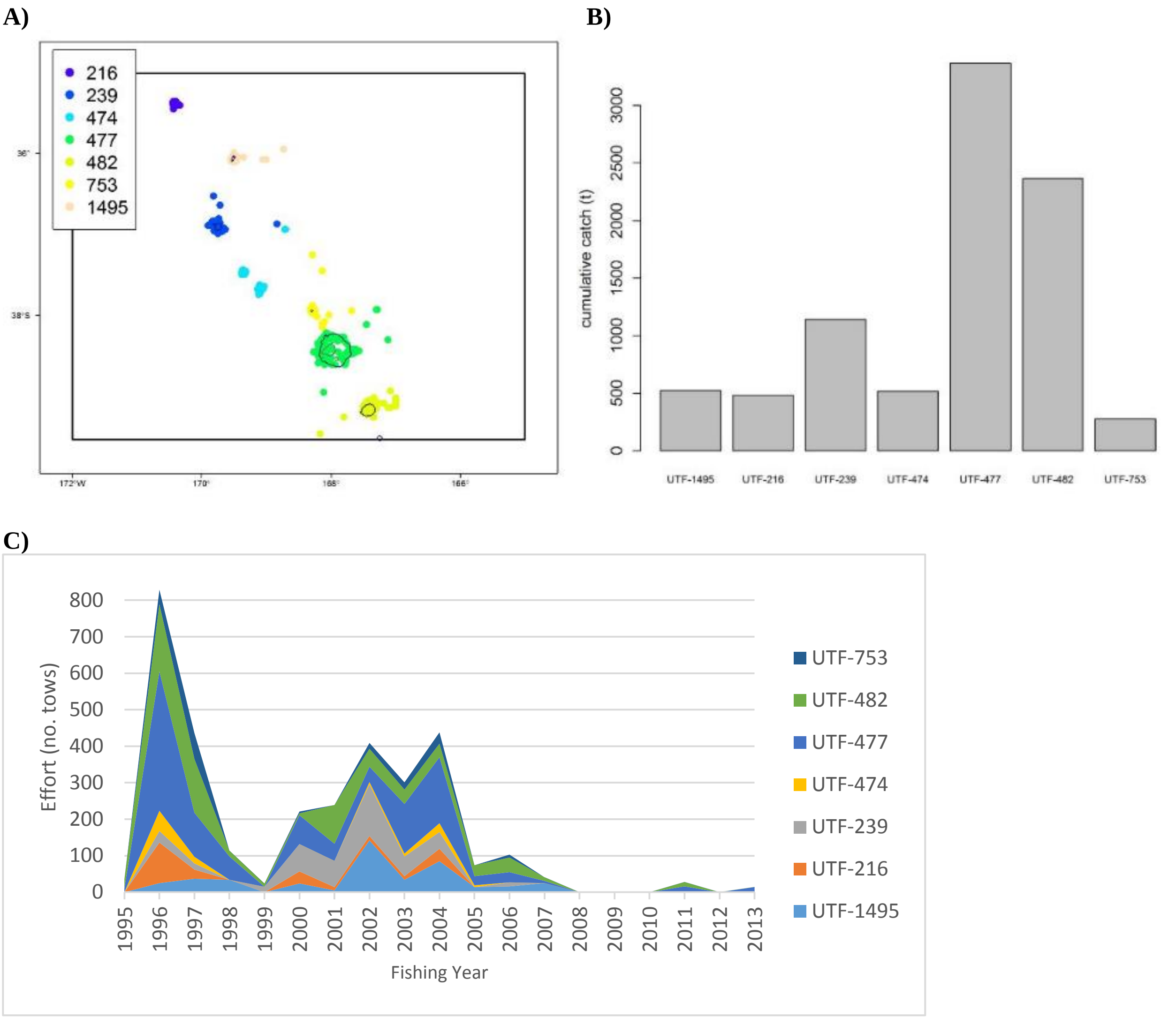


Figure 13: A) Subarea strata (n=7 UTFs) identified for spatial CPUE analyses in the North Louisville Ridge management area (black square); coloured dots are individual tows (n=3343); contour lines (light grey) correspond to the 500 m isobath ; B) Cumulative catch of orange roughy by subarea, 1995–2013. C) Annual effort (no. tows) by UTF subarea.

Table 10: Summary of the final log-normal, interaction-GLM model fitted to CPUE data for orange roughy in the North Louisville management area. df = degrees of freedom; Resid = residual; Dev= deviance.

	df	**Deviance**	**Resid. df**	**Resid. Dev**	**R^2**
Null Model			3 342	12 997.46	
fyear	14	1411.10	3 328	11 586.37	10.86
subarea	6	33.63	3 322	11 552.74	11.12
vessel	24	1604.57	3 298	9 948.17	23.46
fweek	47	805.59	3 251	9 142.57	29.66
fyear:subarea	59	377.01	3 192	8 765.56	32.56

Table 11: Populated and normalised space-time table of standardised CPUE for orange roughy from the North Louisville Ridge, 1995–2013 fishing years. Missing year/subarea data (shown in italics) were populated using the default imputation method (backward/forward imputation using the max/mean of the first/last 3/2 years, respectively).

	Subarea strata						
Fishing year	**UTF-1495**	**UTF-216**	**UTF-239**	**UTF-474**	**UTF-477**	**UTF-482**	**UTF-753**
1995	*2.43*	*2.18*	*2.18*	*4.65*	0.49	1.07	*3.57*
1996	0.51	1.34	1.19	4.65	1.88	1.57	3.57
1997	1.23	2.18	0.72	0.73	0.41	0.73	1.30
1998	2.43	*1.40*	*1.45*	*1.60*	1.66	2.67	*1.07*
1999	*1.57*	*1.40*	2.18	*1.60*	*1.14*	3.52	*1.07*
2000	0.71	0.63	0.59	*1.60*	0.62	0.78	0.85
2001	1.33	0.88	1.71	*1.60*	0.50	1.96	*1.08*
2002	0.94	1.43	1.21	2.47	1.91	0.69	1.31
2003	0.77	0.55	0.77	0.39	1.29	1.00	1.02
2004	0.45	1.09	0.47	0.98	0.35	0.56	0.58
2005	1.48	*0.82*	*0.86*	0.32	0.43	0.54	*0.73*
2006	0.81	*0.82*	1.25	*0.65*	0.95	1.67	0.89
2007	0.96	*0.82*	*0.86*	*0.65*	0.53	0.51	*0.73*
2008	NA	NA	NA	NA	NA	NA	NA
2009	NA	NA	NA	NA	NA	NA	NA
2010	NA	NA	NA	NA	NA	NA	NA
2011	*0.89*	*0.82*	*0.86*	*0.65*	3.08	1.06	*0.73*
2012	NA	NA	NA	NA	NA	NA	NA
2013	*0.89*	*0.82*	*0.86*	*0.65*	0.68	*0.79*	*0.73*

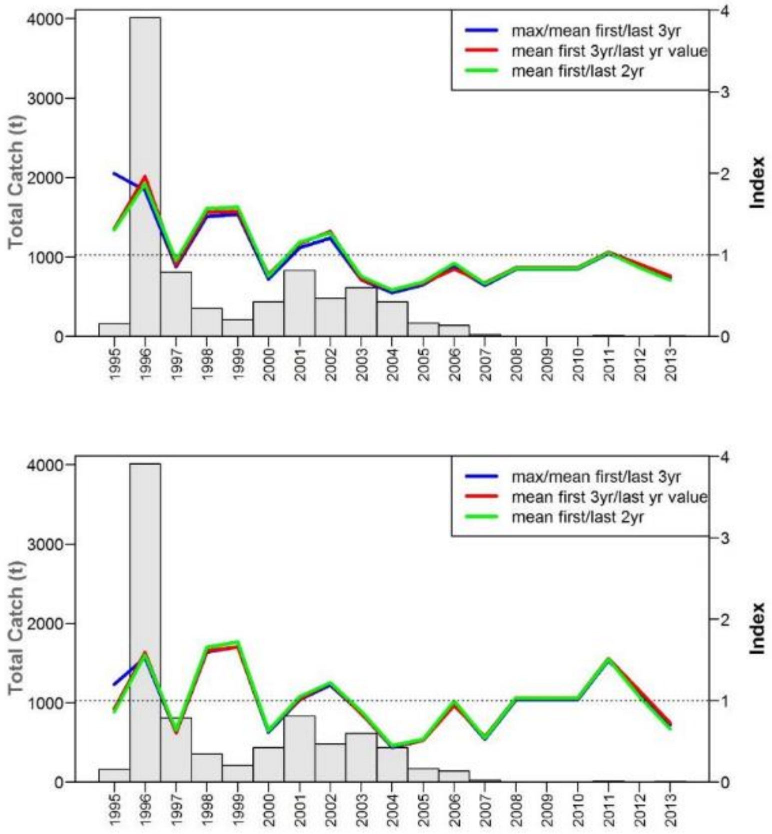


Figure 14. Spatial CPUE for North Louisville orange roughy: index sensitivity to different imputation methods (blue (default, as per Roux & Doonan 2015), red (Walters 2003) and green lines) and subarea weighting (top: all areas equally contribute to total abundance (w_a=1); bottom: subarea contribution to total abundance proportional to cumulative catch (w_a=subarea cumulative catch/total area catch). All indices are normalised. Grey bars = total annual catch in the final dataset.

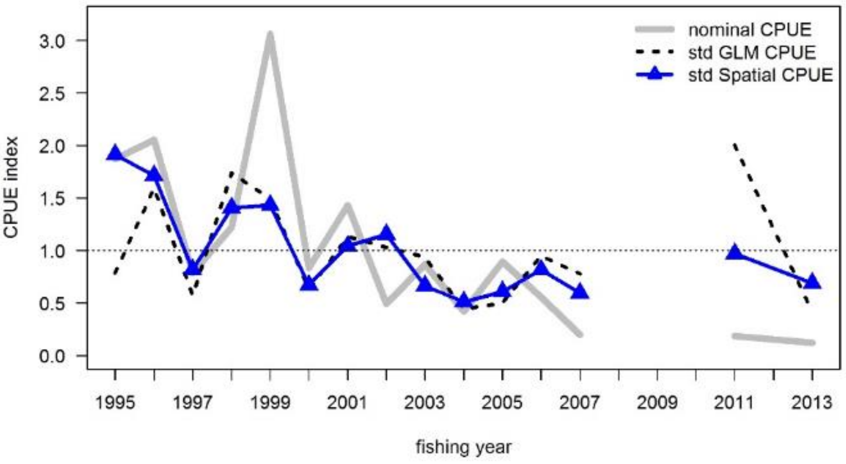


Figure 15: Index comparison for North-Louisville orange roughy: time series of 1) nominal CPUE (grey line); 2) standardised CPUE (using standard GLM procedure) (black dotted line); and 3) standardised spatial CPUE (using the hybrid (interaction GLM with data imputation) method).

3.2.5. Central Louisville Ridge spatial CPUE

Six UTF subareas were distinguished on the Central Louisville Ridge and used to calculate spatial CPUE indices of relative abundance (Figure 16A). The final dataset comprised a total effort of 5858 tows over 21 years (1994 to 2014 fishing years), including two years (2008–2009) in which no fishing occurred. A very large catch was taken in 1995 (over 9000 t orange roughy) (Figure 3B). UTFs located in the middle section of the ridge (i.e., UTF-747, UTF-752 and UTF-754) contributed most of the catch over time (Figure 16B) and consistently accounted for an important fraction of the annual effort (Figure 16C). UTF-754 was the only subarea fished in all years, from 1994 to 2007 and from 2010 to 2014 (Figure 16C). The spatial extent of the fishery was greatest in 1995–1997, when all six UTFs were fished, and lowest in 2010–2014, when fishing resumed following two consecutive years with no fishing (2008–09).

Core vessels selection retained 27 of the 52 New Zealand vessels that fished in the area and 93% of the orange roughy catch. The interaction GLM fitted to the CPUE data for the stock explained a 23% reduction in residual deviance and identified *vessel* and *fishing week* as significant covariates (Table 12). *Subarea* effects were negligible but *subarea-year* interactions explained a 4% reduction in residual deviance.

Standardised and imputed catch rates of orange roughy by UTF strata on the Central Louisville Ridge are shown in Table 13. Different imputation methods and subarea weights/catchability assumptions had virtually no effects on the calculated spatial CPUE abundance index for the stock (Figure 17). The index calculated using the default imputation method and subarea weights proportional to cumulative catch was selected as the final spatial CPUE index of abundance for Central Louisville orange roughy.

The spatial index was higher in year 1 (1994) than the nominal CPUE and the index calculated using the standard GLM-standardisation procedure (Figure 18). Otherwise, spatial and standard GLM methods yielded similar results, although inter-annual variability from 1998 to 2005 was lower in the spatial CPUE relative to the CPUE calculated using the standard GLM-procedure.

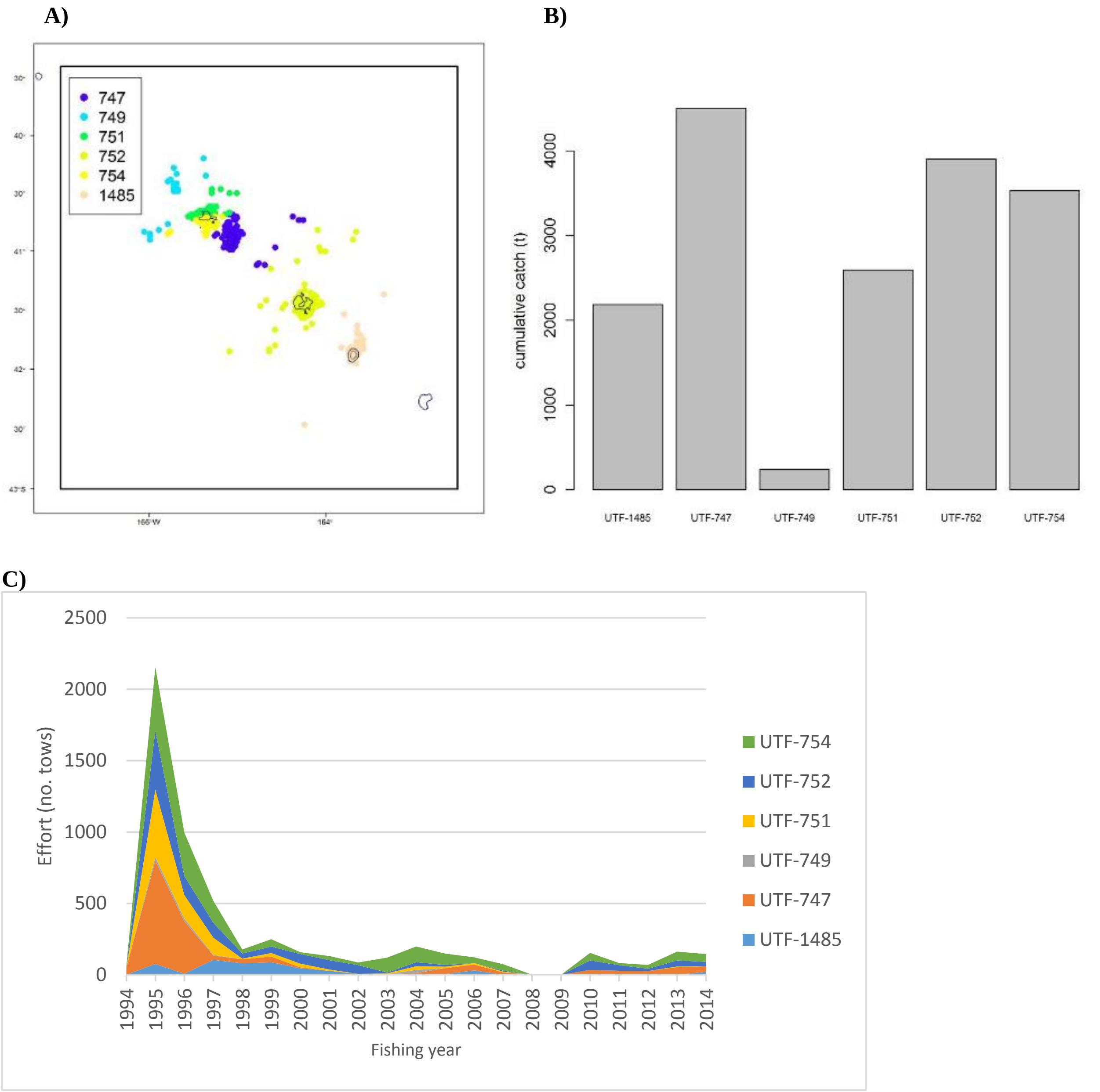


Figure 16: A) Subarea strata (n=6 UTFs) identified for spatial CPUE analyses in the Central Louisville Ridge management area (black square); coloured dots are individual tows (n=3343); contour lines are the 500 m (light grey) and 1000 m (dark blue) isobaths, respectively. B) Cumulative catch of orange roughy by UTF subarea, 1994–2014. C) Annual effort (no. tows) by UTF subarea.

Table 12: Summary of the final log-normal, interaction-GLM model fitted to CPUE data for orange roughy in the Central Louisville Ridge management area. df = degrees of freedom; Resid = residual; Dev= deviance.

	df	**Deviance**	**Resid. df**	**Resid. Dev**	**R^2**
Null Model	NA	NA	5 857	22 544.88	
fyear	18	1389.53	5 839	21 155.35	6.16
subarea	5	36.62	5 834	21 118.73	6.33
vessel	26	1811.44	5 808	19 307.29	14.36
fweek	51	1130.84	5 757	18 176.45	19.38
fyear:subarea	81	900.69	5 676	17 275.76	23.37

Table 13: Populated and normalised space-time table of standardised CPUE for orange roughy from the Central Louisville Ridge, 1994–2014 fishing years. Missing year/subarea data (shown in italics) were populated using the default imputation method (backward/forward imputation using the max/mean of the first/last 3/2 years, respectively).

	Subarea strata					
Fishing year	**UTF-1485**	**UTF-747**	**UTF-749**	**UTF-751**	**UTF-752**	**UTF-754**
1994	*4.16*	3.51	*1.97*	*4.46*	*7.37*	21.51
1995	4.16	3.87	1.97	4.46	7.37	2.47
1996	0.80	1.32	1.03	2.18	1.05	1.56
1997	3.36	0.70	0.68	1.32	1.42	1.12
1998	1.94	1.71	*0.93*	0.73	2.04	0.55
1999	1.01	0.70	*0.93*	0.61	1.85	0.57
2000	1.92	0.33	*0.93*	1.91	1.29	0.51
2001	0.17	0.53	*0.93*	0.66	1.60	1.01
2002	0.25	0.53	*0.93*	*1.03*	0.87	0.87
2003	0.10	0.53	*0.93*	1.39	0.13	1.40
2004	0.05	0.73	1.18	0.87	0.61	0.92
2005	1.39	1.15	*0.93*	0.23	0.46	0.42
2006	1.87	1.84	*0.93*	3.26	*0.38*	0.56
2007	*1.39*	0.76	*0.93*	1.55	0.29	1.11
2008	NA	NA	NA	NA	NA	NA
2009	NA	NA	NA	NA	NA	NA
2010	*1.39*	2.34	*0.93*	*0.81*	1.00	1.30
2011	*1.39*	0.49	*0.93*	*0.81*	0.56	0.31
2012	*1.39*	0.80	*0.93*	*0.81*	1.79	0.46
2013	*1.39*	0.50	*0.93*	0.08	0.49	0.63
2014	0.91	1.04	*0.93*	*0.81*	2.26	1.33

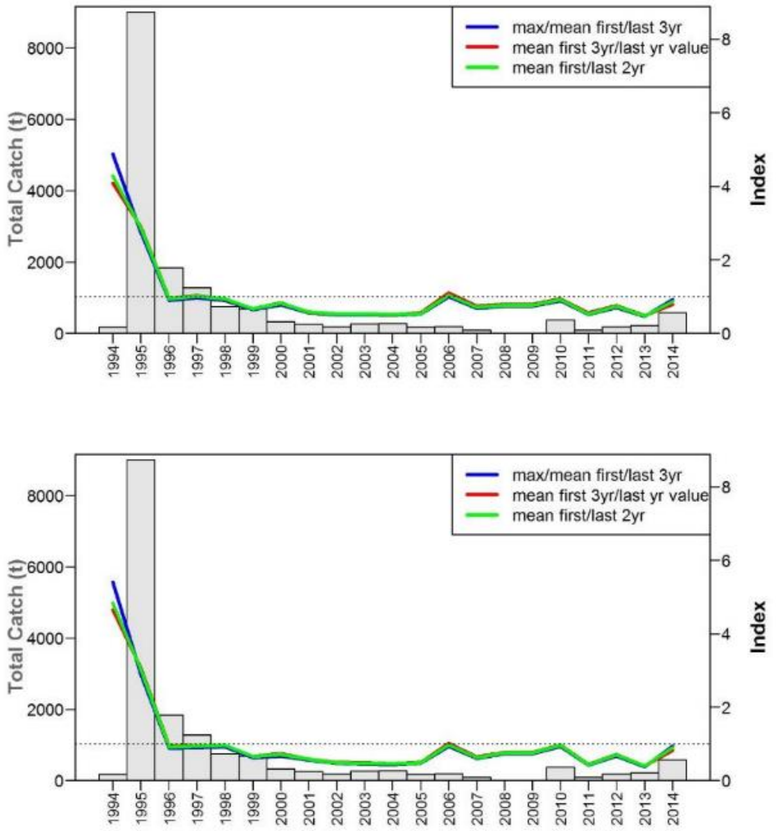


Figure 17. Spatial CPUE in Central Louisville orange roughy: index sensitivity to different imputation methods (blue (default, as per Roux & Doonan 2015), red (Walters 2003) and green lines) and subarea weighting (top: all areas equally contribute to total abundance (w_a=1); bottom: subarea contribution to total abundance proportional to cumulative catch (w_a=subarea cumulative catch/total area catch). All indices are normalised. Grey bars = total annual catch in the final dataset.

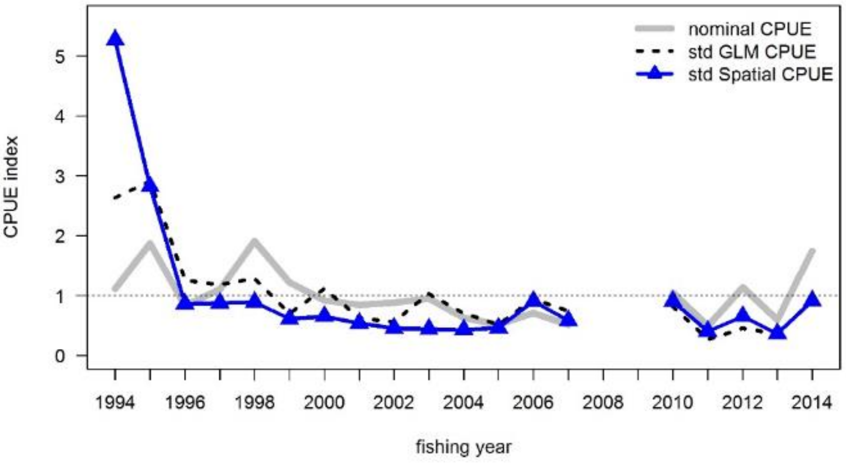


Figure 18: Index comparison for Central Louisville orange roughy: time series of 1) nominal CPUE (grey line); 2) standardised CPUE (using standard GLM procedure) (black dotted line); and 3) standardised spatial CPUE (using the hybrid (interaction GLM with data imputation) method).

3.2.6. South Louisville Ridge spatial CPUE

Six UTF subarea were distinguished on the South Louisville Ridge and used to calculate spatial CPUE indices of relative abundance (Figure 19A). The final dataset comprised a total effort of 2169 tows over 20 years (1995 to 2014 fishing years), including two years (2008–2009) with no fishing. UTF-1526 was the only subarea fished in all years and had the highest cumulative catch of orange roughy (Figure 19B). The fishery began on UTF-1526 and UTF-1490 in 1995–1996 and expanded to other UTFs from 1997 to 2005 (Figure 19C). All six UTFs were fished in 2005 and only two were fished in 2006 and 2007, before the 2008–09 closure. In 2010–2014, effort was restricted to the four southern-most UTFs (UTF-1526, UTF-1525, UTF-1523 and UTF-1492).

Core vessels selection retained 25 of the 43 vessels that fished in the area and 83% of the catch of orange roughy. The interaction GLM fitted to the final dataset explained a 36% reduction in the residual deviance in CPUE for the stock. The model identified *vessel* and *fishing week* as significant covariates (Table 14). *Target species* explained a small proportion (0.7 %) of the residual deviance but was left in the model as an indication of potential differences in fishing patterns in this management area. *Subarea* effects were negligible. *Subarea-year* interactions explained a 6% reduction in the residual deviance in CPUE in the model.

Standardised and imputed catch rates of orange roughy by UTF on the South Louisville Ridge are presented in Table 15. Different imputation methods and subarea weights had negligible or no effects on the spatial CPUE index (Figure 20). The index calculated using the default imputation method and assuming a constant catchability among subarea (w_a=1) was selected as the final spatial CPUE index of abundance for the stock.

The spatial CPUE index was slightly lower initially, and had a more progressive decline from 1999 to 2004 and a more stable lower abundance in 2010–2014, compared with the index calculated using the standard GLM procedure with no spatial effects (Figure 21). Both indices, however, had surprisingly low values in 1997. This may be a product of the standardisation (i.e., result from either vessel or fishing week effects, see Figure 21 part 3), or reflect a change in catchability within subareas that were fished in that year.

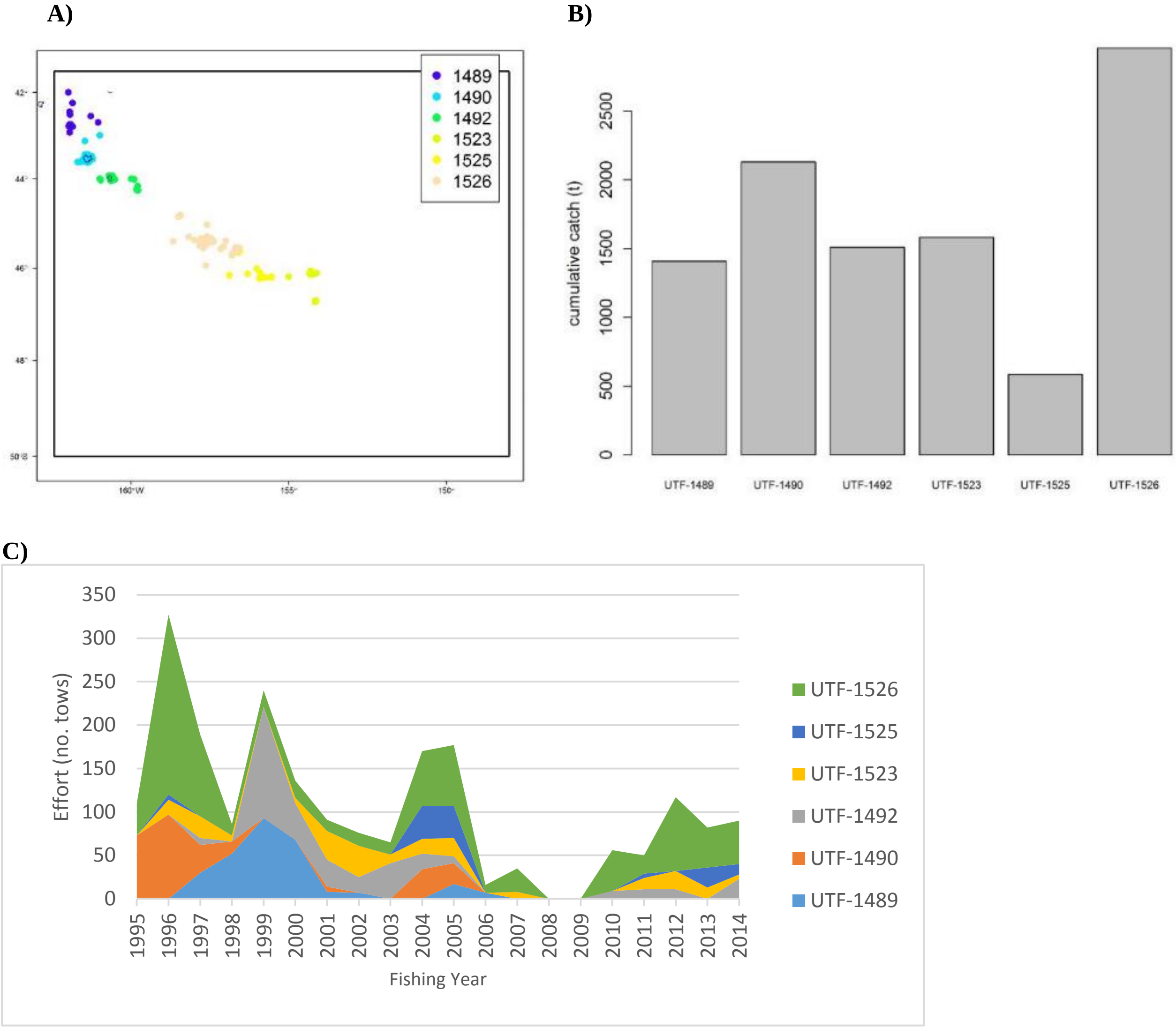


Figure 19: Subarea strata (n=6 UTFs) identified for spatial CPUE analyses in the South Louisville Ridge management area (black square); coloured dots are individual tows (n=2169); contour lines are the 500 m (light grey) and 1000 m (dark blue) isobaths, respectively; B) Cumulative catch of orange roughy by subarea, 1995–2013. C) Annual effort by UTF subarea.

Table 14: Summary of the final log-normal, interaction-GLM model fitted to CPUE data for orange roughy in the West Norfolk Ridge management area. df = degrees of freedom; Resid = residual; Dev= deviance.

	df	**Deviance**	**Resid. df**	**Resid. Dev**	**R^2**
Null Model	NA	NA	2 168	12 712.58	
fyear	17	1271.28	2 151	11 441.30	10.00
subarea	5	69.55	2 146	11 371.76	10.55
vessel	24	1476.62	2 122	9 895.14	22.16
fweek	39	898.28	2 083	8 996.86	29.23
target_sp	4	87.43	2 079	8 909.43	29.92
fyear:subarea	68	791.28	2 011	8 118.16	36.14

Table 15: Populated and normalised space-time table of standardised CPUE for orange roughy from the South Louisville Ridge, 1995–2014 fishing years. Missing year/subarea data (shown in italics) were populated using the default imputation method (backward/forward imputation using the max/mean of the first/last 3/2 years, respectively).

	Subarea strata					
Fishing year	**UTF-1489**	**UTF-1490**	**UTF-1492**	**UTF-1523**	**UTF-1525**	**UTF-1526**
1995	*4.98*	6.90	*2.38*	*9.68*	*3.65*	0.49
1996	*4.98*	3.35	*2.38*	5.57	3.65	1.87
1997	1.33	0.37	0.78	1.68	*2.39*	0.83
1998	4.98	1.24	*1.58*	9.68	*2.39*	1.54
1999	1.94	*2.42*	2.38	*9.58*	*2.39*	0.28
2000	0.33	*2.42*	1.95	9.48	*2.39*	1.69
2001	1.31	3.60	3.09	1.81	*2.39*	1.41
2002	1.38	*2.08*	1.33	1.41	*2.39*	1.16
2003	*0.87*	*2.08*	0.19	1.01	*2.39*	1.14
2004	*0.87*	0.56	0.19	1.58	1.13	0.72
2005	0.36	0.51	0.23	0.28	0.21	0.80
2006	0.88	*0.54*	*1.05*	*0.26*	*0.33*	0.24
2007	*0.62*	*0.54*	*1.05*	0.23	*0.33*	1.39
2008	NA	NA	NA	NA	NA	NA
2009	NA	NA	NA	NA	NA	NA
2010	*0.62*	*0.54*	1.87	*0.20*	*0.33*	2.07
2011	*0.62*	*0.54*	1.52	0.17	0.46	2.32
2012	0.62	*0.54*	0.31	0.71	*0.70*	0.38
2013	0.62	*0.54*	*0.73*	0.26	0.93	0.94
2014	*0.62*	*0.54*	1.16	0.67	0.57	0.98

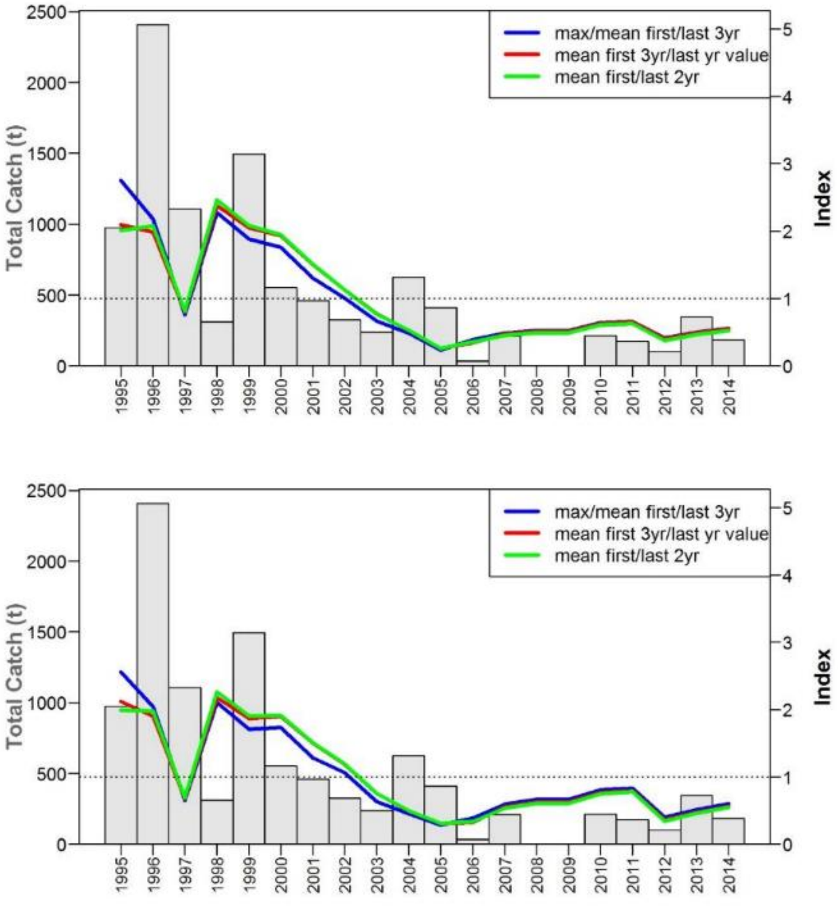


Figure 20. Spatial CPUE in South Louisville orange roughy: index sensitivity to different imputation methods (blue (default, as per Roux & Doonan 2015), red (Walters 2003) and green lines) and subarea weighting (top: all areas equally contribute to total abundance (w_a=1); bottom: subarea contribution to total abundance proportional to cumulative catch (w_a=subarea cumulative catch/total area catch). All indices are normalised. Grey bars = total annual catch in the final dataset.

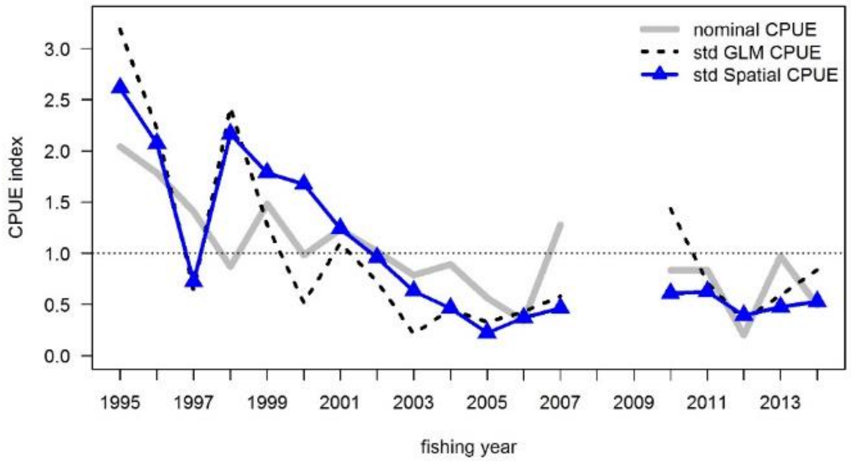


Figure 21: Index comparison for South-Louisville orange roughy: time series of 1) nominal CPUE (grey line); 2) standardised CPUE (using standard GLM procedure) (black dotted line); and 3) standardised spatial CPUE (using the hybrid (interaction GLM with data imputation) method).

3.3 Stock status evaluation using BDM

Two separate BDMs were fitted for each stock. The first model was fitted to the catch series and spatial CPUE index calculated assuming constant catchability among subareas (w_a=1). The second model was fitted to the catch series and spatial CPUE index calculated assuming subarea catchability proportional to cumulative catch (w_a=cc). The most appropriate index of abundance (and corresponding BDM) for each stock was selected by comparing model outputs for *K* – the estimated biomass at unexploited equilibrium (Table 16).

In the West Norfolk Ridge stock, narrower confidence intervals for *K* were obtained using the w_a=cc abundance index (Table 16). The same was true for orange roughy from the Central Louisville Ridge (Table 16). In the North and South Louisville stocks, *K* estimation was improved when BDMs were fitted to the w_a=1 index of abundance (Table 16). In Lord Howe Rise and Northwest Challenger orange roughy, both models yielded poorly constrained estimates of *K* (and unrealistic median values in the case of the Lord Howe Rise) (Table 16). The model fitted to the default (w_a=1) index of abundance was retained in both stocks.

BDM diagnostics (posterior histograms and plots of cumulative parameter values) indicated convergence problems in the Lord Howe Rise and Northwest Challenger models, with *logK* estimates fluctuating between the upper and lower bounds of the prior at each iteration (Figure 22D and 22E). Poor convergence was especially marked in the Lord Howe Rise model. The index of abundance for this stock was poorly fitted by the BDM (Figure 23D) and provided little or no information to the biomass estimation process (Figure 24D). In the Northwest Challenger model, the abundance index was more informative (Figure 24E) but biomass estimates remained poorly constrained, possibly as a result of an incomplete catch series (i.e., non-inclusion of catch data contributed from the international fleet, mostly Australian vessels). In both cases, convergence problems resulted in unconstrained and unreliable BDM outputs in the Lord Howe Rise and Northwest Challenger models (Table 17, Figure 23D and 23E).

Successful convergence was achieved in the three Louisville Ridge and the West Norfolk Ridge models (Figure 22A–C and 22F). The calculated spatial CPUE index of abundance was informative in all four of these stocks (Figure 24A–C and 24F).

In the West Norfolk Ridge model, the posterior distribution for the equilibrium biomass (*K*) had a median value of 4050 t (95% CI 2913–6015). The predicted biomass trajectory suggest that the stock has stabilised at a lower abundance since 2010 (Figure 23F). Current (2013) biomass was estimated at 930 t (95% CI 494–1898), corresponding to a status ($B_{current}/B_0 \approx B_{current}/K$) of 0.23 (95% CI 0.13–0.40) (Table 17). The harvest rate in 2013 was about 2% (95% CI 1%–4%), which is below the calculated median harvest rate at MSY (3%). MSY for the stock was less than 80 t yr^{-1} (median 33 t (95% CI 14–75)).

In the Louisville Ridge models, median *K* estimates ranged from 13 520 t (95% CI 9682–24 551) in the North Louisville, to 13 854 t (95% CI 10 715–21 095) in the South Louisville and 18 526 t (95% CI 15 274–22 627) in the Central Louisville. A higher uncertainty in biomass estimates characterised the North Louisville model (Figure 23A). Predicted biomass trajectories suggested stable low abundance of orange roughy since 2000 in the Central Louisville stock and, since the mid-2000s, in the North and South Louisville stocks (Figure 23A-C).

Current (2013) biomass in the North Louisville stock had a median value of 5937 t (95% CI 3625–13 602). Stock status was estimated to be 0.44 (95% CI 0.32–0.63), higher than in the other Louisville stocks (Table 17). However, recent year fishery information was scarce in the North Louisville model and 'current' results should be regarded with caution. The predicted harvest rate for the stock in the last year of fishing (2013) was very low (less than 0.01%).

The Central and South Louisville models predicted similar, lower status for these two stocks (median $B_{current}/K$ = 0.22) (95% CI 0.15–0.30 and 0.13–0.41, respectively) (Table 17). Current (2014) biomass was estimated to be about 4000 t (95% CI 2751–5801) in Central Louisville and 3000 t (95% CI: 1580–7780) in South Louisville. The predicted harvest rate in 2014 was higher in the Central stock (median 14%, 95% CI 10–21%) than in the Southern stock (median 6%, 95% CI 2–12%). These results suggest that orange roughy from the Central and

South Louisville Ridge are currently harvested at a rate greater than the predicted harvest rate at MSY. MSY estimates were centred around 110 t yr^{-1} (95% CI 49–253) for the North and South Louisville and 210 t yr^{-1} (95% CI 107–343) in the Central Louisville.

Posterior distributions for current status are given for each stock in Appendix 2.

BDM models predicted a higher maximum intrinsic population growth rate *r* (median 0.08) for Central Louisville orange roughy. In other stocks, median estimates of *r* ranged from 0.05 (in Lord Howe Rise, West Norfolk Ridge and North and South Louisville) to 0.06 in the Northwest Challenger Plateau. Confidence intervals however, overlapped in all stocks.

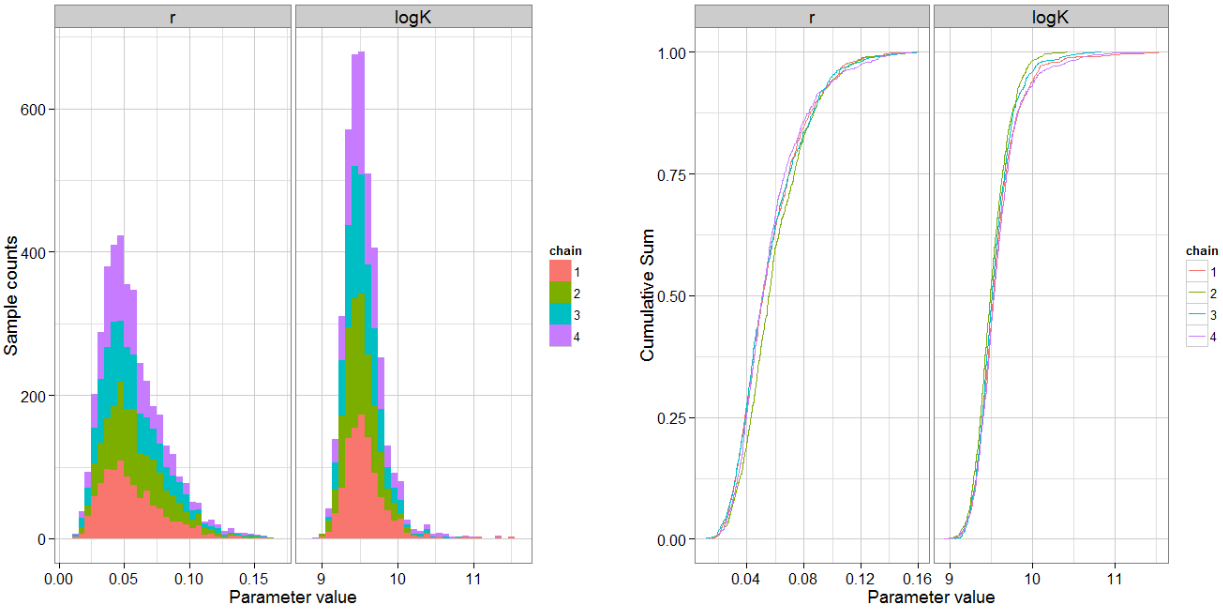
Table 16: Posterior distribution information for *K* (median value, 95% confidence intervals (CI) and the calculated range between the 95% CI), as estimated from BDM fitting to catch series and two different spatial CPUE indices of abundance in each stock. w_a=1 refers to the index calculated assuming equal subarea weights/catchability. w_a=cc is the index calculated using subarea weights/catchability proportional to cumulative catch. Shaded cells indicate the final (selected) BDM model for each stock.

Stock		Index 1	Index 2
		w_a=1	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 17: Summary of BDM outputs, including posterior distributions of estimated model parameters (r and K); estimates of current biomass ($B_{current}$) and harvest rate ($HR_{current}$); MSY-based reference points (MSY, B_{MSY} and HR_{MSY}) and current status relative to K (i.e. $B_{current}/B_0$). All values are medians (95% CI)). Shaded cells indicate more reliable estimates (obtained from successful model convergence).

Stock	r	K	MSY	B_{msy}	$B_{current}$	HR_{MSY}	$HR_{current}$	Status
Louisville North	**0.052** (0.023–0.116)	**13 520** (9682–24 551)	**110** (49–253)	**4056** (2905–7366)	**5937** (3625–13 602)	**0.03** (0.01–0.06)	**8.0E-04** (0.0004–0.0015)	**0.44** (0.32–0.63)
Louisville-Central	**0.075** (0.037–0.131)	**18 526** (15 274–22 627)	**210** (107–343)	**5558** (4582–6788)	**4004** (2751–5801)	**0.04** (0.02–0.07)	**0.14** (0.10–0.21)	**0.22** (0.15–0.30)
Louisville-South	**0.054** (0.022–0.120)	**13 854** (10 715–21 095)	**116** (51–232)	**4156** (3215–6329)	**3004** (1580–7780)	**0.03** (0.01–0.06)	**0.06** (0.02–0.12)	**0.22** (0.13–0.41)
Lord Howe Rise	**0.052** (0.023–0.112)	**1 400 880** (8.3e+03–5.8e+12)	**10 827** (5.9e+01–4.3e+10)	**420 265** 2.5e+03–1.7e+12)	**1 249 890** (4.5e+03-5.0e+12)	**0.03** (0.01–0.06)	**6.3E-05** (1.6E-11–1.8E-02)	**0.79** (0.50–1.11)
Northwest Challenger	**0.061** (0.022–0.150)	**25 811** (1.6E+04–8.6E+10)	**265** (8.5E+01–4.8E+08)	**7743** (4.8E+03–2.6E+10)	**13 964** (7.2E+03-7.4E+10)	**0.03** (0.01–0.07)	**8.0E-03** (1.5E-09–1.5E-02)	**0.55** (0.39–0.86)
West Norfolk Ridge	**0.054** (0.023–0.130)	**4050** (2913–6015)	**33** (14–75)	**1215** (874–1805)	**930** (494-1898)	**0.03** (0.01–0.07)	**0.02** (0.01–0.04)	**0.23** (0.13–0.40)

A. North-Louisville



B. Central-Louisville

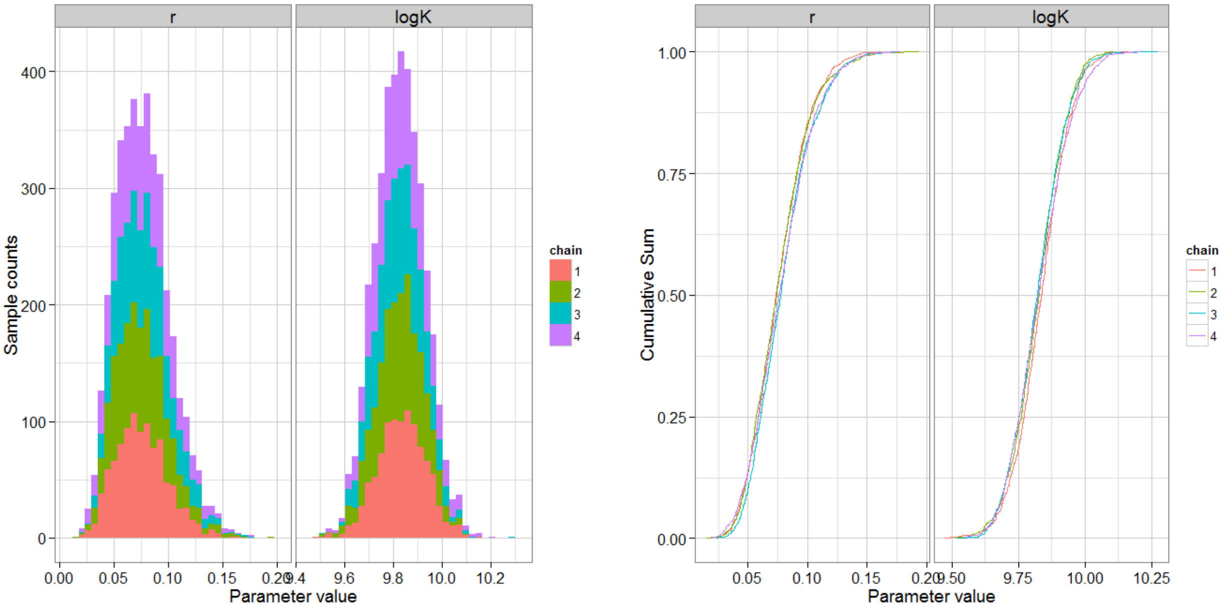
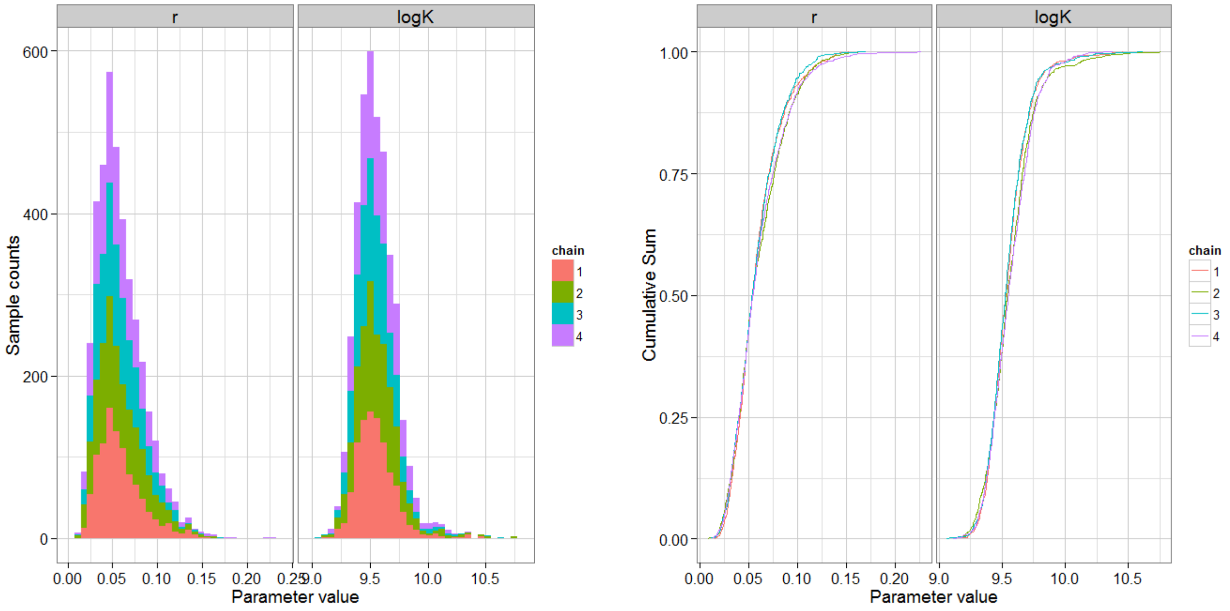


Figure 22: BDM convergence profiles for the parameters of interest (*r* and *K*) among the four iterated Markov chains. Left: posterior histograms; Right: Cumulative parameter values.

C. South-Louisville



D. Lord Howe Rise

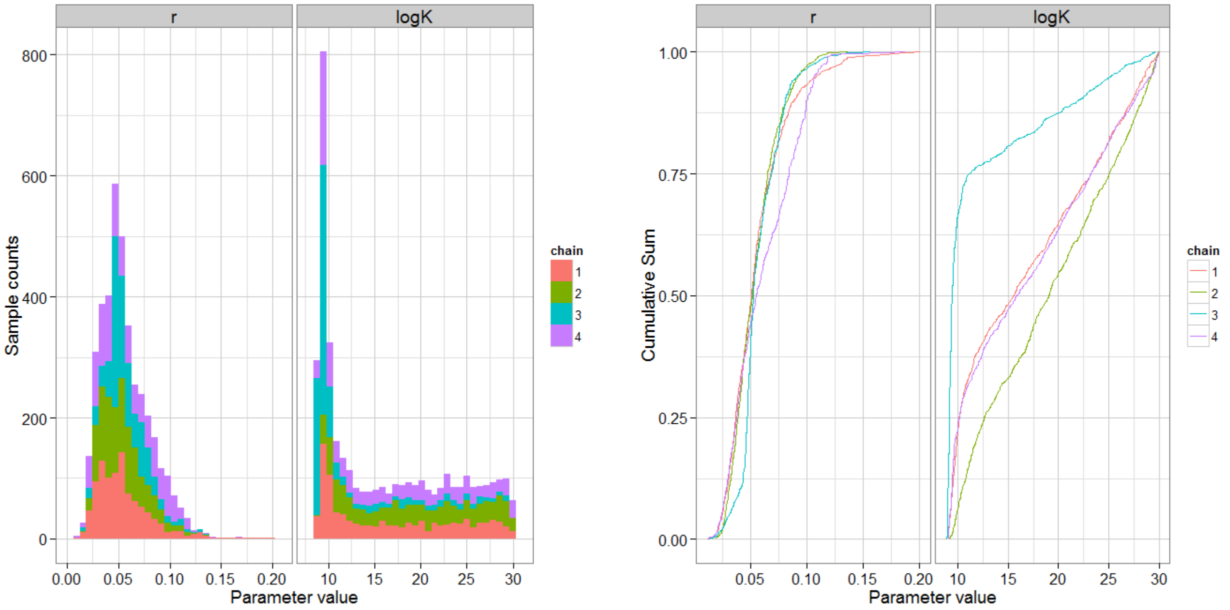
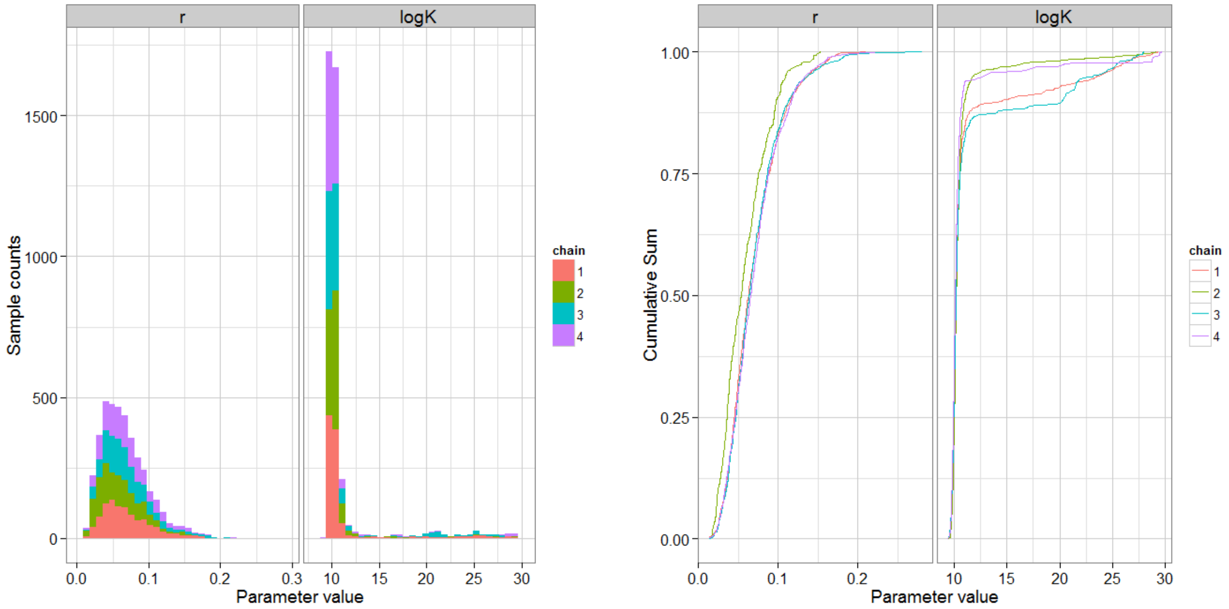


Figure 22 (Cont): BDM convergence profiles for the parameters of interest (*r* and *K*) among the four iterated Markov chains. Left: posterior histograms; Right: Cumulative parameter values.

E. Northwest Challenger Plateau



F. West Norfolk Ridge

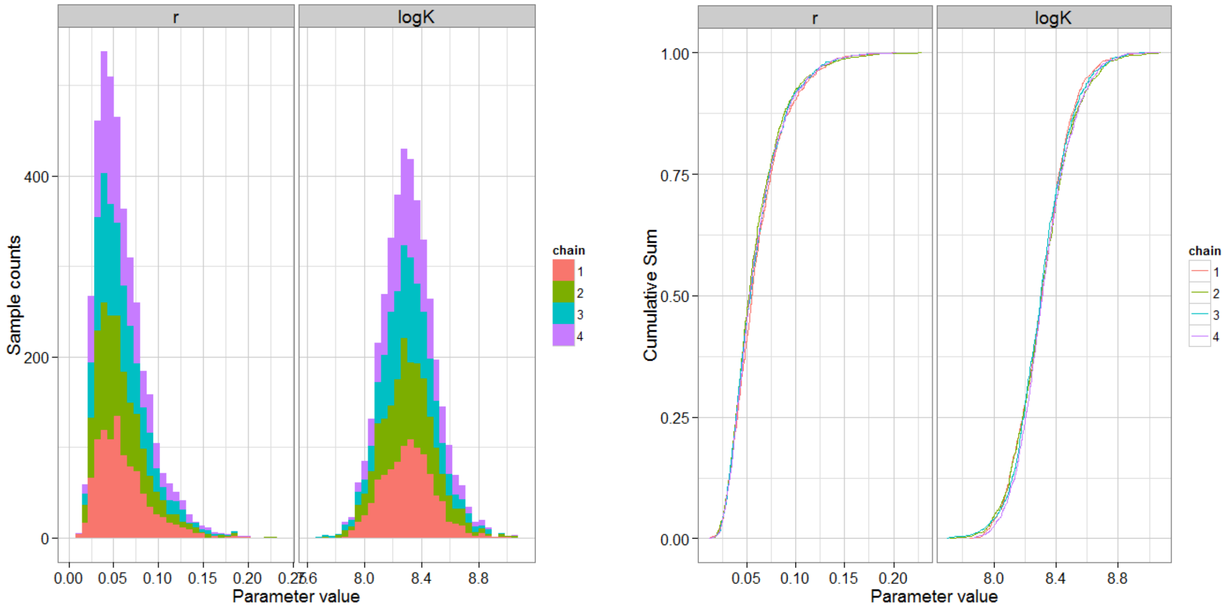
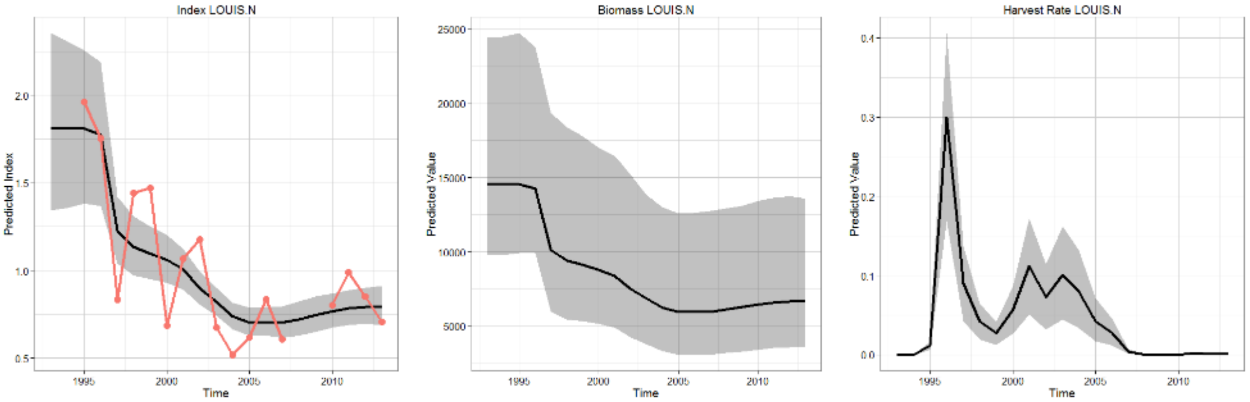
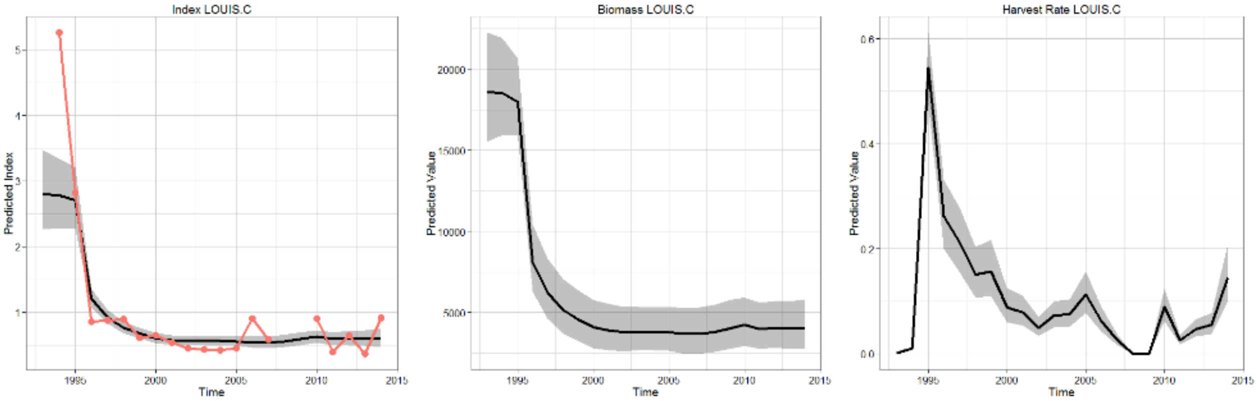


Figure 22 (Cont): BDM convergence profiles for the parameters of interest (*r* and *K*) among the four iterated Markov chains. Left: posterior histograms; Right: Cumulative parameter values.

A. North-Louisville



B. Central Louisville



C. South Louisville

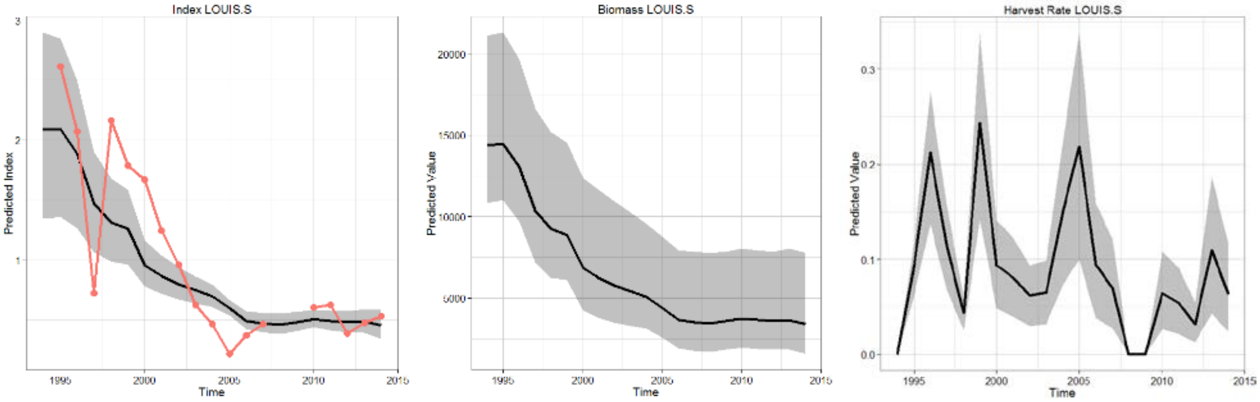
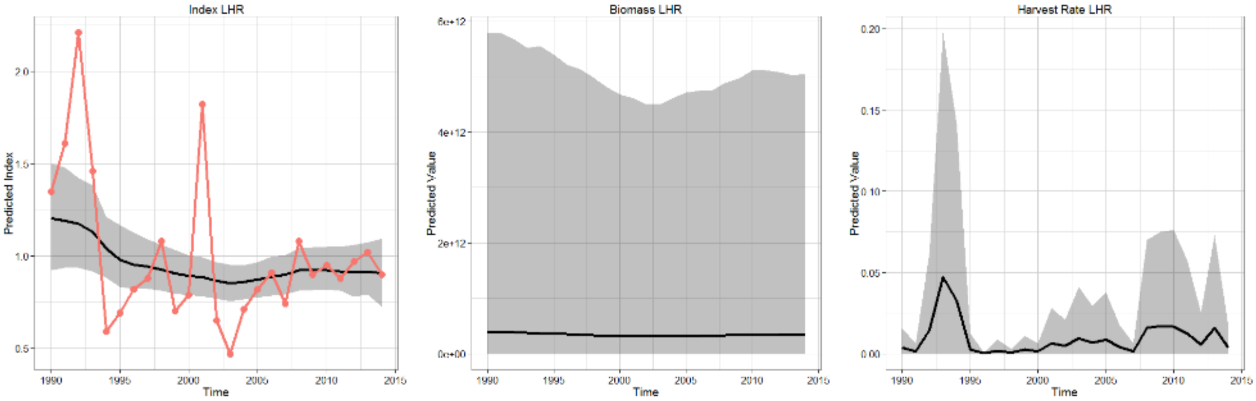
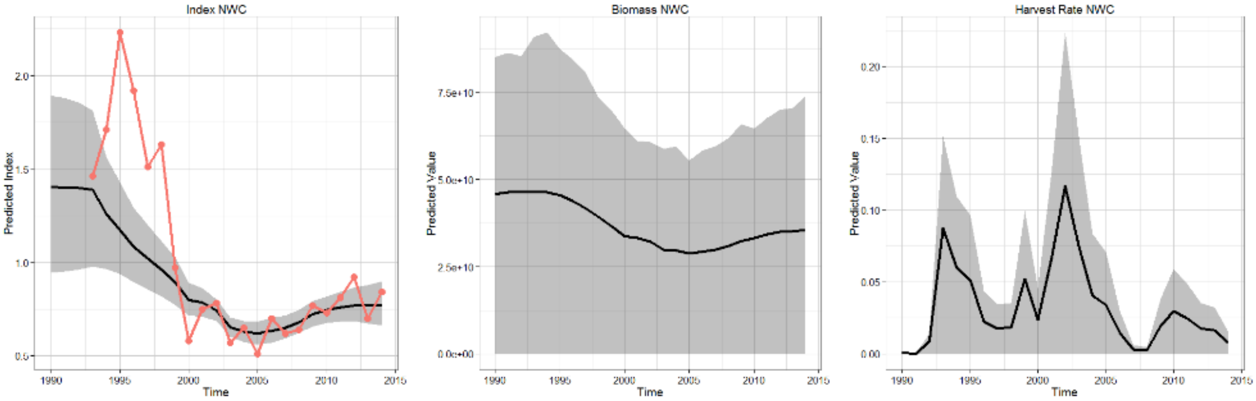


Figure 23: BDM outputs including the fitted (dotted red line) and predicted (black line) index (left); predicted biomass trajectory (centre); and time series of relative harvest rate (right) for each SPRFMO orange roughy stock.

D. Lord Howe Rise



E. Northwest Challenger



F. West Norfolk Ridge

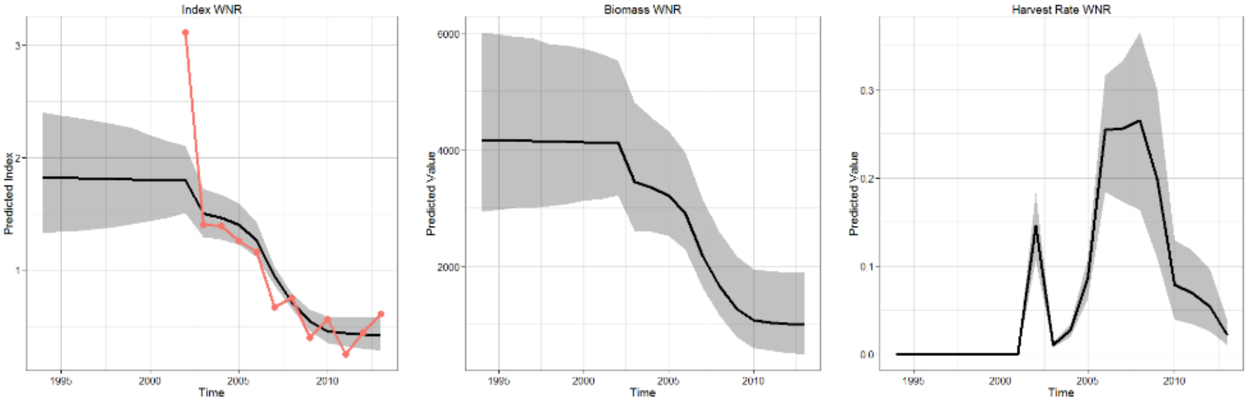
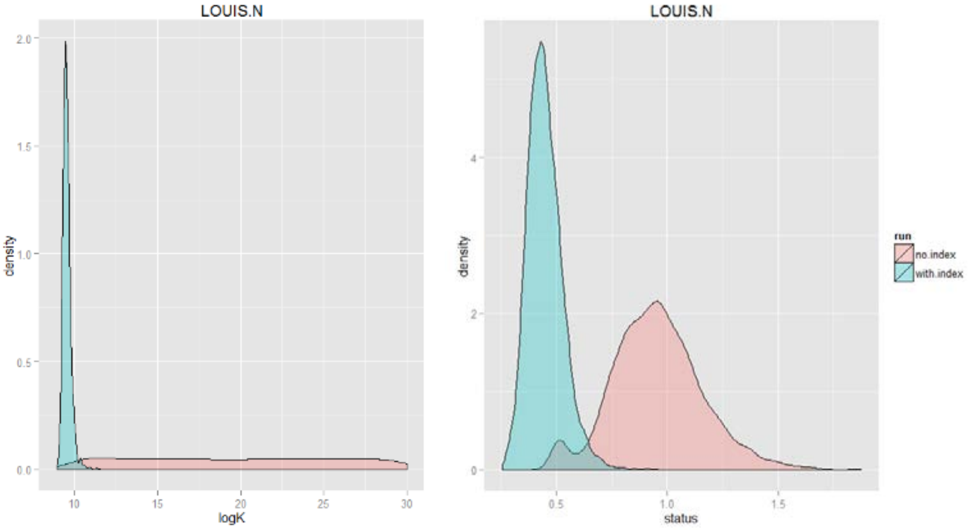


Figure 23 (Cont): BDM outputs including the fitted (dotted red line) and predicted (black line) index (left); predicted biomass trajectory (centre); and time series of relative harvest rate (right) for each SPRFMO orange roughy stock.

A. North-Louisville



B. Central-Louisville

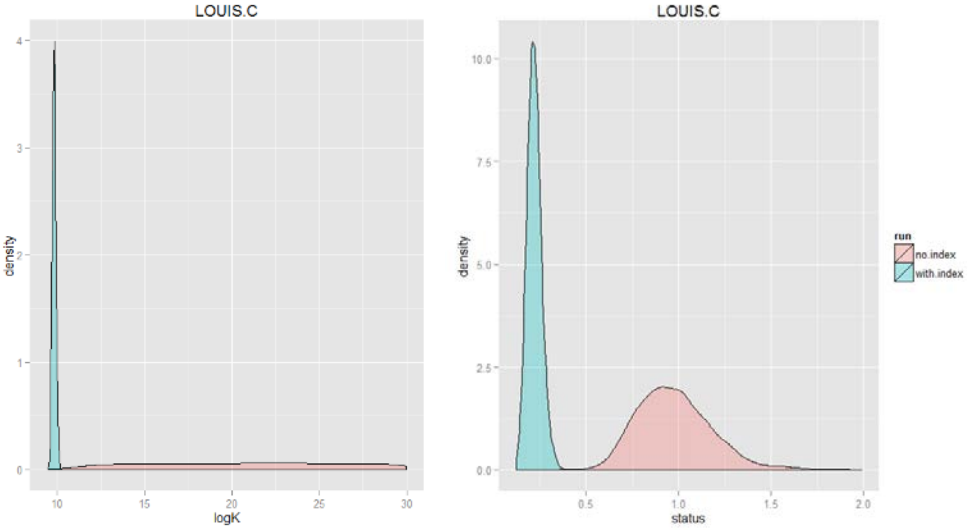
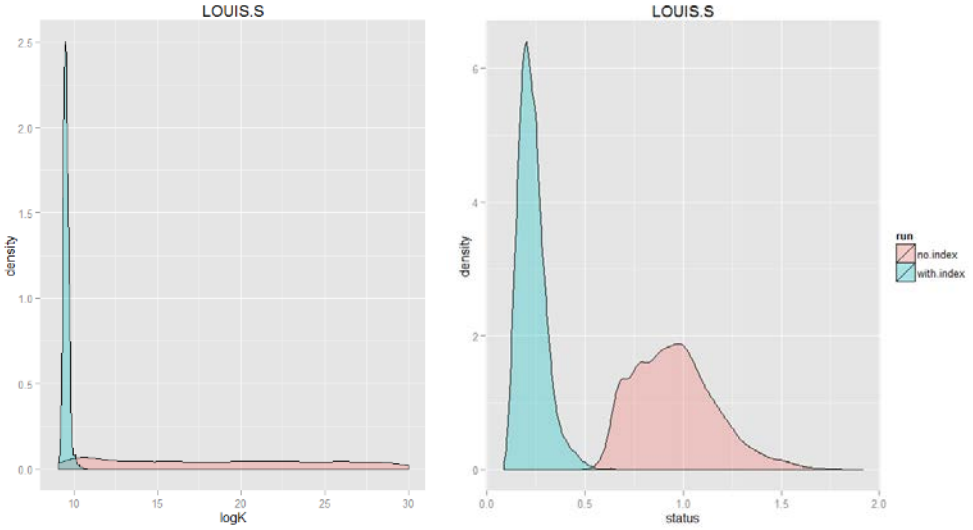


Figure 24: Comparative posterior distributions for *logK* (left) and current status ($B_{current}/K$) (right) for BDM models fitted with and without an index of abundance in each of the six SPRFMO orange roughy stocks.

C. South-Louisville



D. Lord Howe Rise

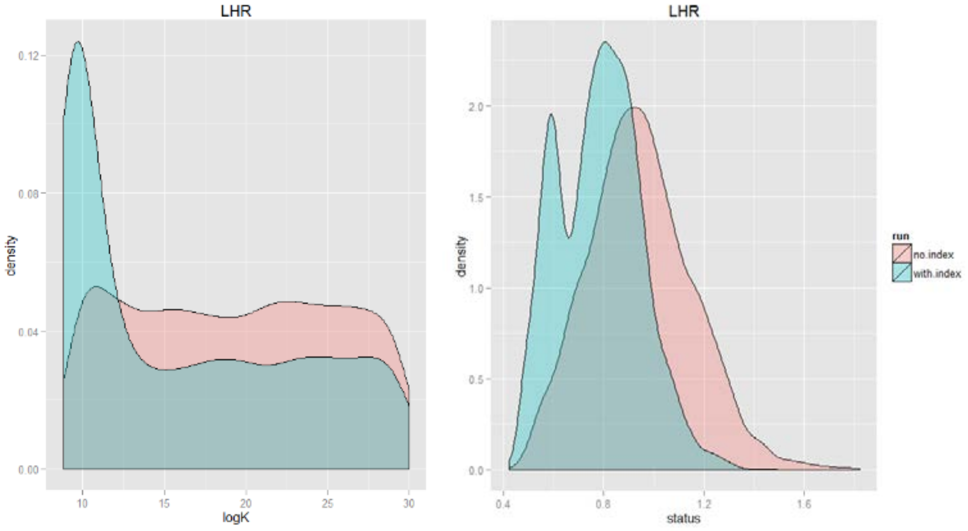
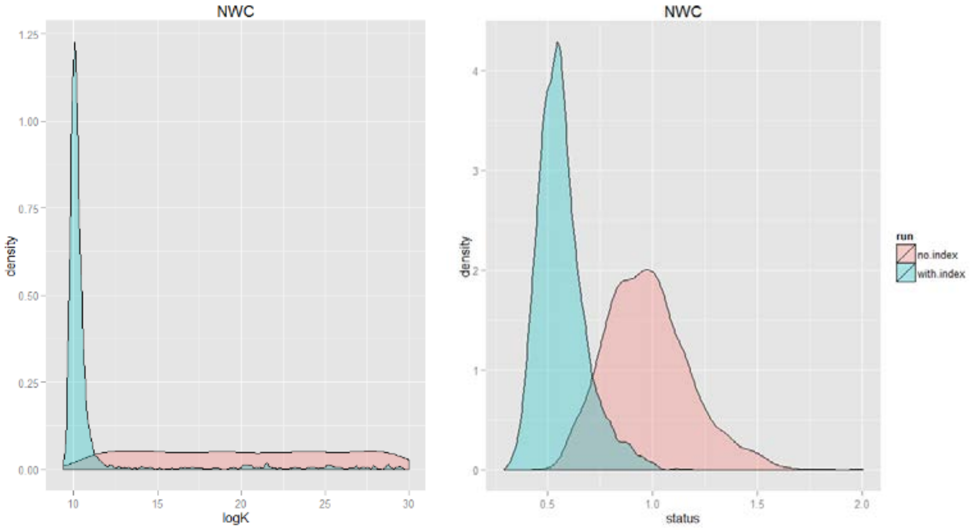


Figure 24 (Cont): Comparative posterior distributions for *logK* (left) and current status ($B_{current}/K$) (right) for BDM models fitted with and without an index of abundance in each of the six SPRFMO orange roughy stocks.

E. Northwest Challenger



F. West Norfolk Ridge

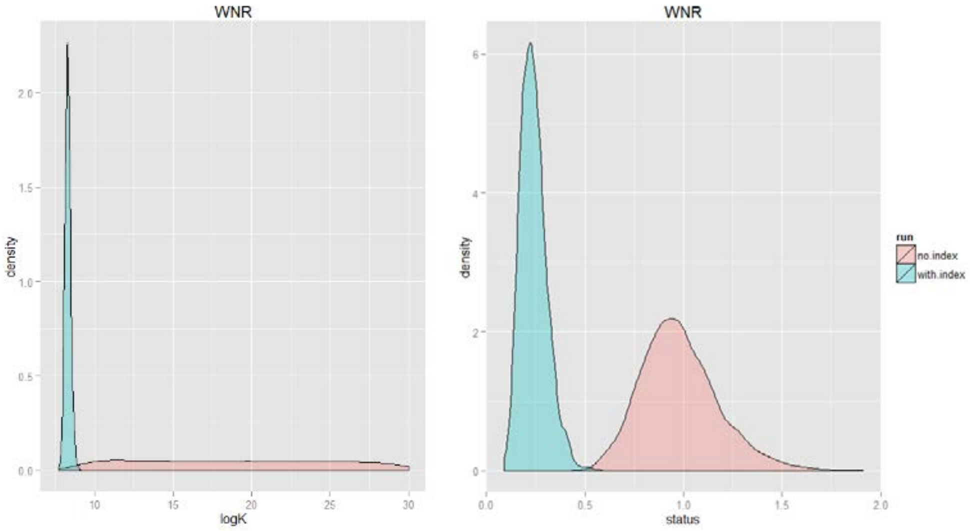


Figure 24 (Cont): Comparative posterior distributions for *logK* (left) and current status ($B_{current}/K$) (right) for BDM models fitted with and without an index of abundance in each of the six SPRFMO orange roughy stocks.

BDM sensitivity analyses and cross validation checks were performed on the Central Louisville Ridge model. Sensitivity testing of the input assumption on B_{MSY}/K, revealed negligible impacts of shape parameter values over the range 0.25–0.60 on estimates of *K* and status relative to *K* (Table 18). Compared with the default B_{MSY}/K value of 0.30 used for all stocks in this study, a value of 0.25 caused a 2% increase in the median estimate for *K* and a 1% increase in the median estimate for current biomass, with no measurable impact on estimates of current status. B_{MSY}/K values of 0.40, 0.50 and 0.60, caused a 2%, 5% and 4% reduction in median *K* values, respectively. Reductions in estimates of current biomass ranged from 2% (in the 0.40 scenario) to 1% (in the 0.50 and 0.60 scenarios). Median status increased from 0.22 (in 0.25, 0.30 and 0.40 scenarios) to 0.23 (in the 0.50 and 0.60 scenarios), but the 95% confidence intervals remained unchanged. Changes in the assumed B_{MSY}/K obviously affected B_{MSY} estimates (by definition) and would affect stock status evaluation relative to B_{MSY} and the surplus production.

Cross validation checks showed consistency in the predicted index, biomass and stock status trajectories when the model was re-fitted without the last 5 years of data (Figure 25), as well as consistency in the estimated posterior distributions for *r*, *K* and *MSY* (Figure 26).

Table 18: Results of sensitivity analyses of BDM outputs to selected input values for the shape parameter $\varphi = B_{MSY}/K$. All models were fitted to the catch series and spatial CPUE abundance index (w_a=cc) for Central Louisville orange roughy. All values are the calculated medians from the posterior distributions. Process error standard deviation was fixed at 5% in all models.

$\varphi = B_{MSY}/K$	r	K	B_{MSY}	$B_{current}$	Status (relative to K)	Status (95% CI)
0.25	0.06	19377	4844	4237	0.22	0.14–0.35
0.30	0.06	18956	5687	4209	0.22	0.14–0.35
0.40	0.06	18595	7438	4134	0.22	0.14–0.35
0.50	0.06	18064	9032	4157	0.23	0.14–0.36
0.60	0.06	18146	10888	4164	0.23	0.14–0.37

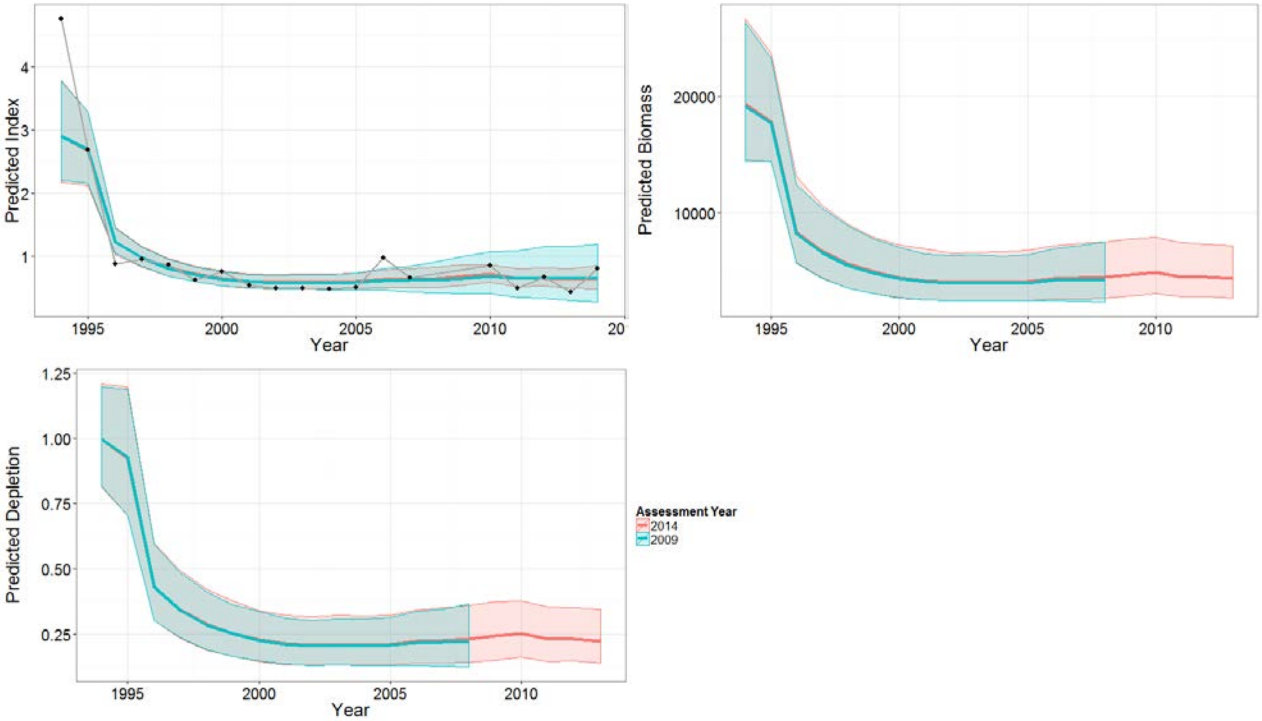


Figure 25: Results of BDM cross-validation checks on Central Louisville orange roughy: predicted index (top left), biomass (top right) and status (relative to *K*) (bottom left) based on the full model fitted to the 1994–2014 time series (red) and the same model re-fitted following the removal of data from the last five fishing years (1994–2009 time series (blue)).

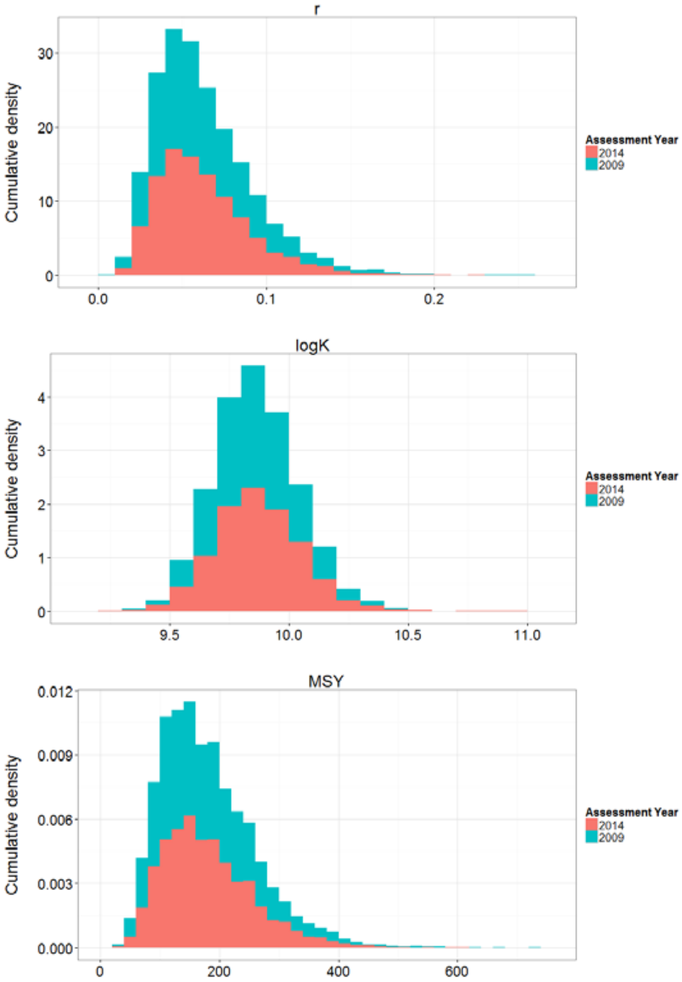


Figure 26: Results of BDM cross-validation checks on Central Louisville orange roughy: posterior histograms for *r*, *logK* and *MSY* for the full model (1994–2014 time series (red)) and the same model re-fitted after removal of data from the last five fishing years (1994–2009 time series (blue)).

4. DISCUSSION

Biomass estimation for orange roughy on the high seas is complicated by a lack of fisheries independent acoustic or trawl survey time series. The use of commercial CPUE data in typical GLM standardisation procedures to calculate annual indices of stock abundance has hitherto tended to provide unreliable results (Clark et al. 2010, O'Driscoll 2003, Clark & Anderson 2001, Clark 1999). There are two main reasons for this. First, fishing for orange roughy tends to be targeted on plumes and/or local aggregations (often associated with underwater topographic features) and is thus highly spatially structured. Unless such spatial structure is considered, the commercial CPUE data will reflect the local availability of aggregations as opposed to total abundance (Penney 2010). Second, non-random fleet movements between subarea (or local aggregations) within the fishing grounds can cause important bias in the abundance trend or year effects (Walters 2003, Campbell 2004, Carruthers et al. 2011).

Evidence of sequential fishing of locations was demonstrated for SPRFMO orange roughy stocks by Clark et al. (2010). The present study confirmed the occurrence of non-random temporal changes in the spatial distribution of effort in all management areas. Observed spatial patterns over time included: 1) fishery transition from a group of subareas to another (spatially-distinct) group of subareas (e.g., within the Lord Howe Rise); 2) fishery expansion from a few subareas to many subareas followed by contraction to only a few subareas (e.g., Northwest Challenger Plateau, North Louisville and South Louisville); and 3) fishery reduction from several subareas to just a few subareas (e.g. Central Louisville Ridge). These patterns were linked to one or more of the following factors: exploratory fishing, local depletion, economic motives and/or management actions.

Accounting for spatial structure and changes in the spatial distribution of fishing through time is required to estimate reliable CPUE indices of stock abundance. Standard GLM procedures serve to handle the influence of significant covariates (i.e., vessel and fishing depth) in the calculation of annual indices. In the absence of spatial effects, these models assume that trends in abundance are the same everywhere and can be extrapolated to the entire fishing ground. The inclusion of time-varying spatial effects (such as a year-subarea interaction term) allows a relaxation of this assumption. GLMs with time varying spatial effects instead assume that trends in abundance in subareas that are fished are representative of trends in abundance in subareas that were not fished. This represents an improvement if the assumption is true, but the approach overlooks missing year-subarea data combinations. If subareas are characterised by different trends in abundance and histories of exploitation, ignoring missing year-subarea data can cause the index to suffer from 'hyper stability' or 'hyper depletion'. Hyper stability will occur if the fishery progressively moves to new subareas having higher fish densities and the total number of subarea that are fished decreases over time. Hyper depletion may occur if fishing activities spread across an increasing number of subarea having lower fish densities over time. Such bias phenomena are well established (Hilborn & Walters 1992) and have been demonstrated using real data or in simulation exercises (Walters 2003, Campbell 2004, Carruthers et al. 2010, 2011). An alternative to ignoring missing year-subarea data is ruled-based imputation (Walters 2003, McKechnie et al. 2013). This approach assumes that relative abundance for a subarea in a year with no fishing is proportional to the abundance in the nearest fishing year, according to a defined and realistic set of rules.

The hybrid GLM/imputation method used in this study consisted of fitting an interaction GLM with spatial effects to estimate relative abundance in year-subarea strata with observations and applying ruled-based imputation to calculate abundance in year-subarea strata with no information. This has been found to be a useful and promising method for dealing with spatial bias in CPUE abundance indices (Carruthers et al. 2011, McKechnie et al. 2013). The method is especially relevant in deepwater fish species and fisheries in which limited dispersal and/or slow mixing and re-distribution of aggregations between subareas is believed to occur, leading to local depletion phenomena (Roux & Doonan 2015).

Preliminary spatial CPUE analyses provided more reliable indices of abundance than earlier efforts (see Clark et al. 2010) for orange roughy in all SPRFMO management areas. Compared with CPUE indices calculated using GLM standardisation with no spatial effects, spatial CPUE indices served to i) adjust the scale of the initial depletion either downwards (Lord Howe Rise) or upwards (all other stocks); ii) minimize hyper stability in relative abundance linked to the spatial contraction of fishing effort over time (Northwest Challenger Plateau, West Norfolk Ridge, and North and South Louisville); and 3) dampen inter-annual variability in estimated abundance (all stocks). Some of the stocks considered here showed upward trends in CPUE indices in the early years of fisheries probably resulting from localised, exploratory fishing. In such cases, the spatial CPUE analysis predicted a higher initial abundance based on contributions from all subareas that would eventually support the fishery later in the time series. Omitting data from initial years in which CPUE was increasing (on the basis that this reflects fishers learning about the area as opposed to being proportional to abundance), may assist with further improving CPUE indices of abundance for orange roughy.

Although these preliminary results confirm the usefulness of the approach, further work is required to refine and validate the spatial CPUE method. Performance evaluation and further simulation testing are needed to ascertain the validity of the method for tracking changes in abundance, as well as to identify and characterise the method's limitations. Ideally, this should be performed on similar stocks for which reliable biomass estimates are available from fisheries independent data and surveys — for orange roughy this could be done using data from stocks inside the EEZ. Stock-specific fine-tuning may also be required, especially in terms of subarea definition. In the present study, individual UTFs were taken to represent separate subareas, while subareas on the slope were distinguished based on commercial trawls aggregation using distance clustering. Whether or not the resulting spatial structure adequately reflects the spatial structure of the stock and constituent aggregations remains to be demonstrated. A useful first step for the validation of subarea would be to compare them against anecdotal information from relevant skippers, other scientists, and fishing industry data maps.

Another issue that requires further consideration is that of subarea weighting and subarea catchability assumptions. Subarea weights determine subarea contributions to total abundance. In this study, we assumed equal and constant (between years) subarea contributions (w_a=1) or constant contributions proportional to cumulative catch (w_a=cc). Sensitivity analyses indicated the different subarea weighting schemes had only a limited effect on the abundance index, but a stronger influence on the variability (calculated CV) of the annual indices. Such differences (which were input into BDM as observation errors) were sufficient to affect BDM outputs and unfished biomass K estimation. Subarea contributions to total abundance will differ among stocks and are likely to vary temporally within stocks. Potential options for refining subarea weighting techniques include the development of more sophisticated methods (e.g., De Lury or Leslie depletion) to estimate subarea-specific catchability; consideration and inclusion of time-varying catchability assumptions (with the inclusion of time-varying subarea weights); and use of specific weights for different types of terrain (i.e., slope versus UTFs) and other fishing pattern variables (such as tow duration) that are likely to differ spatially and affect fishery efficiency.

Finally, a more detailed examination of fishing patterns variables included in CPUE standardisations (i.e., vessel, target species, fishing week, duration, depth, etc.) and their effects in standardisations with year-subarea interactions, would serve to ensure that such effects are credible. This may include influence plots and metrics for significant covariates (Bentley et al. 2012) and consideration of temporal overlap between core vessels and removal of vessels with outlier effects (e.g., vessels with expected catch rates order of magnitude different from others).

The BDM applications gave promising results. Successful BDM convergence in four of the six orange roughy stocks, provided new, preliminary estimates of initial biomass, current status, harvest rate and maximum sustainable yield (MSY), with uncertainty, in the three Louisville Ridge fisheries and the West Norfolk Ridge fishery in the Tasman Sea. These preliminary results obviously rely on the assumption that the spatial CPUE index for each stock was proportional to abundance. BDM convergence problems in other Tasman stocks (Lord Howe Rise and Northwest Challenger) were potentially related to the use of incomplete catch series (in both cases); mismatch between the CPUE index and the catch history; and/or an unrepresentative index of abundance with limited contrast suggesting relatively little fishing effects on the stock (in Lord Howe Rise). The catch series used in this study (which was restricted to New Zealand effort) was incomplete, as data from Australian vessels and other nations often accounted for a large proportion (over 50%) of the annual catch in the Lord Howe Rise and Northwest Challenger Plateau areas from 1988 until the mid-2000s (Clark 2008). In both cases, further work and additional testing are required to assess whether reliable estimates of initial biomass and MSY can be estimated for these stocks using complete catch series and a revised spatial CPUE index of abundance.

For stocks with successful BDM convergence, current status was estimated at 22% of the initial biomass (in Central and South Louisville), 23% (West Norfolk Ridge) and 44% (North Louisville). The upper 95% confidence interval of the posterior distribution for current status exceeded 40% only in the North Louisville stock. The current harvest rates for West Norfolk Ridge and North Louisville orange roughy were below the harvest rate at MSY. In contrast, BDM outputs suggested that Central and South Louisville orange roughy are currently harvested at rates greater than the harvest rate at MSY. While these results should be considered preliminary, we note that the current status of three of these four high seas orange roughy stocks appears to be low compared with limits specified in the Harvest Strategy for New Zealand domestic fisheries (https://www.mpi.govt.nz/document-vault/728).

For orange roughy from the Louisville Ridge, the initial (unexploited equilibrium) biomass estimated using BDM (total 45 900 t across the three stocks) was similar to, but 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.

BDM validation and sensitivity testing was performed by applying a similar model (BSP) to various New Zealand fish stocks (including orange roughy from East Chatham Rise) (McAllister & Edwards 2016). That study demonstrated that a cohort-aggregated state-space biomass dynamic model such as BDM can provide a similar estimate of depletion (relative to MSY or K-based reference points) to that estimated by an age-structured production model such as CASAL. The model is thus useful for estimating biomass trajectories and status relative to K, but may not successfully estimate the absolute scale of current and initial biomass. In the case of orange roughy, a BSP model fitted to an aggregate of stock trend data (including both fishery-dependent and fishery-independent indices), provided good fits and informative estimates of stock size and depletion (McAllister & Edwards 2016). An attempt to fit a CASAL model to the same abundance index and catch at length data could not fit the trend data (continued lack of recovery after catch reductions in the mid-1990s). Instead, the age structured model predicted recovery due to expected recruitment from average unfished conditions up to about 30 years after start of fishery (McAllister and Edwards 2016).

In this study, predictive performance was assessed using a cross-validation test, which showed consistency in model outputs after removal of the last five years of data. Sensitivity testing of the $B_{MSY}/K = 0.30$ input assumption for orange roughy showed that these parameters had only minimal impact on estimates of initial biomass and stock status relative to the initial biomass, but would, by definition, affect stock status evaluation relative to B_{MSY} and the surplus production.

Several development and fine-tuning options exist for BDM and its application to orange roughy. These include 1) the development of a stock-specific prior for the maximum intrinsic population growth rate r (for example using maximum length information available in the observer data to estimate stock-specific natural mortality M); 2) the construction of an informed prior on K (potentially using the outputs from seamount meta-analysis (Clark et al. 2010)); 3) process error estimation; and 4) use in stock projections. The Bayesian state-space estimation framework used in BDM allows uncertainty in fishery data to be partitioned in a way that allows stochastic components of the dynamics to be included when the stock is projected forward in time. This represents an advantage for precautionary or risk based management (Harwood & Stokes 2003). However, we note that explicit modelling of time-dependent stochastic processes was not performed in this case. Following the approach taken in recent applications of this type of model, no attempt was made to estimate the process error variance (e.g. Stanley et al. 2009, McAllister & Duplisea 2012, Yamanaka et al. 2012). Instead, process error variability was accounted for but fixed on input (i.e., between-year stochastic variation in stock biomass was assumed to have a standard deviation of 5%). Sensitivity testing of such process error assumptions, as well as process error estimation, are recommended in future iterations. The former will be necessary to finalise stocks assessments for SPRFMO orange roughy.

Used in conjunction, the spatial CPUE analyses and Bayesian state-space biomass dynamics model applied in this study have a high potential for use as management tools in high seas fisheries for orange roughy, where commercial CPUE data are the only information source available to evaluate stock status. Further testing and fine-tuning of these methods will assist with the development and provision of management measures (i.e., setting of catch limits) to ensure the long-term sustainability of orange roughy stocks within the SPRFMO Convention Area.

5. ACKNOWLEDGMENTS

This study was funded by Ministry for Primary Industries project DEE2014-10. We acknowledge the input and review by members of the MPI South-Pacific Fisheries Working Group, in particular Martin Cryer (MPI) and Geoff Tingley (Sustainable Fisheries Partnership), as well as comments from Jim Ianelli, Chair of the SPRFMO Scientific Committee. We thank Owen Anderson (NIWA) for reviewing and commenting on an earlier version of the manuscript; and Chris Francis for useful comments and discussions.

6. REFERENCES

Andrews, A.H.; Tracey, D.M.; Dunn, M.R. (2009). Lead-radium dating of orange roughy (*Hoplostethus atlanticus*): validation of a centenarian life span. *Canadian Journal of Fisheries and Aquatic Sciences 66*: 1130–1140.

Bentley, N.; Kendrick, T.H.; Starr, P.J.; Breen, P.A. (2012). Influence plots and metrics: tools for better understanding fisheries catch-per-unit-effort standardisations. *ICES Journal of Marine Science, 69*: 84–88.

Bull, B.; Francis, R.I.C.C.; Dunn, A.; McKenzie, A.; Gilbert, D.J.; Smith, M.H.; Bian, R.; Fu, D (2012). CASAL (C++ algorithmic stock assessment laboratory) User Manual.

Campbell, R.A. (2004). CPUE standardization and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research 70*: 209–227.

Carruthers, T.R.; Ahrens, R.N.; McAllister, M.K.; Walters, C.J. (2011). Integrating imputation and standardization of catch rate data in the calculation of relative abundance indices. *Fisheries Research, 109(1)*, 157–167.

Carruthers, T.R.; McAllister, M.K.; Ahrens, R.N. (2010). Simulating spatial dynamics to evaluate methods of deriving abundance indices for tropical tunas. *Canadian Journal of Fisheries and Aquatic Sciences 67:* 1409–1427.

Chambers, J.M.; Hastie, T.J. (1991). Statistical models in S. Wadsworth & Brooks/Cole, Pacific Grove, CA. 608 p.

Clark, M.R. (1999). An update and standardised analysis of New Zealand commercial catch and effort information for the orange roughy (*Hoplostethus atlanticus*) fishery on the Louisville Ridge. New Zealand Fisheries Assessment Research Document 99/47. 17 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.; Anderson, O.F. (2001). The Louisville Ridge orange roughy fishery: an update of commercial catch-effort data and CPUE analysis of the fishery to the end of the 1999–2000 fishing year. *New Zealand Fisheries Assessment Report No. 2001/74*. 31 p.

Clark, M.R.; Dunn, M.R.; Anderson O.F. (2010). Development of estimates of biomass 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.*

Clark, M.R; McMillan; P.J.; Anderson, O.F.; Roux, M.-J. (2016). Stock management areas for orange roughy (*Hoplostethus atlanticus*) in the Tasman Sea and western South Pacific Ocean**.** *New Zealand Fisheries Assessment Report 2016/19.*

Clark, M.R.; Roux, M.-J.; Cryer M. (2015). New Zealand research relevant to the assessment of stocks of orange roughy. Paper to the SPRFMO SWG. 31 pp. (SC-03-DW-02). https://www.sprfmo.int/assets/Meetings/Meetings-2013-plus/SC-Meetings/3rd-SC-Meeting-2015/Papers/SC-03-DW-02-New-Zealand-research-relevant-to-the-assessment-of-stocks-of-orange-roughy.pdf

Cordue, P.L. (2014). The 2014 orange roughy stock assessments. *New Zealand Fisheries Assessment Report 2014/50*. 135 p.

Doonan, I.J.; Fu, D.; Dunn, M.R. (2015). Harvest control rules for a sustainable orange roughy fishery. *Deep-Sea Research I 98*: 53–61.

Edwards, C.T.T. (2016). BDM: Bayesian Biomass Dynamic Model, URL https://github.com/cttedwards/bdm.git

Edwards, C.T.T; McAllister, M.K. (2014). Application of a surplus production model to New Zealand stocks with time series data on catch and abundance. SAM working group meeting, 15th May 2014

Fletcher, R.I. (1978). On the restructuring of the Pella-Tomlinson system. *Fishery Bulletin 76*:515–521.

Francis, R.I.C.C. (1992). Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Canadian Journal of Fisheries and Aquatic Sciences*, *49*(5), 922–930.

Francis, R.I.C.C. (1999). The impact of correlations in standardised CPUE indices. New Zealand Fisheries Assessment Research Document 99/42. 30 p. (Unpublished report held in NIWA library, Wellington.)

Harwood, J.; Stokes, K. (2003). Coping with uncertainty in ecological advice: lessons from fisheries. *Trends in Ecology & Evolution 18*: 617–622.

Hilborn, R.; Walters, C.J. (1992). Quantitative fisheries stock assessment: choice, dynamics and uncertainty. *Reviews in Fish Biology and Fisheries*, *2*(2), 177–178.

McAllister, M.K.; Babcock, E.A.; Pikitch, E.K.; Prager, M.H. (2000). Application of a non-equilibrium generalized production model to South and North Atlantic swordfish: combining Bayesian and demographic methods for parameter estimation. *Collected Volume of Scientific Papers ICCAT* 51:1253–1550.

McAllister, M.K.; Duplisea, D.E. (2012). Production model fitting and projection for Atlantic redfish (*Sebastes fasciatus*) in Units 1 and 2. Department of Fisheries and Oceans Canada (DFO): Canadian Science Advisory Secretariat Research Document **2012/103**:34 p.

McAllister, M.K.; Edwards, C.T.T. (2016). Applications of a Bayesian surplus production model to New Zealand fish stocks. *New Zealand Fisheries Assessment Report 2016/52*. 79 p.

McAllister, M.K.; Pikitch, E.K.; Babcock, E.A. (2001). Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. *Canadian Journal of Fisheries and Aquatic Sciences* 58:1871–1890.

McKechnie, S.; Hoyle, S.; Harley, S. (2013). Longline CPUE series that account for changes in the spatial extent of fisheries. WCPFC-SC9-2013/SA-IP-05.

Ministry for Primary Industries (MPI) (2015). Orange roughy (ORH). Fisheries Assessment Plenary May 2015: Stock Assessments and Stock Status. Compiled by the Fisheries Science Group, Ministry for Primary Industries, Wellington, New Zealand. http://fs.fish.govt.nz/Doc/23846/44_ORHintro_2015_FINAL.pdf.ashx

O'Driscoll, R.L. (2003). Catch-per-unit-effort analysis of orange roughy fisheries outside the New Zealand EEZ: Lord Howe Rise and Northwest Challenger Plateau to the end of the 2001−02 fishing year. *New Zealand Fisheries Assessment Report 2003/36.* 38 p

Penney, A.J. (2010). An approach to estimation of sustainable catch limits for orange roughy in the SPRFMO Area. Paper to the SPRFMO SWG, 11 p. (SWG-09-DW-02).

R Development Core Team. (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. http://www.R-project.org

Roux, M.-J.; Doonan, I.J. (2015). Development of an abundance index for Bounty Plateau smooth oreo using commercial CPUE data from 1994–95 to 2011–12: comparison of standard (GLM) procedures and preliminary spatial CPUE analyses. *New Zealand Fisheries Assessment Report* 2015/24.

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.

Schaefer, M.B. (1954). Some aspects of the dynamics of populations important to the management of commercial marine fisheries. *Bulletin of the Inter-American Tropical Tuna Commission Bulletin* 1:26–56.

Schaefer, M.B. (1957). A Study of the Dynamics of the Fishery for Yellowfin Tuna in the Eastern Tropical Pacific Ocean. *Bulletin of the Inter-American Tropical Tuna Commission Bulletin* 2:247–285.

Sokal, R.R.; Sneath, P.H. (1973). Numerical taxonomy. Freeman. San Francisco.

Stan Development Team (2014). RStan: the R interface to Stan, Version 2.5, http://mc-stan.org/rstan.html.

Stanley, R.D.; McAllister, M.K.; Starr, P.; Olsen, N. (2009). Stock assessment for Bocaccio (*Sebastes paucispinis*) in British Columbia waters. Department of Fisheries and Oceans Canada (DFO): Canadian Science Advisory Secretariat Research Document **2009/055**:200 pp.

Walters, C. (2003). Folly and fantasy in the analysis of spatial catch rate data. *Canadian Journal of Fisheries and Aquatic Sciences*, 60(12), 1433–1436.

Yamanaka, K.L.; McAllister M.K.; Olesiuk, P.F.; Etienne, M.-P.; Obradovich, S.; Haigh R. (2012). Stock Assessment for the inside population of yelloweye rockfish (*Sebastes ruberrimus*) in British Columbia, Canada for 2010. Department of Fisheries and Oceans Canada (DFO): Canadian Science Advisory Secretariat Research Document **2011/129**:131 p.

APPENDIX 1

Summaries of available catch and effort information by fishing year for bottom trawling activities that targeted or caught orange roughy (ORH) in each of the six SPRFMO management areas considered for assessment.

A. Lord Howe Rise (LHR)

Fishing year	No. tows	No. Vessels	ORH catch (t)	ORH CPUE (t/tow)	Zero catch (%)	ORH target (%)
1989–90	65	4	128.80	2.00	23	100
1990–91	15	3	52.30	3.50	13	100
1991–92	77	5	483.30	6.30	16	100
1992–93	887	18	1 496.60	1.70	25	100
1993–94	1 401	21	875.60	0.60	43	99
1994–95	118	8	63.70	0.50	53	97
1995–96	25	3	4.40	0.20	72	100
1996–97	188	6	45.40	0.20	64	99
1997–98	60	5	15.20	0.30	42	98
1998–99	153	16	57.50	0.40	45	93
1999–00	125	8	33.90	0.30	46	97
2000–01	141	6	148.80	1.10	46	98
2001–02	189	10	109.80	0.60	29	99
2002–03	272	9	208.00	0.80	34	99
2003–04	124	8	147.30	1.20	22	100
2004–05	146	11	193.10	1.30	34	95
2005–06	66	6	92.30	1.40	12	77
2006–07	38	3	33.90	0.90	13	100
2007–08	91	3	380.40	4.20	22	100
2008–09	222	5	403.00	1.80	23	100
2009–10	158	3	384.90	2.40	20	100
2010–11	158	4	278.40	1.80	18	99
2011–12	73	4	121.00	1.70	12	97
2012–13	199	3	344.00	1.70	14	100
2013–14	70	2	79.00	1.10	17	99
Totals	**5 061**	**59**	**6 181**			

B. Northwest Challenger Plateau

Fishing year	No. tows	No. Vessels	ORH catch (t)	ORH CPUE (t/tow)	Zero catch (%)	ORH target (%)
1989–90	43	4	25.30	0.60	16	100
1990–91	4	1	1.00	0.20	75	100
1991–92	56	2	229.80	4.10	61	100
1992–93	1 447	19	2 378.20	1.60	26	100
1993–94	1 648	20	1 456.80	0.90	47	100
1994–95	894	12	1 148.90	1.30	41	100
1995–96	230	6	462.30	2.00	35	100
1996–97	356	7	344.70	1.00	40	99
1997–98	247	9	338.30	1.40	34	98
1998–99	741	22	884.80	1.20	31	98
1999–00	633	11	356.60	0.60	26	99
2000–01	1 037	13	988.50	1.00	15	100
2001–02	2 114	20	1 636.90	0.80	10	100
2002–03	1 873	22	914.30	0.50	12	99
2003–04	806	15	469.20	0.60	9	100
2004–05	877	17	391.20	0.40	7	99
2005–06	334	7	171.50	0.50	4	100
2006–07	74	4	35.80	0.50	3	99
2007–08	24	2	30.70	1.30	8	100
2008–09	155	5	261.30	1.70	13	98
2009–10	369	4	416.10	1.10	16	98
2010–11	221	5	346.00	1.60	16	98
2011–12	166	4	255.10	1.50	7	100
2012–13	188	3	231.30	1.20	9	99
2013–14	63	2	111.10	1.80	6	100
Totals	**14 600**	**64**	**13 886**			

C. West Norfolk Ridge

Fishing year	No. tows	No. Vessels	ORH catch (t)	ORH CPUE (t/tow)	Zero catch (%)	ORH target (%)
1993–94	21	6	0.70	<0.01	67	90
1994–95	-	-	-	-	-	-
1995–96	2	2	<0.01	<0.01	50	100
1996–97	-	-	-	-	-	-
1997–98	-	-	-	-	-	-
1998–99	4	2	0	-	100	100
1999–00	8	2	0	-	100	100
2000–01	1	1	0.20	0.20	0	100
2001–02	297	3	589.80	2.00	26	100
2002–03	91	5	35.30	0.40	30	100
2003–04	98	2	90.30	0.90	11	99
2004–05	247	6	273.70	1.10	13	100
2005–06	335	6	726.70	2.20	18	97
2006–07	212	6	542.70	2.60	8	100
2007–08	110	3	422.70	3.80	15	100
2008–09	258	5	236.10	0.90	20	100
2009–10	50	3	77.30	1.50	12	100
2010–11	70	5	65.60	0.90	40	97
2011–12	61	3	49.40	0.80	21	100
2012–13	27	2	19.50	0.70	11	100
Totals	**1 892**	**23**	**3 130**			

D. Louisville North

Fishing year	No. tows	No. Vessels	ORH catch (t)	ORH CPUE (t/tow)	Zero catch (%)	ORH target (%)
1992–93	9	1	1	0.10	44	100
1993–94	13	3	2	0.10	23	100
1994–95	92	15	159	1.70	53	99
1995–96	1 295	18	4 026	3.10	36	100
1996–97	697	12	824	1.20	35	100
1997–98	220	10	355	1.60	44	100
1998–99	103	10	222	2.20	50	100
1999–00	317	8	450	1.40	25	99
2000–01	374	11	844	2.30	32	100
2001–02	641	14	483	0.80	34	100
2002–03	387	6	616	1.60	21	100
2003–04	663	11	437	0.70	32	100
2004–05	133	6	219	1.60	34	100
2005–06	150	5	143	1.00	19	100
2006–07	81	2	21	0.30	44	100
2007–08	-	-	-	-	-	-
2008–09	-	-	-	-	-	-
2009–10	15	2	<1	<0.01	47	100
2010–11	30	2	12	0.40	7	100
2011–12	10	2	3	0.30	20	100
2012–13	19	2	5	0.30	5	100
2013–14	1	1	<1	<0.01	0	100
Totals	**5 250**	**45**	**8 822**			

E. Louisville Central

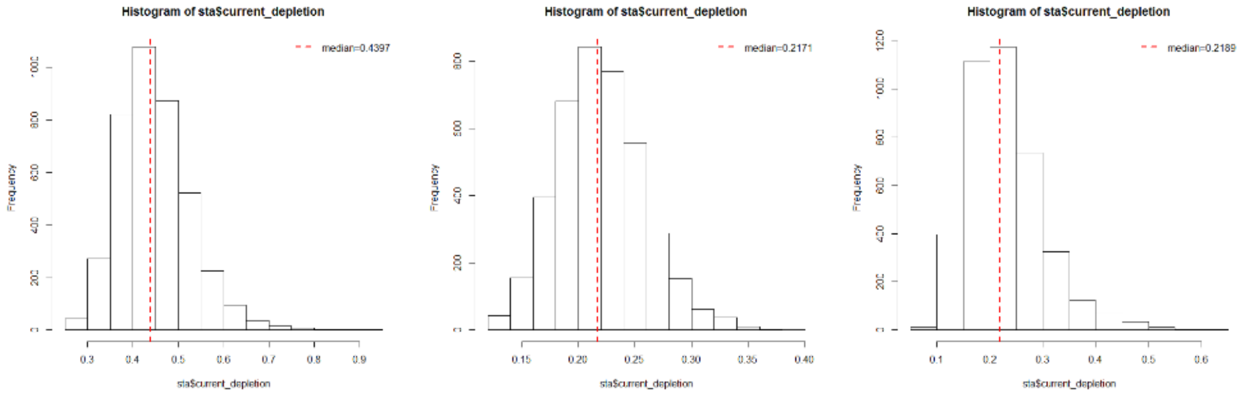
Fishing year	No. tows	No. Vessels	ORH catch (t)	ORH CPUE (t/tow)	Zero catch (%)	ORH target (%)
1989–90	2	1	0	-	100	100
1990–91	-	-	-	-	-	-
1991–92	-	-	-	-	-	-
1992–93	33	2	25	0.80	52	100
1993–94	123	7	187	1.50	40	100
1994–95	3 762	30	9 761	2.60	31	100
1995–96	1 789	23	2 084	1.20	29	100
1996–97	765	13	1 285	1.70	32	100
1997–98	359	10	760	2.10	50	100
1998–99	426	14	704	1.70	38	100
1999–00	294	10	350	1.20	39	100
2000–01	220	9	299	1.40	27	100
2001–02	126	8	182	1.40	25	100
2002–03	184	5	271	1.50	32	100
2003–04	265	9	279	1.10	25	100
2004–05	219	6	415	1.90	21	100
2005–06	203	5	222	1.10	23	100
2006–07	124	2	90	0.70	37	100
2007–08	-	-	-	-	-	-
2008–09	-	-	-	-	-	-
2009–10	188	2	371	2.00	15	100
2010–11	140	3	101	0.70	24	100
2011–12	93	2	185	2.00	22	100
2012–13	177	2	215	1.20	8	100
2013–14	157	2	571	3.60	7	99
Totals	**9 649**	**52**	**18 357**			

F. Louisville South

Fishing year	No. tows	No. Vessels	ORH catch (t)	ORH CPUE (t/tow)	Zero catch (%)	ORH target (%)
1993–94	2	2	-	0.10	50	100
1994–95	450	19	1 325	2.90	57	100
1995–96	805	15	2 685	3.30	50	98
1996–97	383	10	1 112	2.90	48	100
1997–98	221	10	381	1.70	59	100
1998–99	548	17	2 054	3.70	44	100
1999–00	276	11	597	2.20	46	99
2000–01	183	10	463	2.50	49	99
2001–02	115	8	327	2.80	31	100
2002–03	152	9	324	2.10	49	100
2003–04	404	9	703	1.70	49	98
2004–05	389	8	871	2.20	45	95
2005–06	226	4	303	1.30	45	100
2006–07	75	1	212	2.80	35	81
2007–08	-	-	-	-	-	-
2008–09	-	-	-	-	-	-
2009–10	98	2	212	2.20	37	100
2010–11	80	2	172	2.10	38	99
2011–12	191	3	100	0.50	36	100
2012–13	102	2	344	3.40	16	100
2013–14	104	3	183	1.80	12	100
Totals	**4 804**	**43**	**12 368**			

APPENDIX 2

Posterior histograms of current status (Bcurrent/K) for each SPRFMO orange roughy stock, as estimated using BDM fitted to catch series and a spatial CPUE index of abundance.



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

D. Lord Howe Rise **E. Northwest Challenger** **F. West Norfolk Ridge**