B.C. Hand Harvested Invertebrates: 2023-2024 Custom Analyses

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1 Introduction

Year 2 of the hand harvested invertebrates project focused on finalizing operating models and demonstrating the potential uses of closed-loop simulation as a basis for informing management. The goal was to illicit feedback from scientists regarding data and managers regarding objectives, possible management levers and other considerations such as meeting the requirements of the fish stock provisions.

Among the four case studies, custom analyses addressed a number of management issues:

Geoduck

- Summary of regional stock and exploitation status (Kobe plot for Geoduck by Stat. area)
- Projections of current effort scenarios (impact of fractions of current exploitation rate on spawning biomass for Geoduck).
- Projections of natural survival rate based on projected hypotheses (for demonstration purposes only) for sea otter abundance.
- Evaluating the impact of survey precision on performance of a survey-based management procedure (geoduck)
- Evaluating the potential role of geoduck larval dispersal among sub areas on Stat. area – level management outcomes.
- Evaluating the efficacy of geoduck sub-area closures.

Manila Clam

- Projected performance of alternative minimum size limits (manila clam)
- Rebuilding performance of alternative minimum size limits from a range of user-specified current stock status levels (manila clam).

Sea Cucumber

- Evaluation of harvest rate alternatives including varying rotational closures (sea cucumber)
- Testing management procedures for harvest rate / closures that are linked to observed density (e.g. cucumbers per m shoreline).

Green Sea Urchin

- Calculation of MSY reference points given size limits above maturity.
- Testing management procedures for opening/closing based on observed urchin density
- Evaluating the impact of alternative size limits

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2 Geoduck (*Panopea generosa*)

Statistical catch-at-age models were fitted for the 22 statistical areas for which there are age-composition data for geoduck. In all areas, current exploitation rates are estimated to be far below those corresponding with maximum sustainable yield (MSY), and stocks are likely to be close to 'unfished status', well above MSY spawning biomass levels (Tables 2.1 & Tables 2.2, Figure 2.1).

It is therefore not surprising that projected biomass outcomes are not strongly impacted by large reductions in current exploitation rate (Figure 2.2). Similarly, sketching possible impacts of marine predators shows that even the most conservative hypothesis is more likely to impact geoduck status than large changes in current exploitation rate (Figures 2.2 & 2.3). A priority for geoduck is therefore gathering data and information that could be used to characterize non-fishing impacts to stock levels as these are likely to be the primary drivers of biological risk.

An index-based management procedure was developed that sets annual total allowable catches (*TAC*) in the following year (*y+1*) based on the current survey index *I* and the current (2022) ratio of catch (*C*) to index:

$$TAC_{y+1} = \Delta \cdot I_y \cdot C_{2022}/I_{2022}$$

This management procedure was codified and tested in closed loop for varying levels of aggressiveness (target exploitation rate) control by the *Δ* parameter (IR10, IR20, IR30, IR40 with *Δ* values of 1, 2, 3 and 4, respectively).

The index-based management procedures were used to demonstrate how easily management ideas can be codified and tested, and also to show the relative impact of survey precision on management outcomes. It was demonstrated that halving the standard deviation (1/4 the precision) of the survey index had no impact on biomass outcomes, no impact on expected catch outcomes and only a modest impact on catch variability (Figure 2.4).

It was possible also to show that use of smoothers (the function s(), Figure 2.5):

$$TAC_{y+1} = \Delta \cdot \boldsymbol{s}(I_y) \cdot C_{2022}/I_{2022}$$

could help the management procedure overcome high survey imprecision for no additional cost (Figure 2.6).

It was possible to superimpose sub-area spatial structure to evaluate the potential role of larval dispersal on management outcomes. The data from the 19 surveyed subareas of Stat. area 7 were used to define high and low mixing hypotheses (Figures 2.7 & 2.8) based on a hypothesized spatial relationship among sub-areas (this was a demonstration of model capabilities). These demonstration analyses showed that spatial structure and larval dispersal could impact catches given current effort and spatial closures. Closing all but the top-6 highest abundance sub areas, increased fishing efficiency, improving catches for the same effort (Figure 2.9). However, over the longer projected time period, closures were only meaningfully impactful on catches when there was high hypothetical mixing.

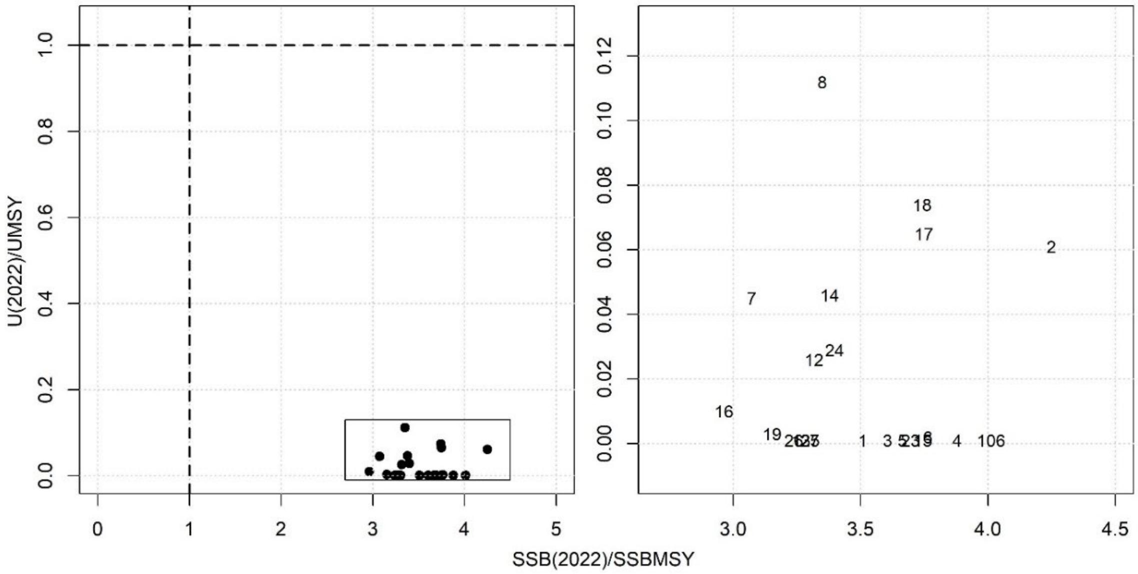

Figure 2.1. Kobe Plot of stock and exploitation status for B.C. Geoduck by Stat. area (the maximum likelihood values of BS and US reported in Table 2.2 below).

Table 2.1. Model estimates among Stat. areas with age-composition data. Estimates include instantaneous natural mortality rate (M) including maximum likelihood estimate (MLE) and 2.5th and 97.5th quantiles, 2022 estimates of harvest rate (U, catch / vulnerable biomass), exploitation rate of fully selected geoduck (F, instantaneous annual rate), stock depletion (D, spawning biomass / unfished spawning biomass), and equilibrium unfished total biomass (B0) and equilibrium unfished spawning biomass (SSB0).

Stat. Area	M MLE	M 2.5%	M 97.5%	U 2022	F 2022	D 2022	B 2022 (t)	B0 (t)	SSB0 (t)
1	0.051	0.011	0.235	0.000	0.000	1.012	1465	1447	1433
2	0.052	0.040	0.067	0.006	0.006	1.177	40860	34712	34514
3	0.077	0.005	1.276	0.000	0.000	1.006	3840	3818	3782
4	0.030	0.013	0.068	0.000	0.000	1.005	23910	23800	23578
5	0.046	0.032	0.068	0.000	0.000	1.004	24071	23966	23713
6	0.054	0.033	0.089	0.000	0.000	1.133	35170	31044	30755
7	0.049	0.042	0.058	0.006	0.007	0.987	26949	27295	27055
8	0.042	0.012	0.151	0.010	0.011	0.968	4298	4440	4422
12	0.036	0.022	0.058	0.003	0.003	0.981	7512	7654	7623
13	0.043	0.031	0.060	0.000	0.000	1.197	1260	1053	1042
14	0.078	0.010	0.626	0.004	0.004	0.934	6978	7475	7434
15	0.073	0.023	0.233	0.000	0.000	1.013	2510	2477	2443
16	0.035	0.001	0.914	0.001	0.001	0.868	3049	3512	3497
17	0.081	0.037	0.180	0.008	0.009	1.373	1418	1033	1017
18	0.048	0.002	0.978	0.007	0.007	0.989	972	983	977
19	0.041	0.006	0.263	0.000	0.000	0.908	1844	2032	2023
23	0.048	0.039	0.060	0.000	0.000	1.058	21140	19973	19813
24	0.066	0.054	0.081	0.003	0.003	0.998	22049	22103	21981
25	0.045	0.033	0.061	0.000	0.000	0.862	3328	3860	3843
26	0.056	0.046	0.067	0.000	0.000	0.932	3039	3262	3234
27	0.033	0.024	0.044	0.000	0.000	0.815	2334	2863	2848
106	0.040	0.001	3.309	0.000	0.000	1.017	4808	4730	4720

Table 2.2. Biomass reference points for Geoduck Stat. areas with age-composition data. Br is SSB at MSY levels relative to unfished (SSBMSY / SSB0), UMSY is the harvest rate (yield / vulnerable biomass) at equilibrium MSY exploitation rate, BS is current (2022) biomass status relative to SSBMSY, US is exploitation rate status relative to MSY levels. For each quantity the maximum likelihood estimate (MLE) and 2.5th and 97.5th percentiles are provided.

Stat. area	Br MLE	BR 2.5%	BR 97.5%	UMSY MLE	UMSY 2.5%	UMSY 97.5%	BS MLE	BS 2.5%	BS 97.5%	US MLE	US 2.5%	US 97.5%
1	**0.27**	0.25	0.28	**0.11**	0.06	0.14	**3.52**	3.26	3.79	**0.00**	0.00	0.00
2	**0.26**	0.24	0.26	**0.11**	0.08	0.12	**4.43**	4.08	5.10	**0.06**	0.05	0.07
3	**0.27**	0.24	0.63	**0.16**	0.10	0.54	**3.60**	2.17	3.96	**0.00**	0.00	0.00
4	**0.25**	0.22	0.27	**0.08**	0.03	0.14	**3.88**	3.60	4.27	**0.00**	0.00	0.00
5	**0.26**	0.24	0.27	**0.11**	0.07	0.14	**3.63**	3.35	3.87	**0.00**	0.00	0.00
6	**0.26**	0.25	0.27	**0.11**	0.08	0.13	**8.99**	3.75	22.69	**0.00**	0.00	0.00
7	**0.26**	0.25	0.26	**0.11**	0.10	0.13	**3.58**	3.41	3.83	**0.05**	0.05	0.06
8	**0.26**	0.24	0.29	**0.08**	0.05	0.22	**5.38**	3.50	15.62	**0.15**	0.06	0.20
12	**0.25**	0.24	0.26	**0.08**	0.06	0.12	**3.75**	3.51	3.97	**0.04**	0.03	0.05
13	**0.26**	0.25	0.27	**0.09**	0.08	0.13	**3.44**	3.22	4.46	**0.00**	0.00	0.00
14	**0.27**	0.25	0.33	**0.15**	0.09	0.51	**3.46**	3.12	4.44	**0.04**	0.01	0.05
15	**0.26**	0.25	0.31	**0.18**	0.13	0.57	**3.63**	3.31	3.93	**0.00**	0.00	0.00
16	**0.24**	0.22	0.25	**0.08**	0.03	0.12	**3.44**	3.29	3.63	**0.03**	0.01	0.05
17	**0.27**	0.25	0.29	**0.15**	0.08	0.22	**4.26**	3.43	5.46	**0.04**	0.04	0.06
18	**0.26**	0.23	0.47	**0.11**	0.05	0.63	**3.81**	2.53	4.12	**0.08**	0.03	0.11
19	**0.26**	0.24	0.32	**0.09**	0.02	0.37	**3.26**	3.05	3.47	**0.01**	0.00	0.02
23	**0.25**	0.25	0.26	**0.11**	0.09	0.13	**3.89**	3.60	4.11	**0.00**	0.00	0.00
24	**0.26**	0.25	0.27	**0.12**	0.11	0.14	**3.60**	3.36	3.80	**0.03**	0.02	0.03
25	**0.26**	0.25	0.26	**0.09**	0.07	0.11	**3.31**	3.12	3.50	**0.00**	0.00	0.00
26	**0.26**	0.26	0.27	**0.12**	0.10	0.13	**3.33**	3.12	3.59	**0.00**	0.00	0.00
27	**0.24**	0.23	0.24	**0.08**	0.06	0.10	**3.36**	3.17	3.64	**0.00**	0.00	0.00
106	**0.25**	0.22	0.45	**0.07**	0.03	0.54	**4.26**	3.95	4.45	**0.00**	0.00	0.00

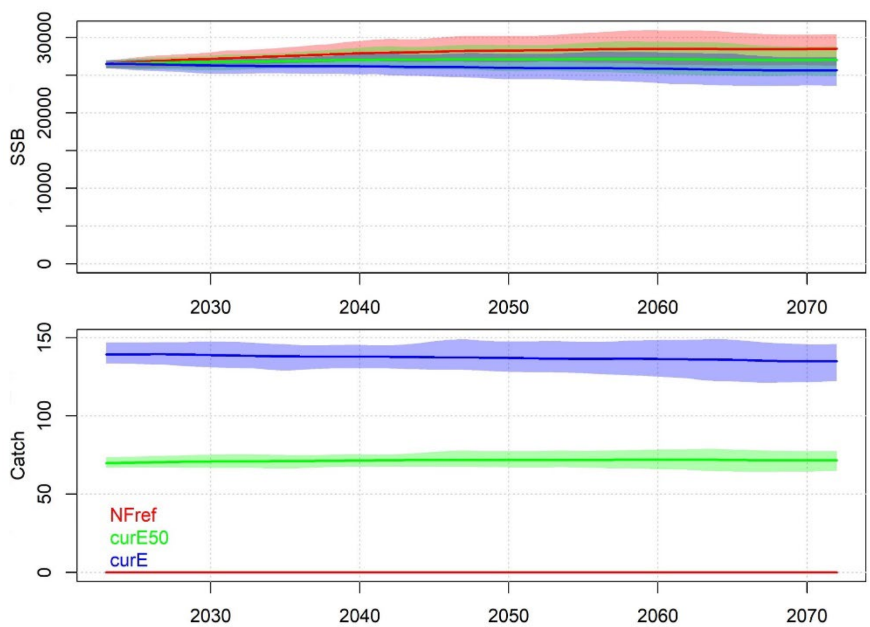

Figure 2.2. The biomass outcomes of three widely varying exploitation rate scenarios for geoduck in Stat. area 7. ‘curE’ is the current exploitation rate, ‘curE50’ halves that rate and ‘NFref’ is zero fishing. The solid lines represent the mean, the shaded regions are the 80% inter quantile range. Exploitation rate is so low, that reducing it by half or even stopping fishing altogether, provides comparable and overlapping spawning biomass outcomes.

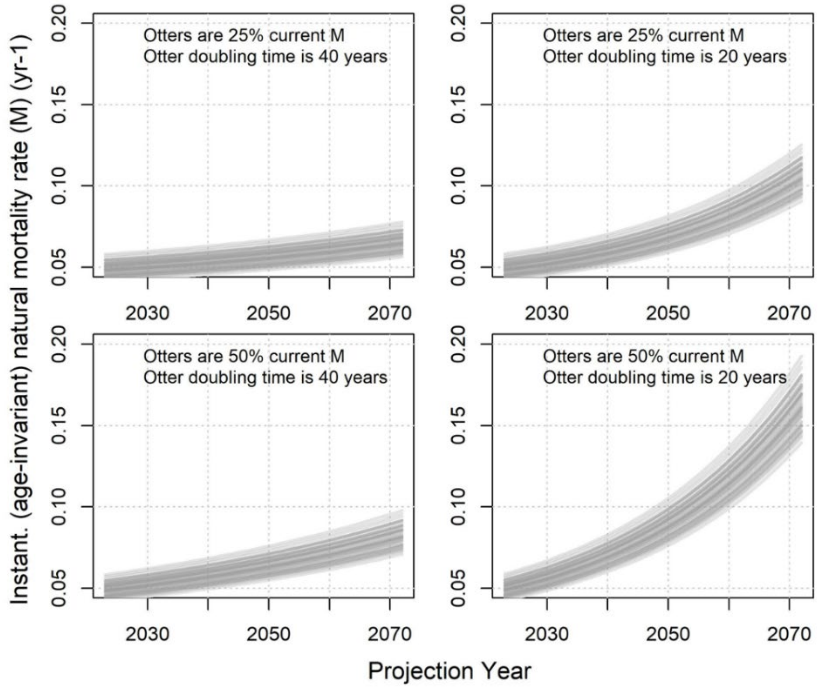

Figure 2.3. Demonstration of the impact of projected natural mortality rate scenarios based on hypothesized abundance, population growth rate and impact on natural survival of geoduck (geoduck Stat area 7).

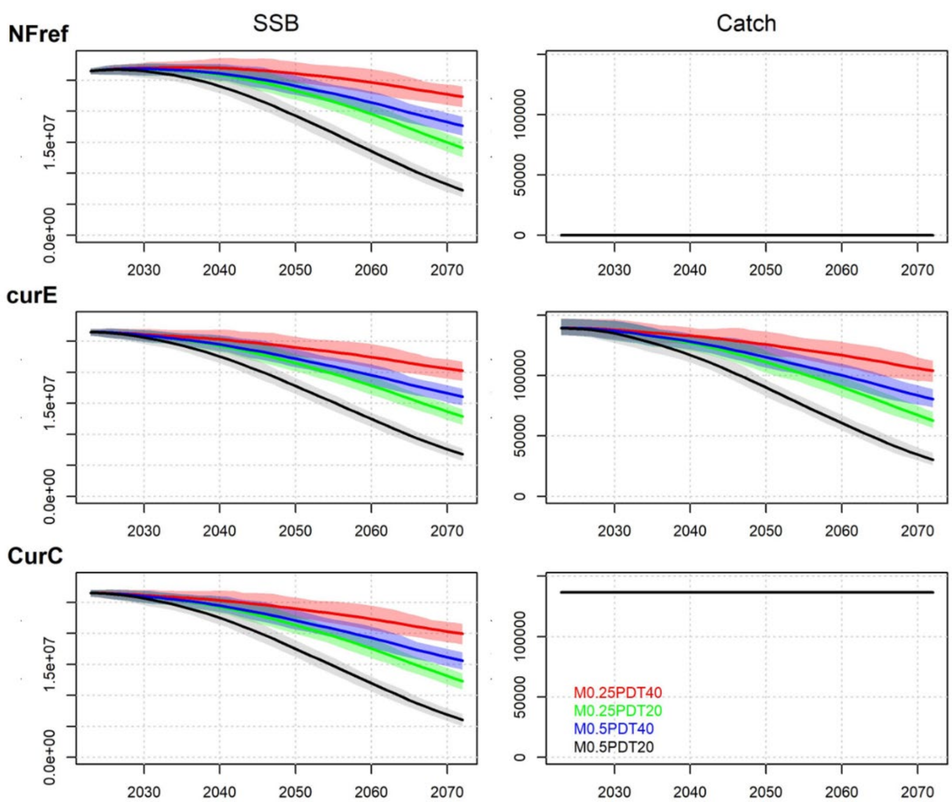

Figure 2.4. The relative impact of natural mortality rate scenarios (of Figure 2.3) relative to either zero fishing ‘NFref’, current exploitation rate ‘curE’ and current catches ‘CurC’. Fishery control (row) is of negligible impact relative to the natural survival hypothesis (colored lines).

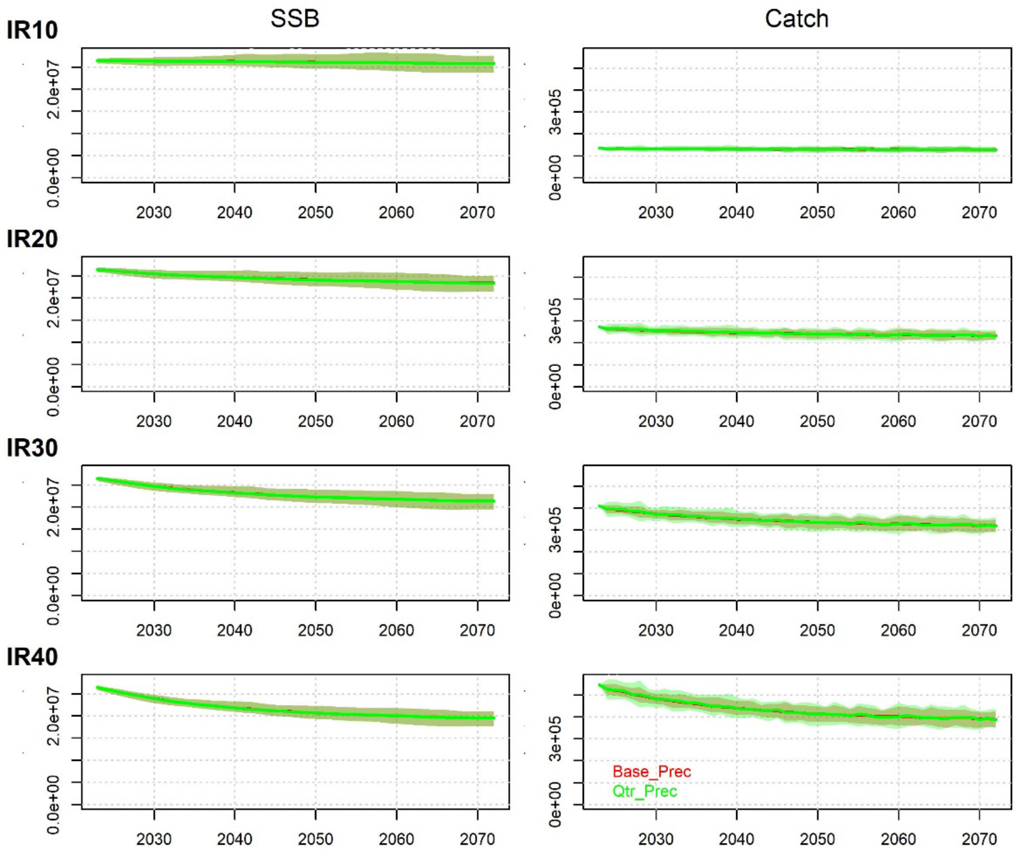

Figure 2.4. The impact of current survey precision (Base_Prec) and ¼ survey precision (Qtr_Prec) on biomass and catch outcomes of four index-based management procedures that aim to fish at 100%, 200%, 300% and 400% of current exploitation rate (IR10 – IR40). Precision had minor impact on the variability in projected catches but no impact on mean catches, mean spawning biomass (SSB) or the range of SSB outcomes.

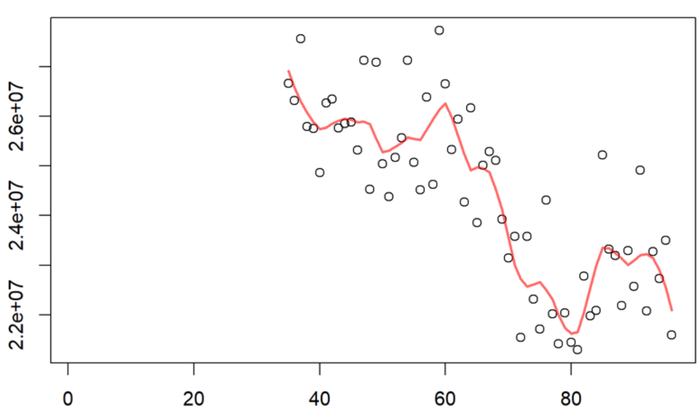

Figure 2.5. The use of a loess smoother (red line) to filter survey index observations (black points) for use in the index-based management procedure. The x-axis is the historical year (year index).

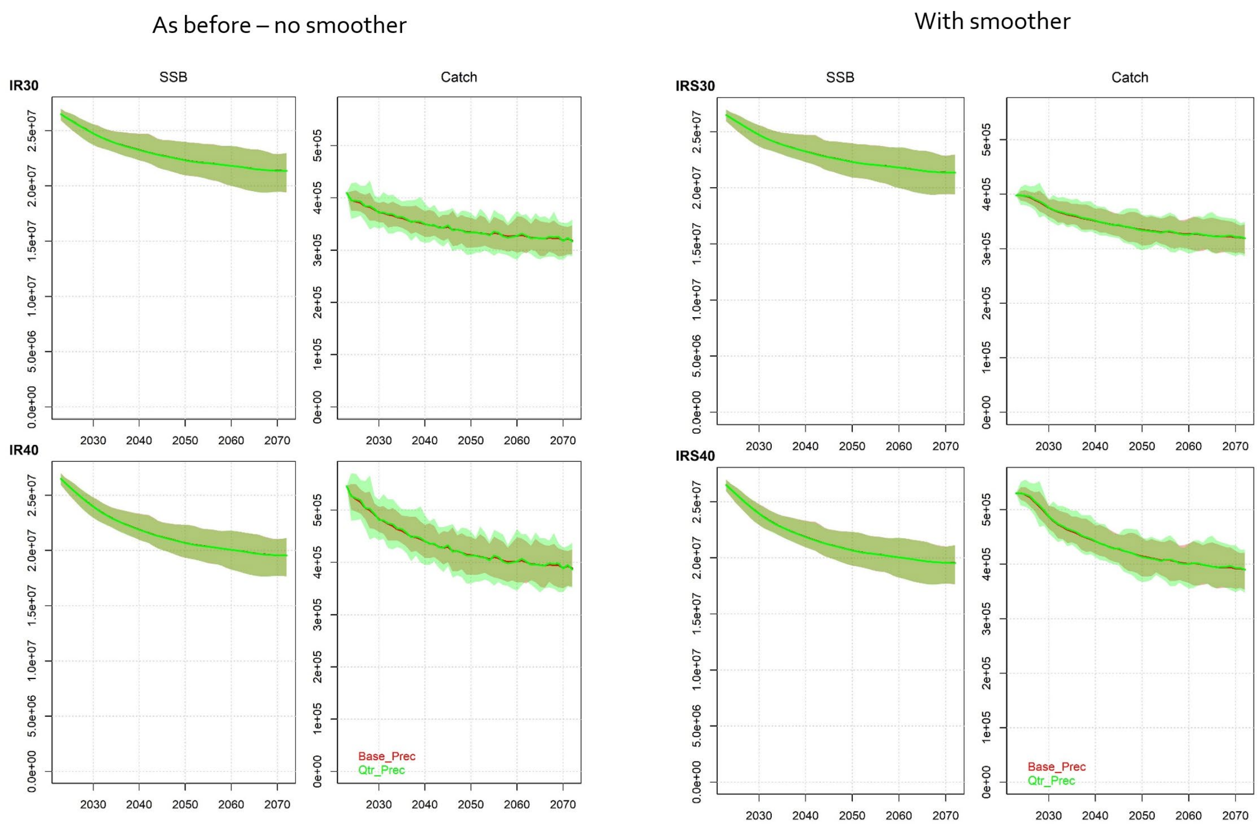

Figure 2.6. Impact of a survey index smoother on MP performance given base (current, red) and ¼ survey precision (green) for two MPs. The use of the smoother goes some way to reducing the catch uncertainty of the index-based MP with no smoother (essentially performance increase for very little cost).

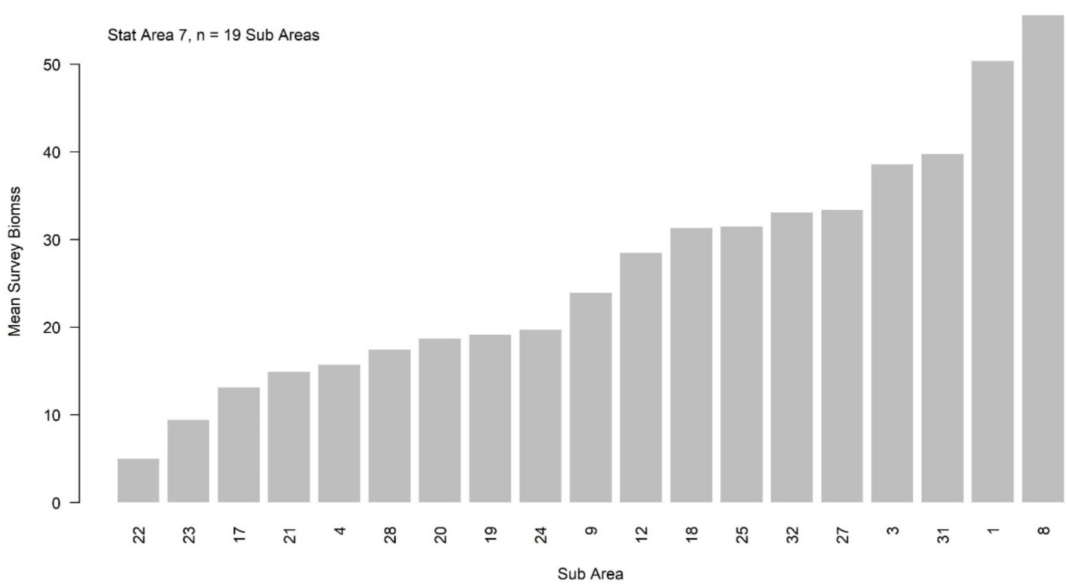

Figure 2.7. The mean survey biomass of geoduck among sub areas in statistical area 7.

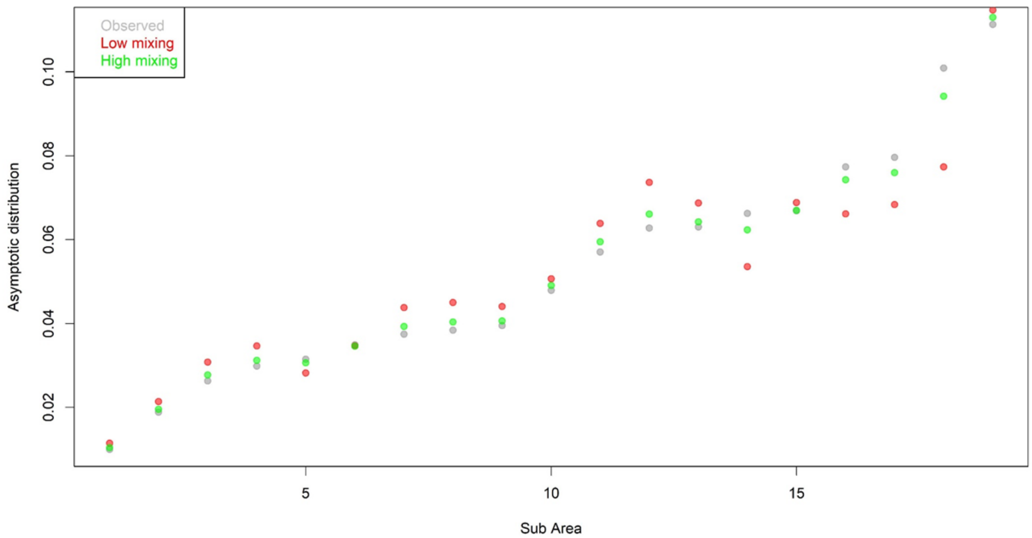

Figure 2.8. Approximation of spatial distribution among sub areas in a model that assumes low mixing (low larval dispersal) and high mixing (high larval dispersal).

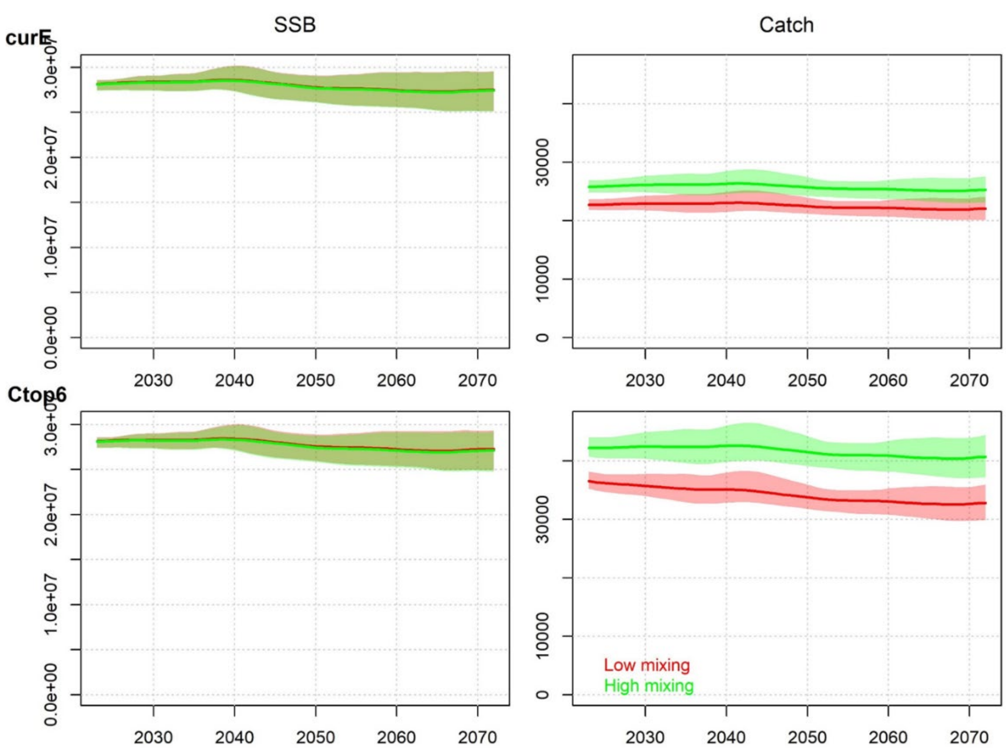

Figure 2.7. The impact of mixing hypothesis on catch and biomass outcomes given current exploitation rate (‘curE’, top row) and closing all but the 6 highest abundance areas (‘Ctop6’, bottom row). Due to low current exploitation rates, mixing hypothesis (colored lines) and management option (row) had virtually no impact on spawning biomass outcomes. High mixing did however lead to 15% higher catches (top right panel). Closing all but the highest abundance areas increased fishing efficiency, improving catch per effort.

3 Manila Clam (*Venerupis philippinarum*)

As the most data-poor case study, Manilla Clam has considerable uncertainty over the scale and status of the resource at the CMA level. It follows that the simulation approach is likely to be of most use in determining the hypothetical robustness of the current minimum size limit to various hypothetical scenarios such as stock depletion, future natural mortality rate, future somatic growth and beach-level variability in exploitation rates.

To demonstrate this aspect of the simulation framework. Various alternative minimum size limits were projected and evaluated for their yield and biomass performance (Figure 3.1). Since manilla clam operating models were configured to include expert input over current stock status level (and precision in current status), it was also possible to demonstrate the potential rebuilding performance of the current and alternative size limits given projections that start from varying stock depletion levels (Figure 3.2).

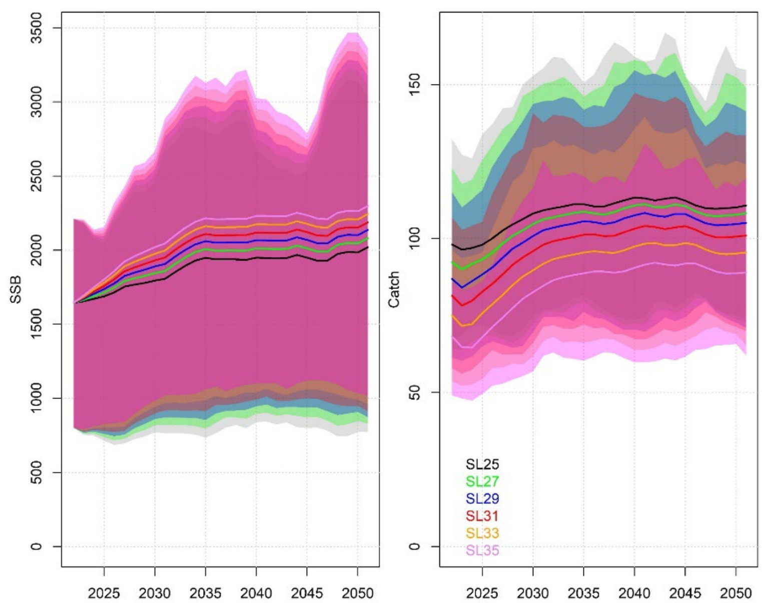

Figure 3.1. The impact of various minimum size limits (from 25 – 35mm, 35mm is current limit) on catch and spawning biomass for manila clam fishery in CMA E. Lines represent the mean outcome, shaded areas are the 80% interval. Catch outcomes were substantially wider than biomass outcomes.

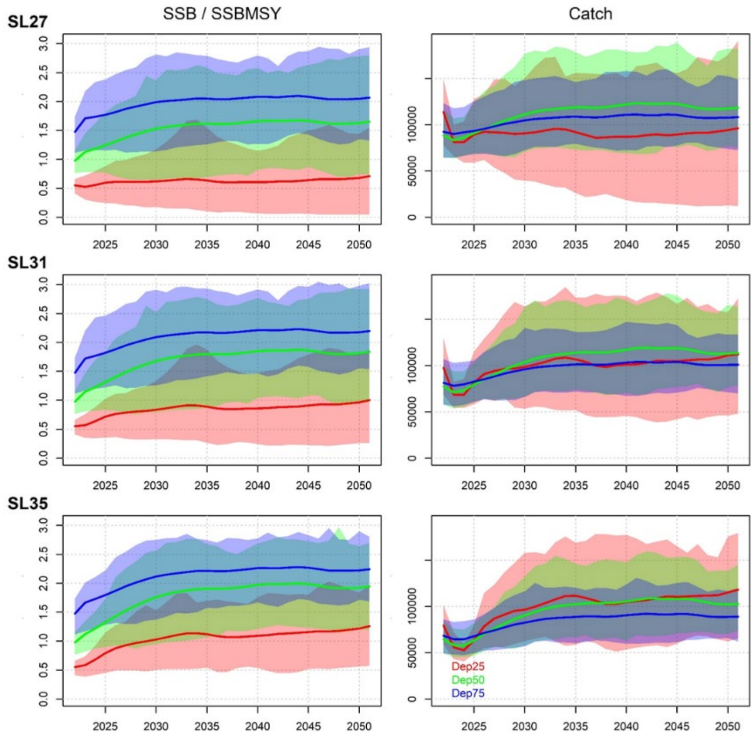

Figure 3.2. Rebuilding performance of various size limits (27mm, 31mm and 35mm) given different assumptions about current stock status levels (25%, 50% and 75% unfished in 2022 – colored lines / shaded aresas). Lines represent the mean outcome, shaded areas are the 80% interval.

4 Giant Red Sea Cucumber (*Apostichopus californicus*)

Although at the quota management area level (QMA) sea cucumber operating models are uncertain about the scale of the resource (the 2024 revision now has these modelled by sub area for which scale is informed by surveys), the models still inform key management reference points relating to the limit reference point and the sustainable rate of exploitation. For example, the Integrated Fishery Management Plan indicates a Limit Reference Point (LRP) at 50% unfished. Model estimates of SSBMSY / SSB0 are closer to 25% an that is is general considered the *target* or *upper stock reference* (USR) point (Table 4.1). Sea cucumber are harvested at targe rates of between 4.2 and 6.7% (for newly reopened QMAs) but this is considerably below the MSY harvest rate that is above 30% (Table 4.1).

Projections of various exploitation rates and rotational closures confirm that current exploitation rate are likely to be precautionary (Figures 4.1 & 4.2). Linking harvest rates to the observed density allowed management procedure evaluation with various control points for the LRP and USR (Figures 4.3 - 4.5).

Table 4.1. Estimates of reference points and sustainable harvest rates for three of the best informed Quota Management Areas (QMAs).

QMA	SSB / SSBMSY			Harvest rate at MSY			SSB 2022 / SSBMSY			SSB2022 / SSB0
	Mean	2.50%	97.50%	Mean	2.50%	97.50%	Mean	2.50%	97.50%	Mean
6A	0.262	0.197	0.325	0.37	0.208	0.649	3.053	1.632	6.549	0.768
7C	0.265	0.212	0.33	0.36	0.167	0.634	2.703	1.309	4.363	0.807
8D	0.265	0.198	0.324	0.363	0.189	0.653	4.644	2.537	7.625	0.893

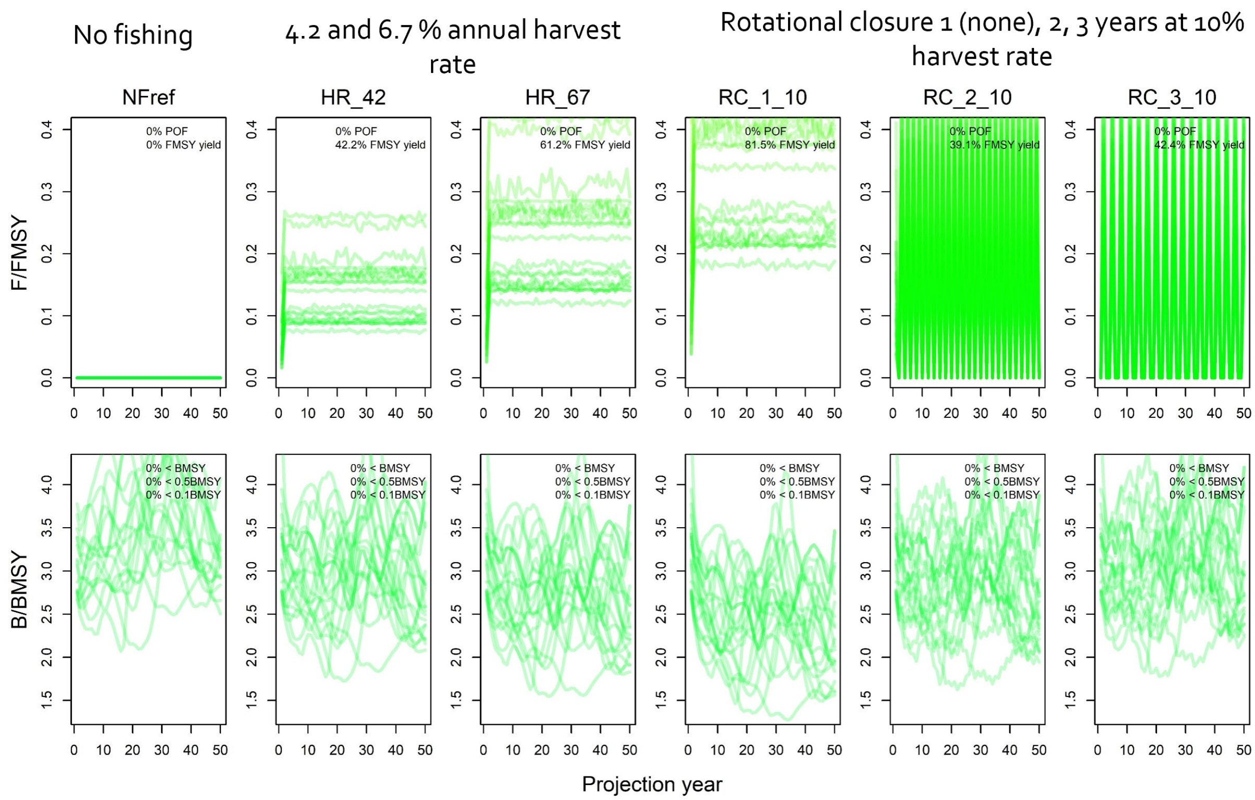

Figure 4.1. Projection of alternative harvest rate options for QMA 7C, including no fishing, 4.2-6.7% and rotational closures of varying interval given a 10% harvest rate.

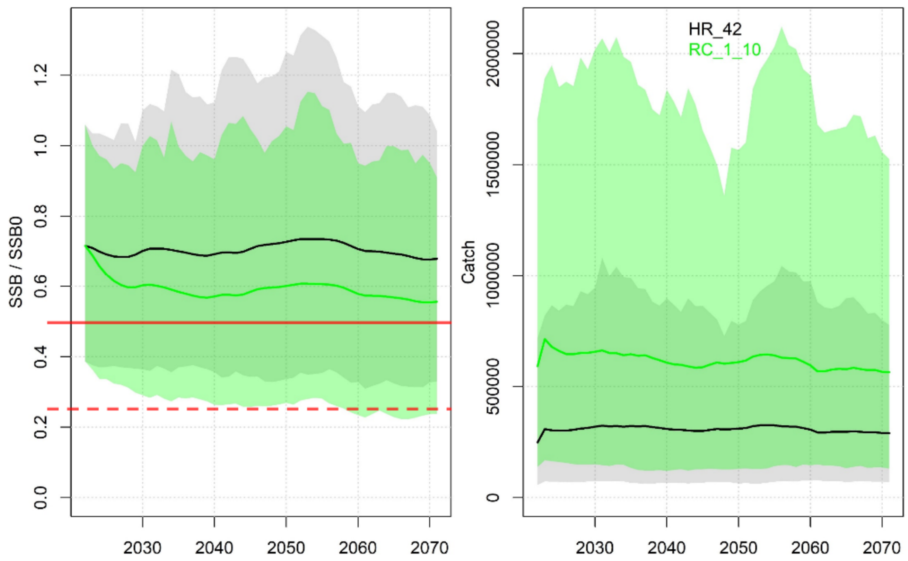

Figure 4.2. Projected biomass and yield performance of 4.2% and 10% harvest rate for quota management area 7C

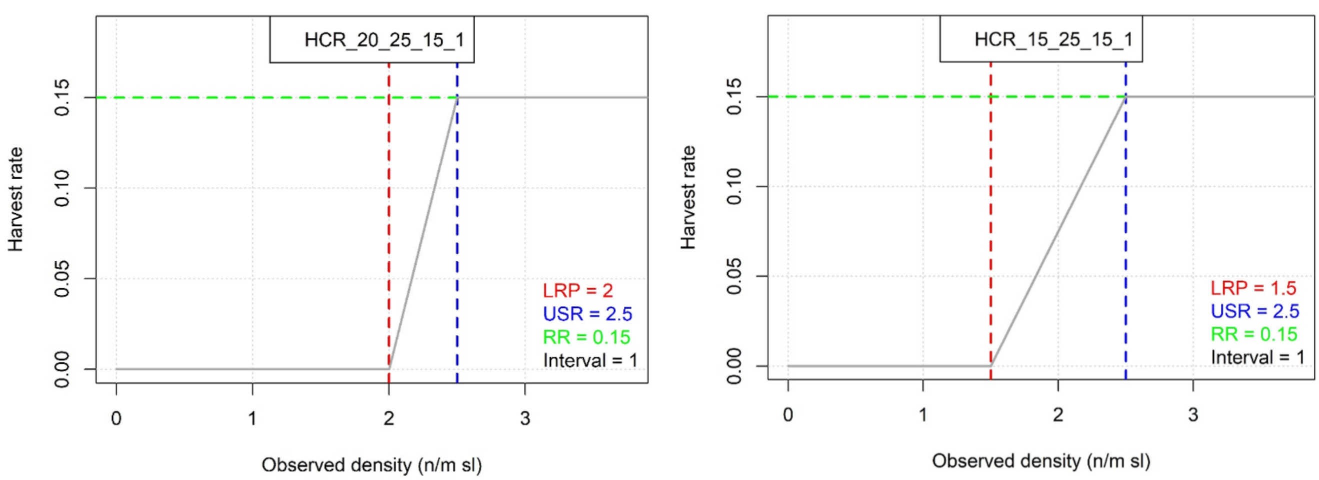

Figure 4.3. Specification of density – index - based management procedures that recommend harvest rates based on a hockey-stick harvest control rule with control points for the Limit Reference Point (LRP), Upper Stock Reference (USR) and Removal Reference (RR). These can also be configured as a rotational closure where interval = 1 mean no closure, interval = 2 closes every other year etc.

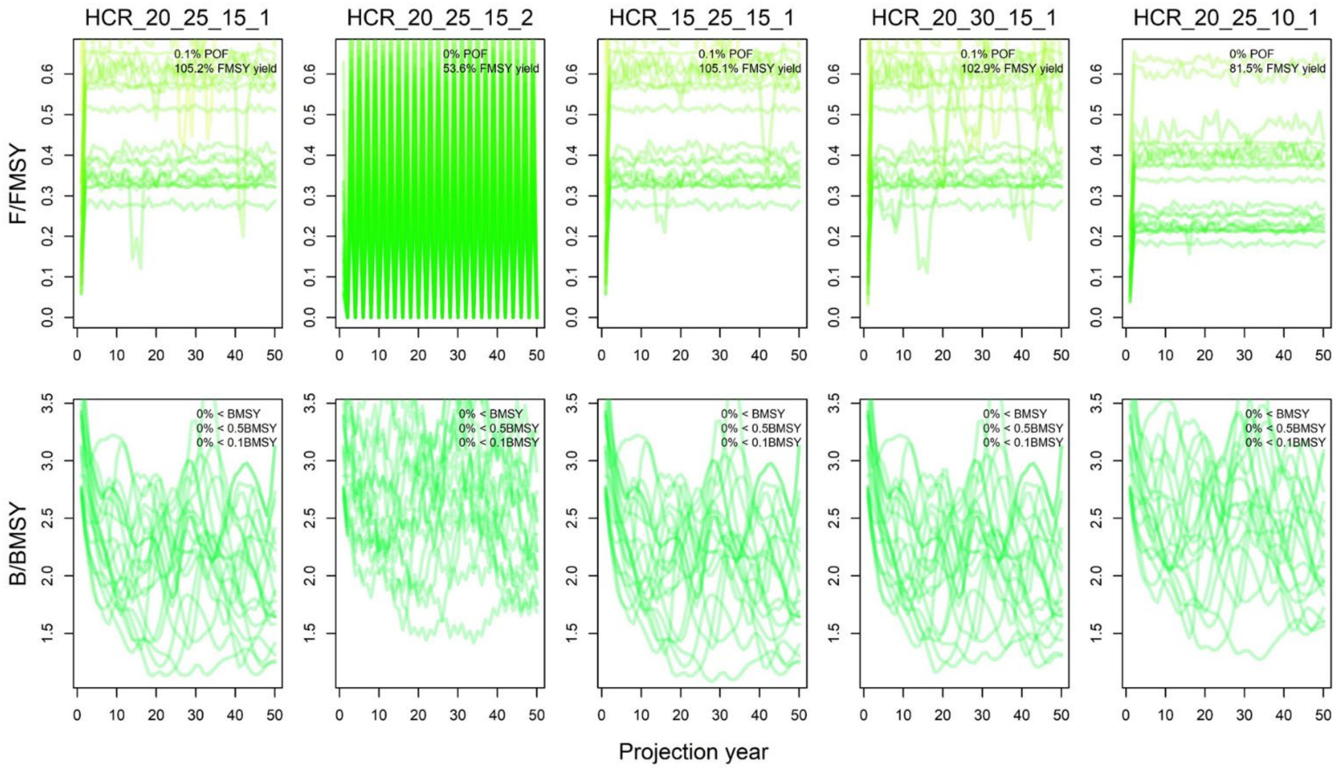

Figure 4.4. Exploitation rate and biomass projections for five management procedures based on the specification described in Figure 4.3.

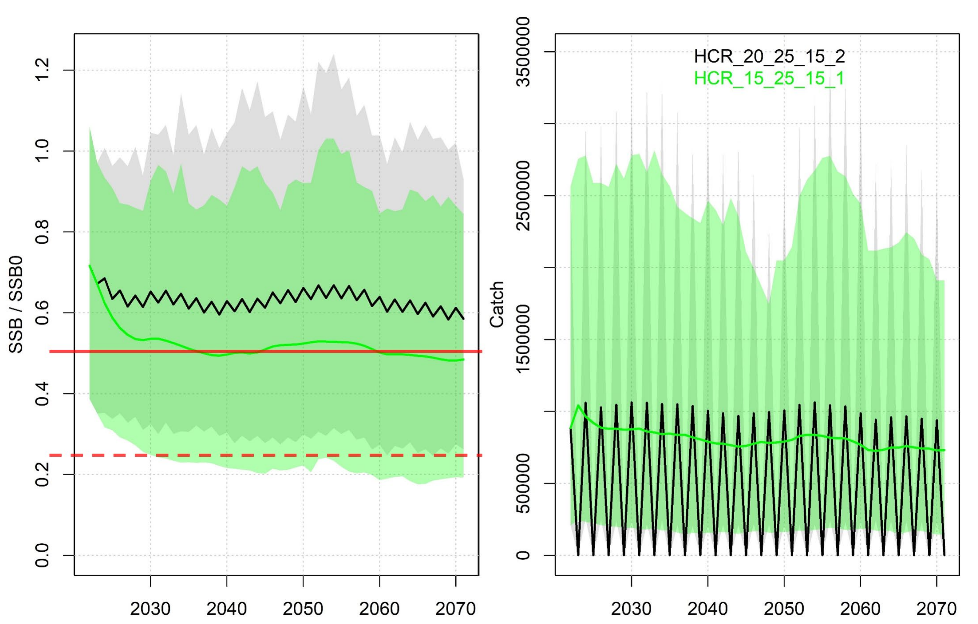

Figure 4.5. Comparison of projection envelopes for biomass and yield for two management procedures.

5 Green Sea Urchin (*Strongylocentrotus droebachiensis*)

The calculation of fishery reference points for Green Sea Urchin demonstrates that MSY reference points may not be appropriate for a species that is caught well above its size at maturity and natural mortality rate is relatively high. In this case, a relatively small fraction of the total biomass is available to fishing and hence MSY spawning biomass relative to unfished levels is very high between 60% and 70% among the five Stat. areas (Table 5.1). Additionally, the MSY harvest rate on that relatively small fraction of vulnerable biomass is also around 60%.

When evaluating potential open/closure rules with management procedures that respond to sea urchin density (figure 5.1), it is clear that current management by size limit is highly precautionary – large differences in catch outcome have little impact on projected biomass (Figure 5.2). The importance of the size limit is further emphasized by the much higher degree of sensitivity to a lower size limit of 35mm (Figure 5.3).

Table 5.1. Reference points and current exploitation rate estimates for Green Sea Urchin for five statistical areas. Due to the selection of only large mature individuals, conventional MSY reference points are potentially problematic as high harvest rates (medians of approximately 60%) are sustainable with a large biomass remaining (median SSBMSY is high relative to unfished at 60-70%).

Stat	Depletion	SSBMSY / SSB0			UMSY			Current U relative to UMSY		
Area	Mean	Median	2.50%	97.50%	Median	2.50%	97.50%	Median	2.50%	97.50%
12	**1.41**	**0.63**	0.42	0.91	**0.61**	0.31	0.66	**0.10**	0.00	0.28
13	**0.67**	**0.67**	0.43	0.93	**0.64**	0.62	0.66	**0.65**	0.48	0.89
18	**0.68**	**0.61**	0.41	0.87	**0.59**	0.22	0.66	**0.00**	0.00	0.00
19	**0.98**	**0.71**	0.43	0.96	**0.63**	0.36	0.68	**0.02**	0.00	0.15
20	**0.59**	**0.63**	0.35	0.93	**0.58**	0.18	0.67	**0.00**	0.00	0.00

Year	Historical density observation
2016	2.767
2018	0.961

Simulated density observations are generated in the future by scaling to 'true' simulated historical stock numbers.

Four MPs were defined with varying density control points:

HCR_0_1
HCR_0_2
HCR_1_2
HCR_2_3

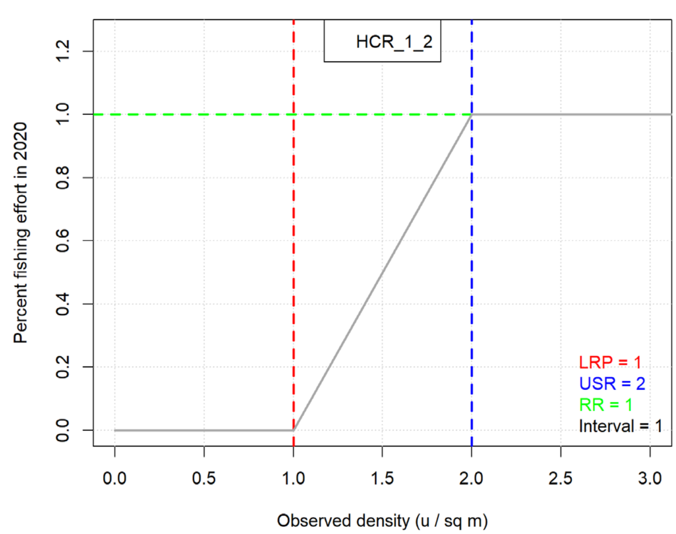

Figure 5.1. Specification of density – index - based management procedures that recommend harvest rates based on a hockey-stick harvest control rule with control points for the Limit Reference Point (LRP), Upper Stock Reference (USR) and Removal Reference (RR). These can also be configured as a rotational closure where interval = 1 mean no closure, interval = 2 closes every other year etc.

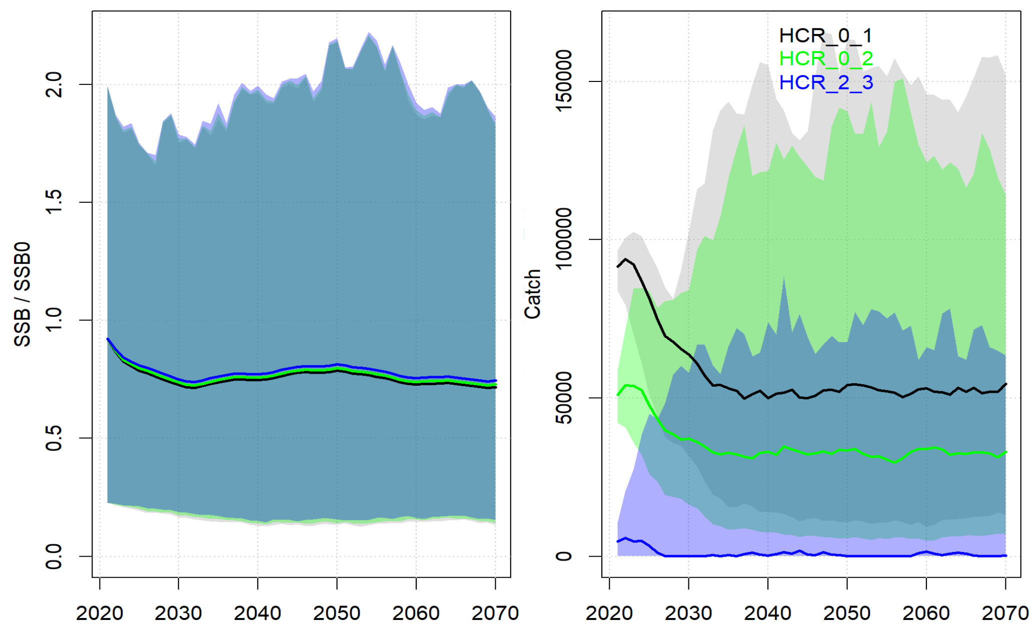

Figure 5.2. Alternative management procedures (see Figure 5.1) based on urchin density, have large consequences for projected catch but little consequence for projected biomass (lines are mean values, shaded areas are the 80% interval).

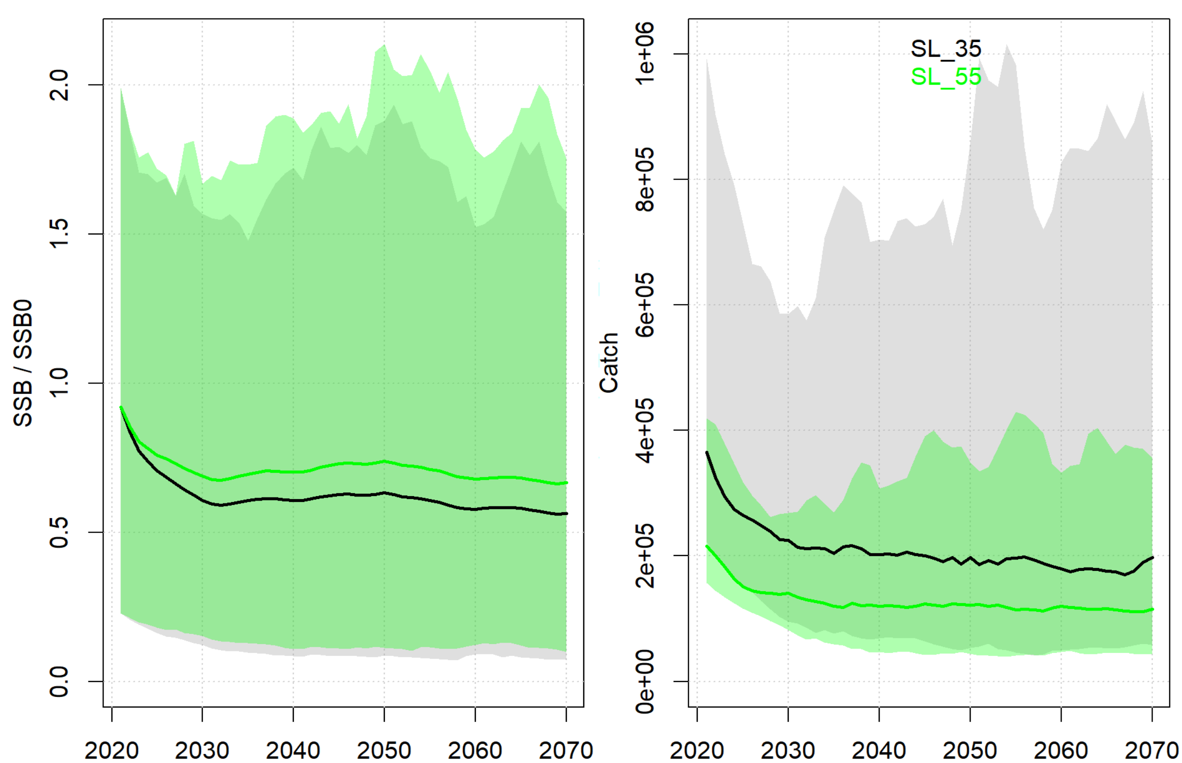

Figure 5.3. Projected catch and biomass outcomes for a minimum size limit at 35mm and a minimum size limit at 55mm.

6 Discussion

These custom analyses were undertaken primarily to demonstrate the capabilities of the MSE framework with respect to key management questions for each of the case studies, to elicit feedback on potential management options to test and key operating model uncertainties. However, the analyses confirm that hand-harvested fisheries differ in many important aspects in comparison to conventional industrial fisheries for fin fish.

In general, the operating models show that precautionary and robust management may be possible in instances where dead discarding is minimal, size limits are enforceable, individuals are selected for size and maturity. This certainty in management outcome in relative terms is informed by operating model projections that may have considerable scientific uncertainty over the magnitude of the resource and its status relative to a productive stock size.

A key aspect of this research will be configuring operating models that encompass a plausible range of uncertainty to demonstrate, implicitly (rather than explicitly in a stock assessment) that management outcomes can be achieved in the face of scientific uncertainty

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8 Materials

All materials can be found on the [CRSF Hand Held Invertebrates Splash Page](#).