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Evaluating the orange roughy population and wider ecosystem impacts of carrying forward of TACs over multiple years

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Evaluating the orange roughy population and wider ecosystem impacts of carrying forward of TACs over multiple years

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1. Purpose

The purpose of this paper is to evaluate the orange roughy population and wider ecosystem impacts of carrying forward of Total Annual Catches (TACs) over multiple years (SC11-DW06). This task includes evaluating the impact of different year gaps in harvesting on: the orange roughy population; the footprint of the fishery and overlap of footprint with predicted distributions of VME indicator taxa. Simulation techniques were used to estimate orange roughy spawning biomass and depletion and predict the fishing footprint for four different year gaps in harvesting with allocated catch carried over. This work will inform SC advice on the appropriateness of carrying forward allocated orange roughy catch over multiple years.

2. Background

In 2022, stock assessment models using catch history, and age and length compositions, were used to estimate the minimum pre-fishing biomass that could have supported historical catches for each stock (Stephenson et al., 2022, SC10-DW01_rev1). Estimates of the minimum pre-fishing biomass (Bmin) were made for Central, South, and North Louisville stocks, West Norfolk stock, Lord Howe Rise stock, and Northwest Challenger stock.

The Bmin estimates replaced the previous Bayesian stock assessments after simulation modelling in 2022 found the data were insufficient to inform the most-likely (median) biomass estimates (B0), and the previous assessments were therefore misleading (Stephenson et al., 2022, SC10-DW01_rev1). Bmin was used as a proxy for B0, with sustainable yields (TACs) calculated by applying a fixed scalar associated with an MCY policy (1.45%) to the Bmin (i.e., sustainable yield = 0.0145 × Bmin). The MCY scalar of 1.45% was intended to be applied to B0, therefore the yields, being calculated using Bmin, were precautionary. The catch limits are shown in Table 1.

Table 1: Orange roughy total allowable catch (TAC) limits (t) in SPRFMO by management stock and fishing year.

Year	Northwest Challenger Stock	Lord Howe Rise Stock	West Norfolk Ridge Stock	Louisville Stock (C/N/S)
2021	396	261	54	1140
2022	396	261	54	1140
2023	160	174	44	581(305/116/160)
2024	160	174	44	581(305/116/160)
2025	160	174	44	581(305/116/160)

The reduced TACs potentially reduced the profitability of the fisheries, because large distances between fishing grounds would still have to be covered, but for reduced catch. This effect might be mitigated if TACs were not annual, but taken in intermittent years, i.e., TACs were carried forward over multiple years. This carry forward would allow a higher catch to be taken when fishing vessels did attend the grounds.

The research objective for 2023 was to evaluate the orange roughy population and wider ecosystem impacts of carrying forward TACs over multiple years (SC11-DW06). Both questions have been addressed here using simulation techniques.

3. Methods

3.1 Impact on the orange roughy stock

The Operating Model (OM) of a fished orange roughy population was based upon the simulation model for the Central Louisville stock, reported by Stephenson et al. (2022, SC10-DW01_rev1), with the following settings for population dynamics:

- One stock, with ages 1 through 150 with a plus group at age 150.
- Logistic maturity-at-age with A_{50} = 30 and A_{to95} = 5.
- One length-at-age relationship with parameters for Schnute female from Cordue (2019).
- One length-weight relationship, parameters from Cordue (2019).
- One fishery, with selectivity-at-age set equal to maturity.
- A simulation 'burn-in' period of 200 years with no catch ("init" period), followed by 27 years of catches following the catch history of the Louisville Central stock ("expl" period); catches being the sum of "cluster3" and "mainpop" fisheries from the Cordue (2019) assessment.
- Following the expl period, 200 years projection with constant catches ("proj" period).
- Stock-recruitment followed a Beverton-Holt model with steepness of 0.75.
- Year class strengths followed a sinusoidal cycle with a minimum value 0.25 and a maximum value of 4, with a random cycle start year for each period "init", "expl", and "proj" in each simulation, and random length of sinusoidal cycle (full period range 6–60 years) (Figure 1).
- A natural mortality rate of 0.045 yr^{-1}.
- A maximum exploitation rate of 80% (although this was not incurred).
- The OM was run with alternative configurations for virgin spawning stock biomass (SB_0), being 18 500 t and 37 000 t. After the init period the 18 500 t and 37 000 t SB_0 were roughly 26 000 t and 52 000 t. There is an increase in SB from the initial because the assumed lognormal year class strengths have a median of 1, but a mean slightly higher than 1 (1.35).

Figure 1: Year class strengths (recruits) in the simulation model ($SB_{initial}$ = 25 968 t). Solid black line, median; blue shaded zone, 40-60% credible interval; orange shaded zone, 25–75% credible interval; yellow shaded zone, 2.5–97.5% credible interval. Thin black, green, and red lines show example alternative YCS trajectories.

The light blue vertical line indicates the end of the initialisation period (beginning of the exploitation period), and the orange vertical line indicates the end of the exploitation period (beginning of the projection period).

The catches during the proj period were set using one of four alternative harvest control rules (HCR). The annual catch was set as 0.0145 × 26 000 t, regardless of which SB_0 was assumed. The harvest control rules applied were:

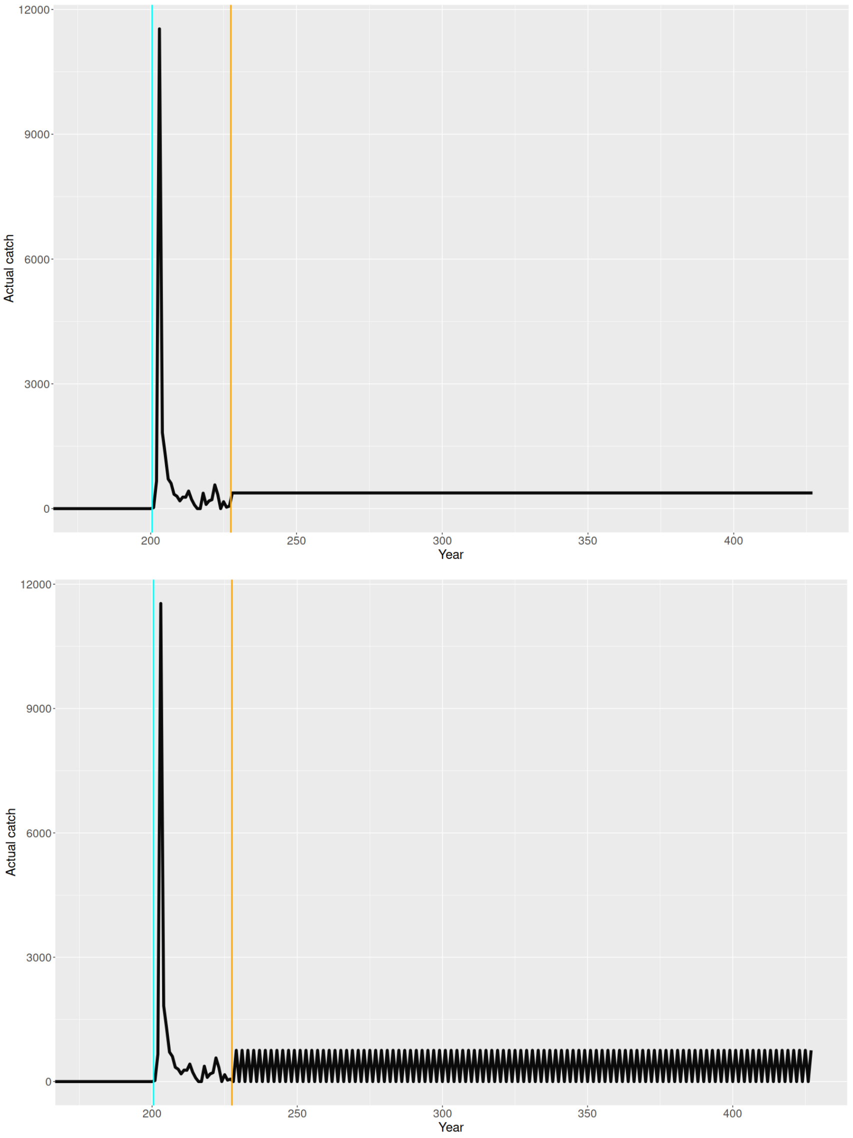
gap 0: catches are 0.0145 * 26 000 t every year

gap 1: catches are 2 * 0.0145 * 26 000 t every other year and 0 catch every other year

gap 2: catches are 3 * 0.0145 * 26 000 t every 3 years, with 0 catch in the other years

gap 3: catches are 4 * 0.0145 * 26 000 t every 4 years, with 0 catch in the other years

The catch histories produced under alternative rules are shown in Figure 2.



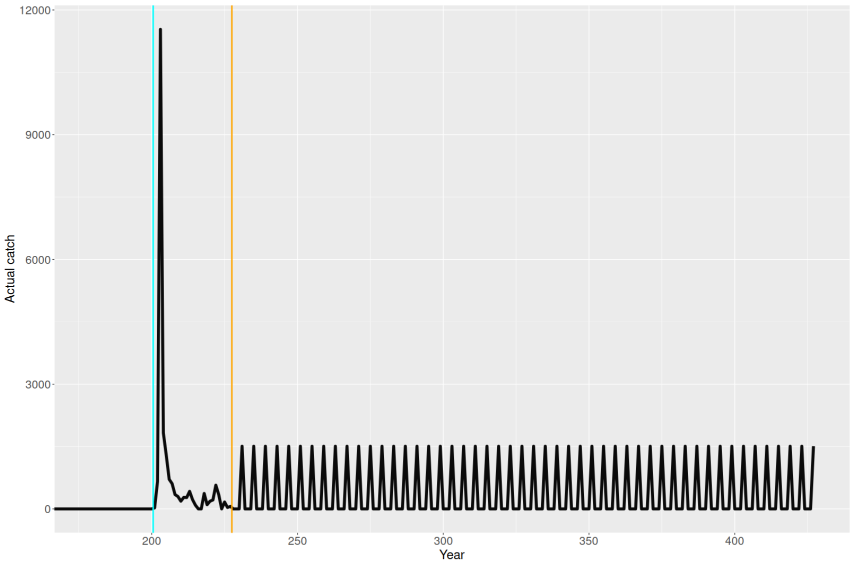


Figure 2: Example HCR catches (SB$_{initial}$ = 25 968 t). Top panel, catch every year; middle panel, catch every other year (year gap = 1); bottom panel, catch every fourth year (year gap = 3). Black line indicates the catch. Blue vertical line marks the end of the burn in. Vertical orange line marks the start of the HCR simulation period.

3.2 Impact on the fishing footprint

We made predictions of the fishery spatial footprint under different catch limits using a simple simulation process, where we sampled without replacement from the recent historical fishing trips until the required catch was achieved. These historical records of catch and effort are supplied to government agencies, and SPRFMO, as part of statutory requirements of the fishing licences. We did not, therefore, try to explicitly model fisher behaviour and catches, but simply assumed these would follow those reported in recent historical years.

Catch and effort data for orange roughy fishing in the SPRFMO Evaluated Area were obtained directly from Fisheries New Zealand and, for Australian vessels, from the SPRFMO Secretariat. No other nations have participated in this fishery in recent years.

Although the current bottom trawl management areas (BTMAs) were introduced in 2019, and it may have been preferable to limit the data used to the period from this date forward, our investigations found this data set to be limited and insufficient. As a result, we included data from earlier years, but only records from within current (or proposed, see below) open areas. The data supplied for Australian fishing (313 records total) covered the period from 2013 to 2020. To avoid introducing any bias resulting from a difference in fishing grounds or fishing strategy between the fleets of the two nations, we limited the New Zealand records to the same set of years (4704 records total).

Fishing for orange roughy between 2013 and 2020 mainly took place in four Fishery Management Areas (FMAs), Central Lord Howe, Northwest Challenger, and Central and South Louisville (Tables 2 & 3), with little fishing in the remaining FMAs, particularly in the more recent years. To be consistent with the stock assessment aspect of orange roughy analysis (Stephenson et al., 2022, SC10-DW01_rev1), the straddling stock on Westpac Bank assessed separately by Fisheries New Zealand (Fisheries New Zealand 2023) was not included.

Table 2: Number of records available for the BTMA-area based simulations (with numbers for PS70% areas in parenthesis), by year and FMA.

Year	Central Lord Howe	Central Louisville	North Lord Howe	North Louisville	Northwest Challenger	South Louisville	West Norfolk
2013	245(184)	174(0)	1(1)	14(14)	198(180)	100(45)	27(23)
2014	90(72)	163(24)	10(10)	3(3)	121(95)	104(25)	17(6)

2015	115(95)	161(28)	0(0)	17(17)	635(370)	37(23)	32(17)
2016	95(63)	20(0)	3(3)	27(27)	642(455)	4(0)	0(0)
2017	173(107)	258(0)	5(5)	25(25)	467(284)	51(22)	24(10)
2018	120(82)	49(0)	3(3)	0(0)	315(244)	30(11)	13(4)
2019	42(20)	0(0)	0(0)	0(0)	147(106)	37(0)	1(0)
2020	14(8)	49(0)	0(0)	0(0)	72(69)	57(16)	6(3)

Table 3: Catch of orange roughy (t) from all records available for the BTMA-area based simulations (with catch for PS70% areas in parenthesis), by year and FMA.

Year	Central Lord Howe	Central Louisville	North Lord Howe	North Louisville	Northwest Challenger	South Louisville	West Norfolk
2013	393(334)	203(0)	0(0)	5(5)	246(228)	343(201)	19(16)
2014	149(115)	568(107)	4(4)	2(2)	195(149)	183(48)	8(3)
2015	165(106)	338(46)	0(0)	7(7)	655(418)	113(107)	20(18)
2016	202(122)	37(0)	0(0)	27(27)	552(361)	10(0)	0(0)
2017	269(139)	158(0)	3(3)	18(18)	374(199)	234(86)	21(1)
2018	178(143)	34(0)	0(0)	0(0)	398(326)	48(2)	5(0)
2019	38(22)	0(0)	0(0)	0(0)	221(187)	139(0)	0(0)
2020	2(1)	31(0)	0(0)	0(0)	76(74)	102(48)	3(3)

Some formatting of the positional information was carried out. The New Zealand vessel trawl positions were adjusted for the gear offset (the horizontal distance of the gear behind the vessel) using the vessel start and finish positions, and the recorded depths using standard methods (SPRFMO 2020). This adjustment was not made for Australian vessel trawl positions as the positions provided were insufficiently accurate (i.e., truncated to 2 decimal places) and no depth data were available. Some tows (from both sources) were very short, or poorly recorded with either no finish position or a finish position identical to the start position: to enable a footprint to be assigned to these records, a short distance was assigned to them (~150 m) centred on the start position.

The width of contact from orange roughy trawls in SPRFMO varies by nationality and according to whether the trawl is on an underwater topographic feature (UTF) or on the surrounding slope. Agreed values for these widths have been published by SPRFMO (https://www.sprfmo.int/assets/Meetings/SC/8th-SC-2020/SC8-DW07-rev-1-Cumulative-Bottom-Fishery-Impact-Assessment-for-Australia-and-New-Zealand.pdf) and are shown in Table 4. All records were therefore assigned as either UTF or slope trawls, based on the distance to the nearest UTF (hill <3 n.miles; knoll <5 n.miles; seamount < 8 n.miles) and trawl duration (<0.5 h for UTF tow). Finally, the calculated trawl distances and tow-type/nation specific widths were used to create individual footprint polygons for all records, using spatial methods implemented in R.

Table 4: Orange roughy trawl contact widths (m) by nationality and seabed terrain type (UTF = underwater topographic feature).

	Trawl contact width (m)	
Tow type	Australian vessels	New Zealand vessels
UTF	85	115
Slope	100	135

Catch limits

Orange roughy catch limits in SPRFMO are allocated by stock rather than FMA (see https://www.sprfmo.int/assets/Meetings/01-COMM/11th-Commission-2022-COMM11/COMM11-Report/Annex-7c-CMM-03a-2023-Deepwater-species.pdf). The distinction in this case affects only the

Lord Howe Rise stock, which comprises two FMAs (Central Lord Howe and North Lord Howe). Catch limits for all stocks were reduced in 2023 and separate limits were introduced for the three stocks differentiated along the Louisville Seamount Chain (Table 1).

Four catch scenarios were simulated: 1, catch limits are fully taken annually (representing the status quo); 2, catches limits are accumulated for two years then fully caught; 3, catches limits are accumulated for three years then fully caught; 4, catches limits are accumulated for four years then fully caught. The annual catches in each management stock associated with each scenario are shown in Table 5.

Table 5: Catch accumulation scenarios. NW Chall – North West Challenger, LHR – Lord Howe Rise, WNR – West Norfolk Rise, LOUR(C/N/S) – Central, North and South Louisville.

Scenario 1: Annual (= status quo), annual catch limits (t) are fully taken in each year

Year	NW Chall Stock	LHR Stock	WNR Stock	LOUR(C/N/S)
2024	160	174	44	581(305/116/160)
2025	160	174	44	581(305/116/160)
2026	160	174	44	581(305/116/160)
2027	160	174	44	581(305/116/160)

Scenario 2: Two years accumulation, annual catch limits (t) are doubled, and fully taken in the second year

Year	NWChall Stock	LHR Stock	WNR Stock	LOUR(C/N/S)
2024	0	0	0	0
2025	320	348	88	1162(610/232/320)

Scenario 3: Three years accumulation, annual catch limits (t) are tripled, and fully taken in the third year

Year	NWChall Stock	LHR Stock	WNR Stock	LOUR(C/N/S)
2024	0	0	0	0
2025	0	0	0	0
2026	480	522	132	1743(915/348/480)

Scenario 4: Four years accumulation, annual catch limits (t) are quadrupled, and fully taken in the fourth year

Year	NWChall Stock	LHR Stock	WNR Stock	LOUR(C/N/S)
2024	0	0	0	0
2025	0	0	0	0
2026	0	0	0	0
2027	640	696	176	2324(1220/464/640)

Simulation process

The New Zealand and Australian catch records were combined as there were insufficient data to split the analysis by nation and separately account for national catch allocations. The data set was restricted to tows within BTMA areas. We conducted a second simulation where data were restricted to tows within a subset of the BTMAs representing a proposed 70% Protection Scenario (Geange et al. 2023, SC11-DW05) The simulation comprised the following steps:

1. Select a year at random, then a trip from that year. All tows within a trip are then selected, one at a time, in the original order
2. As the catch from each tow in the selected trip is taken, the total catch in each Management stock is summed
3. When all tows in the selected trip have been used, remove records from that trip/year from the dataset (i.e., sampling without replacement) then select another year and trip, repeating steps 1

& 2 until all Management stock annual catch limits are reached or data runs out (i.e., the dataset becomes empty)

4. Calculate the total ‘flattened’ footprint of all records selected (km^2), by management stock
5. Repeat steps 1–4 200 times to get 200 estimates of the footprint in each management stock
6. Calculate the mean footprint area (km^2) for each management stock from the 200 replicates
7. Repeat the process for each catch accumulation scenario in Table 5
8. Run the simulation as above but for a single year, with current annual catch limits, to represent the status quo. Do this twice then add the separate footprints to estimate the total footprint from two years of fishing. Repeat for three and four years of fishing annual catch limits.
9. Compare footprint size between status quo fishing and accumulated catch, for each catch accumulation scenario
10. Sensitivity model, repeating steps 1–9 with data set restricted to tows within 70% Protection Scenario areas

This method therefore assumes sampling of each year is independent, but when catch is accumulated over more than one year those annual footprint estimates are added.

Sampling *without* replacement prevents a trip from being repeatedly sampled. Sampling *with* replacement would reduce the variance of the estimate, which in this case means it would reduce the spatial footprint. This occurs through repeatedly sampling the same trip, and this risk is not negligible given the relatively small data set. A simulation assuming sampling *with* replacement would likely be inconsistent with (underestimate) the historical observed footprint.

If a simulated comparison had been made between a single year having low, or high, catches, then simulations sampling *with* or *without* replacement would both estimate a larger footprint with the higher catch, it is just the absolute footprint from sampling *with* replacement would likely to be lower because of the reduced variance.

Further, our method compares the footprint from accumulating independent annual samples with a relatively low catch, with that from a single year of sampling but with a relatively large catch. Given this assumption, sampling *with* replacement would show no difference between catch scenarios, because all trips (specifically those within each year) are assumed to be independent.

Sampling *without* replacement also better mimics the spatial spreading of effort under the implicit hypothesis underpinning the need for this analysis, i.e., that taking 2, 3, or 4 times the annual catch limits in a single year could encourage vessels to fish in more locations than they would if taking the annual catch every year. Whilst the real-world mechanisms within this assumption are many, often speculative, and beyond current simulation, we do know that orange roughy are often disturbed by fishing activity (e.g., Tingley & Dunn 2018), and New Zealand domestic fisheries, outside of those fishing large spawning aggregations, have been characterised by vessels moving deliberately and sequentially between locations to avoid a presumed catch rate reduction caused by fish being disturbed/displaced by prior fishing.

A simple measure of the impact of the fishing footprint on the VME indicator taxa residing within it can be obtained by overlapping the trawl footprint with the grid of predicted abundance of VME indicator taxa in SPRFMO available from Tablada et al. (2023, SC11-DW07), which provided grids of predicted abundance for 15 VME indicator taxa.

Using the outputs from the footprint simulations described above, for the BTMA open areas only, all grid cells contacted by the simulated footprint in each catch accumulation scenario were identified and the cell value (abundance in number of individuals/1000 m^2) extracted. These values were then summed to produce a relative measure of the total impact on the taxa across each Management stock for comparison with equivalent measures based on fishing catch limits annually, in the same way as the fishing footprint.

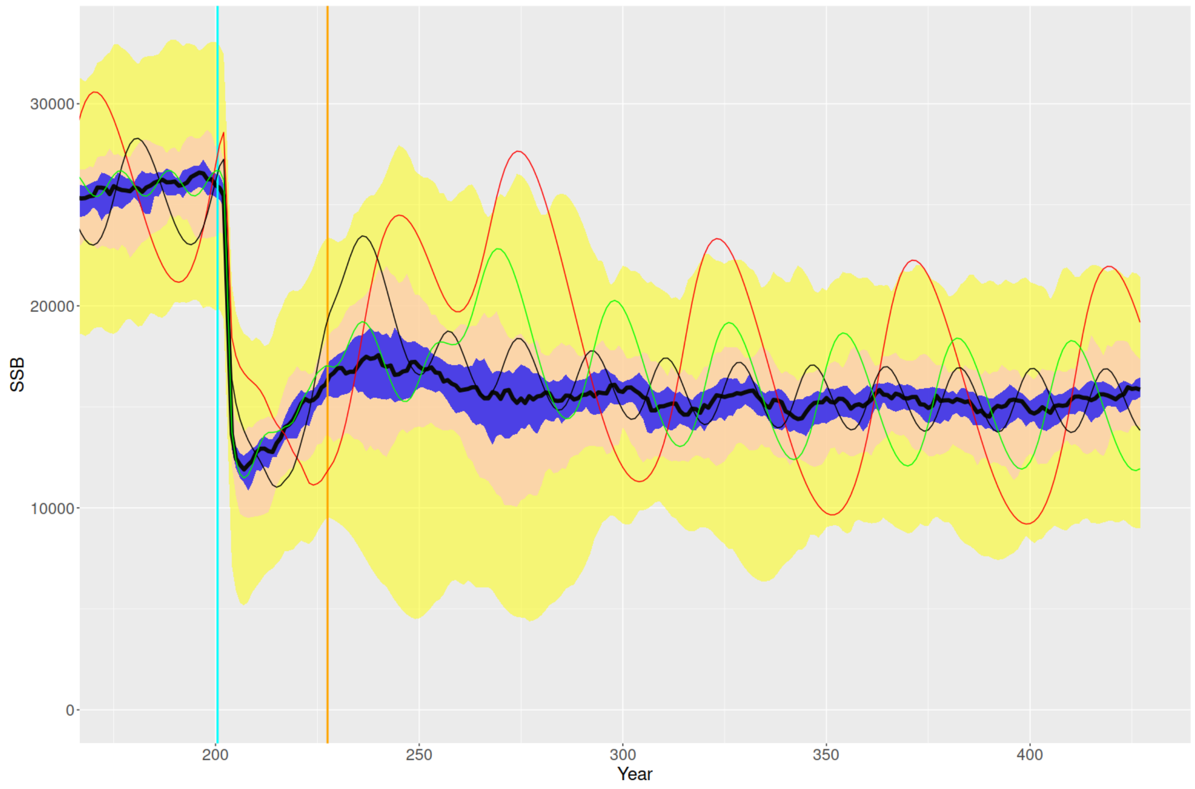
4. Results

4.1 Impact on the orange roughy stock

The alternative HCRs made negligible difference to long term stock depletion, and the alternative stock sizes made no difference except the stock status equilibrated to a different level (Table 6). Taking catches less often caused more SB fluctuation because the stock biomass rebuilt between catches (Figure 3).

Table 6: Simulation model final year spawning biomass (SB) and depletion (SB$_{final}$/SB$_{inital}$) assuming the same yield in all simulations (constant yield of scalar × Operating Model SB$_{initial}$) with different spawning stock sizes (SB$_{initial}$) and four different year gaps between catches; from catches every year to every fourth year. Simulation model assumes parameter settings and a catch history from the Central Louisville stock. The statistical distribution of year class strengths produces an initial equilibrium spawning biomass in the operating model (SB$_{initial}$) that is higher than the nominal operating model spawning biomass (OM SB$_0$).

Yield Scalar	OM SB$_0$	Year gap	Operating Model SB$_{initial}$	Final year SB	Final year depletion
0.0204	18 500	0	25 968	15 851 (7 967 – 22 267)	0.623 (0.291 – 1.097)
0.0204	18 500	1	25 968	15 851 (7 968 – 22 268)	0.623 (0.291 – 1.097)
0.0204	18 500	2	25 968	16 034 (8 129 – 22 442)	0.630 (0.297 – 1.105)
0.0204	18 500	3	25 968	15 849 (7 971 – 22 267)	0.623 (0.474 – 1.097)
0.0102	37 000	0	51 968	42 807 (26 622 – 56 322)	0.851 (0.471 – 1.387)
0.0102	37 000	1	51 968	42 806 (26 622 – 56 322)	0.851 (0.471 – 1.387)
0.0102	37 000	2	51 968	42 992 (26 796 – 56 498)	0.845 (0.474 – 1.391)
0.0102	37 000	3	51 968	42 797 (42 620 – 56 318)	0.851 (0.471 – 1.387)



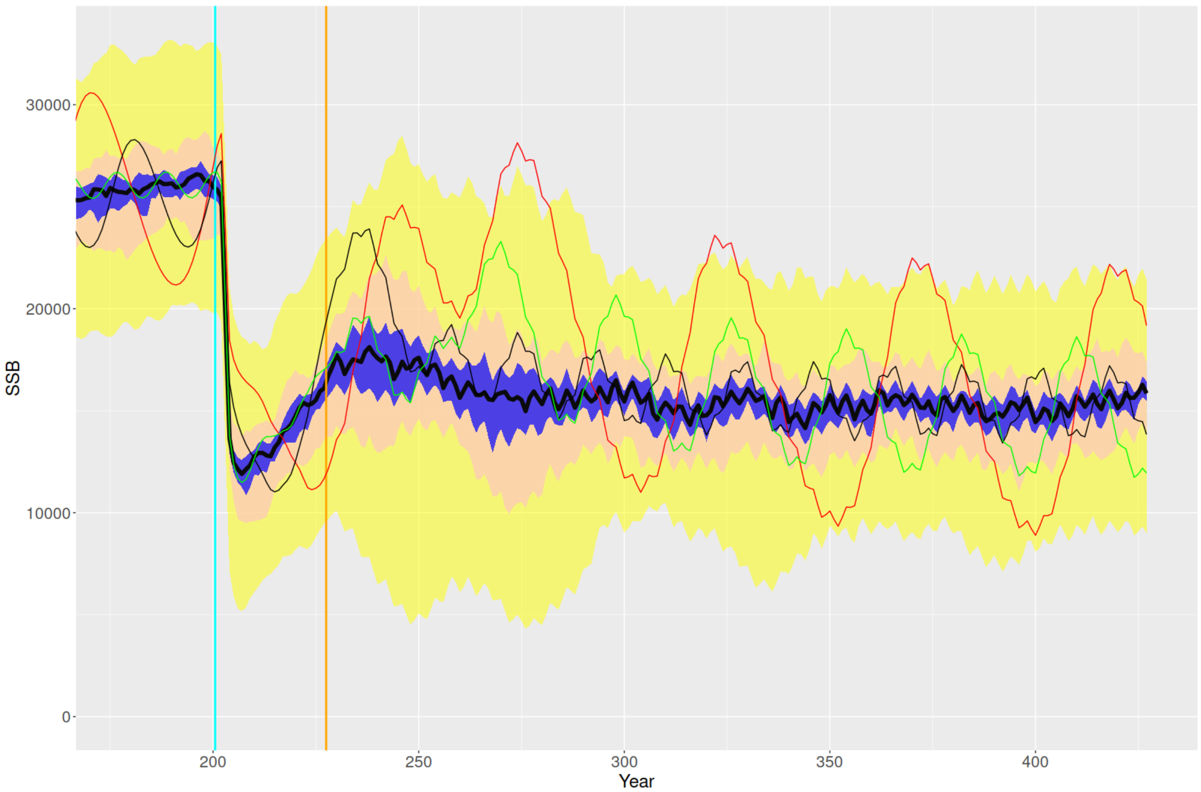


Figure 3: Spawning stock biomass (SSB) estimates for a simulation model ($SB_{initial}$ = 25 968 t) with catches taken every year (top panel) or every fourth year (bottom panel). Solid black line, median; blue shaded zone, 40-60% credible interval; orange shaded zone, 25–75% credible interval; yellow shaded zone, 2.5–97.5% credible interval. Thin black, green, and red lines show example alternative YCS trajectories. The light blue vertical line indicates the end of the initialisation period (beginning of the exploitation period), and the orange vertical line indicates the end of the exploitation period (beginning of the projection period).

4.2 Impact on the fishing footprint

The simulation procedure ran successfully for most of the Management stocks, but for North Louisville there was insufficient catch of orange roughy between 2013 and 2020 to allow a single year of catches to be fully taken, and for West Norfolk Ridge only one full year of catches could be taken. An illustration of the scale and extent of the fishing footprint under different scenarios is shown for the relatively data-rich Northwest Challenger Management stock in Figure 4, providing an indication of how much of the 8-year dataset was required to provide catches sufficient for the catch limit in one year and in four years of accumulated catch.

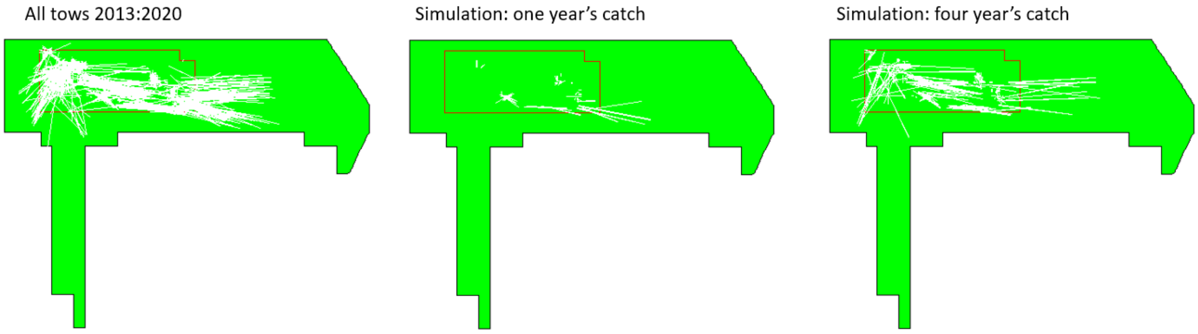


Figure 4: The fishing footprint (white segments) from all recorded orange roughy fishing effort by Australian and New Zealand vessels between 2013 and 2020 in the Northwest Challenger Management stock (green),

and the simulated fishing footprint in that stock after one year of fishing and four years of fishing with accumulated catch limits. The boundary of the proposed 70% Protection Scenario is shown in red.

The fishing footprint increased in each Management stock under the current (status quo) scenario, and either current BTMA open areas or proposed PS 70% open areas, reflecting the accumulation of fishing locations over time (Figure 5).

The simulation predicted the accumulation of catch limits over two, three, or four years, increased the fishing footprint compared to the annual fishing (status quo) scenario.

The increase in footprint with accumulated catch scenarios was greatest in absolute terms for NW Challenger (but lowest as a percentage), and lowest for South Louisville (but greatest as a percentage).

The footprints were mostly lower for the PS 70% areas compared with BTMA, due to the substantially smaller size of the PS 70% areas, and therefore fewer historical records to select from.

Table 7: Simulated changes in footprint size (km^2) over time when catch limits are taken annually (status quo) compared with when catch limits are accumulated over two, three, or four years – by Management stock area (LH, Lord Howe; CL, Central Louisville; NL, North Louisville; NWC, Northwest Challenger; SL, South Louisville; WN, West Norfolk). Left-hand columns assume fishing in current BTMA areas, right-hand columns assume fishing limited to Protection Scenario 70% areas.

Status quo: footprint (km^2) with annual catches

	Assuming BTMA areas							Assuming PS70% areas					
Years	LH	CL	NL	NWC	SL	WN		LH	CL	NL	NWC	SL	WN
One	21.5	25.4	7.8	233.6	6.0	15.6	One	26.6	3.4	7.8	136.7	3.7	11.4
Two	37.6	39.4	7.8	443.3	10.1	20.3	Two	44.5	3.4	7.8	240.7	5.4	11.4
Three	48.6	49.1	7.8	598.7	13.0	21.9	Three	57.3	3.4	7.8	357.4	6.5	11.4
Four	59.7	53.6	7.8	786.7	15.2	22.8	Four	68.1	3.4	7.8	447.4	7.6	11.4

Alternative: footprint (km^2) with accumulated catches

	Assuming BTMA areas							Assuming PS70% areas					
Years	LH	CL	NL	NWC	SL	WN		LH	CL	NL	NWC	SL	WN
One	21.5	25.4	7.8	233.6	6.0	15.6	One	26.6	3.4	7.8	136.7	3.7	11.4
Two	38.9	41.8	7.8	462.0	10.7	24.5	Two	43.9	3.4	7.8	266.4	7.2	11.4
Three	56.4	55.7	7.8	647.7	15.6	24.5	Three	58	3.4	7.8	383.3	9.3	11.4
Four	70.0	69.9	7.8	813.2	20.4	24.5	Four	77	3.4	7.8	486.3	9.6	11.4

Increase in footprint (%) from annual to accumulated catches

	Assuming BTMA areas							Assuming PS70% areas					
Years	LH	CL	NL	NWC	SL	WN		LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0	One	0	0	0	0	0	0
Two	3	6	0	4	6	21	Two	-1	0	0	11	33	0
Three	16	13	0	8	20	12	Three	1	0	0	7	43	0
Four	17	30	0	3	34	7	Four	13	0	0	9	26	0

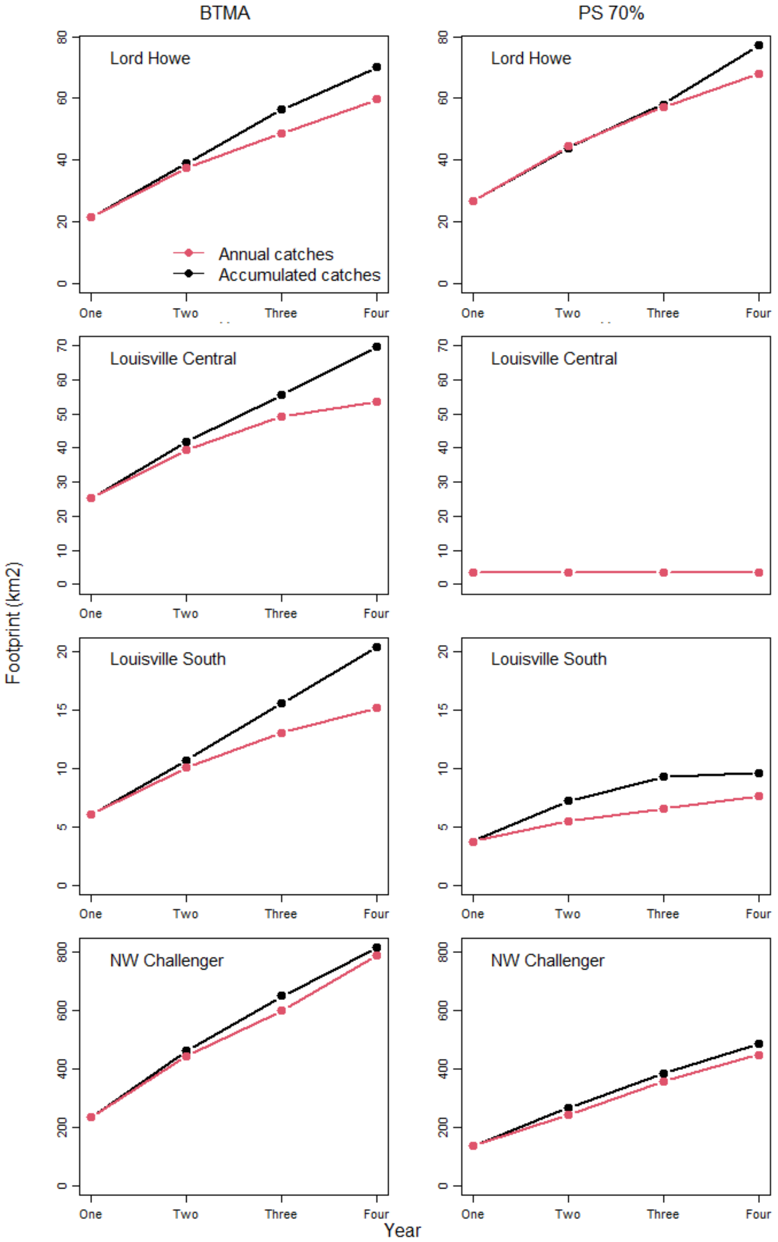


Figure 5: Comparison of the size of the fishing footprint (km^2) from simulations in which SPRFMO orange roughy catch limits are taken annually (status quo, red lines) with simulations in which the catch limits are taken after being accumulated over 2, 3, and 4 years (black lines), by Management stock area and for two alternative closure scenarios. Plots not shown for West Norfolk Ridge or North Louisville due to insufficient catch data to fill catch limits; constant low footprint for Central Louisville (PS 70%) also due to insufficient catches within the 70% PS area.

4.3 Ecosystem effects

The estimated overlap with VME indicator taxa increased in a similar way to the fishing footprint (Table 8). As the footprint increased, so did the number of VME indicator taxa abundance model grid cells that were overlaid by the footprint, and therefore the relative number of individuals impacted (abundance index) also increased.

The abundance index of each taxon impacted increased under the current (status quo) catch limit scenario and current BTMA open areas, reflecting an accumulation of fishing locations (and grid cells encountered) over time. But as shown in in the comparison of footprints, the simulation predicted for all taxa that the abundance index after accumulation of catch limits over two, three, or four years, would be greater than that under the annual fishing (status quo) scenario (Figure 6). Although the predicted numbers of individuals to be impacted by the fishing footprint was a relative measure only, numerically the most impacted taxa were: Bryozoa, gorgonians, and Demospongiae in Lord Howe Rise; *Solenosmilia variabilis* and Zoanthidea in CentralLouisville; Crinoidea and *Solenosmilia variabilis* in SouthLouisville; Demospongiae, Hexactinellidae, Crinoidea, and Actiniaria in NW Challenger (Table 8).

Although the modelled spatial distributions of VME indicator taxa showed considerable variation among taxa (see Tablada et al., 2023), the increases in impacted relative abundance in accumulated catch limits compared to status quo matched closely those of the footprint itself (Table 8).

Table 8: Simulated encounters of 15 taxa of VME indicator taxa, in percentages compared with status quo, in each Management stock area when catch limits are accumulated and fished over two, three, or four years instead of being fished annually. Fishing assumed to be limited to BTMA areas. LH – Lord Howe Rise, CL – Central Louisville, NL – North Louisville, NWC – North West Challenger, SL – South Louisville, WN – West Norfolk Ridge.

Alcyonacea

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	3	6	0	4	6	21
Three	16	13	0	8	20	12
Four	17	30	0	3	34	7

Actiniaria

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	4	8	0	3	3	28
Three	10	24	0	6	21	16
Four	17	46	0	11	29	10

Brisingidae

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	4	9	0	2	3	29
Three	9	27	0	6	21	16
Four	15	49	0	10	31	10

Bryozoa

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	4	8	0	3	3	30
Three	10	25	0	5	21	17
Four	17	51	0	11	28	11

Antipatharia

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	4	8	0	-3	2	29
Three	8	25	0	2	21	16
Four	14	48	0	9	28	10

Stylasteridae

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN

Two	4	8	0	-3	2	29
Three	8	25	0	2	21	16
Four	14	48	0	9	28	10

Crinoidea

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	2	8	0	2	3	29
Three	11	26	0	6	20	16
Four	19	48	0	9	30	10

Demospongiae

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	3	8	0	3	4	27
Three	8	24	0	6	21	15
Four	14	48	0	11	27	10

Goniocorella dumosa

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	4	9	0	1	3	27
Three	10	27	0	5	20	15
Four	17	53	0	11	31	10

Gorgonians

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	3	7	0	3	4	33
Three	8	23	0	7	21	18
Four	13	48	0	13	29	11

Hexactinellidae

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	3	8	0	2	3	27
Three	8	25	0	4	21	15
Four	13	47	0	9	30	10

Hydrozoa

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	3	8	0	3	3	32
Three	10	24	0	6	21	18
Four	17	45	0	11	27	11

Pennatulacea

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	3	7	0	3	3	29
Three	8	24	0	8	21	16
Four	13	47	0	14	32	10

Solenosmilia variabilis

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	4	8	0	2	4	29
Three	9	25	0	5	21	16
Four	15	49	0	10	31	10

Zoanthidea

Increase in relative abundance index (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
Two	3	6	0	4	2	31
Three	8	22	0	6	19	17
Four	14	46	0	10	32	11

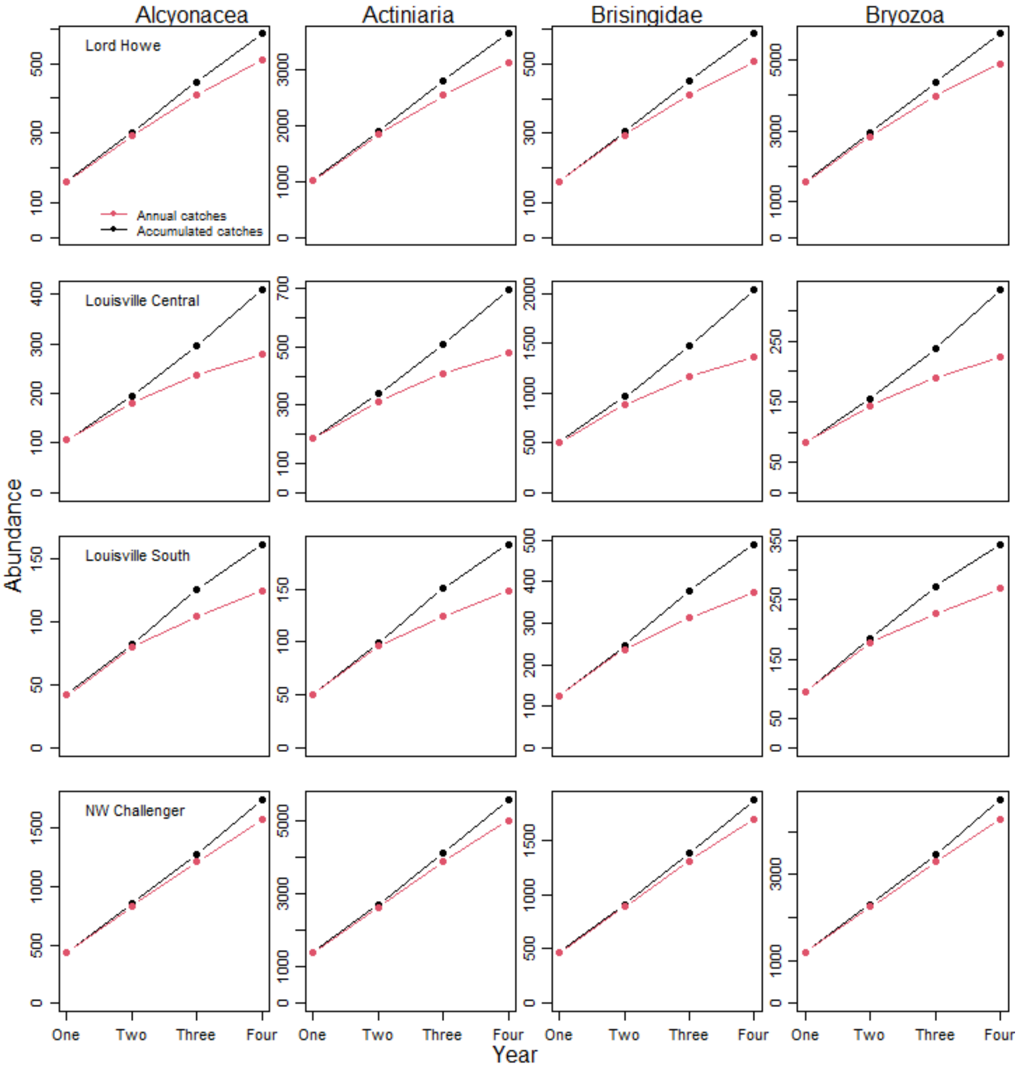


Figure 6: Comparison of the relative number of individuals of VME indicator taxa impacted from simulations in which SPRFMO orange roughy catch limits are taken annually (status quo, red lines) with simulations in which catch limits are taken after being accumulated over 2, 3, and 4 years (black lines), by Management stock Area and VME indicator taxon.

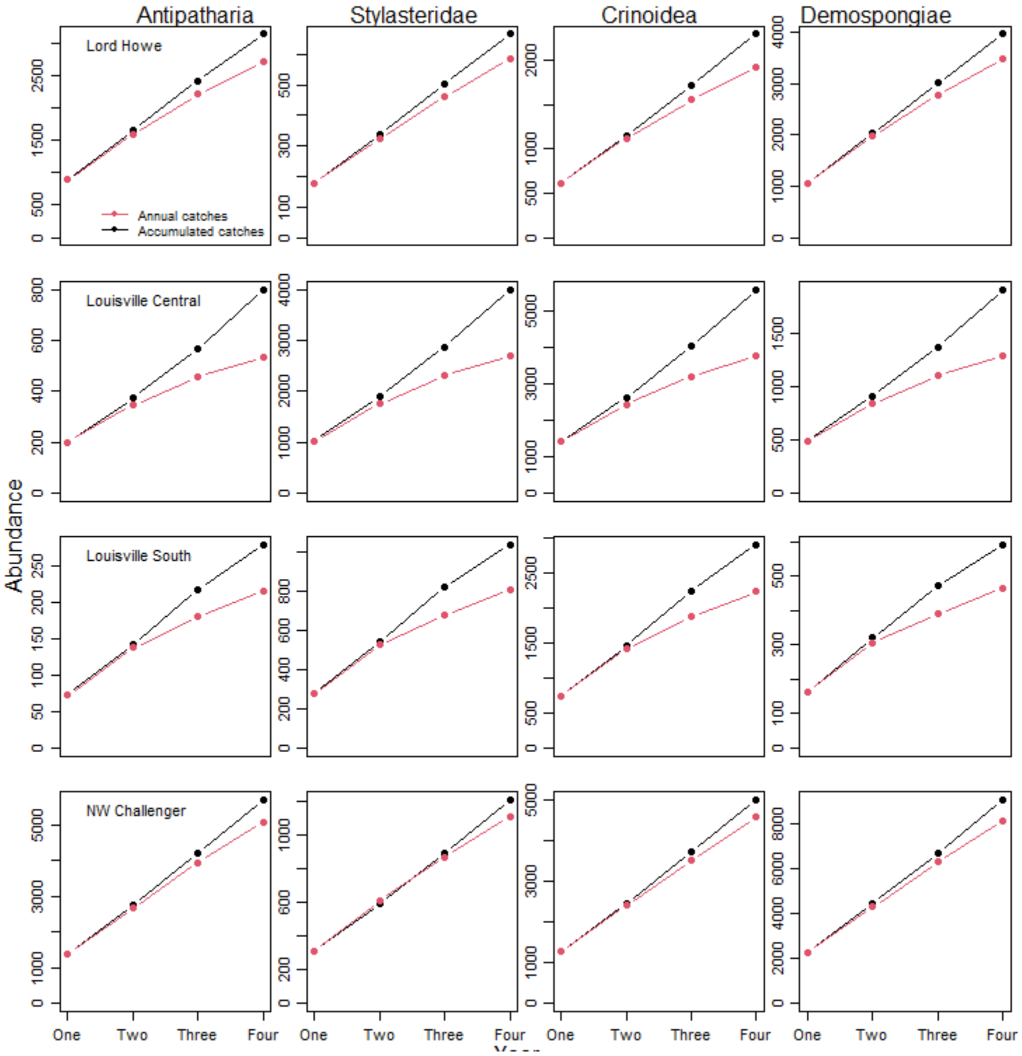


Figure 6—*continued*

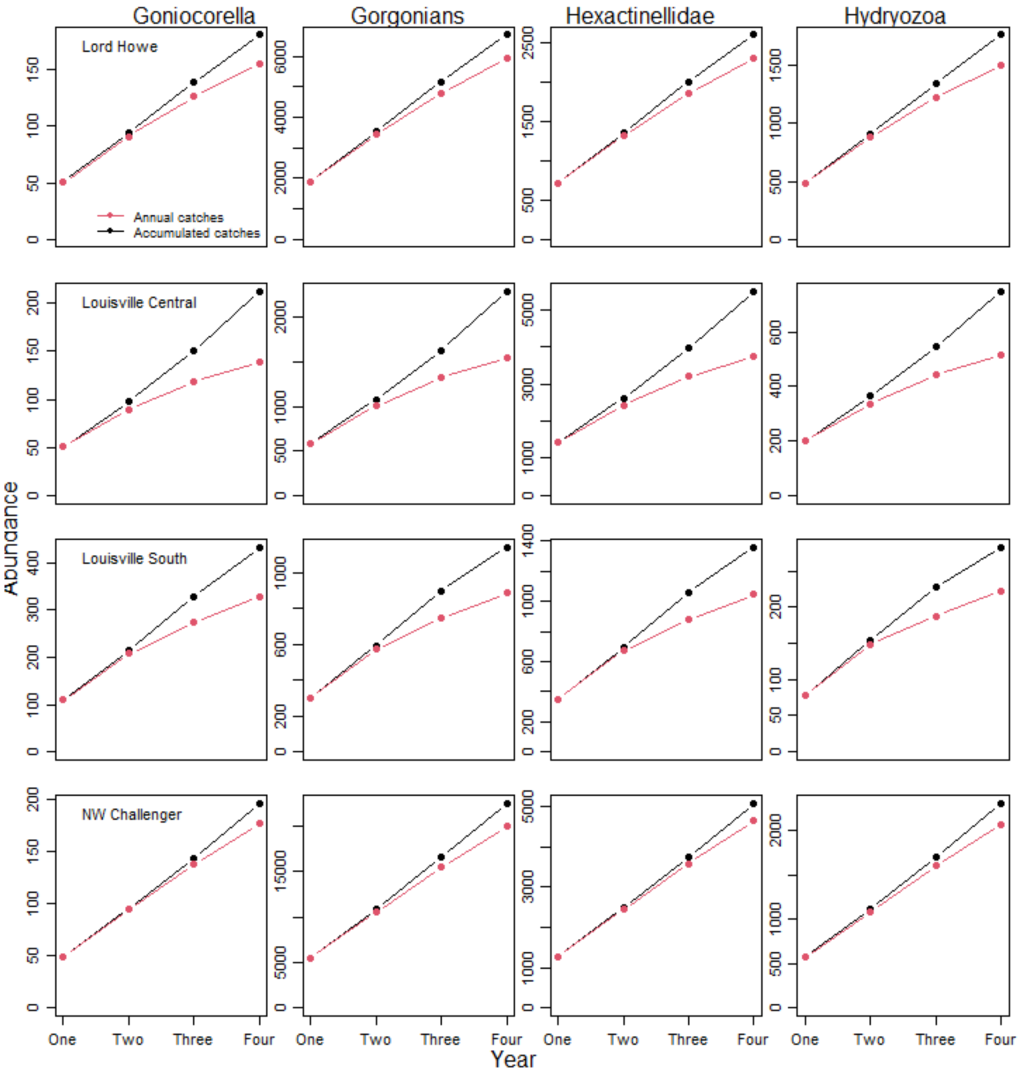


Figure 6—*continued*

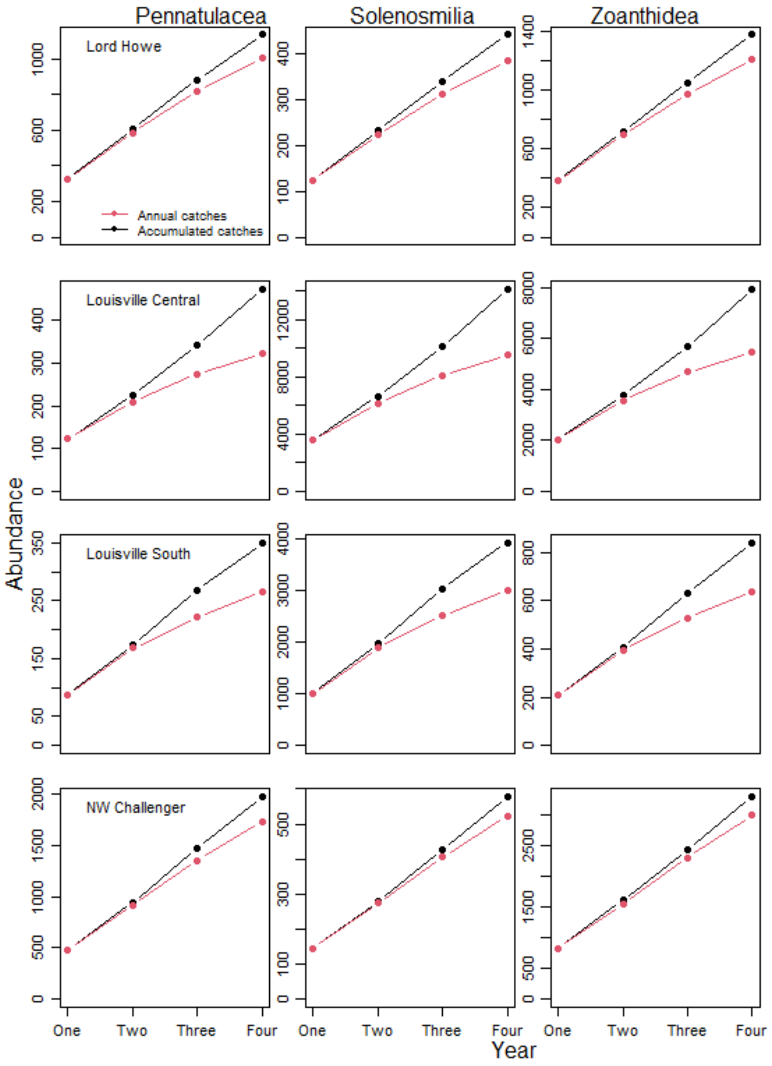


Figure 6—*continued*

5. Discussion

Impact on the orange roughy stock

For the orange roughy population, taking a catch every year, or taking accumulated catches in alternating years, made no difference. This result was expected, given the relatively low exploitation rates and wide number of cohorts in orange roughy populations dampens stock biomass variability.

The assumptions used in the simulations were those used in current New Zealand/Australian stock assessment models: of particular relevance are that the population was closed, recruitment was a function of Spawning Stock Biomass and followed the Beverton-Holt form, natural mortality rate was constant, and the stock had a constant B_0 (virgin stock size).

Impact on the fishery footprint and wider ecosystem

For the fishing footprint and wider ecosystem impacts, if fishing follows our assumptions then taking accumulated catches in alternating years was estimated to produce increases in the fished footprint and number of individual VME indicator taxa impacted compared to annual fishing, and this varied with the stock, and number of years accumulated. The relative impact on VME indicator taxa varied among stocks but the size of the effect of accumulating catches on VME indicator taxa was the same as that for the footprint itself.

If fishing does not follow our assumptions, and does not reflect historical fishing patterns, then the effect of accumulating catches will be speculative. Fishers might choose to remain in locations for longer and reduce the overall footprint, but alternatively might spread fishing further to avoid encountering localized depletion of target species catches.

The increase in footprint reflected the availability of fishing locations. There were relatively few potential locations for West Norfolk and North Louisville, so all known locations were relatively quickly accumulated, and the footprint did not increase as catch limits were increased. There were relatively many fished locations for Central Louisville and South Louisville, so higher catch limits had a relatively high chance of adding new locations. That the increase in the footprint (%) was not incremental for NW Challenger is most likely caused by the fishery including many long tows with a high degree of spatial overlap.

If future fishing was a subset of the total historical trawl footprint (i.e., future fishing was restricted to known tow lines), then the benefits of managing for a reduced spatial footprint (i.e., allowing less accumulation of annual TACs) would only be realised if VME indicator taxa mortality was incomplete during each trawl pass, and/or recovery took place between fishing events, and/or future trawl paths included some areas outside of the historical footprint.

Assumptions, limitations, caveats

- We sampled from historical fishing data to simulate future fisher behaviour and catches because we determined that processes driving future fish distributions and fisher behaviour were insufficiently well known to model. Fisher behaviour may be influenced, for example, by fuel price, crew and vessel availability, the value of the catch, individual fisher strategies influenced by past experience in the fishery, catches achieved on the current trip, and compliance factors such as reaching or approaching area catch limits or exceeding VME indicator taxa catch thresholds. If fisher behaviour changes, then recent fishing patterns are not a valid predictor of future fishing footprint.
- We chose only records from recent fishing but were forced to include data from prior to the introduction of the current BTMAs (in 2019) due to the low level of fishing since then. The date range of 2013–2020 was chosen so as to equally represent the available data from the two nations with recent orange roughy fishing recorded. The outcome of the simulations may have differed slightly if we had allowed earlier New Zealand data, and these had included locations not fished more recently.
- Historical trawls were assigned to BTMA and PS 70% areas based on the start position of the trawl. In some cases the trawl polygons used in the simulations crossed the boundary delimiting those areas. This fact may have only a minor effect on the relative sizes of the footprints among scenarios, but it will overestimate the size (km^2) of the annual footprints.
- If sampling *with* replacement had been applied there would be no difference between the annual catch and accumulated catch scenarios. Simulations selecting records *without* replacement assumed a specific trip would not be repeated. If all historical trips had fished the same locations, then the accumulated catch scenarios would just revisit locations and not increase the footprint. This situation was effectively what occurred for West Norfolk and North Louisville. Where we found the footprint increased, this would be consistent with a hypothesis of there being many potential fishing locations and taking a higher catch limit would result in fishers visiting an increasing proportion of these. A higher catch limit resulting in fewer locations being visited would most likely require an increase in catch rates, due to stock recovery, or perhaps due to a reduction in fishing disturbance (Tingley & Dunn 2018).

- Fishers are known to often restrict trawling on features to known tow-lines that have provided good catch rates in the past, with the additional benefits of reducing the chance of VME encounters and avoiding terrain that might damage the trawl. With variability in the precision of the recorded fishing locations used in the simulations, along with approximations of the gear/vessel offset, the actual overlap of tow polygons may be poorly estimated in the analysis. It is uncertain, however, whether this would over or underestimate the real overlap.
- By resampling from historical data, we assumed the fishers would make the same decisions about moving to a new fishing location, or heading for port, as they did in the past. There are likely to be many considerations when making such decisions, e.g., catch rates, weather, activity of other vessels, motivation to assess other features/grounds, the age of the fish already onboard (on ice). Running out of the New Zealand catch allocation for the Management stock may cause the vessel to head for port but may not often be a motive for moving to a new location.
- The 70% PS areas used in an alternative analysis for the fishing footprint comparisons currently only exist within a Scientific Commission information paper and therefore have not been fully discussed or ratified by SPRFMO.
- When overlaying the footprint with grids of VME indicator taxa abundance, all impacted cells were selected regardless of the degree to which they were impacted (proportion of cell, number of trawl passes). As a result, the number of individuals estimated to be affected was a relative rather than absolute estimate of total impact. Further, as no depletion factor was applied, the numbers presented do not reflect estimates of mortality.
- A further limitation of the analysis of the ecosystem effects of catch accumulation is that the effects on non-target fish species were not considered. It may have been reasonable to include such an assessment in the simulation exercise if observer records of catch and effort had been employed instead of commercial catch records, but the latter were chosen mainly because observer data was not available for Australian fishing activity.

6. Recommendations

It is recommended that the Scientific Committee:

- **Notes**
  - Simulation outcomes are dependent on historical fishing records and fisher behaviour and may not reflect future fisher behaviour. The more fisher behaviour changes from past behaviour, the greater the likelihood that historical fishing patterns are not a valid predictor of future fishing.
  - Modelling was necessarily conducted by sampling from historical fishing records without replacement. If modelling had been done with replacement there would be no difference between the annual catch and accumulated catch scenarios.
  - The analysis of ecosystem impact used a relative measure of impact, and it has not been determined if detected increases in relative impact on VME indicator taxa would correspond to significant adverse impacts on VMEs.
  - While the analysis used data from both New Zealand and Australian fisheries, it is considered to be more reflective of New Zealand fishing patterns

It is also recommended that, based on the analysis presented here, the Scientific Committee:

- **Advises** the Commission that:
  - Orange roughy stock status is very unlikely to be impacted by taking accumulated catches in alternating years.
  - Accumulation of catch limits over two, three, or four years, may increase the overall fishing footprint and relative impact on VME indicator taxa depending on how

future fishing activity takes place; however, the total impact of this on the predicted abundance of VME indicator taxa has not been determined

7. References

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8. Appendix A

Table 8 (part two): Simulated encounters of 15 taxa of VME indicator taxa, in absolute numbers, in each Management area when catch limits are accumulated and fished over two, three, or four years instead of being fished annually. Fishing assumed to be limited to BTMA areas. LH – Lord Howe Rise, CL – Central Louisville, NL – North Louisville, NWC – North West Challenger, SL – South Louisville, WN – West Norfolk Ridge.

Alcyonacea

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	160	106	96	436	42	271
Two	293	182	96	833	80	347
Three	411	238	96	1213	104	387
Four	509	279	96	1569	124	408

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	160	106	96	436	42	271
Two	302	196	96	852	82	450
Three	447	296	96	1277	126	450
Four	585	411	96	1741	161	450

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	3	6	0	4	6	21
Three	16	13	0	8	20	12
Four	17	30	0	3	34	7

Actiniaria

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	1009	185	196	1380	50	698
Two	1828	313	196	2635	96	886
Three	2532	409	196	3869	124	982
Four	3113	478	196	5003	149	1031

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	1009	185	196	1380	50	698
Two	1894	338	196	2708	99	1134
Three	2789	507	196	4104	150	1134
Four	3630	697	196	5562	192	1134

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	4	8	0	3	3	28
Three	10	24	0	6	21	16
Four	17	46	0	11	29	10

Brisingidae

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN

One	162	503	97	465	125	107
Two	295	880	97	886	237	137
Three	412	1162	97	1307	313	153
Four	508	1367	97	1691	374	161

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	162	503	97	465	125	107
Two	306	962	97	905	245	177
Three	450	1472	97	1385	378	177
Four	587	2044	97	1868	490	177

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	4	9	0	2	3	29
Three	9	27	0	6	21	16
Four	15	49	0	10	31	10

Bryozoa

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	1556	83	43	1179	94	1544
Two	2843	144	43	2245	178	1974
Three	3965	190	43	3292	226	2204
Four	4892	223	43	4279	269	2326

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	1556	83	43	1179	94	1544
Two	2945	155	43	2307	184	2572
Three	4369	237	43	3464	272	2572
Four	5730	336	43	4733	343	2572

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	4	8	0	3	3	30
Three	10	25	0	5	21	17
Four	17	51	0	11	28	11

Antipatharia

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	177	1022	791	313	277	2042
Two	323	1755	791	612	529	2592
Three	463	2308	791	874	681	2886
Four	584	2706	791	1115	810	3030

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	177	1022	791	313	277	2042
Two	337	1898	791	593	542	3345
Three	502	2878	791	892	822	3345

Four	667	4012	791	1212	1040	3345

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	4	8	0	-3	2	29
Three	8	25	0	2	21	16
Four	14	48	0	9	28	10

Stylasteridae

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	177	1022	791	313	277	2042
Two	323	1755	791	612	529	2592
Three	463	2308	791	874	681	2886
Four	584	2706	791	1115	810	3030

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	177	1022	791	313	277	2042
Two	337	1898	791	593	542	3345
Three	502	2878	791	892	822	3345
Four	667	4012	791	1212	1040	3345

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	4	8	0	-3	2	29
Three	8	25	0	2	21	16
Four	14	48	0	9	28	10

Crinoidea

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	615	1415	754	1272	747	759
Two	1120	2435	754	2409	1416	969
Three	1555	3200	754	3529	1879	1076
Four	1931	3791	754	4582	2239	1131

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	615	1415	754	1272	747	759
Two	1145	2628	754	2463	1464	1246
Three	1720	4030	754	3724	2257	1246
Four	2300	5608	754	5010	2913	1246

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	2	8	0	2	3	29
Three	11	26	0	6	20	16
Four	19	48	0	9	30	10

Demospongiae

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	1064	486	169	2249	162	3192
Two	1973	836	169	4301	306	3989
Three	2784	1102	169	6284	390	4413
Four	3482	1288	169	8107	465	4611

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	1064	486	169	2249	162	3192
Two	2027	906	169	4440	320	5065
Three	3011	1370	169	6692	472	5065
Four	3971	1908	169	9025	591	5065

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	3	8	0	3	4	27
Three	8	24	0	6	21	15
Four	14	48	0	11	27	10

Goniocorella dumosa

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	50	51	73	50	109	83
Two	91	90	73	95	208	105
Three	126	118	73	138	274	116
Four	155	139	73	177	329	121

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	50	51	73	50	109	83
Two	94	97	73	96	215	133
Three	139	150	73	144	328	133
Four	181	213	73	196	433	133

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	4	9	0	1	3	27
Three	10	27	0	5	20	15
Four	17	53	0	11	31	10

Gorgonians

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	1892	588	428	5531	302	2696
Two	3437	1009	428	10505	574	3497
Three	4800	1324	428	15532	746	3936
Four	5932	1551	428	19952	888	4181

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	1892	588	428	5531	302	2696

Two	3540	1077	428	10819	595	4651
Three	5173	1633	428	16618	899	4651
Four	6712	2299	428	22466	1144	4651

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	3	7	0	3	4	33
Three	8	23	0	7	21	18
Four	13	48	0	13	29	11

Hexactinellidae

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	714	1425	1061	1284	349	2491
Two	1316	2432	1061	2441	672	3138
Three	1861	3194	1061	3590	877	3482
Four	2308	3748	1061	4654	1045	3637

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	714	1425	1061	1284	349	2491
Two	1355	2620	1061	2496	690	4000
Three	2003	3976	1061	3743	1062	4000
Four	2598	5501	1061	5077	1358	4000

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	3	8	0	2	3	27
Three	8	25	0	4	21	15
Four	13	47	0	9	30	10

Hydrozoa

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	486	200	173	573	78	240
Two	882	337	173	1083	149	310
Three	1225	441	173	1598	188	348
Four	1507	516	173	2071	222	370

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	486	200	173	573	78	240
Two	912	364	173	1117	153	410
Three	1349	547	173	1694	227	410
Four	1769	750	173	2301	283	410

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	3	8	0	3	3	32
Three	10	24	0	6	21	18
Four	17	45	0	11	27	11

Pennatulacea

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	326	123	232	483	88	181
Two	587	209	232	917	168	234
Three	819	274	232	1352	222	260
Four	1007	321	232	1730	266	275

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	326	123	232	483	88	181
Two	605	225	232	946	174	303
Three	883	341	232	1462	267	303
Four	1135	474	232	1969	351	303

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	3	7	0	3	3	29
Three	8	24	0	8	21	16
Four	13	47	0	14	32	10

Solenosmilia variabilis

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	124	3558	956	145	995	156
Two	224	6135	956	275	1896	199
Three	313	8098	956	407	2520	221
Four	386	9510	956	524	3003	232

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	124	3558	956	145	995	156
Two	233	6646	956	280	1968	256
Three	341	10135	956	427	3041	256
Four	443	14157	956	578	3929	256

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	4	8	0	2	4	29
Three	9	25	0	5	21	16
Four	15	49	0	10	31	10

Zoanthidea

Status quo: relative abundance (numbers) with annual catches

Years	LH	CL	NL	NWC	SL	WN
One	382	2035	61	826	206	689
Two	695	3552	61	1554	394	886
Three	969	4675	61	2312	530	994
Four	1202	5458	61	3010	638	1047

Alternative: relative abundance (numbers) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	382	2035	61	826	206	689
Two	713	3755	61	1611	403	1163
Three	1050	5700	61	2452	633	1163
Four	1374	7953	61	3305	841	1163

Increase in relative abundance (%) with accumulated catches

Years	LH	CL	NL	NWC	SL	WN
One	0	0	0	0	0	0
Two	3	6	0	4	2	31
Three	8	22	0	6	19	17
Four	14	46	0	10	32	11