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A data-limited approach for assessing small-scale fisheries for Orange roughy
(*Hoplostethus atlanticus*) in the SPRFMO Area

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EXECUTIVE SUMMARY

A spatially-disaggregated catch-per-unit-effort (CPUE) index of stock abundance was developed for low information orange roughy stocks within the SPRFMO Convention Area from. Catch and CPUE data were then used to fit a cohort-aggregated biomass dynamics model for each spatially defined stock. The model fit was able to provide indicative estimates of status and Maximum Sustainable Yield (MSY) reference points for the Louisville stocks (North, Central and South) and the West Norfolk Ridge stock, but the model did not converge for the Northwest Challenger and Lord Howe Rise stocks. Modelling results indicated current depletion below the biomass level consistent with MSY (B_{MSY}) in the Louisville Central stock, and above B_{MSY} in three other stocks (Louisville North and South and West Norfolk Ridge). In the two other Tasman Sea fisheries (Northwest Challenger and Lord Howe Rise), the available data did not permit estimation the stock depletion.

1. Purpose of paper

This paper provides SC-05 with preliminary stock assessment results for SPRFMO orange roughy stocks. Estimates of virgin biomass (B₀), current stock status (2015), and long-term yield are provided.

This paper contains no recommendations for the Scientific Committee. Instead, this paper should be read in conjunction with two separate papers describing different approaches (a delay difference model by Edwards and Roux and a catch-history method by Cordue) and another comparing the results of the two approaches and making recommendations to the committee.

2. Introduction

The assessment of orange roughy *Hoplostethus atlanticus* stocks on the high seas is made difficult by limited data availability and stock structure uncertainties. Within the South Pacific Regional Fisheries Management Organisation (SPRFMO) Convention Area, there are currently no reliable fish age data and fisheries-independent (i.e., trawl and/or acoustic survey) indices of stock abundance for the species. Commercial catch per unit effort (CPUE) data are the principal information source available to evaluate stock status. A data-limited approach was developed and implemented to evaluate stock status and fisheries sustainability (Roux et al. 2017). This approach combined the estimation of spatially-disaggregated CPUE indices of stock abundance, with the fitting of a cohort-aggregated Bayesian biomass dynamics model (BDM), to estimate biomass trajectory and stock status.

In this study, stock assessments were performed using catch series and revised spatial CPUE indices with spatial effects estimated at the scale of 20 minutes latitude/longitude management blocks (a resolution that ensures consistency in spatial management rules among subareas). Results are presented for each of six orange roughy management areas/potential biological stocks (Clark et al., 2016). Until fisheries-independent abundance and age data are available for orange roughy within the SPRFMO convention area, combined spatial CPUE analyses and BDM modelling can provide indicative estimates of stock depletion and maximum sustainable yield (MSY) reference points to inform management decisions.

3. Methods

1. Datasets

Fishery-dependent data sources considered and included in 2017 stock assessments included:

- 1) tow-by-tow catch and effort information from New Zealand and New Zealand-chartered fishing vessels (1979-2015);
- 2) tow-by-tow catch and effort information from Australian fishing vessels (1988-2015);
- 3) spatially and temporally aggregated catch and effort information from Korean fishing vessels (2001-2007); and,
- 4) annual catch statistics from other nations held by the SPRFMO Secretariat (1977-2015).

New Zealand data

Commercial catch and effort data from all fishing events (trawl tows) that targeted or caught orange roughy within and outside the New Zealand EEZ boundaries were extracted from the fishery statistics database managed by the Ministry for Primary Industries (MPI, Replog no. 10889). These data included all fishing effort from New Zealand vessels and New Zealand chartered vessels that occurred within the SPRFMO Area boundaries between 6 April 1989 and 30 September 2016. Earlier data (1978 to 1989) were extracted from the deepwater commercial database (dw_cdb) managed by NIWA. The deepwater commercial data included catch and effort information for all tows that targeted or caught orange roughy or oreo within the New Zealand EEZ and SPRFMO Area boundaries. Both datasets consisted of tow-by-tow information on vessel specifications (i.e., tonnage and flag), start and end date and time, start and end position, target species, bottom depth, fishing speed, and estimated catch of orange roughy (in kg). A few records (n=105)

reported on CELR/HCELR forms that contained information for multiple tows were retained for catch series analyses and removed from the dataset used in CPUE analyses.

Standard error checking and grooming procedures (Roux et al., 2017) were applied to the following data fields: start and end latitude/longitude, bottom depth, trawl speed and tow duration. Missing values and outliers were corrected by median imputation on larger ranges of data (i.e., by assigning missing values or outliers to be the median values calculated using records for the same vessel-day, vessel-week or vessel-management block combination).

Fishing method was not reported in the historical (1978-1989) dataset and all tows were assumed to be bottom trawls. In the more recent (MPI 1989-2016) dataset, bottom and midwater trawl effort was distinguished and missing gear type information was handled by comparing reported fishing depth and bottom depth. Tows for which the reported fishing and bottom depths were identical, or the difference between the two was less than 10 metres, were assumed to be bottom trawls. A difference greater than 10 metres between bottom and fishing depth was assumed to correspond to a midwater tow.

East-West longitude corrections were objectively performed by identifying vessel-start date combinations simultaneously reported in both hemispheres and tabulating the number of fishing events in each. Longitude data were corrected based on the daily modal longitude value. For example, if a vessel reported four fishing events with longitude west and two events with longitude east on the same day, the longitude east events were re-assigned to the western hemisphere. In cases where a vessel reported an equal number of fishing events in each hemisphere on a given day, corrections were made based on the weekly modal longitude. Additional (subjective) corrections were made to re-allocate obvious positional errors south of the Challenger Plateau to the Louisville Ridge (n=300 fishing events).

Australian data

Commercial catch and effort information from Australian fishing vessels operating within SPRFMO orange roughy management areas between 1988 and 2014 were obtained from two sources. Older data (1988-2007) used in earlier work (Clark 2008) were sourced directly from NIWA. These data were initially provided to NIWA by the Australian Fisheries Management Authority (AFMA) via the Bureau of Rural Sciences (BRS) in Canberra. Recent data (2007-2015) were released to MPI and NIWA via the SPRFMO Secretariat. Both data releases were authorised by AFMA on behalf of the Australian government for the purpose of orange roughy stock assessments in the SPRFMO Area. The 1988-2007 dataset consisted of tow-by-tow catch and effort information (fishing event date, duration, start positions (in decimal degrees rounded to 3-digits), vessel name, and estimated catch of orange roughy), for all fishing events that recorded a positive catch of orange roughy (i.e., not including zero catch tows except in 2007). All tows were assumed to be bottom trawls on an orange roughy target. The 2007-2015 data consisted of tow-by-tow catch and effort information (fishing event id, fishing method, target species, vessel id, gear start depth (2015 only) and start and end date, time and position (in decimal degrees rounded to 2-digits)) for all tows that targeted, caught or discarded orange roughy (including zero catch tows). Potential overlap between the two data sources in 2007 was assessed using a vessel-date-position-catch key. No duplicate data were found.

Korean data

Catch information from Korean vessels fishing in the SPRFMO Area in 1999-2007 were released to MPI and NIWA via the SPRFMO Secretariat. Effort information was aggregated in 20 minute (latitude and longitude) blocks for the years 2001, 2002-2006 (combined) and 2007. The data release was authorised by the relevant Korean authorities for the purpose of stock assessments of orange roughy in the SPRFMO Area. Spatially and temporally aggregated effort information were used to calculate annual effort proportions among orange roughy management areas, and allocate annual catches of orange roughy from Korean vessels in 2001-2007 to the different management areas.

FAO Area 81 data

Annual catches of orange roughy in the Pacific Southwest (FAO Area 81) over the period 1977-2015, were obtained from the SPRFMO Secretariat. These included catches reported by Australia, Belize, China, EU, Korea, New Zealand, Russia and Ukraine. Duplicate information reported by Belize and China in 2007

was removed and only the catch reported by China was retained. Korean catches in 1999-2000 were reported to have occurred both on the high seas and within EEZ.

2. Catch series construction

Constructing catch series for each stock consisted of summing annual catches from New Zealand, Australia and selected NZ-chartered vessels by management area, and proportionally adding catches from other flag nations reported to FAO Area 81 (data held by the SPRFMO Secretariat). This approach assumes that catch reporting was complete and that data from joint ventures between New Zealand and flag nations not reporting to FAO Area 81 (e.g., Japan, Norway, etc.) were representative of all fishing activities performed by such nations within the Convention Area. The approach was conservative in that it avoided potential double counting between datasets (NZ, Australia and SPRFMO). It may, however, potentially underestimate the total catch of orange roughy where reporting was incomplete.

For the period 1981-1999, orange roughy catches from New Zealand-chartered vessels were assumed to not have been independently reported to FAO Area 81 (except for Korea in 1999). Annual catch statistics were compiled by summing catches from New Zealand vessels (all forms - including catch reported in CELR and HCEL format), Australia and New Zealand-chartered vessels, by management area. Russian catch data for FAO Area 81 over the period 1977-1991 were not included. Russian catches over that period mainly occurred within the boundaries of the New Zealand EEZ, as evidenced by comparing Russian annual catch totals for FAO Area 81, with those of New Zealand-chartered Russian vessels between 1979 and 1991 (Table 1). Catch totals were comparable in all years but 1979 (when Russia reported a lower catch than reported by NZ-Russia charters). Overall, 99.5% of orange roughy catch and effort by NZ-chartered Russian vessels occurred within the boundaries of the New Zealand EEZ. NZ-Russia charters fished on the high seas in 1982-83, 1986 and 1988. During those years, 50 t of orange roughy were caught (and included) in the Northwest Challenger Plateau management area. Other high seas catch and effort occurred on the South Challenger Plateau, which is a trans-boundary stock subject to stock assessment within the New Zealand domestic quota management system (Cordue 2014).

Table 1. Orange roughy catch and effort information for New Zealand-chartered Russian vessels, 1979-1989, including catch proportions within (% EEZ) and outside (% ET) the boundaries of the New Zealand EEZ; proportions of ET catches located in the Northwest Challenger Plateau (NWC) and South Challenger (SC) management areas; and annual catch totals reported by Russia to FAO Area 81 during those years.

Year	Annual catch orange roughy (t)						Annul Effort (no. tows)		
	FAO Area 81 (Russia)	Total	% ET	NZ-Russia charters			NZ-Russia charters		
				% EEZ	% ET (NWC)	% ET (SC)	Total	% ET	% EEZ
1979	1251	11078	0.0	100.0			740	0.0	100.0
1980	17300	18728	0.0	100.0			3125	0.0	100.0
1981	14076	15407	0.0	100.0			2397	0.0	100.0
1982	8860	7637	3.3	96.7	19.7	80.3	1315	3.6	96.4
1983	7229	5207	1.2	98.8	0.0	100.0	655	0.3	99.7
1984	4028	4058	0.0	100.0			414	0.0	100.0
1985	4306	4405	0.0	100.0			642	0.0	100.0
1986	2475	2438	0.2	99.8	0.0	100.0	320	0.3	99.7
1987	130	167	0.0	100.0			84	0.0	100.0
1988	991	973	0.8	99.2	0.0	100.0	385	1.0	99.0
1989	1132	1390	0.0	100.0			167	0.0	100.0
1990	36	11	0.0	100.0			10	0.0	100.0
1991	506	498	0.0	100.0			126	0.0	100.0
Total	62320	71997	0.5	99.5	15.0	85.0	10380	0.5	99.5

From 2000 onwards (or from 1999 onwards for Korea), catches from flag nations Belize, China, Korea, Russia and the Ukraine were assumed to have been independently reported to FAO Area 81. Annual catches from these nations were allocated to orange roughy management areas based on position data available for temporally overlapping New Zealand-chartered vessels (i.e., 1999-2000 Korean catches and

2000-2004 Ukraine catches); spatial effort information released by Korea for the years 2001-2007; or using annual catch proportions among management areas calculated for New Zealand-flag vessels (i.e., 2003-06 Belize catches; 2001-07 China catches; and 2009 EU catch). Catches from other flag nations that fished under NZ-charters were not reported to FAO Area 81 (but available in the NZ dataset) and were therefore included in annual totals. No duplicate information was found between the Australian dataset and NZ-AUS charters and both catch data were included. Thus, for the period 2000-2015, annual orange roughy catch statistics by management area were derived by summing catches from New Zealand flag vessels; catches from Australian vessels; catches from New Zealand-charters that did not report to FAO Area 81; catches from NZ-AUS charter vessels; and re-allocated catches from Belize, China, Korea, Ukraine and EU independently reported to FAO Area 81.

3. Spatially disaggregated CPUE analyses

Commercial catch per unit effort data (CPUE) were used to develop indices of stock abundance for the six SPRFMO orange roughy management areas considered for preliminary assessments in 2017 (Roux et al. 2017). These included the three management areas on the Louisville Ridge (North, Central and South) and three fisheries in the Tasman Sea (Lord Howe Rise, Northwest Challenger Plateau and West Norfolk Ridge). The data used in CPUE analyses were restricted to positive catch, orange roughy target, bottom trawl tows from both Australia and New Zealand/New Zealand charter vessels.

A spatially-disaggregated approach was used to estimate the annual indices. This approach serves to minimise potential bias from demonstrated non-random temporal changes in the spatial distribution of fishing effort within the SPRFMO orange roughy management areas (Clark et al. 2010, Roux et al. 2017). For each management area, the method consisted of 1) identifying subarea strata; 2) fitting a GLM (Generalised Linear Model) with a year-subarea interaction term and other covariates to estimate standardised CPUE in available year-subarea strata; 3) imputing missing values in year-subarea strata having no CPUE data; 4) assigning a weight to each subarea; and 5) summing across subarea strata in each year to calculate the annual index.

The method implemented this year were broadly similar to those used in preliminary assessments (Roux et al. 2017). A number of key differences and improvements were performed however, in the definition of subarea strata and subarea weights. To ensure consistency in management regime among subareas for a stock, subareas were primarily defined based on the twenty minute latitude/longitude management blocks used by SPRFMO (see Penney and Guinotte 2013 for details). All tows were assigned to a management block based on their start position. Effort occurring on hills or seamounts and effort occurring on the continental slope were distinguished by assigning tows to underwater topographic features (UTFs) listed in the Seamounts database maintained by NIWA (Rowden et al. 2008), following the procedure described in Roux et al. (2017). Each hill/seamount was assumed to constitute an individual subarea with associated hill/seamount effort. Each twenty minute management block was assumed to constitute an individual subarea with associated slope (non-UTF) effort. Exceptions to this were encountered on the Louisville Ridge, where some large oceanic seamounts in some cases spanned several adjacent management blocks characterised by different management regimes (resulting in, for example, a proportion of a seamount subject to a move-on rule while the remaining proportion was either open or closed to fishing). In such cases, the individual seamount was split into two subarea strata subject to different management rules. The resulting subarea strata for each stock are presented in Figure 1.

A number of 'data filters' were applied to the raw CPUE dataset. This included a core vessels selection retaining only data from vessels that fished for a minimum of 2 years with a minimum of 5 tows per year. The resulting 'core vessels' dataset was limited to years in which a minimum total effort of 10 tows was recorded, and to subareas with a minimum of 50 tows over the entire time series and a minimum of five years of observations. Following GLM standardisation, and prior to imputing values in year-subarea strata with no data, an additional 'minimum effort threshold' filter was applied that excluded standardised indices corresponding to year-subarea strata in which effort was less than 5 tows. The resulting catch and effort datasets for each stock (total catch, effort and number of vessels) are presented in Appendix 1. Note that in previous analyses, the New Zealand fishing year (1 October to 30 September of the following calendar year) was used, whereas in the present analyses, calendar year is used throughout the assessment.

The CPUE standardisation involved fitting a GLM with a year-subarea interaction to the log-transformed catch-effort data (tonnes per tow), following the procedure described in Roux et al. (2017). Available covariates offered in the GLM standardisation were vessel, fishing month, year-quarter and flag nation. Year effects and year-subarea effects were extracted from the final GLM model for each stock and used to predict standardised CPUE in year-subarea strata in which fishing occurred.

In year-subarea strata with no fishing activities, missing data were imputed using the 'default imputation method' described by Roux et al. (2017), with backward imputation (prior to the start of fishing) performed by assigning the maximum standardised CPUE recorded during the first three years of fishing to earlier years; forward imputation (following the cessation of fishing) performed by assigning the mean standardised CPUE from the last three years of fishing to subsequent years; and linear interpolation performed to populate missing data in between non-consecutive years.

Subarea weights were estimated based on the extent of 'fishable habitat' and relative density (inferred based on catch information). 'Fishable habitat' for management block subareas was defined as the area (in km²) of the 0-1600 m depth range (i.e., up to the 1600 m depth contour corresponding to the approximate maximum fishing depth) in each management block (see Penney and Guinotte 2013 for details). In the case of hills and seamounts subareas, 'fishable habitat' was defined as the calculated area (in km²) of individual underwater topographic features, as available in the seamounts database (Rowden et al. 2008). Relative density was assumed proportional to a subareas contribution to cumulative catch (i.e., subarea catch/total catch over the time series and entire management area).

In Tasman Sea fisheries, which comprised both slope and hill effort, there was a need to calculate a 'net fishable area' for each management block by subtracting the area of any hills located inside the block from the 'fishable habitat' (0-1600 m depth) area for that block. In cases where hills were located on two or more management blocks boundaries (and effort on the hill was spread across adjacent blocks), the net 'fishable area' for these blocks was calculated by subtracting an area of the hill proportional to hill effort in each block (for example, if a hill was located on the boundary between blocks A and B and 80% of the hill tows occurred in block A and 20% occurred in block B, the 'net habitat area' for block A was calculated as the 'fishable habitat area' for block A minus 80% of the hill area; and the 'net habitat area' for block B was calculated as the 'fishable habitat area' minus 0.20 times the hill area. A similar approach was taken in the Louisville Ridge fisheries where individual seamounts were split into two subareas characterised by different management regimes. In such cases, the total seamount area was split between subareas based on the proportion of effort in each subarea. This approach was very *ad-hoc* and can only be considered as indicative of fishable habitat area for orange roughy. Ideally, more refined GIS work and data layers should be used to more accurately estimate the extent of fishable habitat (or best, suitable or preferred orange roughy habitat) in subareas considered in CPUE analyses.

Subarea weights w_a were estimated by calculating the net fishable habitat area (h_a), normalising it to sum to one across subarea strata, and combining it with the proportional total catch contribution (across the complete time series) from each subarea (referred to as a density proxy d_a), so that:

$$w_a = (h_a + d_a) / 2$$

This approach gives an equal weight to both habitat and density proxies in determining the relative contribution of each subarea strata to total abundance for a stock (i.e., the subarea weights).

The weighted CPUE data were summed across subareas in each year to give the annual indices. All analyses were performed in R software (R Development Core Team 2017).

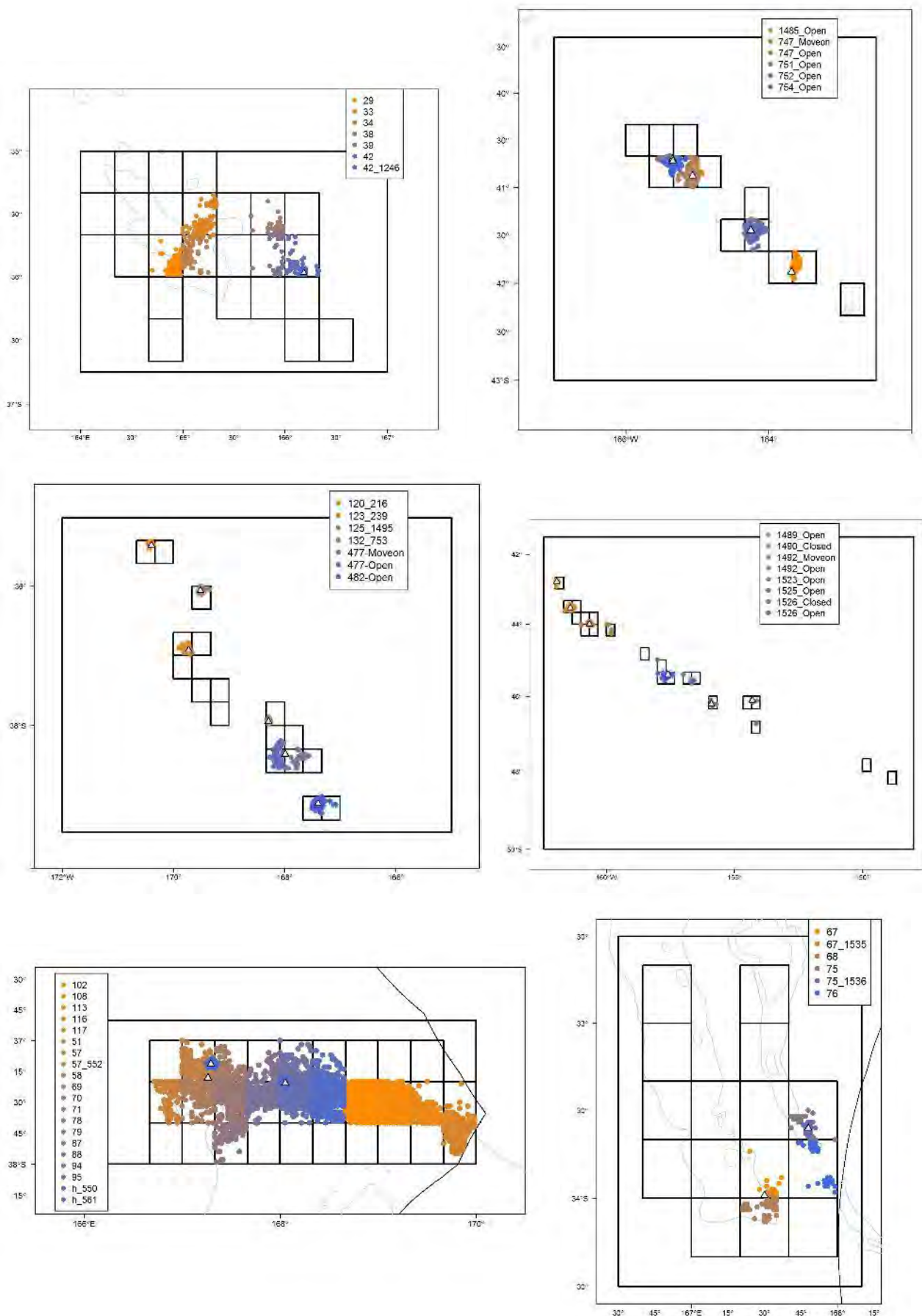


Figure 1. Subarea strata considered for spatial CPUE analyses for each of size orange roughy management area (top left: Lord Howe Rise; top right: Louisville North; middle left: Louisville Central; middle right: Louisville South; bottom left: Northwest Challenger; bottom right: West Norfolk Ridge). Squares correspond to the 20 minute latitude/longitude management blocks. Coloured dots are tow start positions as allocated to different block or hills/seamount subareas.

4. Biomass dynamic modelling

A cohort-aggregated Bayesian biomass dynamic model was fitted to the constructed catch series and spatially-disaggregated CPUE time series for each stock. A detailed description of the model as implemented in the **bdm** R-package (Edwards 2016) and applied to SPRFMO orange roughy stocks was given in Roux et al. (2017). Model validation and testing on a more data-rich orange roughy stock within the New Zealand EEZ was given by McAllister and Edwards (2016).

An informative species-specific log-normal prior for r (the maximum intrinsic population growth rate as biomass approaches zero) was constructed for orange roughy using available life history data from New Zealand stocks (Table 2) using the **lhm** R-package (Edwards 2016). The same prior was offered in all model runs and for all stocks. The ratio of B_{MSY}/K (shape parameter of the productivity function) was given a fixed value of 0.224 in all model runs. This was derived directly from an assumption of Beverton-Holt recruitment with a shape parameter of $h = 0.75$ (Edwards and Roux 2017) and is the same as assumed in age-structured stock assessment models for orange roughy stocks within the New Zealand EEZ (Cordue 2014). To test the sensitivity of assessment results to this assumption, alternative model runs were performed with B_{MSY}/K equal to 0.3 or 0.5. Process error was fixed on input, with a log-normal standard error of 0.05 in all models. Observation error corresponding to the annual standard errors for the spatial CPUE indices was either fixed at 0.20 in all years or adjusted based on the number of observations in each year. In cases for which observation error was adjusted per year, annual estimates for which the number of observations was below the median observed over the entire time series were given a higher standard error (0.45 or 0.50); those with a number of observations close to the median were given a standard error of 0.25; and those with a large number of observations (above the median value) were given a lower standard error of 0.10 or 0.05. Models were run with and without the adjusted standard errors and model selection was based on convergence profiles and fits to the available abundance indices.

Bayesian estimation of the parameters was performed in R using the **RStan** package (Stan Development Team 2016), which implements a Markov Chain Monte Carlo routine.

Table 2. Orange roughy life history data used to construct an informed prior on r . The coefficient of variation (cv) for each parameter was fixed on input. A higher cv (0.30) was given to age-related parameters.

Parameter	Notation	Value	cv
Asymptotic age (yr)	a_{inf}	130	
Natural Mortality	M	0.045	0.3
Age at Maturity (yr)	a_{mat}	38	0.3
Growth (von Bertalanffy)	l_{inf}	37.63	0.3
(cm)	k	0.065	0.3
	t_0	-0.5	0.3
Length-weight	a	0.0921	0.2
	b	2.71	0.2
Recruitment steepness	h	0.75	0.2

4. Results and Discussion

The finalised catch series for eight orange roughy management areas in the western region of the SPRFMO Convention Area are presented in Table 3. These include the six management areas/potential biological stocks considered in stock assessments, as well as the South Tasman Rise and North Lord Howe Rise. Clark (2008) estimated that over 6000 t of orange roughy were caught in the Lord Howe Rise management area during fishing years 1987-88 and 1988-89, including effort by Norway, Japan, South Africa and possibly other nations. No data were available to support these figures (data from NZ-flag and NZ-chartered vessels only gave a total catch of 1943 t orange roughy in the Lord Howe Rise in 1989), but general consensus was reached among members of MPI's South Pacific Working Group (SPACWG) for stock assessment sensitivities to consider including an additional catch of at least 4000 t orange roughy in the Lord Howe Rise in 1988. This was not done in the present assessment but should be considered in the future.

The CPUE indices of stock abundance are presented in Figure 2. The indices were indicative of stock decline in Louisville Central and West Norfolk Ridge. In the Louisville North and South management areas, the CPUE index indicated stable abundance. In Northwest Challenger and Lord Howe Rise, the CPUE indices were generally noisy and suggested increasing abundance in recent years. Deviance tables for the standardisation GLMs fitted with a year-subarea interaction for each stock are presented in Appendix 2. Significant covariates in all but one standardisation were vessel and month. Comparisons between the spatial CPUE, nominal and standardised GLM indices estimated without year-subarea interactions, and imputation, are presented in Appendix 2. In all cases, the spatially-disaggregated approach reduced the extent of the initial biomass reduction. Sensitivities were performed on imputation and subarea weights assumptions in the spatial CPUE, and on the assumption that the CPUE was indexing 100% of the available biomass. The results of such sensitivities are not presented in this report. All sensitivities revealed limited effects on the overall trend. Scenarios including alternative unfished biomass proportions however, did flatten the abundance trend in some areas (not shown).

The spatial CPUE analyses and results were based on the assumption that SPRFMO management blocks were adequate to describe spatial and temporal variations in commercial fishing effort in Tasman Sea fisheries, and for individual seamounts subject to different management rules on the Louisville Ridge. A comparison of spatial CPUE indices estimated using the management blocks to define subarea strata, against the same indices estimated using subarea strata defined by applying an objective distance clustering algorithm, would be desirable and is recommended. This exercise should be accompanied by appropriate GIS work to calculate the 'habitat area' of each resulting cluster.

Time series of spatial CPUE indices of abundance and associated standard errors used in selected BDM runs for each stock are presented in Table 4.

Table 3. Finalised catch series for orange roughy in the SPRFMO Convention Area, 1981-2015, including five management areas in the Tasman Sea (LHN = North Lord Howe Rise; LHR = Lord Howe Rise; NWC = Northwest Challenger; WNR=West Norfolk Ridge; STR= South Tasman Rise); and three management areas on the Louisville Ridge (Louis north (LOUIS.N), central (LOUIS.C) and south (LOUIS.S). Annual figures include orange roughy catches from New Zealand vessels (all forms), Australian vessels and NZ-chartered vessels (1981-1999), as well as catches reported to FAO Area81 by Belize, China, EU, Ukraine (2000-2009) and Korea (1999-2007).

Calendar year	LHN	LHR	NWC	WNR	STR	LOUIS.N	LOUIS.C	LOUIS.S	Total (annual)
1981	0	0	19	0	0	0	0	0	19
1982	0	0	50	0	0	0	0	0	50
1983	0	0	84	0	0	0	0	0	84
1984	0	0	0	0	0	0	0	0	0
1986	0	0	5	0	0	0	0	0	5
1987	0	0	3	0	0	0	0	0	3
1988	0	0	4	0	2	0	0	0	6
1989	0	933	113	0	1	0	0	0	1047
1990	0	127	25	0	11	0	0	0	163
1991	0	52	1	0	0	0	0	0	53
1992	0	484	230	0	0	0	0	0	714
1993	61	1942	2512	0	0	1	25	0	4541
1994	0	744	1698	1	0	1	657	29	3130
1995	0	70	888	0	0	213	9566	1416	12153
1996	0	21	475	0	4	3842	1889	2639	8870
1997	0	125	378	0	1813	684	1277	1178	5455
1998	2	46	489	0	3447	354	760	313	5411
1999	45	463	1083	0	3475	222	712	2138	8139
2000	4	82	633	0	829	495	332	602	2977
2001	0	467	1451	217	169	1023	371	537	4235
2002	0	130	2358	593	102	261	251	421	4116
2003	16	330	1212	38	11	841	443	542	3433
2004	34	392	896	198	49	739	509	1254	4070
2005	94	434	598	497	12	316	630	1314	3894
2006	4	221	262	1023	0	246	272	465	2494
2007	6	59	231	741	0	21	117	294	1470
2008	0	380	31	426	0	0	0	0	837
2009	0	518	336	300	0	0	0	0	1154
2010	0	385	420	79	0	0	371	212	1467
2011	1	280	342	65	0	13	101	172	974
2012	0	173	257	51	0	3	185	100	769
2013	0	393	231	19	0	5	215	344	1207
2014	7	150	124	10	0	0	571	183	1045
2015	0	162	550	20	0	7	341	113	1193
Total (time series)	274	9563	17989	4278	9925	9287	19595	14266	85178

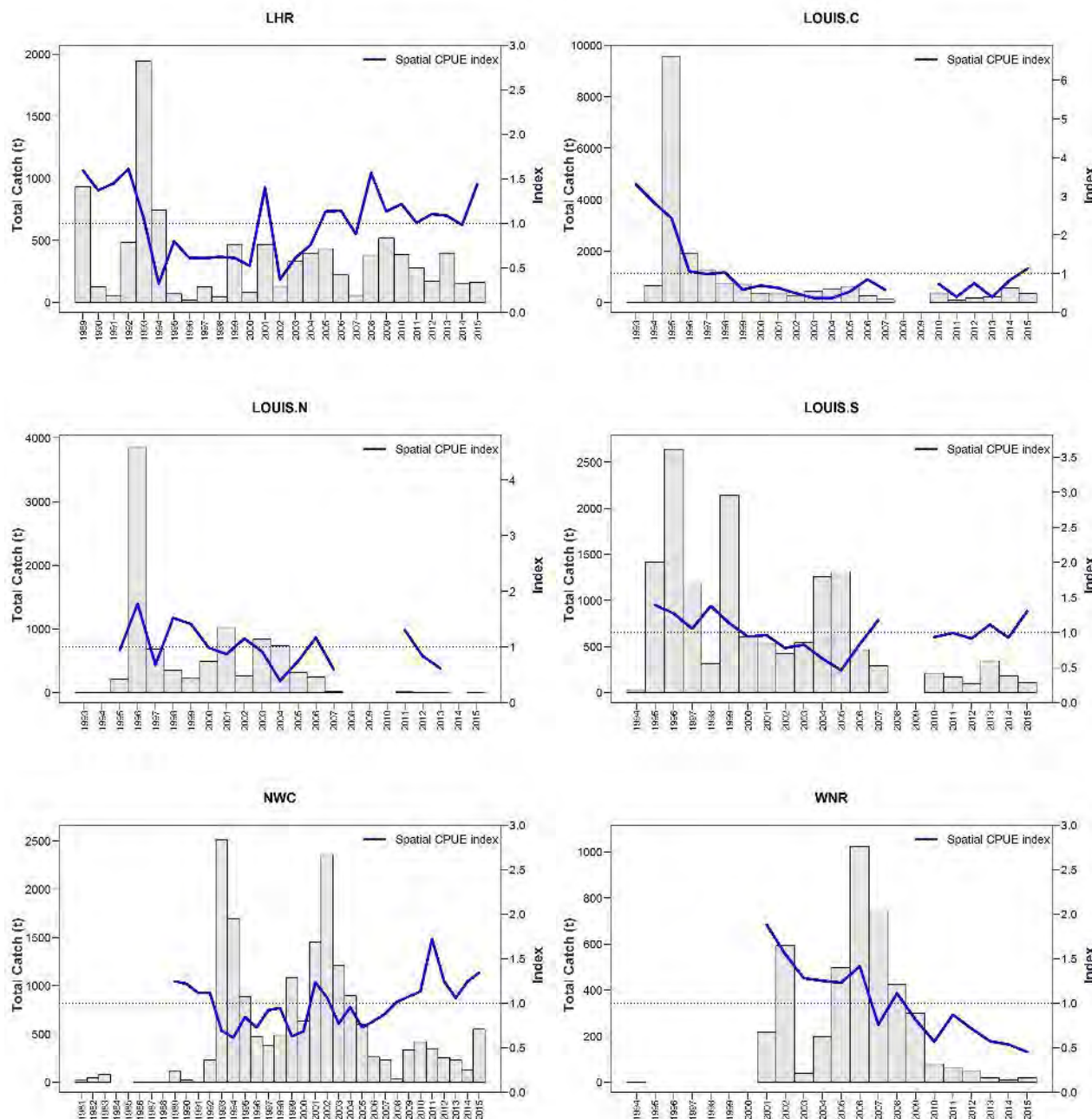


Figure 2. Final spatial CPUE indices of stock abundance for the six orange roughy management areas considered in stock assessments, with annual catch series. The CPUE series is broken for years with no catch.

Table 4. Annual indices of relative abundance and associated standard errors (SE; for some indices the SE was scaled by the number of observations in each year relative to the median across years for that series).

Year	NWC		LHR		WNR		LOUIS.N		LOUIS.C		LOUIS.S	
	index	SE	index	SE	index	SE	index	SE	index	SE	Index	SE
1989			1.00	0.45								
1990	1.00	0.45	0.86	0.45								
1991	0.98	0.45	0.91	0.45								
1992	0.90	0.45	1.01	0.45								
1993	0.90	0.10	0.66	0.10					1.00	0.45		
1994	0.56	0.10	0.20	0.10					0.86	0.10		
1995	0.49	0.25	0.50	0.45			1.00	0.25	0.74	0.10	1.00	0.25
1996	0.68	0.45	0.39	0.45			1.88	0.10	0.32	0.10	0.92	0.05
1997	0.58	0.25	0.38	0.25			0.72	0.10	0.30	0.10	0.76	0.05
1998	0.74	0.25	0.39	0.45			1.61	0.25	0.31	0.45	0.99	0.50
1999	0.76	0.10	0.38	0.25			1.49	0.45	0.18	0.10	0.81	0.05
2000	0.50	0.25	0.33	0.25			1.04	0.25	0.21	0.25	0.68	0.05
2001	0.55	0.10	0.88	0.10	1.00	0.20	0.92	0.25	0.19	0.25	0.69	0.25
2002	0.99	0.10	0.23	0.10	0.83	0.20	1.22	0.10	0.15	0.45	0.56	0.25
2003	0.85	0.10	0.38	0.10	0.68	0.20	0.97	0.10	0.11	0.25	0.60	0.50
2004	0.62	0.10	0.48	0.25	0.66	0.20	0.42	0.10	0.11	0.10	0.45	0.05
2005	0.77	0.10	0.71	0.25	0.65	0.20	0.78	0.45	0.16	0.25	0.33	0.05
2006	0.58	0.25	0.72	0.45	0.75	0.20	1.23	0.25	0.26	0.45	0.60	0.50
2007	0.64	0.45	0.55	0.45	0.40	0.20	0.63	0.45	0.17	0.45	0.85	0.50
2008	0.71	0.45	0.98	0.25	0.59	0.20						
2009	0.81	0.45	0.71	0.10	0.43	0.20						
2010	0.86	0.25	0.76	0.10	0.30	0.20			0.22	0.25	0.67	0.50
2011	0.91	0.25	0.63	0.10	0.46	0.20	1.37	0.45	0.12	0.45	0.71	0.50
2012	1.38	0.45	0.69	0.25	0.38	0.20	0.88	0.45	0.23	0.45	0.66	0.25
2013	1.00	0.25	0.68	0.10	0.30	0.20	0.65	0.45	0.12	0.10	0.80	0.25
2014	0.85	0.45	0.62	0.25	0.28	0.20			0.25	0.25	0.66	0.25
2015	1.00	0.25	0.90	0.25	0.24	0.20	1.16	0.45	0.34	0.25	0.94	0.50

A Bayesian biomass dynamics model (BDM) was successfully fitted to catch series and spatial CPUE indices of relative abundance in five stocks, and provided indicative estimates of current depletion and MSY-based reference points in four stocks (Table 5). Only the Louisville Central stock appeared to be substantially depleted, with a current stock size being 0.19 (0.14-0.25) of the unfished biomass at equilibrium. Both North and South Louisville stocks were estimated to currently be at about half of the unfished biomass, however with broad confidence intervals (0.35-0.70). The West Norfolk Ridge stock in the Tasman Sea had a current status of 0.38 (0.26-0.57). In all stocks, the harvest rate (catch over biomass) at the maximum sustainable yield (MSY) reference point was below 1%. Model fits to the abundance index and depletion trajectories for each stock (including the Lord Howe Rise) are presented in Figure 3 and 4. Convergence trace plots and histograms of estimated parameters are shown in Figure 5. In the case of the Lord Howe Rise, the model was able to fit the abundance index and estimate the unfished biomass, but the fit resulted in a posterior distribution for r well outside the biologically plausible range for orange roughy (mean 0.79 (range 0.59-1.05)). The resulting depletion estimates were therefore deemed unreliable and discarded. The CPUE index for Lord Howe Rise suggested stable or increasing biomass in recent years. A similar trend was observed for the Northwest Challenger stock. The available data for Northwest Challenger did not permit an estimate of the equilibrium biomass (and thus stock status) using the biomass dynamics model (i.e. the model did not converge). Increasing relative abundance over the recent period in the two Tasman Sea fisheries suggested that stock structure assumptions may be

wrong or violated by orange roughy immigration and recruitment to the assessment areas, that the CPUE index is not indicative of abundance, or a combination of both.

The results from sensitivity analyses in which B_{MSY}/K was fixed at alternative values are also shown in Table 5. In all cases, the estimate of current depletion was more optimistic for higher values of B_{MSY}/K , although the effect was only noticeable for Louisville North. Consistent with the assumption of higher productivity implicit in changes to the shape of the production function, the MSY estimates were also higher. Nevertheless, although it is worth noting that despite these results, the qualitative conclusions from these assessments were not materially different.

Finally, we emphasise that the assessments results presented here were constrained by the simplistic assumptions of a cohort-aggregated modelling approach. Nevertheless, in lieu of further data being collected, this approach can provide indicative estimates of depletion and MSY reference points to inform management (McAllister and Edwards 2016).

Table 5. Stock assessments results for successful model fits to orange roughy stocks within the SPRFMO Convention Area, including estimates of current biomass (B), depletion (D), harvest rate (HR), MSY-based reference points and updated r_{max} values from BDM fits. All values are medians of the posterior distributions with 95% credible intervals (intervals are omitted for when both upper and lower bounds are the same as the median). Results are shown for three alternative runs for each stock, assuming a B_{MSY}/K of 0.224, 0.3 or 0.5.

STOCK	B_{MSY}/K	B ₂₀₁₅	D ₂₀₁₅	HR ₂₀₁₅	MSY	B _{MSY}	HR _{MSY}	r_{max}
Louisville North	0.2	6909 (4123-13170)	0.50 (0.35-0.73)	<0.01	101 (38-255)	3050 (2210-4845)	0.03 (0.01-0.09)	0.06 (0.02-0.17)
	0.3	6806 (4278-12658)	0.53 (0.37-0.75)	<0.01	141 (52-329)	3854 (2825-5998)	0.04 (0.01-0.10)	0.07 (0.03-0.20)
	0.5	6643 (4353-10966)	0.59 (0.40-0.83)	<0.01	229 (97-435)	5616 (4139-8341)	0.04 (0.02-0.09)	0.08 (0.03-0.18)
West Norfolk Ridge	0.2	2745 (1700-5474)	0.38 (0.26-0.57)	0.01 (<0.01-0.01)	37 (14-92)	1626 (1075-2856)	0.02 (0.01-0.05)	0.04 (0.02-0.10)
	0.3	2693 (1662-5652)	0.39 (0.26-0.56)	0.01 (<0.01-0.01)	46 (19-112)	2122 (1411-3894)	0.02 (0.01-0.05)	0.04 (0.02-0.09)
	0.5	2554 (1632-5208)	0.39 (0.27-0.57)	0.01 (<0.01-0.01)	66 (28-143)	3297 (2355-5656)	0.02 (0.01-0.04)	0.04 (0.02-0.08)
Louisville Central	0.2	3719 (2760-5048)	0.19 (0.14-0.25)	0.09 (0.07-0.12)	234 (119-346)	4348 (3596-5411)	0.05 (0.03-0.09)	0.11 (0.05-0.17)
	0.3	3713 (2781-5106)	0.20 (0.15-0.26)	0.09 (0.07-0.12)	271 (146-393)	5666 (4708-7017)	0.05 (0.02-0.07)	0.10 (0.05-0.15)
	0.5	3594 (2694-4972)	0.20 (0.15-0.26)	0.09 (0.07-0.13)	389 (218-572)	9164 (7722-11251)	0.04 (0.02-0.07)	0.08 (0.04-0.13)
Louisville South	0.2	12760 (7389-27765)	0.53 (0.39-0.71)	0.01 (<0.01-0.02)	210 (80-500)	5399 (3584-10130)	0.04 (0.01-0.10)	0.07 (0.03-0.21)
	0.3	11621 (6904-24614)	0.54 (0.40-0.72)	0.01 (<0.01-0.02)	286 (110-582)	6443 (4244-12080)	0.04 (0.01-0.11)	0.09 (0.03-0.22)
	0.5	10585 (6652-21120)	0.57 (0.43-0.76)	0.01 (0.01-0.02)	374 (174-632)	9274 (6413-16403)	0.04 (0.02-0.08)	0.08 (0.03-0.16)

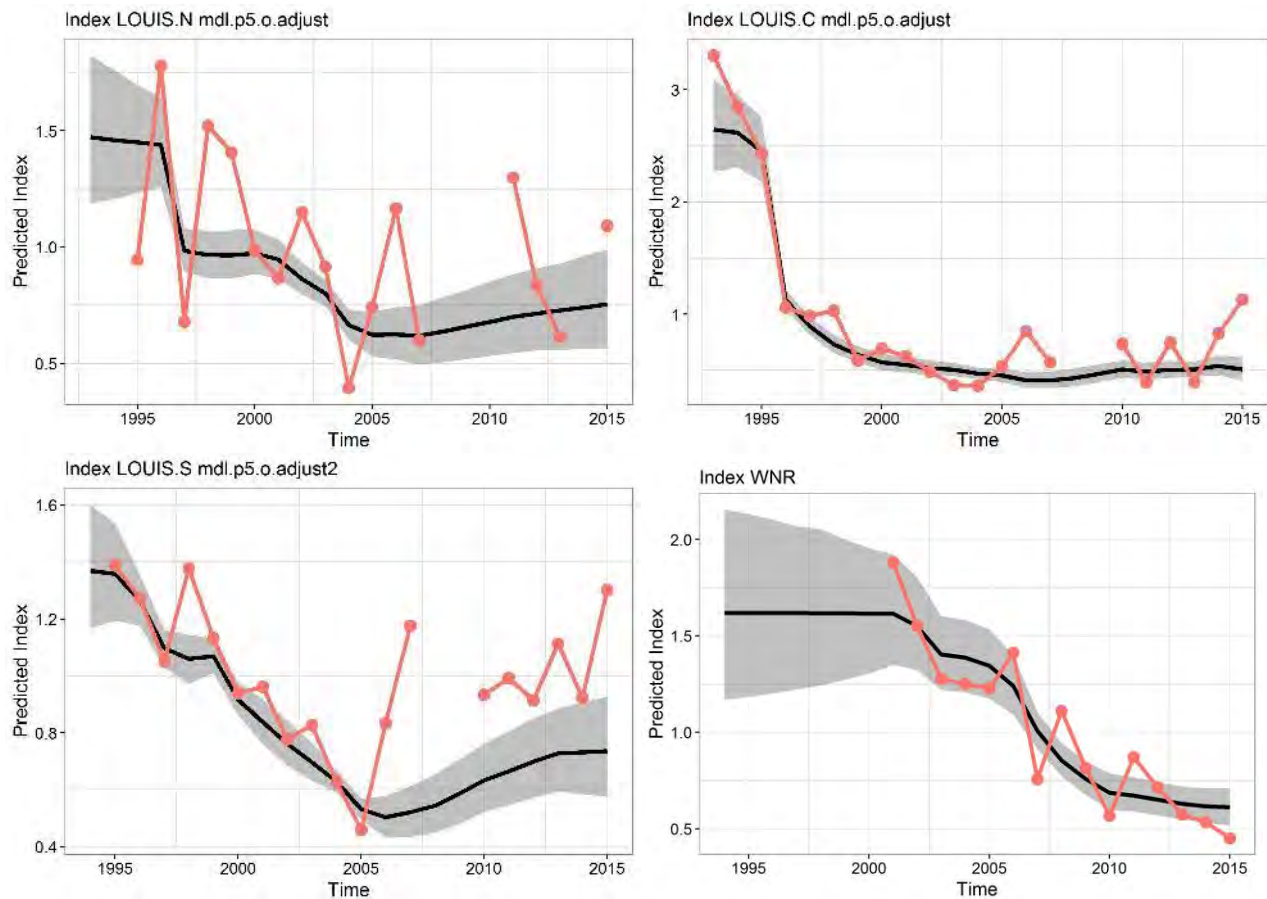


Figure 3. Successful BDM model fits to the spatial CPUE index for four stocks (Louisville North; Louisville Central; Louisville South; West Norfolk Ridge). The predicted CPUE (median and 95% credible intervals are shown with the observed points). The model did not converge for the Lord Howe Rise or Northwest Challenger stocks, and these results are not shown.

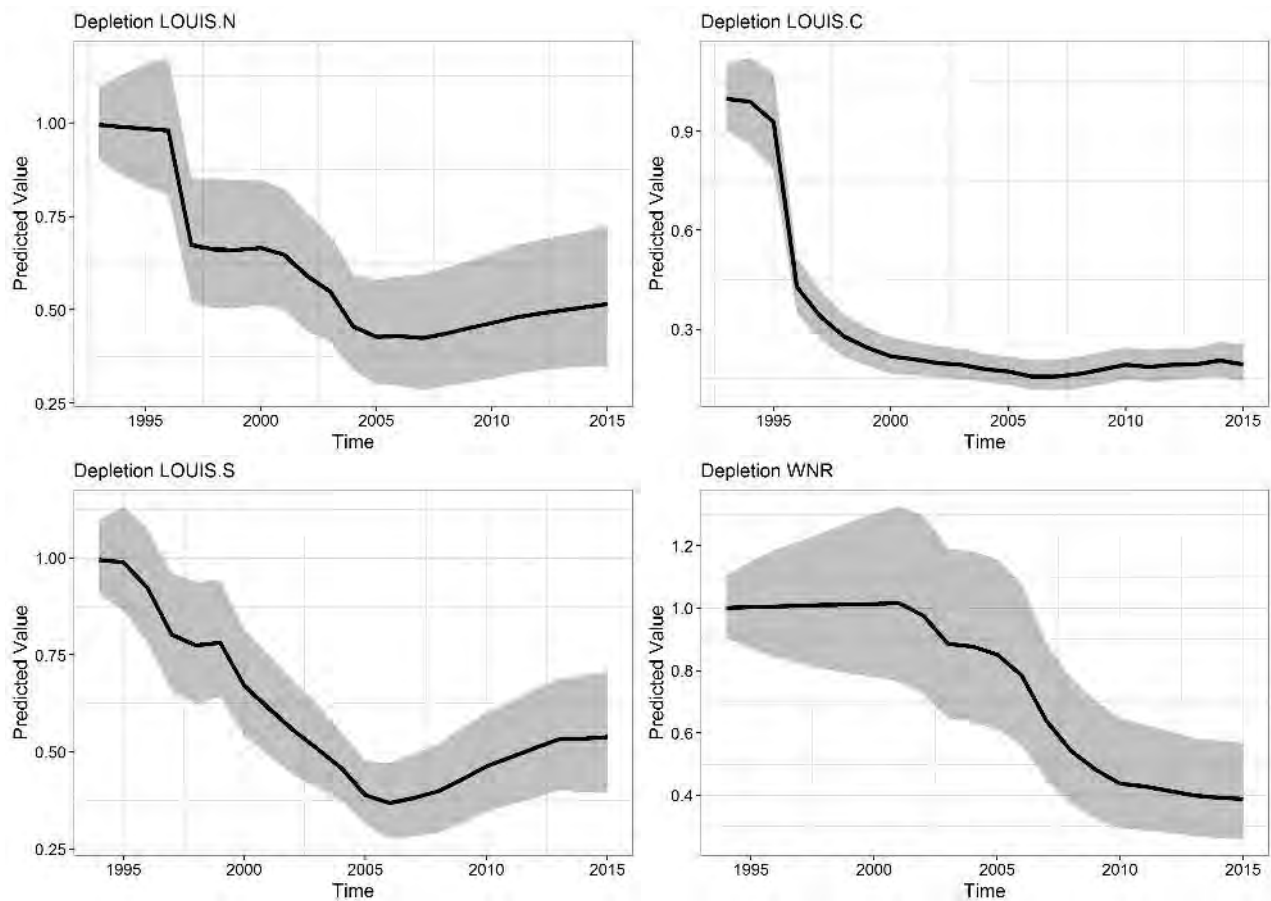


Figure 4. Estimated depletion (median and 95% credible intervals) in four SPRFMO orange roughy stocks (Louisville North; Louisville Central; Louisville South; West Norfolk Ridge). The model did not converge for the Lord Howe Rise or Northwest Challenger stocks, and these results are not shown.

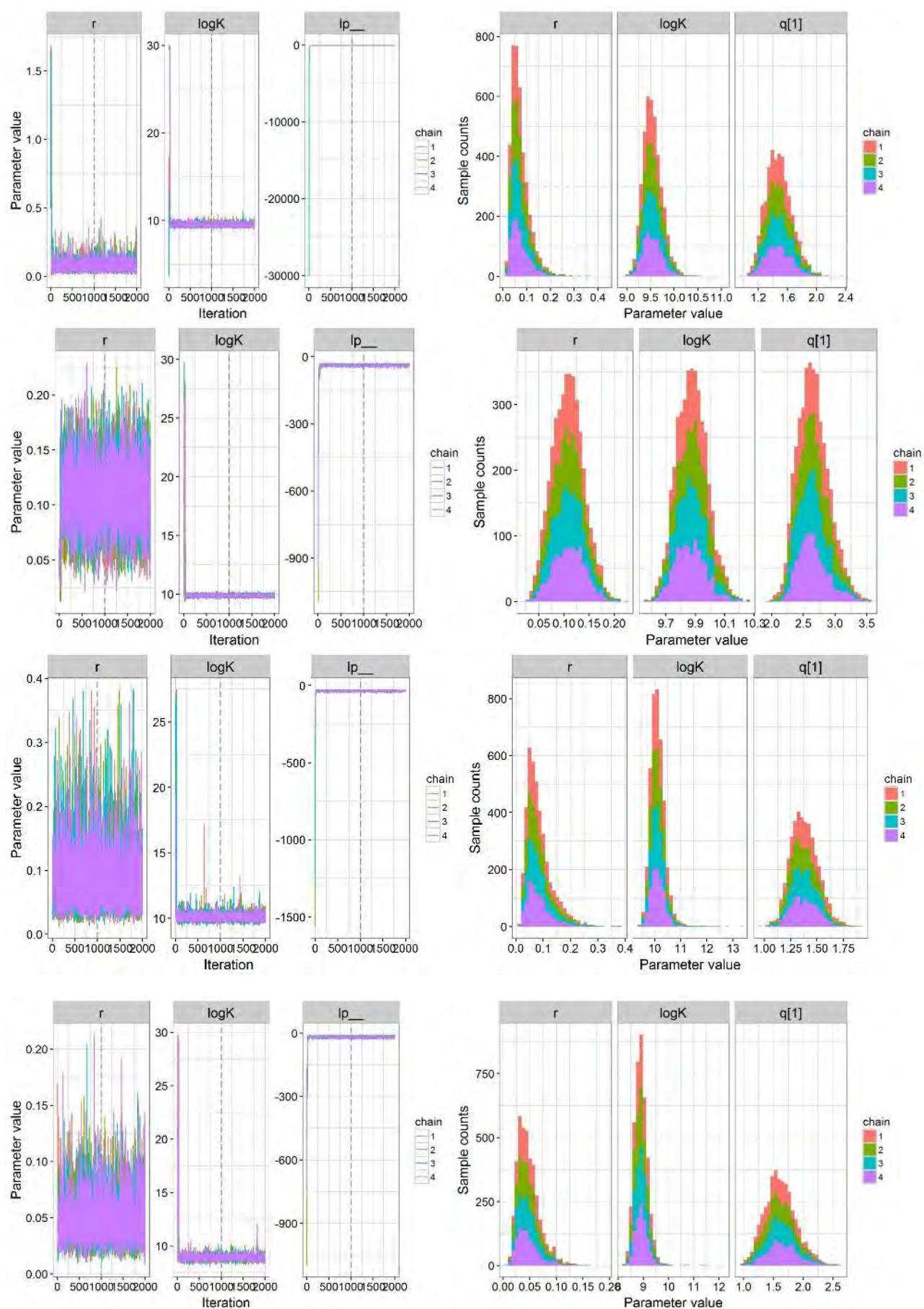


Figure 5. Convergence profiles (trace plots, left) and estimated parameters posterior distributions (right) for BDMs fitted to orange roughy catch and spatial CPUE data in four SPRFMO management areas. Top row: Louisville North; second row: Louisville Central; third row: South Louisville; bottom row: West Norfolk Ridge.

5. Conclusions

We have shown that an approach combining the estimation of spatially-disaggregated CPUE indices of stock abundance and a cohort-aggregated biomass dynamics model can provide indicative estimates of status and MSY reference points for low information orange roughy stocks within the SPRFMO Convention Area. This year's assessments were performed using all available catch information and revised spatial CPUE indices with spatial effects estimated at the scale of 20 minute latitude/longitude SPRFMO management blocks (to ensure consistency in spatial management rules among subareas). BDM modelling results indicated current depletion below B_{MSY} in the Central Louisville stock, and above B_{MSY} in three other stocks (Louisville North and South and West Norfolk Ridge). In the two other Tasman Sea fisheries (Northwest Challenger and Lord Howe Rise), the available data did not permit estimation the depletion using this approach.

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APPENDIX 1

Summary of the datasets used to estimate spatial CPUE indices of abundance for SPRMO orange roughy (ORH) stocks.

LORD HOWE RISE

Year	No. tows	No. Vessels	ORH catch (t)
1989	49	4	129.4
1990	13	1	11.1
1991	3	1	1.2
1992	53	5	366.1
1993	345	11	1 083.3
1994	473	10	434.1
1995	43	5	67.0
1996	40	3	20.8
1997	78	5	118.5
1998	62	6	45.5
1999	96	8	406.8
2000	75	5	30.6
2001	125	9	433.1
2002	104	10	102.5
2003	177	6	257.1
2004	102	9	281.3
2005	79	9	322.9
2006	54	6	197.3
2007	43	4	43.1
2008	68	3	361.1
2009	149	5	362.3
2010	125	3	328.9
2011	103	5	205.1
2012	93	3	157.8
2013	214	4	392.5
2014	77	3	148.9
2015	84	4	145.8
Total	2 927	30	6 454

LOUISVILLE NORTH

Year	No. tows	No. Vessels	ORH catch (t)
1995	115	10	209.06
1996	605	11	2 828.89
1997	298	9	592.52
1998	117	9	301.89
1999	30	7	207.12
2000	216	5	433.72
2001	239	10	819.10
2002	397	12	469.89
2003	295	7	610.15
2004	389	8	340.94
2005	72	5	165.59
2006	101	4	134.32
2007	45	2	20.87
2008	-	-	-
2009	-	-	-
2010	-	-	-
2011	28	2	12.16
2012	-	-	-
2013	17	2	5.24
2014	-	-	-
2015	15	1	6.98
Total	2 979	24	7 158

LOUISVILLE CENTRAL

Year	No. tows	No. Vessels	ORH catch (t)
1993	15	2	25.3
1994	168	6	563.8
1995	2 160	21	8 235.26
1996	759	14	1 511.63
1997	433	12	1 062.20
1998	108	9	467.5
1999	240	12	661.7
2000	135	5	307.2
2001	130	8	246.6
2002	92	8	176.8
2003	127	4	263.6
2004	167	7	255.3
2005	146	5	171.0
2006	125	4	200.4
2007	77	2	89.6
2008	-	-	-
2009	-	-	-
2010	158	2	371.2
2011	105	3	100.7
2012	70	2	185.1
2013	162	2	215.5
2014	145	2	566.8
2015	145	3	341.4
Total	5 667	29	16 018.48

LOUISVILLE SOUTH

Year	No. tows	No. Vessels	ORH catch (t)
1995	131	10	995.5
1996	223	10	1 966.75
1997	173	6	1 084.49
1998	73	9	276.1
1999	271	14	1 662.62
2000	139	8	591.3
2001	87	9	449.0
2002	78	6	326.9
2003	73	9	235.3
2004	157	6	547.1
2005	156	7	279.5
2006	25	3	33.3
2007	34	1	209.8
2008	-	-	-
2009	-	-	-
2010	60	2	212.1
2011	48	2	171.4
2012	117	3	100.3
2013	86	2	343.9
2014	90	2	182.8
2015	35	2	113.5
Total	2 056	24	9 781.5

NORTHWEST CHALLENGER PLATEAU

Year	No. tows	No. Vessels	ORH catch (t)
1989	25	2	30.4
1990	30	2	23.0
1991	-	-	-
1992	20	2	184.6
1993	556	6	1 248.8
1994	836	13	1 579.3
1995	302	9	860.0
1996	152	4	463.8
1997	201	6	375.7
1998	206	9	400.7
1999	562	18	831.7
2000	416	10	345.4
2001	906	13	1 237.8
2002	1 839	22	1 636.3
2003	1 534	20	888.1
2004	697	14	584.5
2005	739	14	390.7
2006	293	7	154.1
2007	152	5	212.6
2008	22	2	30.7
2009	131	5	261.0
2010	303	4	412.1
2011	164	5	339.4
2012	153	4	253.5
2013	168	3	230.5
2014	78	3	124.0
2015	516	6	547.3
Total	11 001	39	13 646

WEST NORFOLK RIDGE

Year	No. tows	No. Vessels	ORH catch (t)
2001	14	2	110.85
2002	212	2	419.39
2003	41	2	23.43
2004	94	1	105.01
2005	237	2	310.6
2006	175	3	635.21
2007	170	4	514.42
2008	96	4	421.19
2009	177	4	228.48
2010	45	4	38.25
2011	28	4	62.75
2012	44	2	48.89
2013	23	2	19.26
2014	-	-	-
2015	28	2	20.42
Total	1 384	6	2 958.14

APPENDIX 2

Deviance tables for GLM standardisations fitted with a year-subarea interaction to estimate spatial CPUE indices of relative abundance.

Lord Howe Rise

	df	Deviance	Resid. Df	Resid. Dev	Rsqr
NULL	NA	NA	2926	15571.25	0.00
year	26	1082.04	2900	14489.21	6.95
subarea	6	394.03	2894	14095.18	9.48
vessel	29	1117.34	2865	12977.84	16.66
month	11	323.57	2854	12654.27	18.73
year:subarea	103	571.69	2751	12082.58	22.40

Louisville North

	Df	Deviance	Resid. Df	Resid. Dev	Rsqr
NULL	NA	NA	2978	11389.6	0.0
year	15	1157.7	2963	10231.9	10.2
subarea	6	122.2	2957	10109.7	11.2
vessel	23	1141.4	2934	8968.3	21.3
month	11	582.6	2923	8385.7	26.4
year:subarea	67	578.1	2856	7807.6	31.5

Louisville Central

	Df	Deviance	Resid. Df	Resid. Dev	Rsqr
NULL	NA	NA	5666	22041.5	0.0
year	20	1160.6	5646	20880.9	5.3
subarea	5	46.4	5641	20834.5	5.5
vessel	28	1965.5	5613	18869.0	14.4
month	11	613.7	5602	18255.3	17.2
year:subarea	86	889.7	5516	17365.6	21.2

Louisville South

	Df	Deviance	Resid. Df	Resid. Dev	Rsqr
NULL	NA	NA	2055	12340.7	0.0
year	18	1179.5	2037	11161.2	9.6
subarea	7	132.5	2030	11028.7	10.6
vessel	23	1401.3	2007	9627.4	22.0
month	11	405.1	1996	9222.4	25.3
year:subarea	82	808.2	1914	8414.2	31.8

Northwest Challenger

	Df	Deviance	Resid. Df	Resid. Dev	Rsqr
NULL	NA	NA	11000	30657.8	0.0
year	25	1056.6	10975	29601.1	3.5
vessel	38	2319.6	10937	27281.5	11.0
month	11	489.1	10926	26792.4	12.6
subarea	19	373.6	10907	26418.7	13.8
year:subarea	324	2092.7	10583	24326.0	20.7

West Norfolk Ridge

	Df	Deviance	Resid. Df	Resid. Dev	Rsqr
NULL	NA	NA	1383	36274.38	0.00
year	13	2186.06	1370	34088.32	6.03
subarea	5	1644.32	1365	32443.99	10.56
year:subarea	53	3355.12	1312	29088.87	19.81

APPENDIX 3

Comparison between spatial CPUE time series used in stock assessments, nominal CPUE, and standardised annual indices estimated using standard GLM procedure without year-subarea interactions.

