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DEVELOPING THE DECISION PROCESS FOR SETTING THE TAC FOR ABALONE IN WESTERN ZONE VICTORIA, PARTICULARLY WITH REFERENCE TO RECOVERY OF AVG-IMPACTED REEFS.

Western Abalone Divers Association
June, 2017

FRDC TRF Project 2012/236

With Reports from:

CSIRO

ISBN **978-0-9870470-3-8**

Title:	Developing the decision process for setting the TAC for abalone in Victoria, particularly with reference to recovery of AVG-impacted reefs. Western Abalone Divers Association. Principal Investigator: Harry Peeters
Series:	FRDC Final Report 2012/236 Tactical Research Fund:
Year:	2017
Dewey Number:	
Year:	

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1 Acknowledgments

WADA would like to acknowledge the contribution of abalone scientists from around Australia who participated in Workshops to develop the approach to this project. Keith Sainsbury and Duncan Worthington, in particular, contributed to the development, implementation and completion of the project. Fay Helidoniotis and Malcolm Haddon were responsible for implementing the MSE approach. Finally, WADA would also like to acknowledge the contribution by Industry, and particularly commercial divers, to the essential observations and conservative management on which this work is based.

2 Executive Summary

2.1 The approach

Management Strategy Evaluation (MSE) methods are used to examine the performance of prospective Harvest Control Rules for calculating the Total Allowable Catch (TAC) for the Western Zone (WZ) Abalone Fishery. Of particular importance is recovery of the stock following the combined effects of previous fishing and Abalone Viral Ganglioneuritis (AVG) mortality in 2006/7. The prospective Harvest Control Rules (HCRs) examined are:

1) A constant harvest fraction that is multiplied by the estimated biomass each year to give the TAC (i.e. the Constant Harvest Fraction or CH HCR).
2) A harvest fraction that increases as the stock size increases and is multiplied by the estimated biomass each year to give the TAC (i.e. the Stock Harvest fraction or SH HCR).
3) The proportional change in TAC being adjusted each year according to the gradient of the catch per unit effort (CPUE) in the fishery over the previous four years (i.e. the Gradient CPUE or GC HCR).

Performance of the prospective Harvest Control Rules is measured by:

1) Total catch in the period 2014 to 2020;
2) The average annual variability of catches in the period 2014 to 2020;
3) Mean length of abalone caught;
4) Spawning stock depletion in 2020 relative to the unfished level;
5) Spawning stock depletion in 2020 relative to 2013; and
6) Exploitable biomass depletion in 2020 relative to 2013.

MSE methods use an Operating Model of the fishery resource to test the performance of alternative management strategies, and in this case of the alternative HCRs within a management strategy. The Operating Model does not have to be an exact representation of the fishery resource, but it does need to reasonably reflect the kinds of dynamics and situations that the HCR is likely to encounter from the real resource. So while the Operating Model should represent the fishery resource as well as possible it is particularly important that it represents the likely range of resource dynamics so that the robustness of the HCR can be tested. To achieve this the Operating Model consists of several different models of the resource that represent different possible dynamics and circumstances that the HCR may confront.

The Operating Model for the WZ Abalone Fishery used separate models of three different reef systems; The Crags (Port Fairy Area), Mills-Killarney (Warrnambool Area) and Watersprings (Portland Area). These were chosen to cover the geographical range of the fishery and to encompass a wide range of stock productivity, level of historical illegal and legal fishing, and AVG mortality.

Abalone exhibit a high level of spatial variability in their population parameters (growth, maturity etc) and larval dispersal is limited so that most young abalone settle within 10s-100s on meters from their parents. This results in a reef being occupied by what are effectively sub-populations with different biological characteristics and dynamics. In the operating model the abalone population on a reef system is represented by a number of sub-populations, each with different population parameters drawn from a probability distribution characteristic of the reef system. The Crags was represented by 8 sub-populations, Mills-Killarney by 6 and Watersprings by 4. Detailed MSE methods and results are described for The Crags and summary results using the same methodology are provided for Mills-Killarney and Watersprings.

2.2 Implementation and results

For each reef system the biological parameters are determined from a combination of biological studies, previous modelling studies, the available size composition information and the catch (legal and illegal) history of the reef system. The stock-recruitment parameters are determined by a Stock Reduction Analysis of the catch history 1965-2006. In this analysis the stock-recruitment parameters are found that match the catch history and result in the spawning stock depletion in 2006 (relative to the unfished spawning stock) being at realistic values. Three different values of the possible 2006 depletion are used, each giving different stock-recruitment parameters, to reflect the possibility of different stock status when the AVG mortality occurred in 2006/7. These 2006 depletions are 0.3, 0.25 and 0.2. In addition various possible values of AVG mortality in 2006/7 are considered in the analysis. These are 0.7 and 0.8 for The Crags; 0.6, 0.7, 0.8 and 0.9 for Mills-Killarney; and 0.6 and 0.7 for Watersprings.

The credibility of each of the three different 2006 depletions combined with the possible AVG mortality values are examined for each reef system by comparing the predicted exploitable biomass with the actual catches each year between 2009 (when fishing resumed after the AVG) and 2013. Interpretations of the level of 2006 depletion, and the associated stock-recruitment parameters for that level of depletion, combined with the 2006 AVG mortality would not credible if the predicted exploitable biomass in any year was a very large fraction of, or was less than, the actual catch taken. From this several combinations of 2006 depletion and AVG mortality can be excluded as implausible (i.e. they predict insufficient biomass to provide the observed catches) and the most plausible combinations can be identified. The conclusions from this are:

- The Crags: The most plausible interpretation is a 2006 depletion of 0.3 and AVG mortality of 0.7. This implies that the depletion immediately post-AVG was 0.09. All other interpretations are implausible.
- Mills-Killarney: The most plausible interpretation is a 2006 depletion of 0.2 and AVG mortality of 0.7, but this is not definitive. Interpretations across a range of 2006 depletion from 0.2-0.3 and of AVG mortality from 0.6-0.7 are all reasonably plausible. Interpretations of AVG mortality as high as 0.8-0.9 are implausible. Subsequent MSE testing for Mills-Killarney was for two interpretations; one with 2006 depletion 0.2 and AVG mortality 0.7 (implying a post-AVG depletion of 0.06) and the other with 2006 depletion 0.3 and AVG mortality 0.6 (implying a post-AVG depletion of 0.12).
- Watersprings: The most plausible interpretation is 2006 depletion 0.3 and AVG mortality 0.6. This implies a post-AVG depletion of 0.12. An interpretation of 2006 depletion 0.25 and AVG mortality 0.6 has some plausibility but all other interpretations are implausible.

The stock-recruitment parameters, combined with the other biological parameters, are used to calculate several quantities; the average recruitment to the unfished population, the size of the unfished population, the maximum sustainable yield (MSY), and the harvest fraction and depletion giving the MSY. The MSY harvest fraction is 0.26 and the spawning stock depletion at MSY is 0.35 of the unfished level.

It is notable that the relationships are relatively flat toped. So at The Crags for example taking catches of about 27t per year, instead of the MSY 32.7t per year, would use a harvest fraction of about 0.1 and result in a spawning stock depletion of about 0.6. Because for a Legal Minimum Length (LML) of 120mm and a low harvest fraction the spawning biomass and exploitable biomass are similar this would be reflected in a catch rate that is about double the catch rate when taking the MSY. This flatness is even more pronounced for Mills-Killarney where very close to the MSY catch is taken with over a wide range of harvest fractions (0.2 and greater) and a wide range of depletions (greater than about 0.3), though for higher harvest fractions the exploitable biomass and hence fishery catch rate would be depressed. Maximising economic returns rather than total catches in this situation would employ a harvest fraction significantly lower than the MSY harvest fraction and result in catch rates considerably greater than those at MSY.

These MSY relationships illustrate two features:

- While the MSY changes with LML the difference is not very large. When the stock is fully recovered the MSY is similar over a wide range of LML for each reef system; however the selection of LML gives different characteristics during recovery.
- The current large LMLs are very protective of the spawning stock. For a LML of 132mm at The Crags the depletion when the stock is fully recovered is above 0.4 even if very high harvest fractions are applied, though the exploitable biomass and hence fishery catch rate will decrease at high harvest fractions. Similarly, for a LML of 130mm at Mills-Killarney the depletion when fully recovered is above about 0.5.

The Constant Harvest fraction (CH) and Stock size dependent Harvest fraction (SH) HCRs require an estimate of the exploitable biomass. In the Western Zone there are three information sources for these estimates; scientific surveys, structured fishing with data loggers and free fishing with data loggers. For MSE testing the estimated exploitable biomass is assumed to be measured with multiplicative lognormal error such that 95% of the estimated biomass values would be in the range of approximately 0.8 to 1.25 of the true value. This range is based on experience with relating commercial catch rate to exploitable biomass in the Tasmanian Abalone Fishery.

Without fishing the median spawning biomass in 2036 has increased from less than 50t to about 275t, while with fishing at a constant harvest fraction of 0.1 it has increased to about 175t. The trajectories show relatively small increase in the period 2006 to about 2013, followed by a more rapid increase starting in about 2015. The initial period of slow increase is mainly because for about 7y after 2006 the yearclasses joining the spawning biomass are all significantly and similarly depleted in numbers by AVG, and the yearclasses immediately after that are small because of the very low post-AVG spawning biomass. During this period the main mechanism for increase in the spawning biomass is reduced fishing mortality to maintain numbers and allow somatic growth of the survivors to accumulate as spawning biomass. While the increase in spawning biomass in this period is slow the proportionate increase from the low starting base is significant; biomass about doubles, which is similar to what is has been seen in biomass estimates from the scientific surveys (which were not used in the MSE model conditioning). From about 2015 the more rapid increase results from the greater post-AVG survival of the yearclasses through to the age at maturity and increased recruitment as the spawning biomass increases.

The MSE performance measures applied to the different HCRs focus on the more immediate period to 2020, rather than the longer time horizon. Of the performance measures examined the total catch and spawning biomass depletion are the most useful in judging the trade-off between commercial catch and stock rebuilding.

As expected, increasing the constant harvest fraction increases the catch and decreases the spawning stock recovery. All constant harvest rates examined for The Crags result in an increase in spawning stock. The median depletion in 2020 is well above 0.2 for all of the harvest fractions examined, and above 0.24 for harvest fractions up to and including 0.1. For The Crags there is a chance of the depletion remaining below 0.2 in 2020 for all harvest fractions. There is a small chance of this even in the absence of fishing and it becomes more appreciable (greater than about 10%) for harvest fractions of 0.1 and higher. Depletion below 0.2 is commonly regarded as undesirable.

The CPUE gradient HCR as implented does not perform well. Recovery of the spawning stock is slow and variable. Over the period to 2020 the median recovery is similar to a constant harvest fraction of about 0.15 but variability gives some depletions as low as those from a constant harvest fraction of 0.2. This HCR was not evaluated for the other reef systems.

The stock size dependent harvest fraction HCR as configured delivered an average harvest fraction to 2020 of nearly 0.1, and it performed similar to a constant harvest fraction of 0.1. However this SH HCR performs slightly better than CH0.1, with slightly higher total catch and spawning stock rebuilding. This is a result of the stock size dependent harvest fraction rule keeping the harvest fraction low while the stock is small but having the ability to increase it as the stock size increases. It would be expected that the SH HCR would perform increasingly well for longer time horizons that would encompass a wider range of biomass outcomes. In future the automatic change in harvest fraction delivered by this HCR is likely to be highly desirable. But in the next few years its performance is very similar to a constant harvest fraction of about 0.1 and there is likely to be a desire to build experience with the harvest fraction approach before ‘locking in’ a particular SH HCR. So this HCR was not examined for the other reef systems.

Both of the combinations of 2006 depletion and AVG mortality for Mills-Killarney imply a relatively productive stock, and recovery is rapid even under the highest harvest fraction tested. This is despite the 0.7_0.2 interpretation implying a severe depletion post-AVG of the spawning biomass to 0.06 of the unfished level. For all harvest fractions tested the median biomass depletion by 2020 is greater than 0.28 and there is zero chance of outcomes less than a depletion of 0.2.

Recovery at Watersprings similar is to, but slightly faster than, The Crags. The median depletion in 2020 is well above 0.2 for all of the harvest fractions examined, and above 0.25 for harvest fractions up to and including 0.15. For Watersprings there is a chance of the depletion remaining below 0.2 in 2020 for all harvest fractions. There is a small chance of this even in the absence of fishing and it becomes more appreciable (greater than about 10%) for harvest fractions of 0.15 and higher.

2.3 Conclusions and application

The MSE testing confirms several of the conclusions from previous modelling about management of the stock following the AGV mortality, indicates that recovery is expected under a wide range of harvest strategies, demonstrates the trade-off between catches and the speed of recovery, and provides guidance on what harvest control rules are robust to the considered uncertainties and would be appropriate and for the next few years.

- It confirms the earlier conclusions, which have been the basis of management since the AVG mortality, that recovery is slow in the years of low spawning biomass after the AVG and that catches must be low in that period to allow significant rebuilding.
- The trade-off between rebuilding and catch in the period to 2020 is clear in the graphs above.
- In the present stock situation the chosen HCR must reliably deliver stock rebuilding. Under all of the constant harvest fractions examined (0-0.2) the population rebuilt from the very low depletions immediately post-AVG. The post-AVG depletions were 0.06-0.12 across the different reefs but by 2020 the median depletion is expected to be above 0.2 for all reefs even for the highest harvest fraction examined (0.2). For a harvest fraction of 0.2 the median depletion in 2020 ranged from 0.22 (The Crags) to 0.28 (Mills-Killarney). If recovery is assumed to be at depletion 0.35 (approximately the depletion for maximum sustainable yield) then based on median outcomes the population is expected to be about 62-80% recovered by 2020 under a harvest fraction of 0.2. However it is not only the median that is relevant but also the range of possible outcomes, and in particular the chance that by 2020 the population has not rebuilt above 0.2. The MSE testing indicates no chance of this outcome at Mills-Killarney for any of the harvest fractions examined. In contrast there is a small chance of this outcome for The Crags and Watersprings even without fishing. A constant harvest fraction up to 0.15 has a low chance of this outcome

for The Crags but for Watersprings this chance becomes more appreciable (about 10% or greater) for harvest fractions greater than 0.1; the rebuilding performance at these higher harvest fractions is less robust to uncertainty about 2006 depletion and AVG mortality across the reef systems.

- The CPUE gradient HCR did not perform well, and in particular it gave a very wide range of stock rebuilding outcomes. The stock size dependent harvest fraction HCR performed well. It gives slightly higher catches and biomass recovery than a constant harvest fraction HCR that applies a similar average harvest fraction (0.1) over 2014-2020 and gives better recovery behaviour than higher constant harvest fractions (i.e. 0.15 and 0.2). The stock size dependent harvest fraction HCR can be expected to perform increasingly well as the time horizon for testing is increased beyond 2020 because this would provide greater opportunity for the HCR to apply low harvest fraction while the stock is small but increase it as the stock grows. This HCR may be appropriate in the longer term but in the next few years it is not expected to provide major advantages over a constant harvest fraction of 0.15 or less, and a constant harvest fraction is a simpler approach with which to gain experience of harvest fraction HCRs.

Overall a constant harvest fraction HCR with the harvest fraction up to 0.1 or 0.15 is expected to deliver significant stock rebuilding with little chance of poor stock rebuilding outcomes (i.e. depletion below 0.2) by 2020. The catches taken increase directly as the harvest fraction is increased. These results are robust to all of the uncertainties examined and across the three reef systems that were chosen to encompass the range of biological circumstances in the fishery.

In operation a chosen constant harvest rate could be used as a limit to the catches determined through the existing consultative and decision process used in the fishery. This would effectively allow a constant harvest HCR to be introduced alongside the existing processes while experience was gained with it. Within this approach there are two different ways to apply the current MSE results: (1) select and apply the same constant harvest fraction to all reef codes, ensuring that the harvest fraction is safe for all reef codes (e.g. up to 0.1-0.15), and (2) classify all reef codes into categories that reflect their likely dynamics (e.g. categorise as being similar to Watersprings, The Crags or Mills-Killarney) and apply a different constant harvest fraction to each category. Option (2) has the advantage of applying low harvest fractions where this is desirable without placing the same restrictions on reef systems that can quickly recover under higher harvest fractions.

Practical application of a harvest fraction HCR requires that an estimate of the exploitable biomass is available. In the Western Zone fishery there are three information sources for such estimates; scientific surveys, structured fishing with data loggers and free fishing with data loggers. Biomass estimates based on all three source are currently available for many, but not for all, reef codes. All reef codes have estimates available for at least one information source. A statistical analysis and comparison of the different estimates should be made; there has been good data logger coverage in the WZ since 2006 so there is already about 8y of estimates from many reefs for comparison. In initial application of a harvest fraction HCR estimates of biomass from all available information sources should be calculated and considered, with the most credible estimate used in the HCR. As comparisons and experience with the different biomass estimates accrue there can be focus on the most appropriate biomass estimation methods.

Any selected HCR for the fishery should be interim and must be subject to ongoing monitoring and review. The WZ abalone stock condition and uncertainties about future dynamics are such that 'set and forget' is not a reliable option. Key indicators are spawning biomass and the numbers of abalone recruiting to the exploitable stock (which can be measured by the scientific surveys for abalone larger than about 100mm length). Spawning biomass should be monitored to ensure that it is responding within the range expected. Numbers of abalone recruiting to the exploitable biomass should be monitored to ensure that the expected increase in their numbers after about 2015 eventuates. The optimism for stock recovery depends on this increase occurring, and if this is not seen in the next few years then some core assumptions made in this analysis will have been incorrect and management of the fishery would need to be reconsidered.

The current LMLs in the fishery are highly protective of the spawning stock. This provides a very significant safety buffer against errors and uncertainties in assessment and management of the fishery. The large LML relative to the size at maturity means that much of the spawning biomass is unavailable to the fishery and is protected even if the fishery TAC was inadvertently set too large. At some point during stock recovery the need for this safety buffer will reduce and a lower LML could be considered.

Keywords: *Haliotis rubra*, Management Strategy Evaluation, Harvest Strategy.

3 Introduction

The Western Zone Abalone Fishery in Victoria commenced in the late 1960s, and has historically produced about 200 t of abalone per year, worth about $8 million at current prices. Abalone Viral Ganglioneuritis (AVG) was first observed causing catastrophic mortality of blacklip abalone in western Victoria in abalone famrs and then during May 2006, in wild populations adjacent to the farms, and continued to spread. As a consequence, there was a large reduction in Total Allowable Catch for the fishery with consequent reductions in GVP and profitability. Further, the AVG-related mortality led to great uncertainty about the status of the abalone populations (e.g. depletion) and its productive ability (e.g. catch). Populations affected by AVG were closed to fishing for 3-5 years, and have gradually been re-opened through a process involving fishery-independent abundance surveys, biomass estimates and structured fishing to deliver information about stocks. Combined with routine monitoring, a substantial amount of data has now been collected about the on-going recovery of abalone stocks to inform their management.

Prior to AVG, the Western Zone Abalone Divers Association (WADA) developed a process for finer scale assessment and management advice for the fishery. Workshops with significant Industry input and consideration of fine scale stock assessment are now used in most state's abalone fishery. With the reestablishment of fishing in western Victoria, and greater information about the productive capacity of the stock, there is now a strong need to consolidate the data available and develop their interpretation as performance indicators for the fishery. An important component of this will include the use of the performance indicators in developing flexible decision criteria and investigating scenarios of recovery for the fishery from a population model, updating earlier scenarios generated prior to the resumption of fishing. The Victorian Central Zone fishery has also been impacted by AVG, and will also benefit from greater coordination of the data available from multiple sources and its interpretation as fishery performance indicators with flexible decision criteria, as part of their TAC setting process.

4 Objectives

1. Facilitate a workshop to consolidate existing data, review analysis, interpretation and use as performance indicators in the TAC setting process, including development of a future monitoring plan.
2. Implement the short-term outcomes of the workshop, particularly related to development of the performance indicators, their use in updating population model scenarios of recovery, and combination in the TAC Setting process.

5 Methods

WADA facilitated several Workshops, involving the pre-eminent abalone scientists from around Australia, to develop the approach to this project. The Workshops were presented with existing data, analyses and stock assessments (i.e. where available) for the WZ fishery, considered alternative approaches to monitoring, assessment and management of the fishery, and made a range of recommendations about development of this project. The primary recommendation of the Workshops was the immediate development and implementation of a Management Strategy Evaluation (MSE) approach to assessing alternative Harvest Strategies for the fishery. CSIRO, and particularly Fay Helidoniotis and Malcolm Haddon, were contracted to develop the MSE and implement the analysis identified by the Workshops. Two reports were produced by CSIRO describing the development and application of the MSE approach to assessment of possible alternative Harvest Strategies in WZ, and are included here as Supplementary Reports. A draft Harvest Strategy was also prepared by Dr Keith Sainsbury, and is also included here as a Supplementary Report.

6 Results and Discussion

A summary of the two reports prepared by CSIRO, and included in full later in this report, are presented here. For each reef system, biological parameters are determined from a combination of biological studies, previous modelling studies, the available size composition information and the catch (legal and illegal) history of the reef system. The stock-recruitment parameters are determined by a Stock Reduction Analysis of the catch history 1965-2006. In this analysis the stock-recruitment parameters are found that match the catch history and result in the spawning stock depletion in 2006 (relative to the unfished spawning stock) being at realistic values. Three different values of the possible 2006 depletion are used, each giving different stock-recruitment parameters, to reflect the possibility of different stock status when the AVG mortality occurred in 2006/7. These 2006 depletions are 0.3, 0.25 and 0.2. In addition various possible values of AVG mortality in 2006/7 are considered in the analysis. These are 0.7 and 0.8 for The Crags; 0.6, 0.7, 0.8 and 0.9 for Mills-Killarney; and 0.6 and 0.7 for Watersprings.

The credibility of each of the three different 2006 depletions combined with the possible AVG mortality values are examined for each reef system by comparing the predicted exploitable biomass with the actual catches each year between 2009 (when fishing resumed after the AVG) and 2013. Interpretations of the level of 2006 depletion, and the associated stock-recruitment parameters for that level of depletion, combined with the 2006 AVG mortality would not credible if the predicted exploitable biomass in any year was a very large fraction of, or was less than, the actual catch taken. From this several combinations of 2006 depletion and AVG mortality can be excluded as implausible (i.e. they predict insufficient biomass to provide the observed catches) and the most plausible combinations can be identified. The conclusions from this are:

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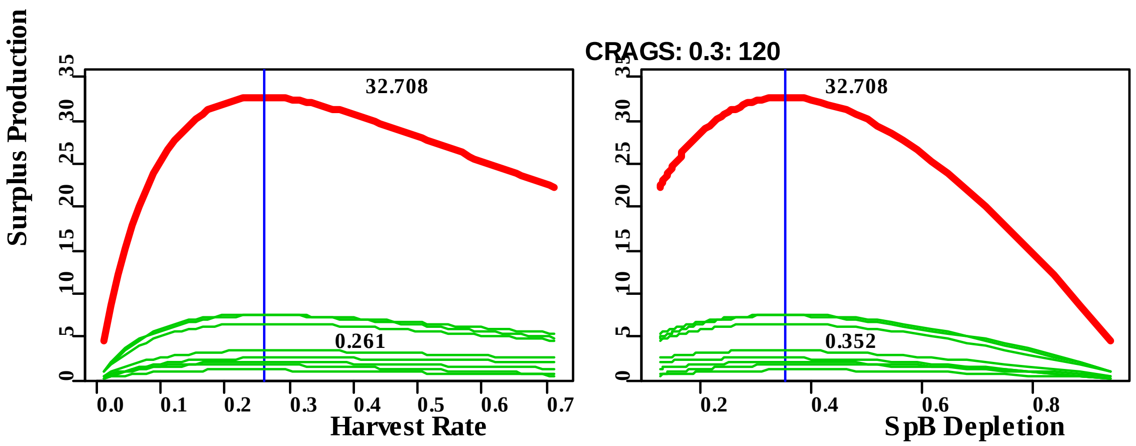
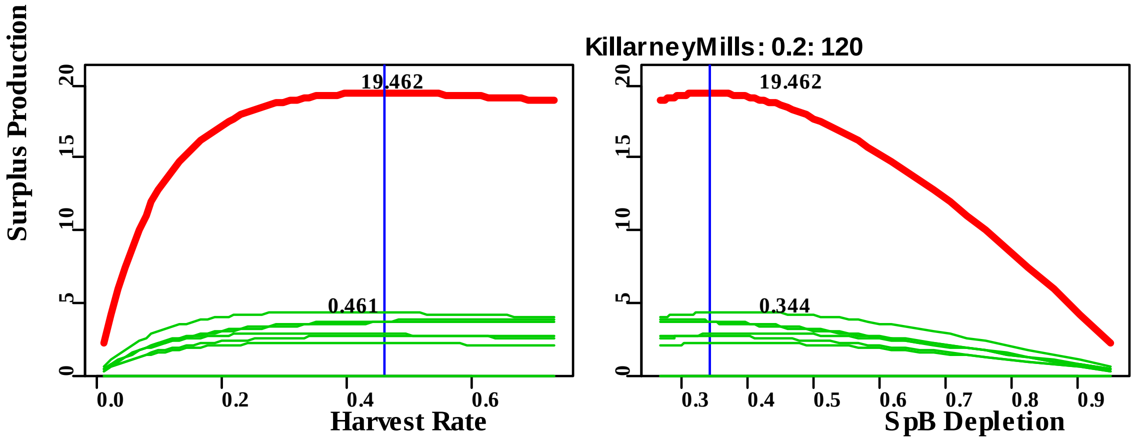
- Watersprings: The most plausible interpretation is 2006 depletion 0.3 and AVG mortality 0.6. This implies a post-AVG depletion of 0.12. An interpretation of 2006 depletion 0.25 and AVG mortality 0.6 has some plausibility but all other interpretations are implausible.

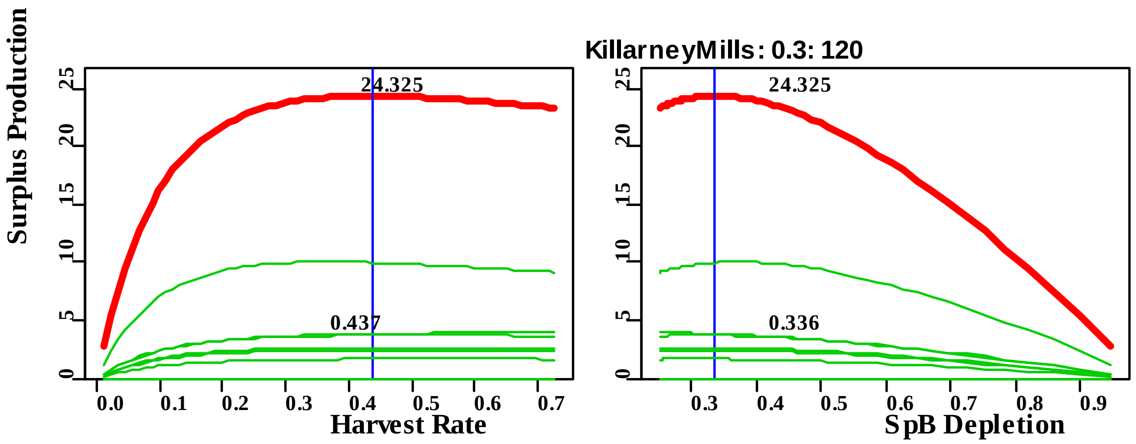
The stock-recruitment parameters, combined with the other biological parameters, are used to calculate several quantities; the average recruitment to the unfished population, the size of the unfished population, the maximum sustainable yield (MSY), and the harvest fraction and depletion giving the maximum sustainable yield. The relationships between maximum sustainable yield and harvest fraction and spawning biomass depletion, relative to the unfished spawning biomass, for The Crags reef system and a LML of 120mm are:

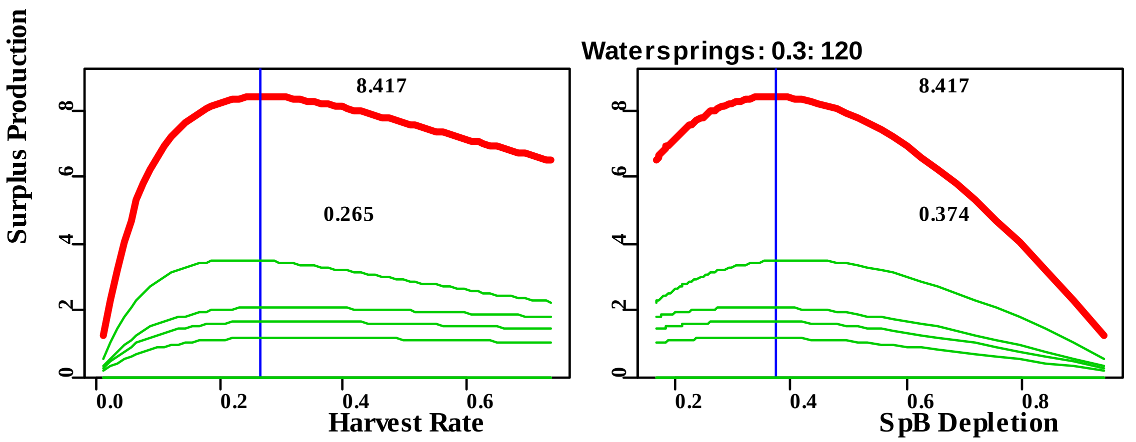


The MSY harvest fraction is 0.26 and the spawning stock depletion at MSY is 0.35 of the unfished level.

The MSY relationships for Mills-Killarney (for 2006 depletion of 0.2 and 0.3) and Watersprings for a LML of 120mm are:







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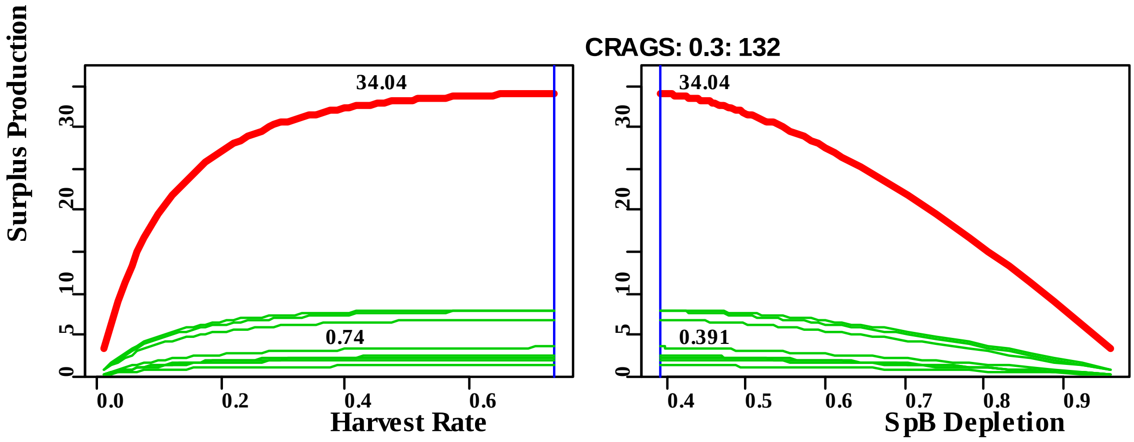
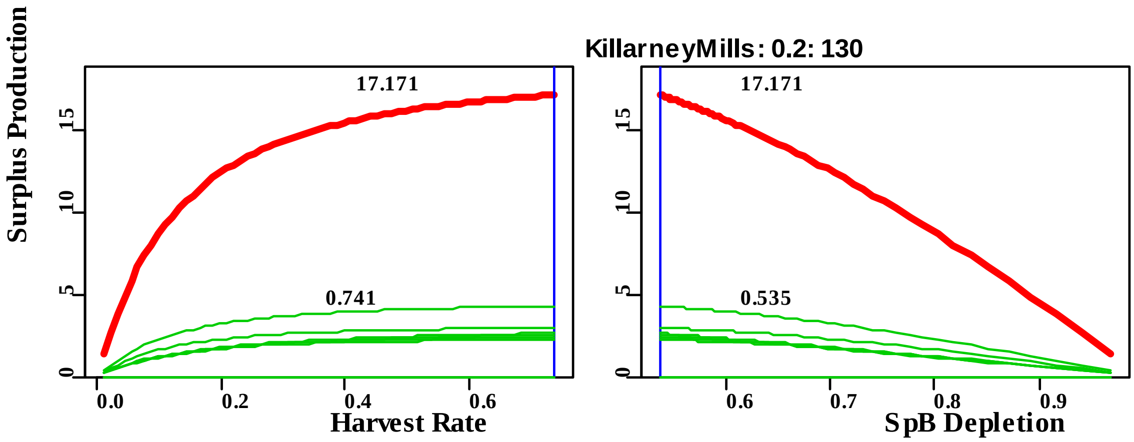
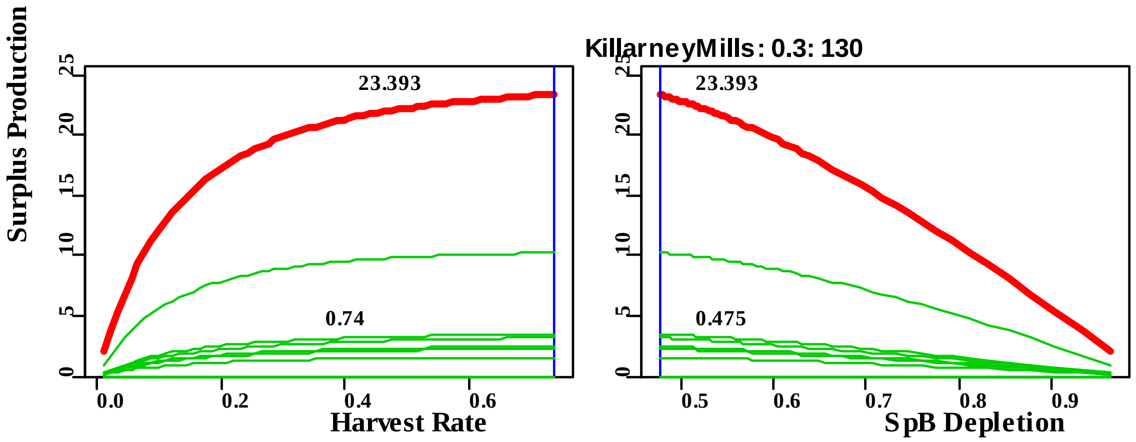
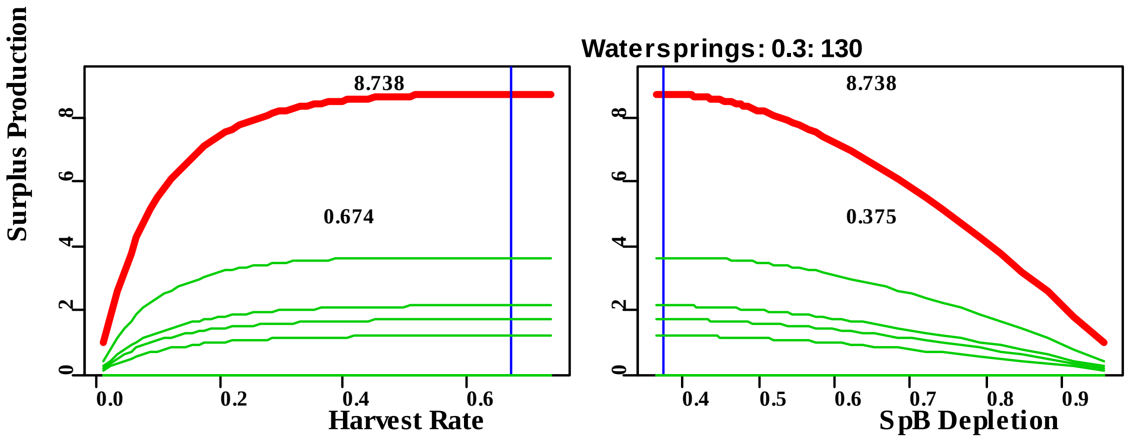
The MSY and depletion relationships can also be calculated for the precautionary LML that has been used in the fishery recently; 132mm for Crags and 130mm for Mills-Killarney and Watersprings. These are shown below.









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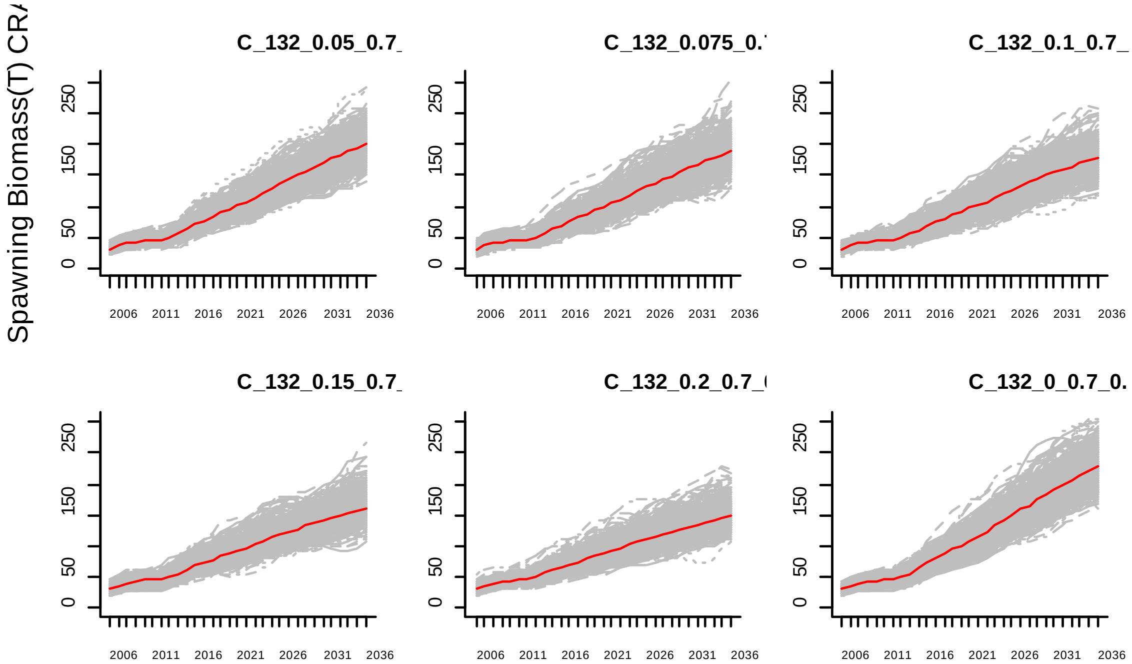
The Constant Harvest fraction (CH) and Stock size dependent Harvest fraction (SH) HCRs require an estimate of the exploitable biomass. In the Western Zone fishery there are three information sources for these estimates; scientific surveys, structured fishing with data loggers and free fishing with data loggers. For MSE testing the estimated exploitable biomass is assumed to be measured with multiplicative lognormal error such that 95% of the estimated biomass values would be in the range of approximately 0.8 to 1.25 of the true value. This range is based on experience with relating commercial catch rate to exploitable biomass in the Tasmanian abalone fishery.

The trajectory of recovery of the spawning biomass is close to linear over the next few decades under harvest fractions from zero to 0.2. For example the recovery trajectories for The Crags (with 2006 depletion of 0.3 and AVG mortality of 0.7) from 2006 through to 2036 with a range of constant harvest fractions (zero to 0.2) and a legal minimum legal (LML) of 132mm are:

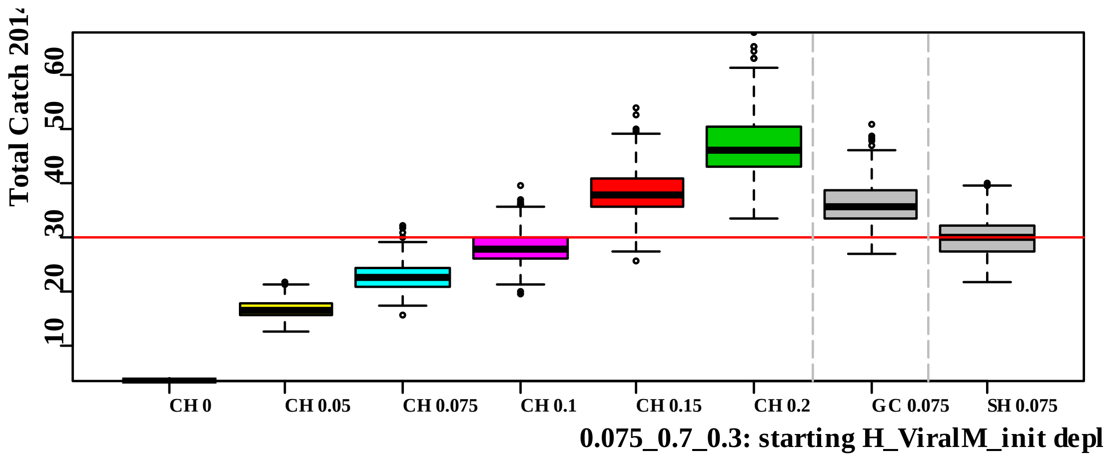


Without fishing the median spawning biomass in 2036 has increased from less than 50t to about 275t, while with fishing at a constant harvest fraction of 0.1 it has increased to about 175t. The trajectories show relatively small increase in the period 2006 to about 2013, followed by a more rapid increase starting in about 2015. The initial period of slow increase is mainly because for about 7y after 2006 the yearclasses joining the spawning biomass are all significantly and similarly depleted in numbers by AVG, and the yearclasses immediately after that are small because of the very low post-AVG spawning biomass. During this period the main mechanism for increase in the spawning biomass is reduced fishing mortality to maintain numbers and allow somatic growth of the survivors to accumulate as spawning biomass. While the increase in spawning biomass in this period is slow the proportionate increase from the low starting base is significant; biomass about doubles, which is similar to what is has been seen in biomass estimates from the scientific surveys (which were not used in the MSE model conditioning). From about 2015 the more rapid increase results from the greater post-AVG survival of the yearclasses through to the age at maturity and increased recruitment as the spawning biomass increases.

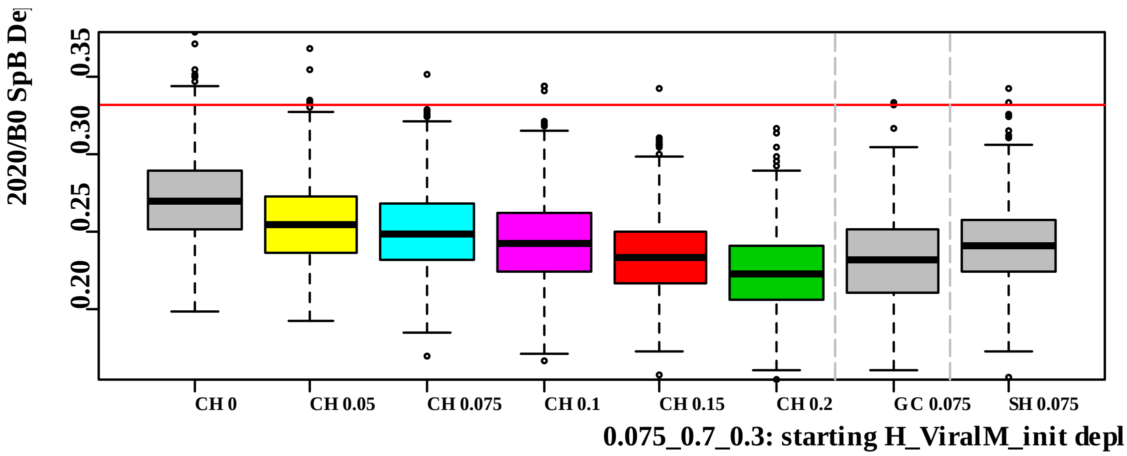
The Watersprings and Mills-Killarney recovery trajectories also follow similar patterns, though the absolute biomass values are different because of the different population parameters.

The MSE performance measures applied to the different HCRs focus on the more immediate period to 2020, rather than the longer time horizon. And of the performance measures examined the total catch and spawning biomass depletion are the most useful in judging the trade-off between commercial catch and stock rebuilding.

The total catch 2014-2020 and spawning biomass depletion for The Crags reef system and the various HCRs with a LML of 132mm are shown below. CH0 is a zero harvest fraction (no fishing), CH0.05 to CH0.2 are the constant harvest fraction rules, GC is the CPUE gradient rule and SH0.075 is the stock size dependent harvest fraction rule starting with harvest fraction 0.075 in the first year of application (2014).



On this total catch figure the horizontal red line is to aid comparison.



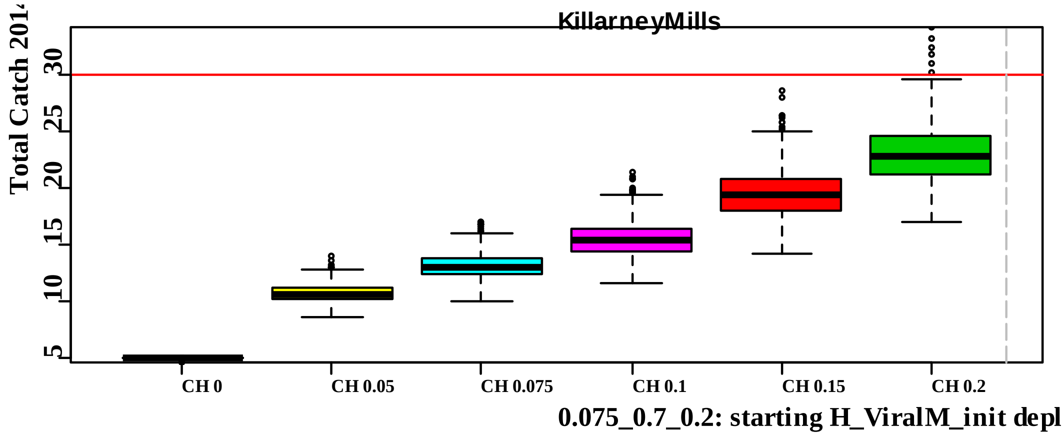
On this spawning biomass depletion figure the horizontal red line indicates the approximate depletion at MSY.

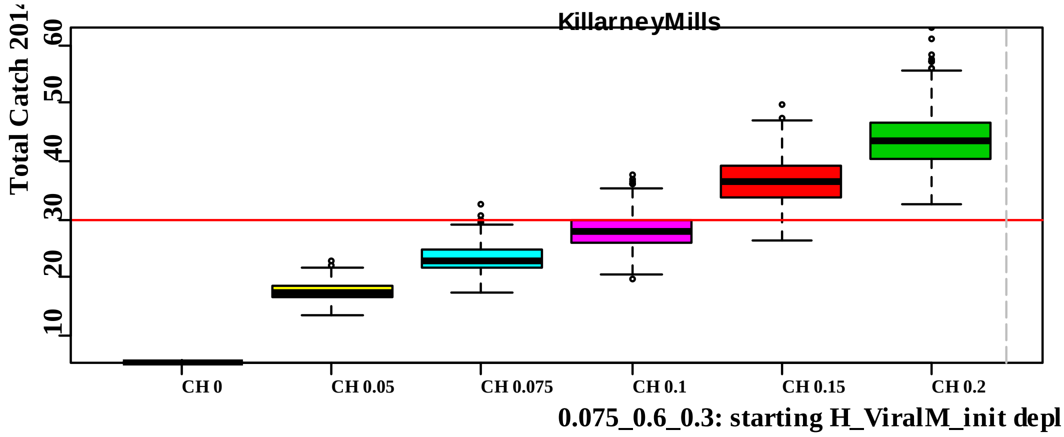
As expected, increasing the constant harvest fraction increases the catch and decreases the spawning stock recovery. All constant harvest rates examined for The Crags result in an increase in spawning stock. The median depletion in 2020 is well above 0.2 for all of the harvest fractions examined, and above 0.24 for harvest fractions up to and including 0.1. For The Crags there is a chance of the depletion remaining below 0.2 in 2020 for all harvest fractions. There is a small chance of this even in the absence of fishing and it becomes more appreciable (greater than about 10%) for harvest fractions of 0.1 and higher. Depletion below 0.2 is commonly regarded as undesirable.

The CPUE gradient HCR as configured does not perform well. Recovery of the spawning stock is slow and variable. Over the period to 2020 the median recovery is similar to a constant harvest fraction of about 0.15 but variability gives some depletions as low as those from a constant harvest fraction of 0.2. This HCR was not evaluated for the other reef systems.

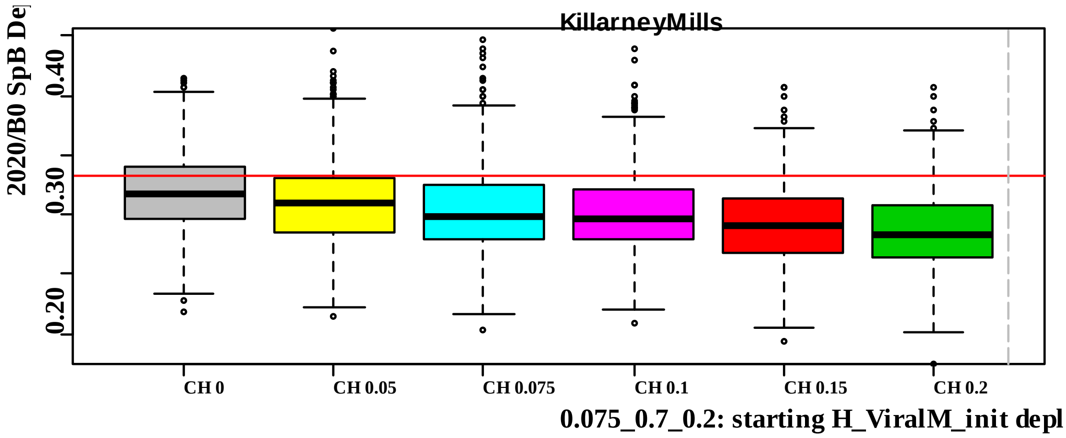
The stock size dependent harvest fraction HCR as configured delivered an average harvest fraction to 2020 of nearly 0.1, and it performed similar to a constant harvest fraction of 0.1. However this SH HCR performs slightly better than CH0.1, with slightly higher total catch and spawning stock rebuilding. This is a result of the stock size dependent harvest fraction rule keeping the harvest fraction low while the stock is small but having the ability to increase it as the stock size increases. It would be expected that the SH HCR would perform increasingly well for longer time horizons that would encompass a wider range of biomass outcomes. In future the automatic change in harvest fraction delivered by this HCR is likely to be highly desirable. But in the next few years its performance is very similar to a constant harvest fraction of about 0.1 and there is likely to be a desire to build experience with the harvest fraction approach before ‘locking in’ a particular SH HCR. So this HCR was not examined for the other reef systems.

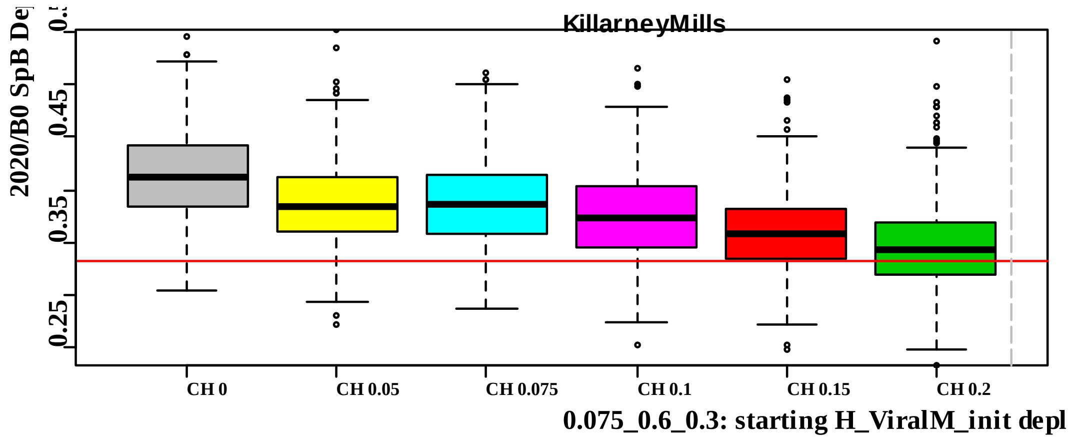
The total catch 2014-2020 and spawning biomass depletion for the Mills-Killarney reef system and the constant harvest fraction HCRs, with harvest fractions from zero to 0.2 and LML 130mm, are shown below. These are shown for the range of plausible combinations of 2006 depletion and AVG mortality (i.e. 0.7_0.2 and 0.6_0.3). The Mills-Killarney total catches are:





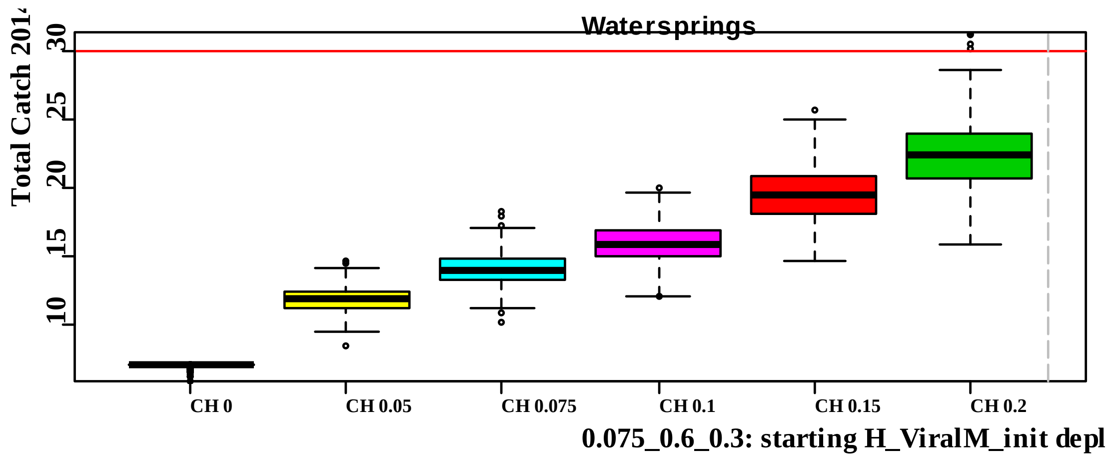
And the Mills-Killarney spawning biomass depletions are:

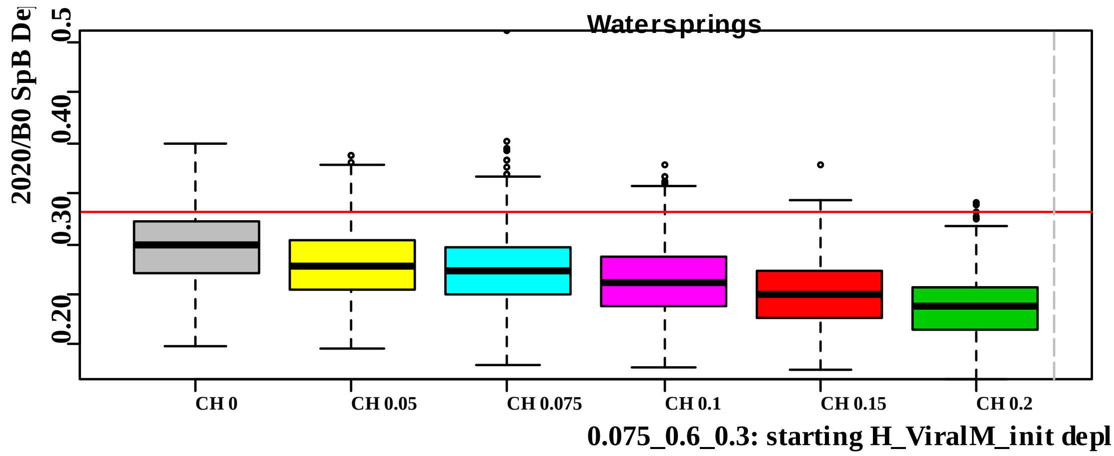




Both of the combinations of 2006 depletion and AVG mortality for Mills-Killarney imply a relatively productive stock, and recovery is rapid even under the highest harvest fraction tested. This is despite the 0.7_0.2 interpretation implying a severe depletion post-AVG of the spawning biomass to 0.06 of the unfished level. For all harvest fractions tested the median biomass depletion by 2020 is greater than 0.28 and there is zero chance of outcomes less than a depletion of 0.2.

The total catch 2014-2020 and spawning biomass depletion for the Watersprings reef system and the constant harvest fraction HCRs, with harvest fractions from zero to 0.2 and LML 130mm, are shown below.





Recovery at Watersprings similar is to, but slightly faster than, The Crags. The median depletion in 2020 is well above 0.2 for all of the harvest fractions examined, and above 0.25 for harvest fractions up to and including 0.15. For Watersprings there is a chance of the depletion remaining below 0.2 in 2020 for all harvest fractions. There is a small chance of this even in the absence of fishing and it becomes more appreciable (greater than about 10%) for harvest fractions of 0.15 and higher.

7 Conclusions, Implications and Recommendations

The MSE testing confirms several of the conclusions from previous modelling about management of the stock following the AGV mortality, indicates that recovery is expected under a wide range of harvest strategies, demonstrates the trade-off between catches and the speed of recovery, and provides guidance on what harvest control rules are robust to the considered uncertainties and would be appropriate and for the next few years.

- It confirms the earlier conclusions, which have been the basis of management since the AVG mortality, that recovery is slow in the years of low spawning biomass after the AVG and that catches must be low in that period to allow significant rebuilding.
- The trade-off between rebuilding and catch in the period to 2020 is clear in the graphs above.
- In the present stock situation the chosen HCR must reliably deliver stock rebuilding. Under all of the constant harvest fractions examined (0-0.2) the population rebuilt from the very low depletions immediately post-AVG. The post-AVG depletions were 0.06-0.12 across the different reefs but by 2020 the median depletion is expected to be above 0.2 for all reefs even for the highest harvest fraction examined (0.2). For a harvest fraction of 0.2 the median

depletion in 2020 ranged from 0.22 (The Crags) to 0.28 (Mills-Killarney). If recovery is assumed to be at depletion 0.35 (approximately the depletion for maximum sustainable yield) then based on median outcomes the population is expected to be about 62-80% recovered by 2020 under a harvest fraction of 0.2. However it is not only the median that is relevant but also the range of possible outcomes, and in particular the chance that by 2020 the population has not rebuilt above 0.2. The MSE testing indicates no chance of this outcome at Mills-Killarney for any of the harvest fractions examined. In contrast there is a small chance of this outcome for The Crags and Watersprings even without fishing. A constant harvest fraction up to 0.15 has a low chance of this outcome for The Crags but for Watersprings this chance becomes more appreciable (about 10% or greater) for harvest fractions greater than 0.1; the rebuilding performance at these higher harvest fractions is less robust to uncertainty about 2006 depletion and AVG mortality across the reef systems.

- The CPUE gradient HCR did not perform well, and in particular it gave a very wide range of stock rebuilding outcomes. The stock size dependent harvest fraction HCR performed well. It gives slightly higher catches and biomass recovery than a constant harvest fraction HCR that applies a similar average harvest fraction (0.1) over 2014-2020 and gives better recovery behaviour than higher constant harvest fractions (i.e. 0.15 and 0.2). The stock size dependent harvest fraction HCR can be expected to perform increasingly well as the time horizon for testing is increased beyond 2020 because this would provide greater opportunity for the HCR to apply low harvest fraction while the stock is small but increase it as the stock grows. This HCR may be appropriate in the longer term but in the next few years it is not expected to provide major advantages over a constant harvest fraction of 0.15 or less, and a constant harvest fraction is a simpler approach with which to gain experience of harvest fraction HCRs.

Overall a constant harvest fraction HCR with the harvest fraction up to 0.1 or 0.15 is expected to deliver significant stock rebuilding with little chance of poor stock rebuilding outcomes (i.e. depletion below 0.2) by 2020. The catches taken increase directly as the harvest fraction is increased. These results are robust to all of the uncertainties examined and across the three reef systems that were chosen to encompass the range of biological circumstances in the fishery.

In operation a chosen constant harvest rate could be used as a limit to the catches determined through the existing consultative and decision process used in the fishery. This would effectively allow a constant harvest HCR to be introduced alongside the existing processes while experience was gained with it. Within this approach there are two different ways to apply the current MSE results: (1) select and apply the same constant harvest fraction to all reef codes, ensuring that the harvest fraction is safe for all reef codes (e.g. up to 0.1-0.15), and (2) classify all reef codes into categories that reflect their likely dynamics (e.g. categorise as being similar to Watersprings, The Crags or Mills-Killarney) and apply a different constant harvest fraction to each category. Option (2) has the advantage of applying low harvest fractions where this is desirable without placing the same restrictions on reef systems that can quickly recover under higher harvest fractions.

Practical application of a harvest fraction HCR requires that an estimate of the exploitable biomass is available. In the Western Zone fishery there are three information sources for such estimates; scientific surveys, structured fishing with data loggers and free fishing with data loggers. Biomass estimates based on all three source are currently available for many, but not for all, reef codes. All reef codes have estimates available for at least one information source. A statistical analysis and comparison of the different estimates should be made; there has been good data logger coverage in the WZ since 2006 so there is already about 8y of estimates from many reefs for comparison. In initial application of a harvest fraction HCR estimates of biomass from all available information sources should be calculated and considered, with the most credible estimate used in the HCR. As comparisons and experience with the different biomass estimates accrue there can be focus on the most appropriate biomass estimation methods.

Any selected HCR for the fishery should be interim and must be subject to ongoing monitoring and review. The WZ abalone stock condition and uncertainties about future dynamics are such that ‘set and forget’ is not a reliable option. Key indicators are spawning biomass and the numbers of abalone recruiting to the exploitable stock (which can be measured by the scientific surveys for abalone larger than about 100mm length). Spawning biomass should be monitored to ensure that it is responding within the range expected. Numbers of abalone recruiting to the exploitable biomass should be monitored to ensure that the expected increase in their numbers after about 2015 eventuates. The optimism for stock recovery depends on this increase occurring, and if this is not seen in the next few years then some core assumptions made in this analysis will have been incorrect and management of the fishery would need to be reconsidered.

The current LMLs in the fishery are highly protective of the spawning stock. This provides a very significant safety buffer against errors and uncertainties in assessment and management of the fishery. The large LML relative to the size at maturity means that much of the spawning biomass is unavailable to the fishery and is protected even if the fishery TAC was inadvertently set too large. At some point during stock recovery the need for this safety buffer will reduce and a lower LML could be considered.

8 Extension and Adoption

The draft Harvest Strategy developed as part of this project (see Suplementary Reports) was supported by Fisheries Victoria and Industry for use in the TAC Setting process in the Western Zone Victoria TAC Setting process for 2017-18. This included preparation of a stock assessment specifically assessing performance indicators detailed in the draft Harvest Strategy (WADA, in press). The draft Harvest Strategy is currently being considered by the Victorian Abalone Harvest Strategy Working Group for implementation as part of the need to implement harvest strategies for all three zones in Victoria.

9 Supplementary Reports

See two reports from CSIRO, and a draft Harvest Strategy prepared by Keith Sainsbury, on following pages.

Report 1: Modelling the Potential for Recovery of Western Victorian Abalone Stocks: Methodology and Application to The Crags Reef System

Modelling the Potential for Recovery of Western Victorian Abalone Stocks: Methodology and Application to The Crags Reef System

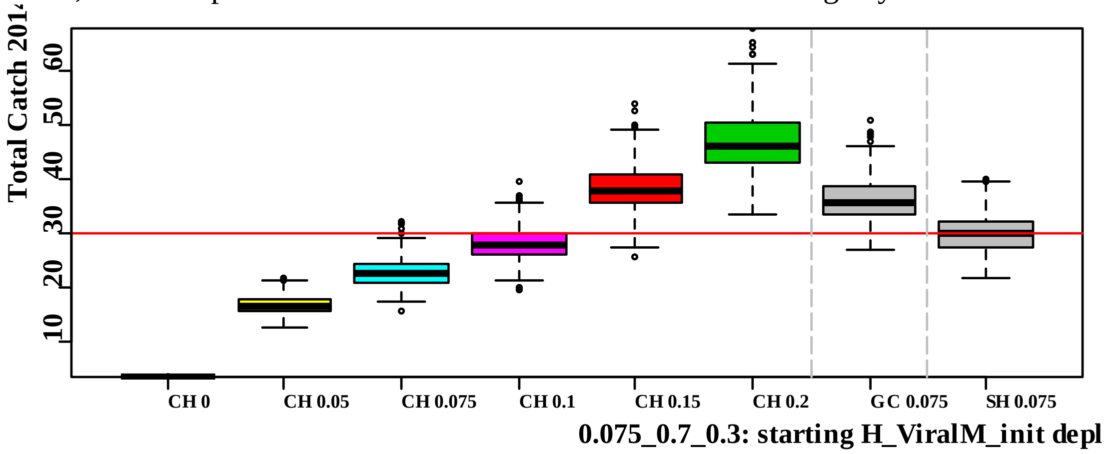
Fay Helidoniotis and Malcolm Haddon

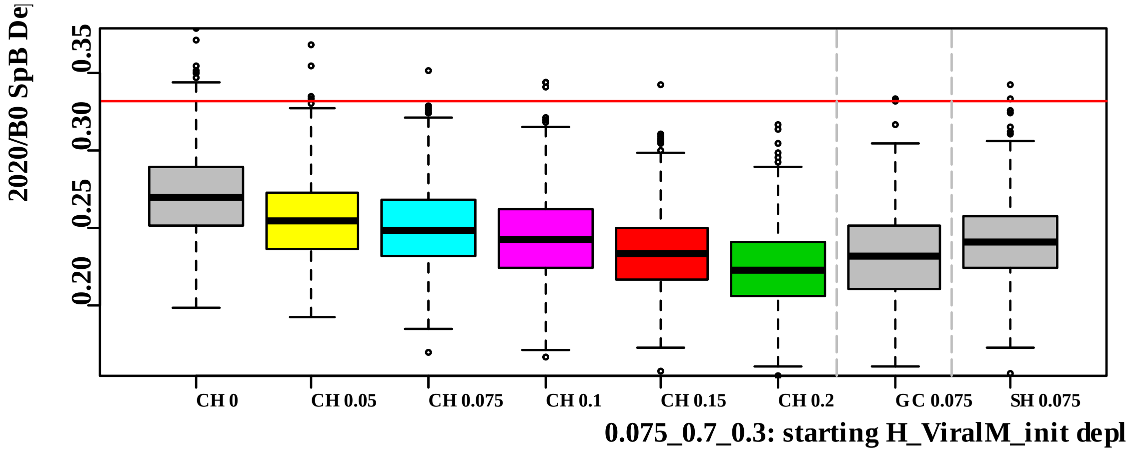
CSIRO Wealth from Oceans Flagship, GPO Box 1538, Hobart, TAS 7001, Australia.

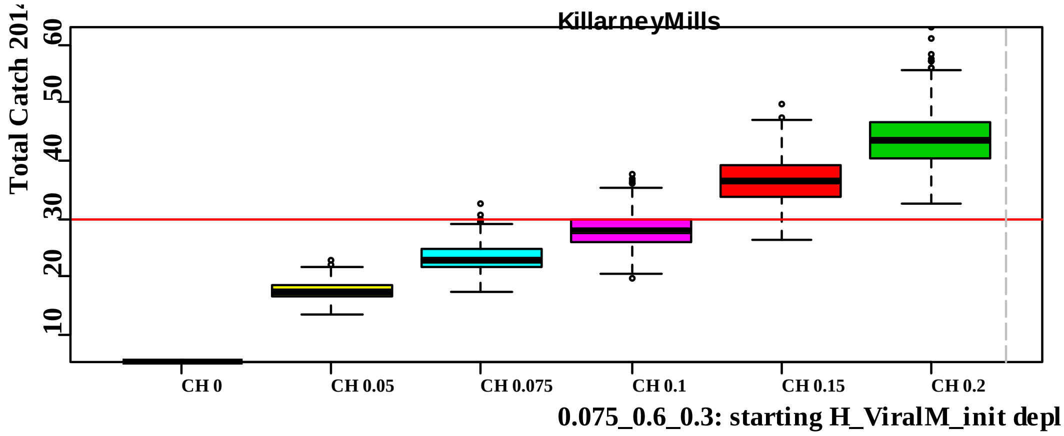
November 2014

1 Non-Technical Summary

According to the Constant Harvest HCR (CH), the rebuilding of both spawning biomass and exploitable biomass by 2020 continues at all harvest rates considered (0, 0.05, 0.075, 0.10, 0.15 and 0.20; Figure 1). The 9.856t taken in 2012 appears to have been at a harvest rate higher than any of the harvest rates examined in detail and may have led to short lived declines in mean length, spawning biomass, and exploitable biomass. It demonstrates that care is still required to control the harvest rate.
The Gradient CE HCR (GC) resulted in similar outcomes as a constant harvest rate of 0.15 or 15% both in terms of total catch and spawning biomass depletion (compare GC 0.075 to CH 0.15). The Stock size HCR (SH) resulted in similar outcomes as a constant harvest rate of 0.10 or 10% also both in terms of total catch and spawning biomass depletion (compare SH 0.075 to CH 0.10). The GC HCR results in a higher harvest rate than the SH HCR and therefore will return a recommendation for a higher annual TAC.
Catches increased with increasing harvest rates (refer to CH HCR), when the Legal Minimum Length remains constant (at 132mm); there is a clear trade-off between higher catches and lower levels of rebuilding. Rebuilding includes an increase of spawning biomass, which implies greater security and scale of recruitment, as well as an increase of exploitable biomass, which implies an increase in catch rates and ease of taking any TAC.






KillarneyMills
Total Catch 2014
10
20
30
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CH 0
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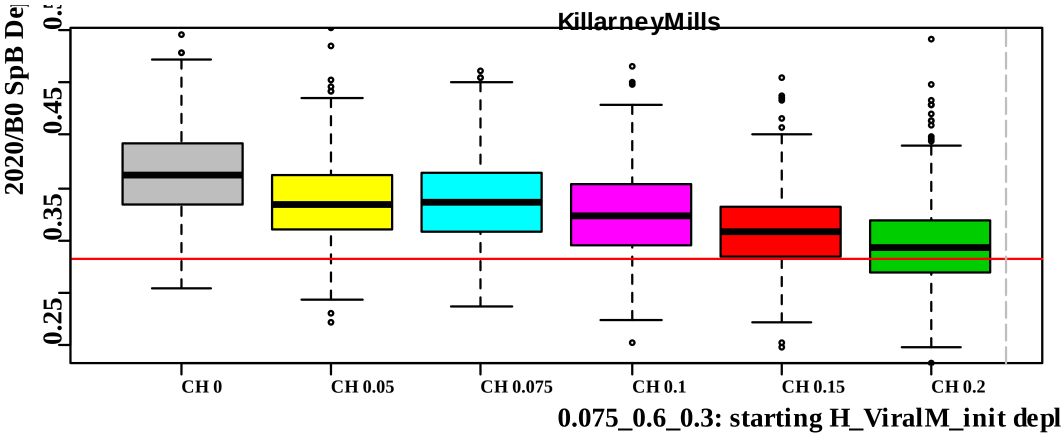
0.075_0.6_0.3: starting H_ViralM_init depl


KillarneyMills
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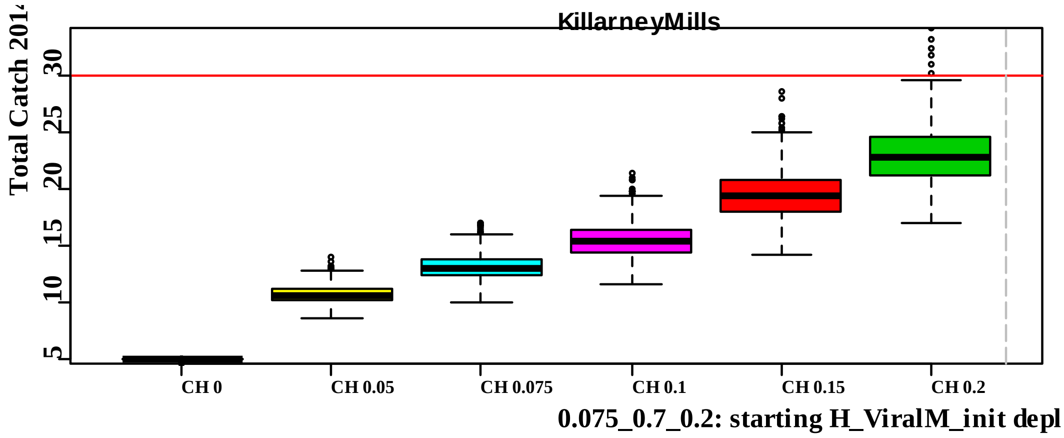
KillarneyMills
Total Catch 2014
5
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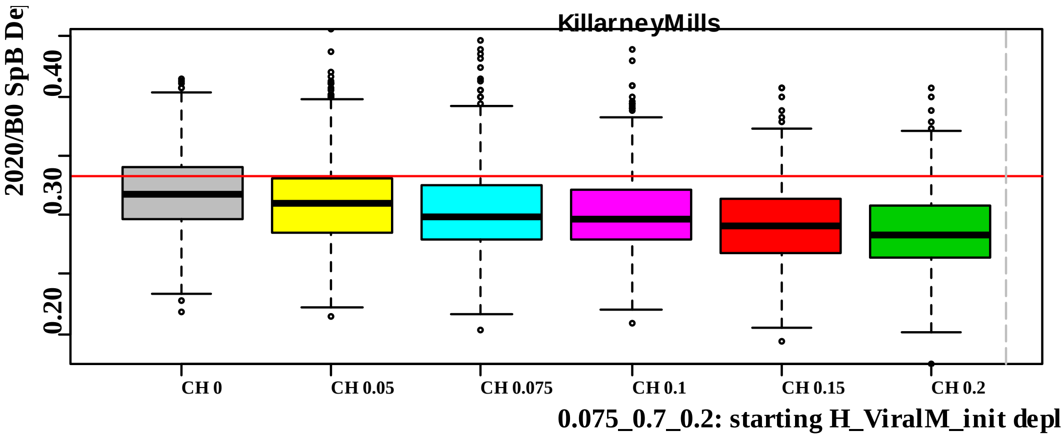
CH 0
CH 0.05
CH 0.075
CH 0.1
CH 0.15
CH 0.2
0.075_0.7_0.2: starting H_ViralM_init depl


KillarneyMills
2020/B0 SpB De
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0.075_0.7_0.2: starting H_ViralM_init depl

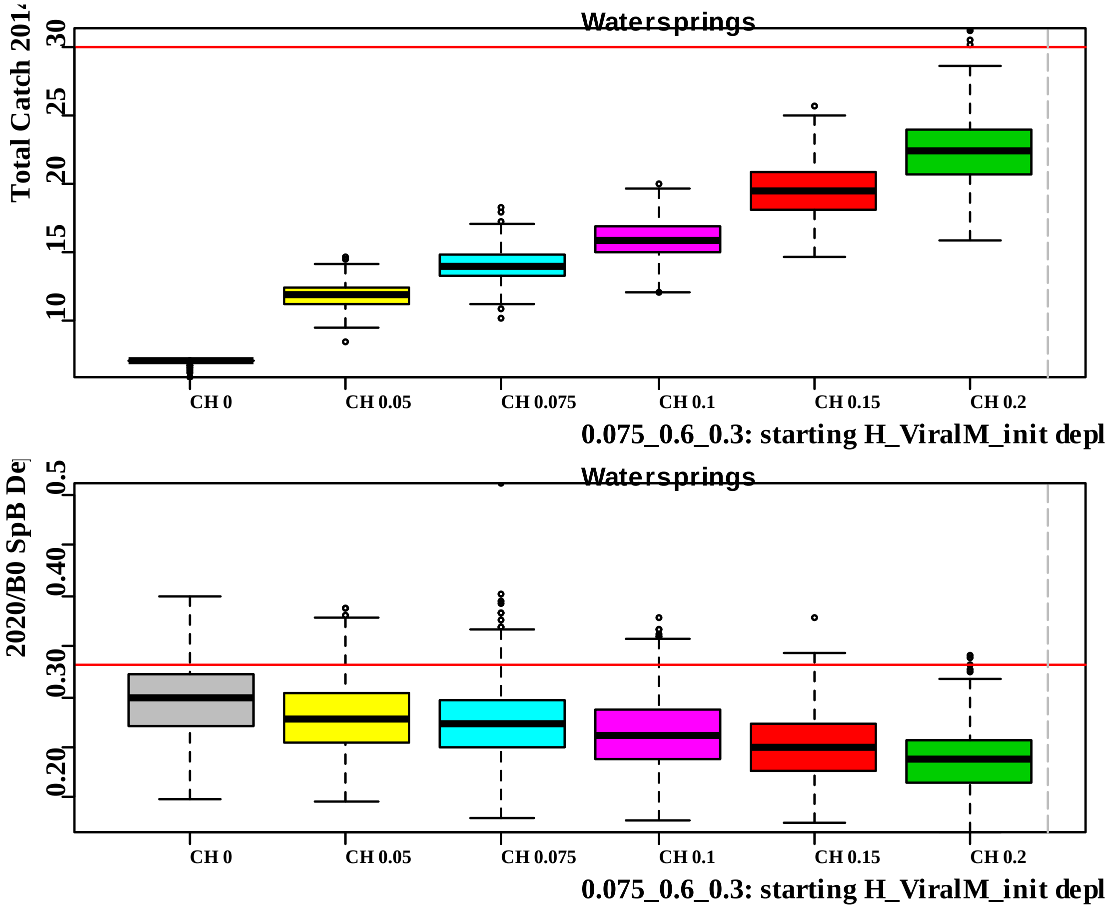


Figure 1. A comparison of the expected total catch from 2014 – 2020 and the depletion level of the spawning biomass at five different constant harvest rates. The maximum productivity (MSY) is expected between 31 – 35% depletion level. The red horizontal line indicates a depletion level at an approximate MSY according to Figure 2

Catches in 2012 (Table 1) may have been at a harvest rate of 0.23 – 0.44 available exploitable biomass because at that rate the total catch 2014 – 2020 will be 68.9 tonnes (9.587 tonnes catch in 2012 * 7 years = 68.9 tonnes at an LML of 132 mm). Catches may need to decrease over the next few years, especially if the target harvest rates is to be maintained at 0.05 or 0.075, and the exploitable biomass decreases. A harvest rate of 0.05 or 0.075 harvest rate will allows an fairly similar increase in biomass, and a rebuilding objective is one of the priorities of this fishery.

2 Introduction

2.1 The Western Zone Abalone Fishery

The western Victorian abalone zone has 14 licence holders and includes all waters between the South Australian/Victorian border and the Hopkins River Mouth (142° 31' E).

In 2006 there was a serious outbreak of Abalone Viral Ganglioneuritis (AVG), which spread along the coast imposing sometimes severe mortality on all size classes within each reefcode. During the period of the virus attack there was no commercial fishing across most of the reefs. Since 2009 relatively small catches have been taken in exploratory fishing to help determine the current status of the stocks on the various reefcodes and whether there are signs of recovery following the viral mortality (Table 1). This commercial fishing has also included some structured fishing designed to obtain an abundance index through time.

Table 1. The catches reported against year for the Crags reefcode. The catches in 2006 occurred before the viral outbreak. The catch in 2006 is only for part of the year; each year is a fishing season from May to April the following year. Highlighted are the years where fishing resumed following viral mortality.

Year	Catch (t)	Year	Catch (t)
1978	24.445	1996	41.833
1979	26.984	1997	24.396
1980	40.306	1998	37.614
1981	46.091	1999	28.870
1982	27.665	2000	25.060
1983	33.914	2001	31.022
1984	38.840	2002	19.633
1985	33.745	2003	22.701
1986	22.898	2004	26.138
1987	42.718	2005	23.607
1988	20.812	2006	10.983
1989	17.410	2007	0.000
1990	26.337	2008	0.000
1991	43.329	2009	3.368
1992	34.800	2010	3.667
1993	32.176	2011	4.683
1994	29.796	2012	9.857
1995	30.327	2013	5.314

There is naturally great interest in knowing the likely rate of recovery of this previously valuable stock and to what degree this recovery rate will be compromised by allowing a limited commercial fishery to operate prior to a full recovery. A previous modelling exercise (Gorfine *et al*., 2008) indicated that: "… the modelling results ….. suggest that unless it is known with certainty that disease-induced mortalities have been moderate (less than 40%), then any resumption of fishing in the near term risks the future of the fishery." (Gorfine et al, 2008, p.2).

Fishing resumed in April 2009 on the Crags reefcode at a Legal Minimum Length of 135mm, an increase on the 125mm which had been used voluntarily since 2003. Diver reports indicate that abalone are available in sizes up to 160 mm and acceptable commercial abundance. The collection and availability of more recent data warranted further examination of possible harvest startegies since the viral outbreak..

The scope of the current project is initially focussed on the Crags reefcode, which is considered one of the more productive reefs in the region. Additonal areas included Killarney and Watersprings. The MSE used is based on an earlier production of a spatially explicit, multi-population management strategy evaluation simulation modelling framework as part of an FRDC project (2007/020 *Identification and evaluation of performance indicators for abalone fisheries*; Haddon and Helidoniotis, 2013).

2.2 Need and Objectives

Abalone mortalities (due to viral ganglioneuritis) subsided about 2008. It has since been almost five years since mortalities were reported on the fishing grounds in Western Victoria. The disease outbreak effectively caused fishing to cease in 2006 and this led to the closure of the fishery for a further two years from mid-late 2006 – 2008. In 2009 fishing resumed with only minor catches being been taken (e.g. 3 - 10 tonnes from the Crags reefcode) in an effort to continue at least a small commercial fishery and to gather data to determine the relative health of the stocks on the different reef codes. Previous modelling work in 2007 considered a number of reefcodes immediately following the outbreak. This indicated that if the virus induced mortality was anything except minor (minor mortality being < 40%) then stock recovery would be prolonged by any amount of commercial fishing; although the time and extent of recovery might not be as long if the catches were maintained at low levels, especially in locations where the viral impact was relatively low.

Since that time some regulations in the fishery have changed (e.g. the Legal Minimum Length was increased to 135mm in 2009 – 2013 and then reduced to 132 mm for the 2014 quota season). There have been direct attempts to gather extra data relating to length frequencies and relative abundance through sampling during structured fishing (DPI surveys have been carried out throughout the fishing areas). There remains a strong motivation to fish the resource while allowing for any stock recovery.

One major problem is the uncertainty about stock productivity in many large areas; it is unknown whether the growth rates and reproductive capacity have been altered. Unlike fishing, an outbreak in viral mortality affects all size classes and while the exploitable biomass may appear to be "normal" the undersize stock – the "reserve" stock - is significantly depleted. In addition, the initial state of stock depletion and the percent viral mortality are also uncertain, especially the latter. In these uncertain circumstances rather than experimenting with different catch levels and potentially causing serious set-backs for any recovery it was decided to resume work on modelling the resource as a means of scoping the current productivity. The Western Abalone Divers Association applied for and received a FRDC Tactical Research Fund project to run various workshops and support the modelling work. The CSIRO Abalone team were asked to use the previously developed Abalone Management Strategy Evaluation (MSE) simulation framework (Haddon and Helidoniotis, 2013; detailed in Haddon et al., 2014, FRDC 2007/020) to model possible fishing scenarios on limited reefcodes in the western Victorian abalone zone. Given the limited time available before this information would be required in the annual Total Allowable Catch setting process (meeting held in January 2014) initially only one reefcode, the Crags, was to be modelled to determine the plausibility of successful modelling after such radical population changes have occurred.

Currently the two main objectives for the Western Zone abalone fishery are 1) to ensure rebuilding of the stock following the viral outbreak of 2006, and 2) maintain a commercial fishery without overly compromising the stock recovery. These two objectives are not mutually exclusive but do imply that there will need to be a trade-off between the size of any current commercial fishery and the rate of recovery of the stocks on the different reefcodes. One approach used to understand those trade-offs, is to use the management strategy evaluation framework to compare the predicted outcomes of the alternative management or harvest strategies.

2.2.1 Objectives

- Modify the MSE simulation framework to more closely reflect the biology and fishery in Western Victoria.
- Use available data from various surveys, previous modelling, and any other sources, to condition the model to reflect the biology and potential productivity of the resources; in particular at the Crags reefcode.
- Characterize the uncertainties in what is is currently knwn about the abalone biology and resources, and the impact of the virus on reefcodes in the western zone in Victoria.
- Select an array of scenarios that will encompass the present uncertainties concerning growth, stock status prior to the viral outbreak, and the viral impact, and use the modified MSE to conduct projections under different harvest levels.
- Compare alternative harvest control rules based on different annual harvest rates.
- Provide management advice regarding potential future harvest rates and recovery times with their associated likelihood of being achieved in time for a meetings in January and November 2014.

3 Methods

Due to the length of the methods section (over 40 pages) it was considered more convenient to describe the methods in the Appendix section and present the Results and Discussion. The Appendix includes a description of the operating model and the simulation framework including the justification of the parameters used and sources of information and data. A detailed description of the mathematical specification of the model is also presented in the Appendix, in Haddon and Helidoniotis (2013), and in Haddon et al. (2014). Following is a short precis to the methods described in the Appendix.

3.1 Model Structure and Specification

A management strategy evaluation simulation (MSE) framework is used here to examine the consequences of alternative management options for an abalone fishery impacted by a viral outbreak. An MSE length based abalone stock assessment model was previously developed as part of the FRDC Project No 2007/020 (Haddon et al, 2014). When that model was developed it was in conjunction with types of data available in the Tasmanian abalone fishery therefore the main data requirements are growth, size at maturity and length to weight, which is data typically collected in most fisheries programs. However, it is unavoidable that data sources may differ or not be fully representative or otherwise inadequate and therefore render a stock assessment less informative and these uncertainities need to be taken into account. The typical data requirements remain, although an additional requirement for the Victorian fishery would be abundance data pre- and post-viral outbreak.

The operating model is a statistical numbers at length based model and a key feature is that it can incorporate fine scale variation in life history traits between populations. This is particularly relevant for abalone fisheries because populations are spatially heterogeneous in their biological properties at small spatial scales, even down at a scale of 100 m, (Prince et al. 1987; Helidoniotis et al. 2011). The model can account for population specific uncertainties in growth, size at maturity, stock recruitment, and maximum local abundance and can also accommodate different hypotheses about population parameters that are specified by stakeholders. The description and background in making appropriate choices in parameter estimation and of distributions is described in the Appendix.

3.2 Conditioning the Operating Model

The structure of the operating model, in terms of its population dynamics, selected size classes, and annual time-step, are described in the Appendix. The most important aspects of the the population dynamics within the operating model that required conditioning to each reefcode include, size at maturity, somatic growth and historical catches.

3.2.1 Constants

Constants across populations within a reefcode

pMe	natural mortality for emergent abalone
pMc	instantaneous rate of natural mortality for cryptic abalone
DLMax	Inverse Logistic growth model parameter
L50	Inverse Logistic growth model parameter, length at which the growth increment is 50% of the maximum
L50inc	the interval between L50 and L95 of the inverse logistic. The L95 being the length at which the growth increment is 5% of the maximum
pSigMax	
pWtb	the gradient parameter of the weight at length equation
pWtbtoa	the gradient parameter of the relationship between a and b of the weight to length equation
pSaMa	parameter of the maturity ogive
pL50mat	the length at which 50% of the population is mature
pL50C	parameter for the size at emergence ogive
pL95C	parameter for the size at emergence ogive
MaxCEpars	Maximum catch rate of unfished populations, inferred from earlier dynamics in (tonnes/hr)
Numpop	number of populations in each reefcode
$\ln R_0$	natural logarithm of recruitment at B_0
defsteep	steepness parameter of the Beverton Holt stock recruitment relationship
recthreshold	determines whether a zone wide recruitment occurs, setting this to 1.0 turns it off.
LML	legal minimum length in year *t*.
ViralM	Viral Mortality in the year of the viral outbreak

3.2.2 Parameters values for the three reefcodes

In addition to the Crags reefcode, another two reefcodes were selected on the basis of their contrasting productivity; Watersrpings and Mills-Killarney (Table 2). The intention is to test potential Harvest Control Rules for their performance (outcomes and robustness) across likely uncertainties and a range of ecological circumstances and stock productivity in the Western Zone. This enables the HCRs to be tested across a number of other reefs that, with the Crags, broadly encompass the range of uncertainties and circumstances in the Western Zone.

There was variation between reefs in AVG mortality patterns for legal-sized and sub-legal sized abalone:

- The Crags had large legal sized mortality and very large sub-legal sized mortality
- Mills-Killarney had medium legal sized mortality and large sub-legal sized mortality
- Waterspings had patchy viral mortality

Table 2. Model specification for the constant parameters and their variation for each of the three reefcodes.

	Crags	Watersprings	Mills-Killarney
pMe	0.2 (0.001)	0.2 (0.001)	0.2 (0.001)
pMc	0.2 (0.001)	0.2 (0.001)	0.2 (0.001)
DLMax	19.6747 (1.25)	20 (1.25)	18 (1.25)
L50	109.4345 (2.0)	100 (2.0)	105.4345 (2.0)
L50inc	37.7837 (4.0)	60 (4.0)	37.5 (4.0)
pSigMax	4.75 (0.09)	4.75 (0.09)	4.75 (0.09)
pWtb	2.8573 (0.1140)	2.8573 (0.1140)	2.8573 (0.1140)
pWtbtoa	2916.018 (-15.173802)	2916.018 (-15.173802)	2916.018 (,-15.173802)
pSaMa	-15.0 (2.3)	-15.0 (2.3)	-15.0 (2.3)
pL50mat	102.0 (2.0)	95.93 (2.0)	100 (2.0)
pL50C	102.5 (0.5)	95.9 (0.5)	102 (0.5)
pL95C	112.5 (1.0)	105.9 (1.0)	112.4 (1.0)
Numpop	8	4	6
lnRo	11.5 (0.5)	11 (0.5)	13.3 (0.5)
h	0.5 (0.02)	0.5 (0.02)	0.55 (0.02)
ViralM	0.7, 0.8	0.6, 0.7	0.6, 0.7, 0.8

3.3 Harvest Control Rules

The harvest strategies used describe the methods by which each year's TAC is decided. Currently in the Western Victorian abalone zone the relative exploitable biomass of abalone on the selected reefcodes is estimated and a constant proportion of that biomass is allocated as the TAC at an LML of 132 mm. Each harvest strategy involves collecting information from the fishery and assessing the status of the stock in some way (which need not involve a formal stock assessment). The outcome of the assessment is then fed into a harvest control rule and the following year's TAC comes from that.

In this present work the same data and assessments were assumed and the outcomes of alternative constant harvest levels used to set the TAC are compared.
Three harvest control rules (HCRs) were compared: Constant Harvest HCR (ConstH), Stock Size HCR (StockH) and Gradient CPUE HCR (GradCE).

3.3.1 Constant Harvest HCR

This very simple control rule requires an estimate of exploitable biomass in units of tonnes. It assumes this estimate is made with log-normal residual error hence the simulation algorithm constitutes obtaining the exploitable biomass from the operating model, multiplying that with log-normal error to simulate sampling error and then multiplying the resulting exploitable biomass estimate by the selected constant proportion (harvest rate) to generate the next year's TAC (equation 1).

$$TAC_{y+1} = constH \times ExB_y \times e^{N(0,sigmaCE)} \qquad (1)$$

where constH is the selected annual harvest rate, ExBy is the exploitable biomass in year y, and sigmaCE is the variation assumed to be inherent in the estimates of catch rates and of exploitable biomass.

3.3.2 Stock Size Dependent HCR

This HCR is dependent upon the estimate of exploitable biomass (in tonnes), which is assumed to include a log-normal error term. The assumption is made that, given a constant LML the exploitable biomass can be expected to increase in this highly depleted stock by up to six times (an assumed upper limit). This biomass estimate is compared with the estimate from a selected reference year to produce a ratio, and the TAC is adjusted according to a fixed linear relationship between the expected harvest rate and the ratio (Figure 1). Harvest rate is low at low stock size, and increases as exploitable biomass increases until a target harvest rate is reached which is 0.2 (equation 2; Figure 1).

This HCR is designed with the assumption that it would be replaced or revised as knowledge accumulates about the fishery.

$$
\begin{aligned}
&Ex\hat{x}B = ExB \times e^{N(0,sigmaB)} \\
&\hat{H} = 0.05 + 0.025 \times \left(ExB / ExB_{REF} \right) \qquad (2) \\
&TAC = Ex\hat{x}B \times \hat{H}
\end{aligned}
$$

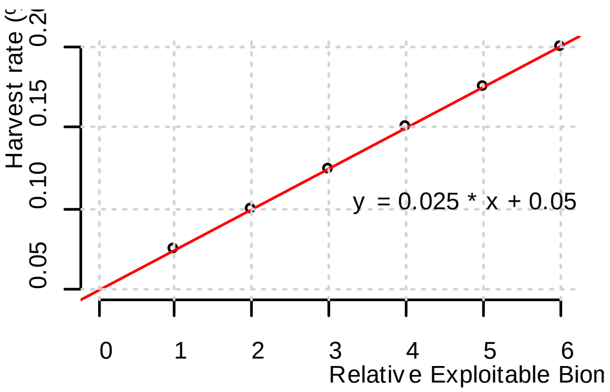


Figure 1. Expected response of exploitation rate with respect to the exploitable biomass relative to some selected reference year. Given a maximum limit on the Harvest rate the harvest rate in each year is based the ratio of the current exploitable biomass relative to reference year.

3.3.3 Gradient CPUE

The gradient CPUE HCR relies on the trend of the previous four years of CPUE data, with the last point being the most recent year. These are converted into proportional changes since the first year or the four considered, then a linear regression is fitted to the four proportions (the first = 1.0 by definition) and the gradient is then added to 1.0 and used as the multiplier on the previous year’s TAC to obtain the next year’s TAC (equation 3):

$$
\begin{aligned}
pCPUE &= CPUE_y \,/\, CPUE_4 && y = 1..3 \\
pCPUE &= const + grad \times y && y = 1..4 \\
Mult &= 1 + grad && \\
TAC_5 &= TAC_4 \times Mult &&
\end{aligned}
\qquad (3)
$$

4 Results and Discussion

4.1 Comparison of current with previous simulation

The operating model generates simulated outputs about the productivity of the fished stock. The outcome of the previous modelling work, presented in Gorfine *et. al.* (2007), was considered a useful model for assessment purposes, and here the outputs between studies are compared (Table 3).

Table 3. Comparison between outputs of the Bardos model (Gorfine *et. al.* 2007) and Haddon MSE model used in the current assessment.

Output	Bardos [a]	Haddon	
B0 (spawning biomass -Tonnes)	635 (figure 7)	625	
recruitment	$8.4*10^5$ (baseline IUU)	$8.2758*10^5$ [b]	
	$1.05*10^6$ (high IUU)		
spawning biomass end 2005 (just before virus)	185 T	192.024 [c]	
Depletion level in 2005/early 2006	29.13%	30.7%	
Viral mortality in 2006	80% (approx)	70%	80%
spawning biomass, 2006, after virus	37-40 T	54	35
ExBiomass in 2012(at LML =125)	25 (T) (figure 7)[d]	42 [d]	22 [d]
(at LML =135)	n.a	18[e]	14.6[e]
5% harvest (of ExBiomass in 2012)	1.12 T [d]		
10%	2.5 [d]		
20%	5 [d]		
Harvest rate if 9.857 tonnes was taken (at LML =125)	39.2% [d]	23% [d]	44.8% [d]
(at LML =135)	-	55% [e]	68% [e]

[a] baseline scenario: 80% mortality, baseline IUU, refer to figure 7 in Gorfine (back section)
[b] 11.5 is the natural log at an initial depletion of 30% (i.e 2006) so exp(11.5) = 98716 then multiply by 8 (because there is 8 populations in the zone) = $7.89726*10^5$. But [b]$8.27577*10^5$ is what is actually selected after the appropriate rand seed is applied.
[c] with 30% initial depletion at end of 2005 /beginning of 2006 (just before virus) and baseline IUU
[d] LML = 125 (presumably Bardos might have used an LML125mm given his report is in 2007, and not possible to forecast the LML in 2012)
[e] LML = 135mm in 2012
n.a = not applicable; the exploitable biomass was not estimated at an LML = 135 mm

Although the estimates in spawning biomass are similar between the models, the productivity between the two vary. The main similarities and differences are as follows:

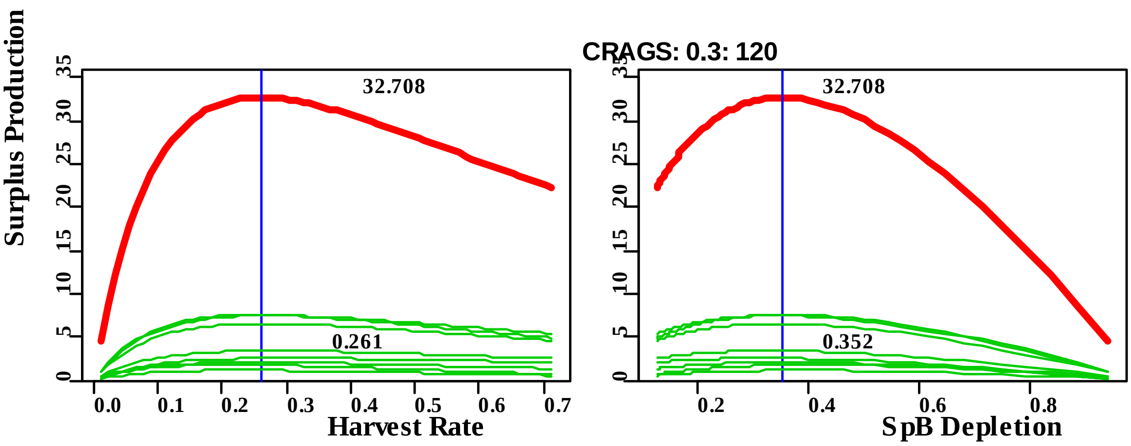
- Bardos model had higher recruitment but the Haddon model has higher growth rates.
- Initial depletion in 2006 is the same in both (Bardos = 29.13, Haddon = 30.7%) just prior to the viral outbreak in 2006
- After the same level of viral mortality (80%) both have similar spawning biomass (Bardos = 37- 40 T, Haddon = 35 T)

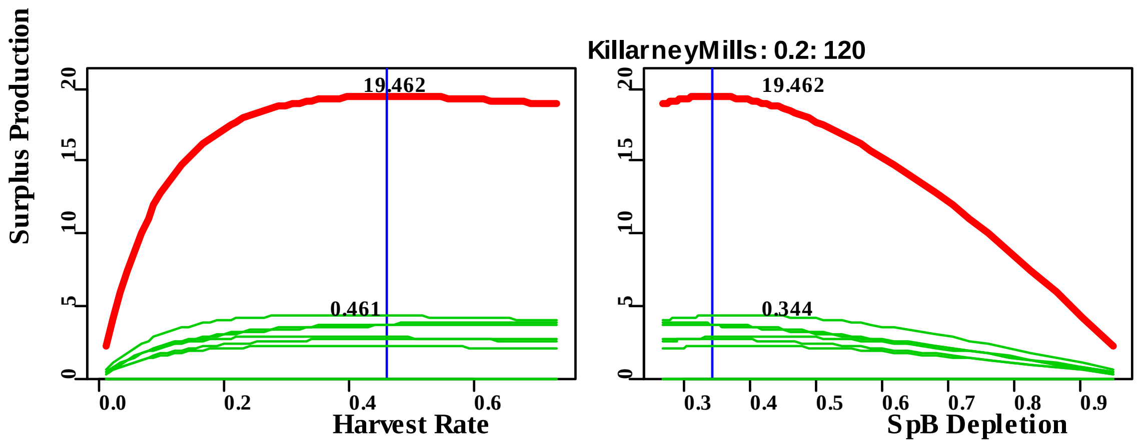
- Exploitable Biomass in 2012: similar in both models for an LML of 125mm (Bardos = 25 T, Haddon = 22 T)

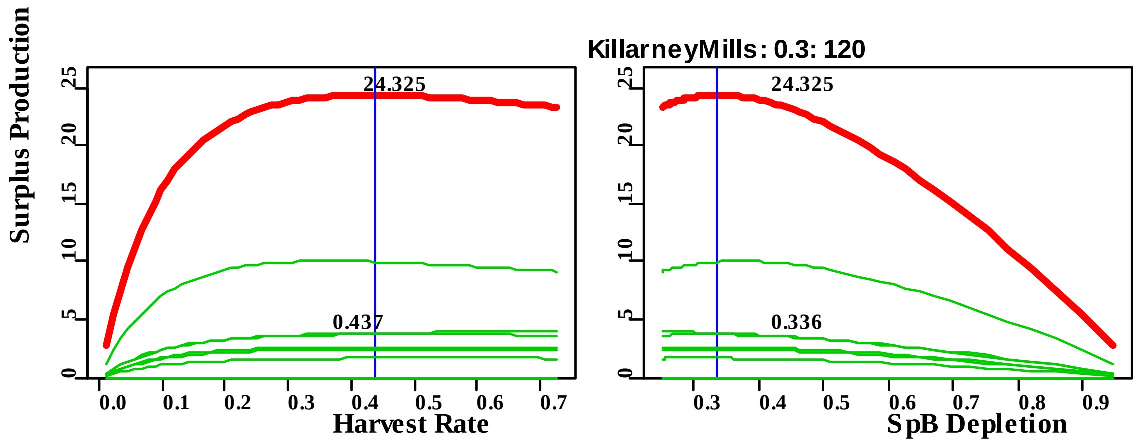
Immediately subsequent to the virus in 2006, the spawning biomass, was similar in both models. However, the two models reached the same biomass via different inputs; the Bardos model had higher recruitment than the Haddon model but the Haddon model had higher growth rate than Bardos. So although the underlying dynamics differed between the two the outputs converged to similar estimates in the spawning biomass for 2006. The Bardos model was fitted to scientific length frequency data (see figure 5 in Gorfine *et al* 2007) and this resulted in a slower growth rate that the Haddon model. Haddon, on the other hand, made growth consistent with (i.e not fitted) to the commercial length frequency data and then increased the growth further following stakeholder advice (fitting to data was not carried out to allow for stakeholder input). The more recent commercial length frequency data (2009 – 2012; the data used in the Haddon model) had slightly larger abalone than the pre 2007 data used in the previous modelling by Bardos in 2007, so even without stakeholder input the growth model in Haddon was going to lead to larger abalone by default.

4.2 Surplus production

According to the estimates of surplus production the spawning biomass depletion at MSY would be 0.352 and the harvest rate at MSY would need to be 0.261 for an LML of 120mm (Figure 2a). A catch of approximately 33 tonnes will result in a depletion level of 0.352 at MSY. However the maxima of the surplus production curve may be considered to be quite flat indicating that a level of catches similar to the MSY (only slightly lower) can be taken at a much reduced harvest rate of 0.1 - 0.2. At a harvest rate of 0.1 the catch is approximately 27T however the depletion level improves, being only 0.6. This effectively doubles the available biomass and would approximately double the CPUE. This has positive economic implications in that will a harvest rate of 0.1 the CPUE the fishery will run more efficeintoy in terms of capture costs. Therefore the Maximum Economic Yield (MEY) will be at a lower harvest rate than MSY and result in higher biomass and CPUE.







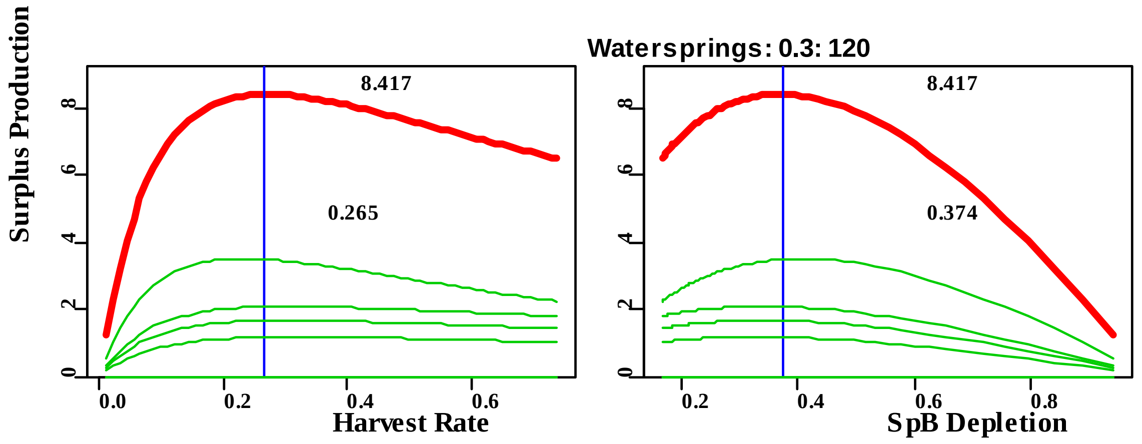
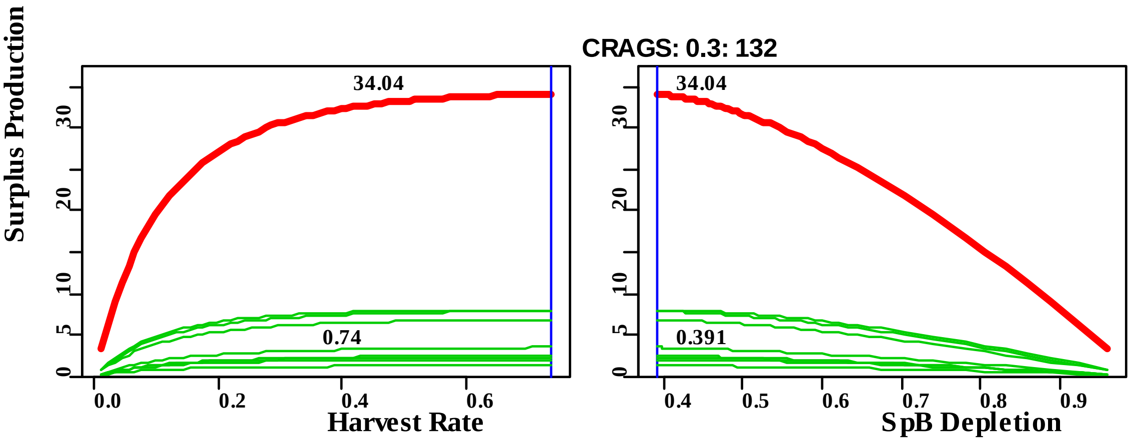
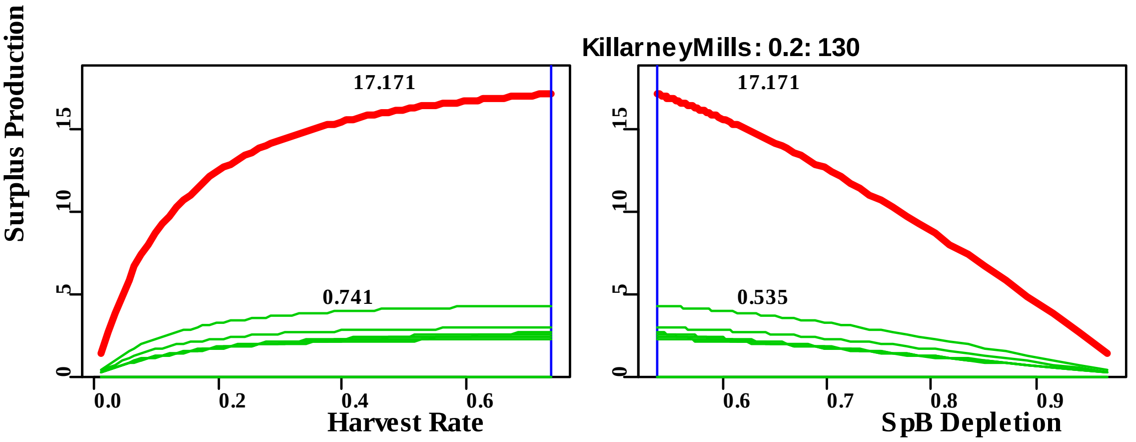
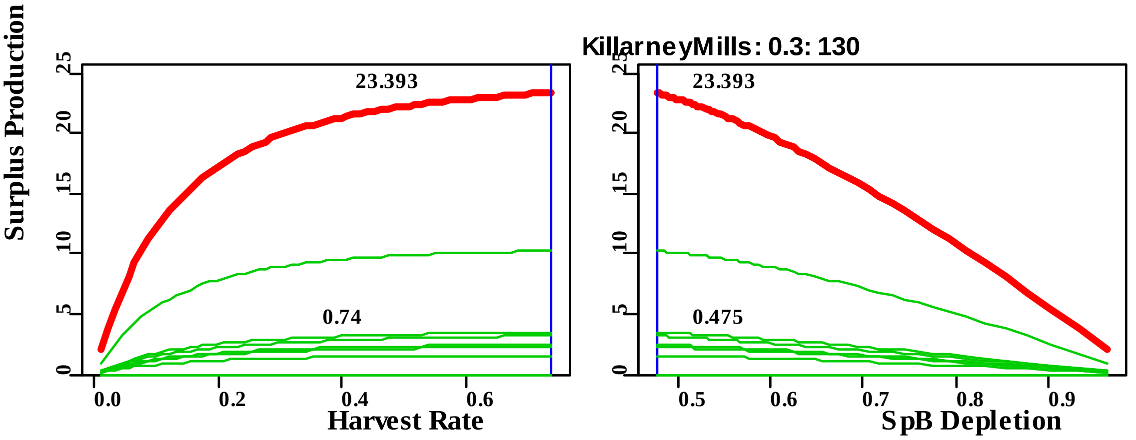


Figure 2a. Surplus production vs harvest rate and depletion for the three simulated reefcodes: Crags (2006 depletion 0.3), Mills-Killarney (2006 depletion 0.2 and 2006 depletion 0.3 respectively) and Watersprings (2006 depletion 0.3). All are for a LML of 120mm. The curves for the individual populations are in green (eight populations for the Crags, six for Mills-Killarney and four for Watersprings).

The MSY and depletion relationships can also be calculated for the current precautionary LML that has been used in the fishery; 132mm for Crages and 130mm for Mills-Killarney and Watersprings. These are shown in Figure 2b. They indicate that while the MSY changes with LML the difference is not very large. They also illustrate the highly protective nature of the higher LMLs. For an LML of 132mm at The Crags the depletion at equilibrium cannot be lower than about 0.4 even if very high harvest fractions are applied. Similarly for an LML of 130mm at Mills-Killarney the depletion at equilibrium cannot be lower than about 0.5.







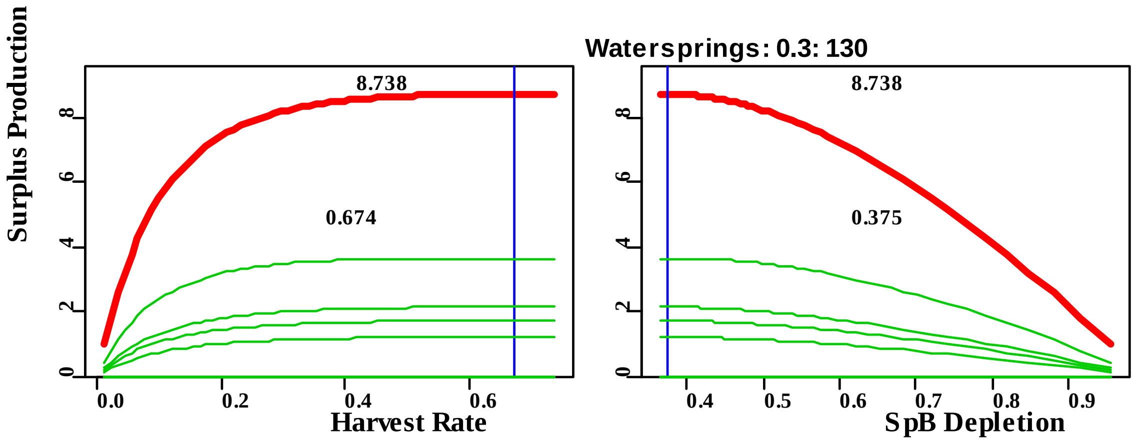


Figure 3b. Surplus production vs harvest rate and depletion for the three simulated reefcodes: Crags (2006 depletion 0.3), Mills-Killarney (2006 depletion 0.2 and 2006 depletion 0.3 respectively) and Watersprings (2006 depletion 0.3). The LML is the currently applied size for each reefcode; 132mm for Crags and 130mm for Mills-Killarney and Watersprings. The curves for the individual populations are in green (eight populations for the Crags, six for Mills-Killarney and four for Watersprings).

4.3 HCR and Scenario Results

4.3.1 Scenario Plausibility

The current MSE model is conditioned on data from the Crags fishery it is not fitted to that data. Rather, the relative plausibility of the alternative possible arrangements are determined instead. Between 2009 and 2013 the observed catches (Table 1) can be compared to the predicted exploitable biomass to determine the relative plausibility of the harvest rate with that which was predicted to have occurred.This is during the period when the intention was to apply an annual harvest rate of 0.05; that is before the alternative HCR described here were considered in the simulation. Up to 2013 there is no change in harvest rate or HCR and the scenarios assumed for the initial depletion and the viral mortality are based upon previous industry beliefs (Table 4). The plausibility analysis is therefore focussed on six combinations of viral mortality and initial depletion (Figure 4, Table 4, Table 5). Furthermore there are 6 replicate groups (deriving from the 6 harvest rates tested) of 500 replicate zones for each of the six combinations of initial depletion and viral mortality (6 x 6 = 36), and therefore there are 6 estimates of failure rate for each scenario (for the Constant H harvest Control rule). These estimates provide a mean value of the relative plausibility of the catches with a spread about that mean (Figure 4).

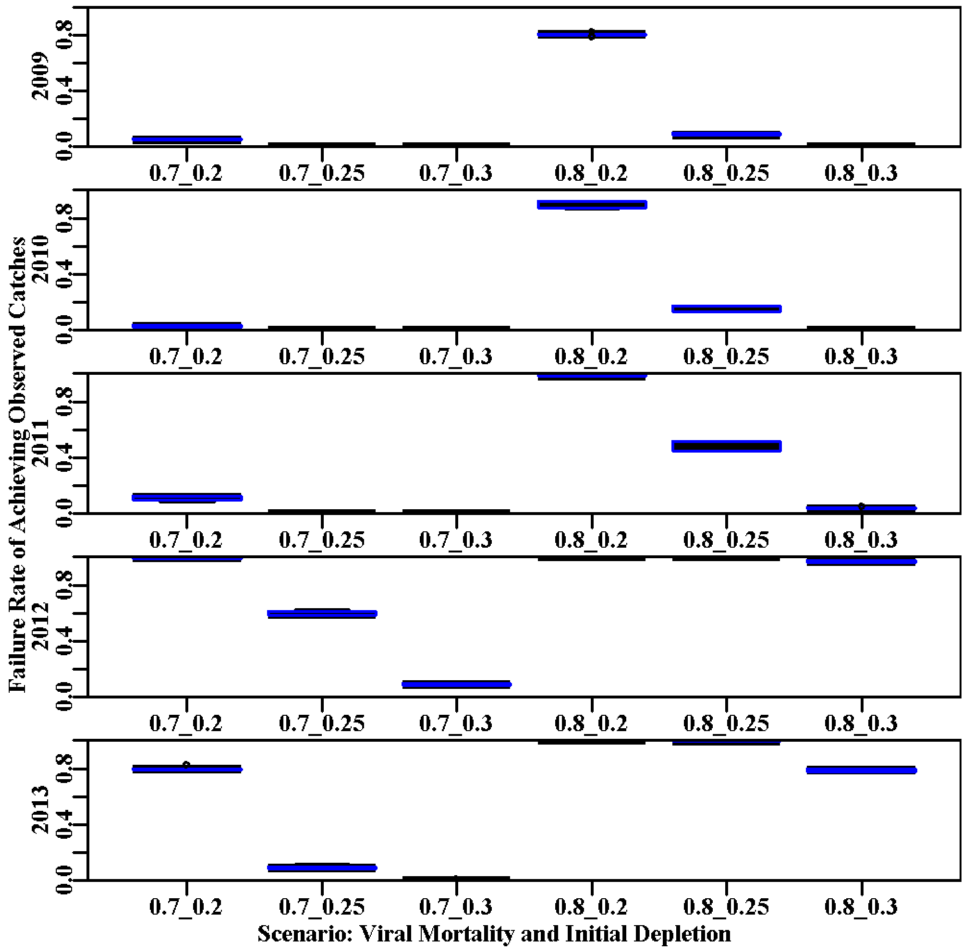


Figure 4. The relative failure rate of the different scenario combinations of viral mortality and initial depletion. The smaller the value the greater the plausibility.

Earlier trials, not shown here, indicated that scenarios with an initial depletion of only 15% of unfished spawning biomass (B_0) implied that only 0.4% of 500 simulations, succeeded in having sufficient biomass remaining to achieve a 9.856 t in 2012, unless the viral mortality was very low, i.e < 50%, and even then the outcome was variable and low success. Hence the depletion levels were therefore restricted to 20, 25, and 30% initial depletion. (Once the final total catch in the 2014/2015 season is known this too can be included in the analysis and this may improve the estimates of plausibility).

As the fishery progresses the ongoing updates of catch, catch rate, and size distribution will be of direct value in assessing the rate of recovery of the various reefcodes that are monitored.

Table 4. Catch failure rates across observed catches in 2009 – 2013 across 6 replicates for each scenario of viral mortality and initial depletion. Each of the 6 replicates consists of 500 replicate simulations. A value of 0 indicates a zero failure rate and 1 indicates 100% failure rate. The Group is the combination of viral mortality (0.7 and 0.8) and initial depletion level (0.2, 0.25, 0.3) against which the rates were assessed.

Group	Y2009	Y2010	Y2011	Y2012	2013
0.7_0.2	0.048	0.024	0.086	0.994	0.778
0.7_0.2	0.056	0.018	0.11	0.994	0.788
0.7_0.2	0.054	0.042	0.126	0.992	0.794
0.7_0.2	0.052	0.038	0.132	1	0.798

0.7_0.2	0.054	0.026	0.096	1	0.8
0.7_0.2	0.056	0.038	0.128	0.986	0.828
0.7_0.25	0	0	0.004	0.574	0.078
0.7_0.25	0	0	0.006	0.588	0.084
0.7_0.25	0	0	0	0.614	0.092
0.7_0.25	0.002	0	0	0.594	0.098
0.7_0.25	0	0	0.004	0.596	0.102
0.7_0.25	0.002	0	0.002	0.628	0.12
0.7_0.3	0	0	0	0.092	0
0.7_0.3	0	0	0	0.07	0.002
0.7_0.3	0	0	0	0.096	0.002
0.7_0.3	0	0	0	0.084	0.002
0.7_0.3	0	0	0	0.096	0.002
0.7_0.3	0	0	0	0.102	0.012
0.8_0.2	0.8	0.92	0.992	1	1
0.8_0.2	0.806	0.876	0.984	1	1
0.8_0.2	0.784	0.88	0.984	1	1
0.8_0.2	0.802	0.868	0.988	1	1
0.8_0.2	0.818	0.912	0.994	1	1
0.8_0.2	0.802	0.92	0.984	1	1
0.8_0.25	0.084	0.154	0.45	1	0.994
0.8_0.25	0.088	0.134	0.512	1	0.996
0.8_0.25	0.102	0.154	0.45	1	0.998
0.8_0.25	0.086	0.132	0.452	1	0.998
0.8_0.25	0.102	0.178	0.514	1	0.998
0.8_0.25	0.09	0.172	0.514	1	1
0.8_0.3	0.002	0.002	0.034	0.954	0.772
0.8_0.3	0	0.002	0.054	0.966	0.778
0.8_0.3	0.002	0	0.042	0.978	0.788
0.8_0.3	0.004	0.002	0.044	0.96	0.792
0.8_0.3	0.002	0.004	0.038	0.976	0.796
0.8_0.3	0	0.002	0.038	0.984	0.812

Table 5. A summary of the mean success rate and plausibility of the various scenario combinations of viral mortality and initial stock depletion (6 scenarios in total). The larger the number the higher the success rate (this contrasts with the failure rate illustrated in Table 4 i.e 1- Table 9 values). The mean is the mean of the 6 replicates within of each of the six scenarios.

Year	Catch	0.7_0.2	0.7_0.25	0.7_0.3	0.8_0.2	0.8_0.25	0.8_0.3
2009	3.368	0.947	0.999	1	0.198	0.908	0.998
2010	3.667	0.969	1	1	0.104	0.846	0.998
2011	4.683	0.887	0.997	1	0.012	0.518	0.958
2012	9.857	0.006	0.401	0.910	0	0	0.030
2013	5.314	0.202	0.904	0.997	0	0.003	0.210

The relative plausibility of the different scenarios is lowest when the initial depletion is at its lowest (0.2 = 20% depletion) and the viral mortality at its highest (0.8 = 80%; Figure 4; Table 4). At an initial depletion level of only 0.2, even the viral mortality of 0.7 has a low success rate in 2012 and 2013 (0.6% and 20.2% respectively). A viral mortality rate of 0.8 with an initial depletion level of 0.2 results in an overall low success rate (<20%, Table 5) in achieving observed catches in each of the five years (Figure 4, Table 5). This indicates that, given the assumed productivity (recruitment plus growth) if the viral mortality was as high or higher than 80%, the initial stock size would need to be higher in order to accommodate the observed catches at that level of viral mortality. However as noted in Gorfine et al (2007) if the stock size is increased to supply this level of catch and viral mortality, then the recovery of the population would be slightly faster.

"We see that for heavy viral impact, the typical effect of higher IUU is to ... slightly advance recovery (Julia Percy Island and the Crags)" (p17 in the back section of the Gorfine report, note there are two sets of page numbers in the supplied report).

Part of the usefulness of conducting an MSE is to consider worse case scenarios and develop contingency plans. While including a high viral mortality of >80% may be considerd a worse case scenario, the stock size required for this is higher and therefore may not be considered a worse case scenario. Therefore what may be considered a worse case scenario in one aspect may not necessarily be a worse case scenario in another aspect.

4.4 Performance indicators

Six performance indicators were formulated. Each scenario within each HCR was evaluated against each of the performance indicators: 1) Total Catch between 2014 – 2020, 2) Variability in Catch between 2014 – 2020 (AAV), 3) Mean length of catch, 4) Spawning stock depletion in 2020 (relative to B_0), 5) Spawning stock depletion in 2020 relative to 2013, 6) Exploitable Biomass depletion 2020 relative to 2013. These are described in technical detail in Appendix 6.14.

4.4.1 Total Catch 2014 – 2020

The smaller the viral mortality the larger the total catch between 2014 and 2020 (Figure 5, Table 6 regardless of initial depletion. Similarly a stock depleted down to 0.3 of the intial biomass results in higher total catch than stock depleted down to 0.25 and 0.2. Each boxplot for the total catch demonstrates the variation between replicates. The variation (range of catches between the 6 replicates) appears to be greater in the 0.7 (70%) viral mortality scenarios relative to their equivalents at 0.8 viral mortality (compare the range of the whiskers in the boxplot). Not surprisingly, the higher the harvest rate selected the larger the total catch, irrespective of with scenario was considered.

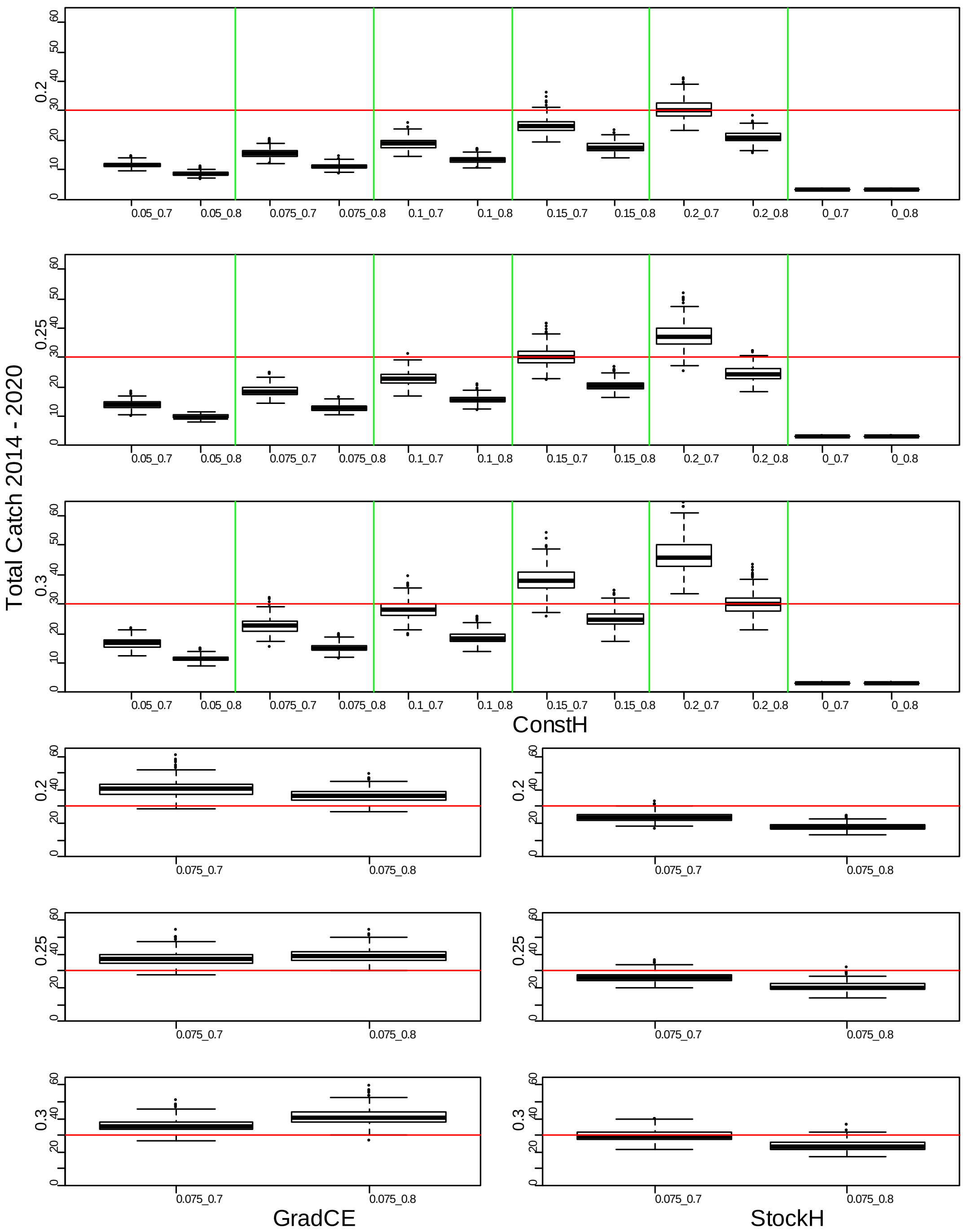


Figure 5. Sum of the predicted catch taken on the Crags between 2014 – 2020. Three HCRs are presented: a) Constant Harvest HCR, b) Stock Harvest HCR and c) Gradient CE HCR. The harvest rate (of 0.075) is the harvest rate at 2013. In each set of boxplots consists of a different pre-viral 2006 depletion level (20%, 25%, and 30%). The red line at 30 tonnes is there to simplify comparison between scenarios and HCRs.

Table 6. Quantiles of total cummulative catch (2014:2020) across replicate runs in each scenario for three harvest control rules. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

Constant Harvest

Scenario	0	25	50	75	100
0.05_0.2_0.7	8.346	9.595	10.053	10.601	12.608
0.05_0.2_0.8	6.083	7.365	7.660	7.959	9.750
0.05_0.25_0.7	8.672	11.226	11.967	12.660	15.802
0.05_0.25_0.8	7.187	8.184	8.518	8.995	10.157
0.05_0.3_0.7	10.687	13.374	14.274	15.334	18.496
0.05_0.3_0.8	8.117	9.383	9.920	10.495	12.949
0.075_0.2_0.7	10.256	12.550	13.225	13.988	17.452
0.075_0.2_0.8	7.566	9.156	9.616	10.152	12.473
0.075_0.25_0.7	12.244	14.876	15.861	16.983	20.867
0.075_0.25_0.8	9.008	10.523	11.082	11.675	13.922
0.075_0.3_0.7	13.381	17.689	19.205	20.642	27.147
0.075_0.3_0.8	9.771	12.301	12.980	13.737	16.723
0.1_0.2_0.7	12.388	15.021	15.952	17.037	21.636
0.1_0.2_0.8	9.165	10.954	11.534	12.137	14.444
0.1_0.25_0.7	14.610	18.100	19.476	20.711	26.186
0.1_0.25_0.8	10.557	12.582	13.202	14.031	17.593
0.1_0.3_0.7	16.555	22.070	23.679	25.328	33.090
0.1_0.3_0.8	11.911	14.744	15.780	16.894	21.704
0.15_0.2_0.7	16.707	19.705	20.965	22.436	30.293
0.15_0.2_0.8	11.870	14.033	14.912	15.944	19.925
0.15_0.25_0.7	18.976	24.058	25.504	27.304	34.773
0.15_0.25_0.8	14.064	16.339	17.337	18.187	22.672
0.15_0.3_0.7	21.727	29.917	32.044	34.488	45.545
0.15_0.3_0.8	14.846	19.449	21.015	22.617	28.950
0.2_0.2_0.7	19.849	23.972	25.663	27.542	34.562
0.2_0.2_0.8	13.268	16.833	17.803	18.820	23.878
0.2_0.25_0.7	21.460	29.389	31.207	33.544	43.584
0.2_0.25_0.8	15.752	19.327	20.620	21.990	26.807
0.2_0.3_0.7	28.269	36.118	38.816	42.471	56.958
0.2_0.3_0.8	18.289	23.378	25.167	26.974	36.431

Stock Harvest HCR

Scenario	0	25	50	75	100
0.075_0.2_0.7	14.35	18.41	19.71	21.25	27.30
0.075_0.2_0.8	11.41	13.87	14.82	15.77	20.58
0.075_0.25_0.7	16.81	20.14	21.59	23.30	30.69
0.075_0.25_0.8	12.13	15.96	17.08	18.64	25.98
0.075_0.3_0.7	18.37	22.98	24.92	27.06	33.43
0.075_0.3_0.8	14.51	18.43	19.82	21.75	30.15

Gradient CE HCR

Scenario	0	25	50	75	100
0.075_0.2_0.7	24.30	31.37	33.68	36.16	49.50
0.075_0.2_0.8	23.29	28.71	30.60	32.40	40.87
0.075_0.25_0.7	23.24	29.12	31.15	33.24	44.70
0.075_0.25_0.8	25.40	30.24	32.49	34.65	45.08
0.075_0.3_0.7	22.78	28.08	29.83	32.04	41.95
0.075_0.3_0.8	22.53	31.54	33.92	36.31	48.85

4.4.2 Variation of Catches between Years Across All Scenarios

The AAV (Average Anual Variation) is the year-to-year variation within replicates or in other words the stability of catches for each scenario. While the range of catches appears to be larger in the 0.7 viral mortality scenarios (Figure 5) the absolute annual variability of catches is lower in the 0.7 viral mortality scenarios (Figure 6, Table 7). The median variation is not uniform between scenarios. This statistic is somewhat distorted because the Average Annual Variation (AAV) is more useful as an index for a developed fishery rather than one that is recovering. If the average trajectory of the 500 replicate runs are considered for any scenario a large part of the variation in catches is derived from the increase in catches as the stock recovers.

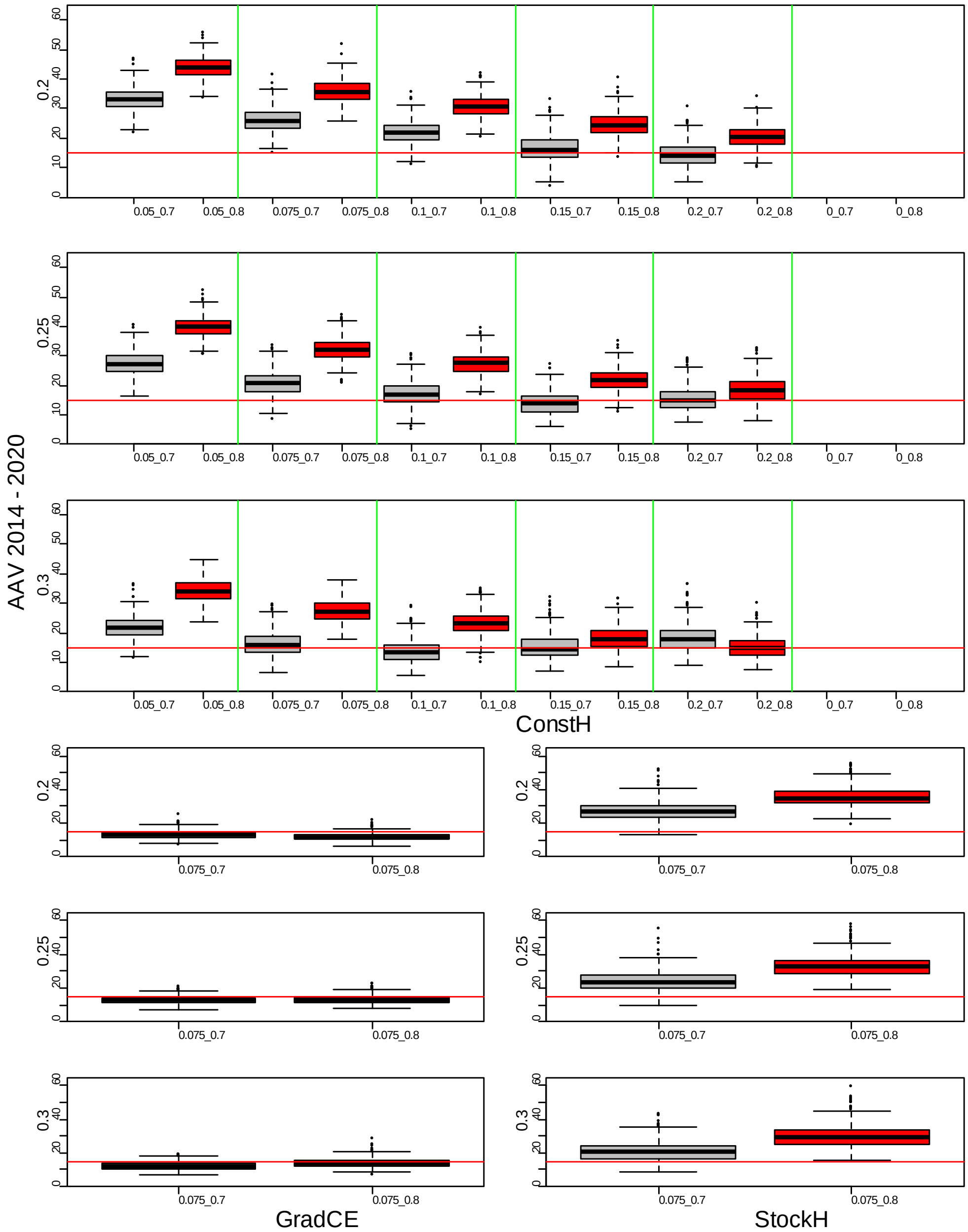


Figure 6. Average Annual Variation of the predicted catch taken on the Crags between 2014 – 2020. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR. Each set of boxplots represents a different pre-viral 2006 depletion level (20%, 25%, and 30%). The red lines at 15 tonnes is there to simplify comparison between scenarios.

Table 7. Percent quantiles (0%, 5%, etc) of the AAV across replicate runs in each scenario between 2014 – 2020. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

Constant Harvest

Scenario	0	25	50	75	100
0.05_0.2_0.7	21.83	30.47	33.04	35.51	46.79
0.05_0.2_0.8	33.68	41.30	43.71	46.18	55.56
0.05_0.25_0.7	16.33	24.65	27.24	30.26	40.40
0.05_0.25_0.8	30.77	37.58	39.80	42.03	52.22
0.05_0.3_0.7	11.36	19.36	21.69	24.36	36.36
0.05_0.3_0.8	23.74	31.62	34.16	37.04	45.00
0.075_0.2_0.7	14.75	23.31	25.68	28.57	41.53
0.075_0.2_0.8	25.93	33.33	35.81	38.32	51.96
0.075_0.25_0.7	8.37	17.98	20.76	23.35	33.56
0.075_0.25_0.8	20.95	29.82	32.31	34.68	43.65
0.075_0.3_0.7	6.58	13.35	16.02	19.01	29.67
0.075_0.3_0.8	17.61	24.68	27.07	30.02	37.80
0.1_0.2_0.7	11.11	19.48	21.85	24.31	35.56
0.1_0.2_0.8	20.38	28.32	30.68	33.08	42.02
0.1_0.25_0.7	5.28	14.29	16.73	19.77	30.65
0.1_0.25_0.8	17.11	24.85	27.52	29.85	39.33
0.1_0.3_0.7	5.62	11.04	13.48	16.02	28.92
0.1_0.3_0.8	10.19	20.59	23.14	25.59	35.11
0.15_0.2_0.7	3.86	13.52	16.19	19.51	33.10
0.15_0.2_0.8	13.51	21.96	24.32	27.02	40.51
0.15_0.25_0.7	6.32	11.22	13.74	16.27	26.96
0.15_0.25_0.8	10.96	19.51	21.85	24.42	34.93
0.15_0.3_0.7	7.12	12.41	14.55	17.64	32.02
0.15_0.3_0.8	8.59	15.16	17.67	20.91	31.58
0.2_0.2_0.7	5.10	11.48	13.95	16.79	30.79
0.2_0.2_0.8	10.31	18.01	20.34	22.86	34.26
0.2_0.25_0.7	7.51	12.56	15.04	18.05	29.02
0.2_0.25_0.8	7.88	15.31	18.18	21.37	32.73
0.2_0.3_0.7	8.77	15.06	17.63	20.58	36.56
0.2_0.3_0.8	7.30	12.61	15.00	17.40	29.97

Stock Harvest HCR

Scenario	0	25	50	75	100
0.075_0.2_0.7	12.88	23.14	26.84	30.31	51.95
0.075_0.2_0.8	19.45	32.01	35.02	38.91	55.19
0.075_0.25_0.7	9.90	20.05	23.36	27.44	54.96
0.075_0.25_0.8	18.99	28.98	32.44	36.16	58.19
0.075_0.3_0.7	9.11	16.61	20.34	24.11	43.50
0.075_0.3_0.8	15.82	25.39	29.11	33.21	59.22

Gradient CE HCR

Scenario	0	25	50	75	100
0.075_0.2_0.7	6.77	11.83	13.35	14.70	24.83
0.075_0.2_0.8	6.38	10.14	11.52	13.02	21.77
0.075_0.25_0.7	7.16	11.31	12.73	14.15	20.39
0.075_0.25_0.8	7.77	11.60	12.79	14.46	22.79
0.075_0.3_0.7	6.67	10.39	11.91	13.53	19.23
0.075_0.3_0.8	6.92	12.44	13.93	15.80	28.67

4.4.3 Ratio of Mean Length of Catch of 2020/2013

Mean length is not a very sensitive performance measure and it is difficult to interpret. It should be noted that the mean length may not neccessarily increase if the numbers of animals above the LML size increase. The reason for this is that although the numbers at larger sizes may increase so do those at the smaller size classes; and if the smaller size classes increase more than the larger sizes the mean size may decline. This is not necessarily a bad outcome for stock condition however this performance measure needs further consideration as the dynamics associated with the mean length become better known. If the proportion at length changes very little during large change in relative abundance then no length based measure will be useful as an index of recovery. It is possible, given the simulation outputs, that there can be a small amount of contrast in mean length when the stock is very badly depleted. Thus, mean length might be used as a warning sign and confirmation that a stock is seriously depleted, but diver awareness of underwater conditions should already have identified this. Although there is an increase in total catches for a stock that is depleted to 0.3 (Figure 5) the mean length in catch is lowest in the 0.3 dpelted stock (Figure 7) because its possibly an indication that a greater proportion of new recruits (i.e smaller size classes closer to the LML) are contributing to the overall biomass thereby causing the mean length to decrease.

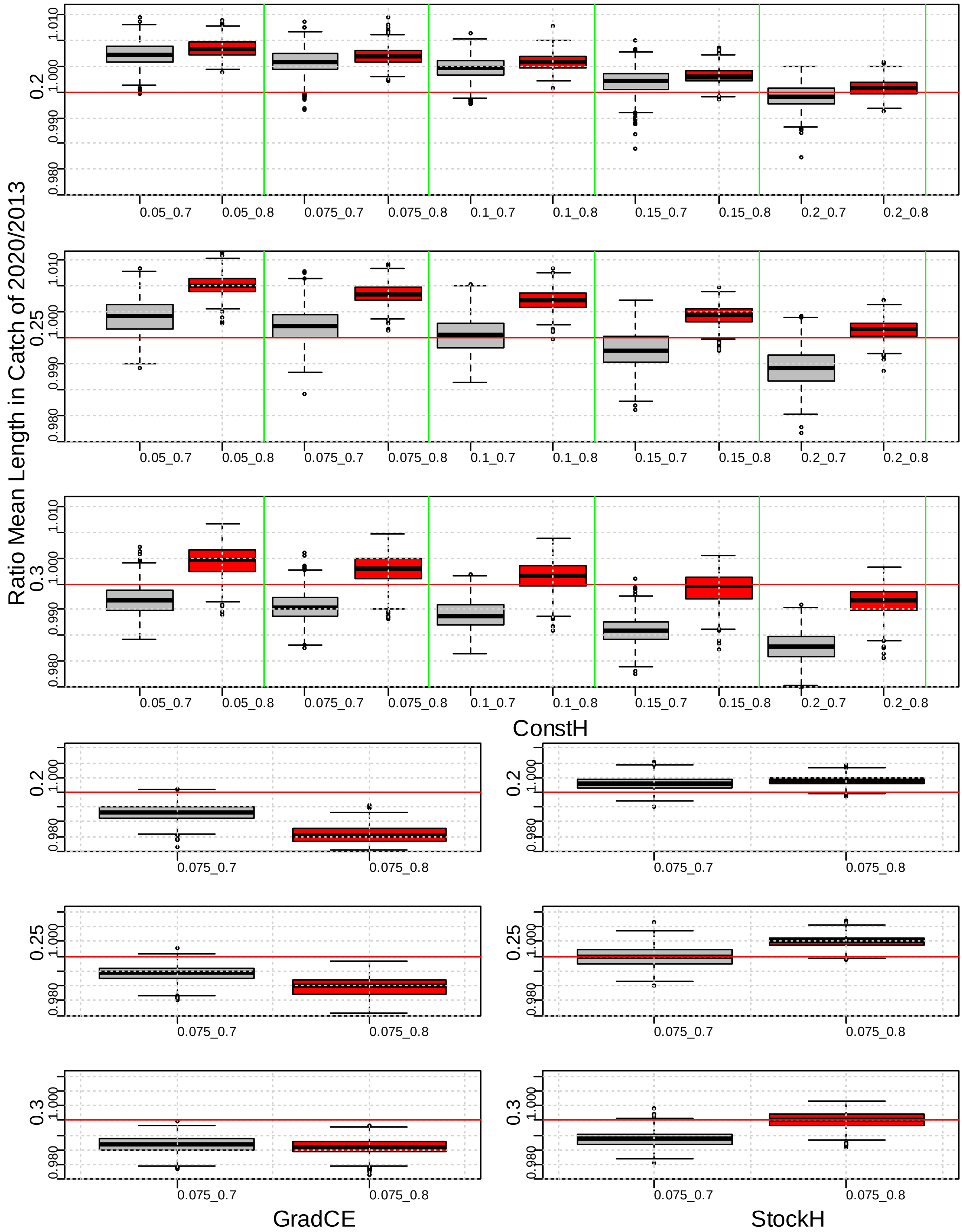


Figure 7. The ratio of the mean length in the commercial catch between 2020 and 2013 (2020/2013). Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR. The initial depletion level in 2006 is the annotation to the left of each set of boxplots and each combination of initial H and viral mortality rate is listed under each separate boxplot. The horizontal red line is at 1.0 to aid identification of scenarios that lead to a decline in mean length.

Table 8. Percent quantiles (0%, 5%, etc) of the distribution of the ratio of mean length in 2020/2013 in catches across replicate runs in each scenario from 2013 – 2020. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

Constant Harvest

Scenario	0	25	50	75	100
0.05_0.7_0.2	0.999619	1.005705	1.007186	1.008765	1.01441
0.05_0.7_0.25	0.994281	1.001753	1.004165	1.00638	1.013423
0.05_0.7_0.3	0.989334	0.994923	0.996831	0.998675	1.007063
0.05_0.8_0.2	1.003852	1.007269	1.008372	1.009529	1.013908
0.05_0.8_0.25	1.002937	1.008923	1.010172	1.011453	1.016854
0.05_0.8_0.3	0.994096	1.002517	1.004538	1.006595	1.011582
0.075_0.7_0.2	0.996626	1.004333	1.005886	1.007338	1.013471
0.075_0.7_0.25	0.989028	0.999979	1.002161	1.004544	1.012766
0.075_0.7_0.3	0.987715	0.993673	0.995534	0.997289	1.005994
0.075_0.8_0.2	1.002112	1.005864	1.006869	1.007996	1.014501
0.075_0.8_0.25	1.001303	1.00723	1.00844	1.009778	1.014148
0.075_0.8_0.3	0.99325	1.001013	1.003088	1.004992	1.009647
0.1_0.7_0.2	0.997565	1.003158	1.004713	1.006118	1.011387
0.1_0.7_0.25	0.991278	0.997979	1.000645	1.002863	1.010414
0.1_0.7_0.3	0.986397	0.992006	0.993732	0.995948	1.00195
0.1_0.8_0.2	1.000798	1.004665	1.005657	1.00682	1.012826
0.1_0.8_0.25	0.999839	1.005946	1.007324	1.008646	1.013516
0.1_0.8_0.3	0.991059	0.999534	1.001586	1.003555	1.008797
0.15_0.7_0.2	0.988885	1.000421	1.002092	1.003398	1.009856
0.15_0.7_0.25	0.986089	0.99516	0.997532	1.000216	1.007186
0.15_0.7_0.3	0.979208	0.989192	0.991044	0.992713	1.001137
0.15_0.8_0.2	0.998615	1.00213	1.002995	1.004216	1.008531
0.15_0.8_0.25	0.997403	1.003214	1.004375	1.005484	1.009743
0.15_0.8_0.3	0.987192	0.997217	0.999586	1.001147	1.005394
0.2_0.7_0.2	0.987381	0.997656	0.999159	1.000688	1.004876
0.2_0.7_0.25	0.981541	0.991698	0.994187	0.996629	1.004188
0.2_0.7_0.3	0.978905	0.986065	0.987913	0.989853	0.996007
0.2_0.8_0.2	0.996379	0.999671	1.00082	1.001801	1.005714
0.2_0.8_0.25	0.993562	1.000432	1.001839	1.002849	1.007273
0.2_0.8_0.3	0.985531	0.994766	0.996744	0.998604	1.00321

Stock Harvest HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	0.995	1.001	1.003	1.005	1.010
0.075_0.7_0.25	0.990	0.997	1.000	1.002	1.011
0.075_0.7_0.3	0.986	0.992	0.994	0.995	1.004
0.075_0.8_0.2	0.998	1.003	1.004	1.005	1.009
0.075_0.8_0.25	0.999	1.004	1.005	1.006	1.012
0.075_0.8_0.3	0.991	0.998	1.000	1.002	1.007

Gradient CE HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	0.981	0.991	0.993	0.995	1.001
0.075_0.7_0.25	0.985	0.992	0.994	0.996	1.003
0.075_0.7_0.3	0.984	0.990	0.992	0.994	0.999
0.075_0.8_0.2	0.980	0.983	0.985	0.988	0.995
0.075_0.8_0.25	0.981	0.987	0.990	0.992	0.998
0.075_0.8_0.3	0.978	0.989	0.991	0.993	0.998

4.4.4 Spawning Biomass Depletion in 2020 Relative to B0

Scenarios with 0.7 viral morality led to a better recovery than those with a viral mortality of 0.8. The total spawning biomass remaining in 2006 following both intial depletion and viral mortality as a fraction of the B_0 is as follows (initial dep_viral mortality): 0.3_0.7 = 0.09 (9%), 0.3_0.8 = 0.06 (6%), 0.25_0.7 = 0.075 (7.5%), 0.25_0.8 = 0.05 (5%), 0.2_0.7 = 0.06 (6%), 0.2_0.8 = 0.04 (4%). All the scenarios are greater than these values for total spawning biomass depletion (Figure 8, Table 9) which indicates a rebuilding of stock at all scenarios. The maximum depletion level as a result of fishing is only 5% approx (Figure 8) (the difference between the 0 and 0.2 harvest rate in the 0.7 viral mortality and 0.3 initial depletion scenario). Part of the reason these differences are small is because there is a large proportion of spawning biomass below the LML that is protected from fishing, and such protection is attributed to a relatively large LML of 132 mm.

However, it should be noted that the maximum productivity of the reefcode occurs at between 31 – 35% spawning biomass depletion (Figure 2) and all scenarios were below this level of productivity. It is also the case that the produciton curve is relatively flat near and around the optimum harvest rate with sustainable yields remaining relatively high at quite high harvest rates; it can be presumed that while yield only drops off a small amount, catch rates would drop off more dramatically.

The analyses are still in progress and it is too early to suggest that the objective to rebuild towards a target of about 35% should be adopted. These simulations remain based upon highly uncertain assumptions and data and more years of fishery data post-viral outbreak are required to determine whether reefcode abalone stocks have retained their previous productivity levels.

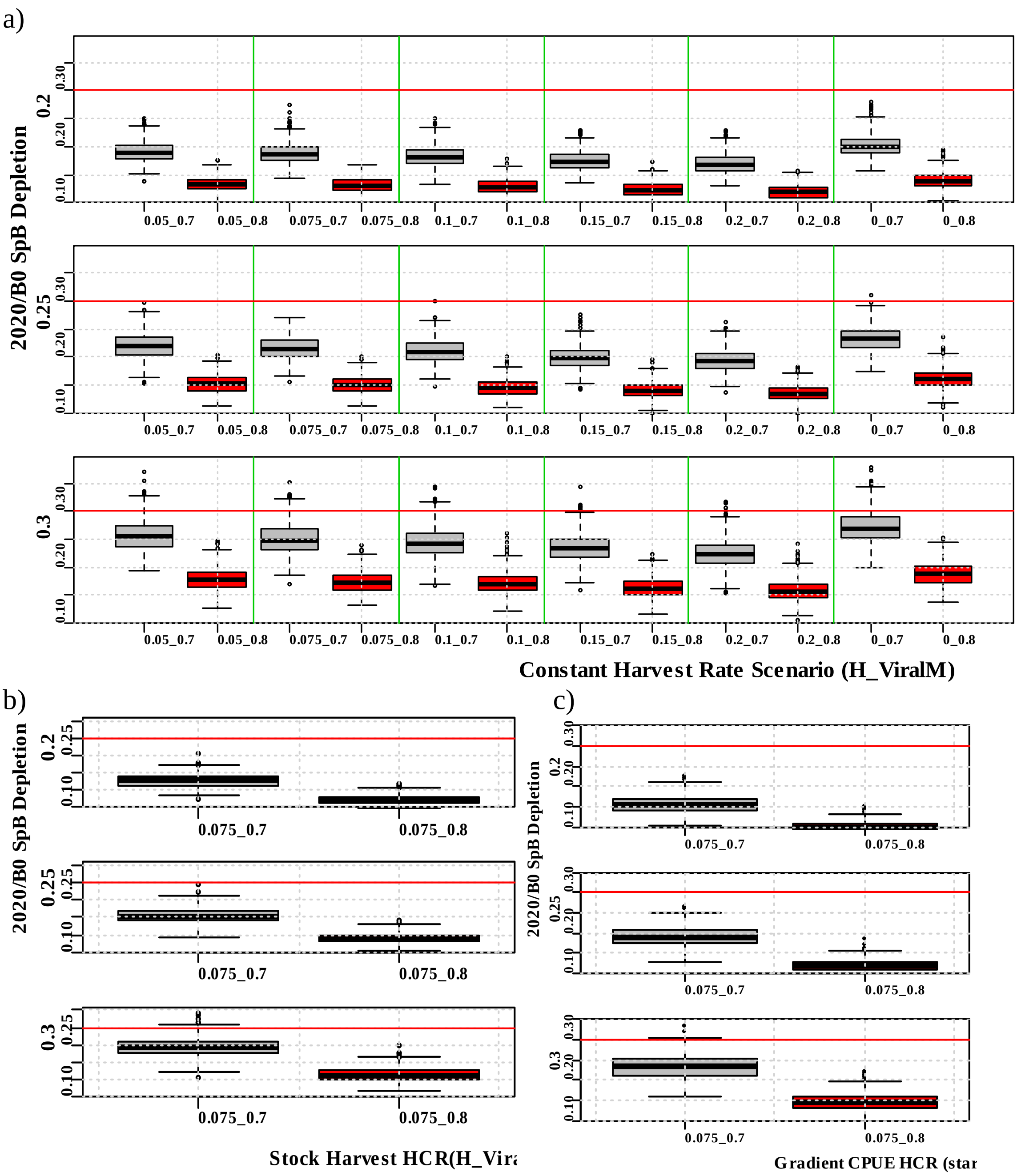


Figure 8. Spawning Biomass Depletion in 2020 relative to the B_0 for 6 scenarios within each of the HCRs. Three HCRs are presented: a) Constant Harvest HCR, b) Stock Harvest HCR and c) Gradient CE HCR. The initial depletion level in 2006 is the annotation to the left of each set of boxplots and each combination of initial H and viral mortality rate is listed under each separate boxplot. Note the y-axis begins at 0.1.

Table 9. Percent quantiles (0%, 5%, etc) of Spawning Biomass Depletion in 2020 relative to B_0. Three HCRs are presented: a) Constant Harvest HCR, b) Stock Harvest HCR and c) Gradient CE HCR.

Constant Harvest

Scenario	0	25	50	75	100
0.05_0.7_0.2	0.138	0.178	0.190	0.202	0.251
0.05_0.7_0.25	0.152	0.204	0.219	0.236	0.296
0.05_0.7_0.3	0.193	0.237	0.255	0.273	0.369
0.05_0.8_0.2	0.093	0.124	0.133	0.142	0.177
0.05_0.8_0.25	0.113	0.141	0.152	0.163	0.203
0.05_0.8_0.3	0.126	0.164	0.177	0.191	0.248
0.075_0.7_0.2	0.143	0.176	0.186	0.198	0.274
0.075_0.7_0.25	0.155	0.200	0.214	0.230	0.271
0.075_0.7_0.3	0.170	0.232	0.249	0.268	0.353
0.075_0.8_0.2	0.092	0.122	0.131	0.141	0.168
0.075_0.8_0.25	0.113	0.139	0.150	0.161	0.201
0.075_0.8_0.3	0.133	0.160	0.172	0.187	0.241
0.1_0.7_0.2	0.133	0.169	0.181	0.195	0.251
0.1_0.7_0.25	0.146	0.195	0.209	0.224	0.298
0.1_0.7_0.3	0.167	0.225	0.242	0.262	0.344
0.1_0.8_0.2	0.094	0.119	0.129	0.138	0.178
0.1_0.8_0.25	0.111	0.134	0.145	0.155	0.201
0.1_0.8_0.3	0.122	0.159	0.171	0.184	0.259
0.15_0.7_0.2	0.136	0.162	0.174	0.185	0.229
0.15_0.7_0.25	0.143	0.185	0.197	0.211	0.276
0.15_0.7_0.3	0.158	0.217	0.234	0.250	0.343
0.15_0.8_0.2	0.087	0.116	0.123	0.132	0.174
0.15_0.8_0.25	0.099	0.131	0.140	0.150	0.197
0.15_0.8_0.3	0.116	0.151	0.163	0.176	0.224
0.2_0.7_0.2	0.130	0.156	0.168	0.181	0.228
0.2_0.7_0.25	0.138	0.180	0.193	0.207	0.261
0.2_0.7_0.3	0.154	0.207	0.223	0.241	0.317
0.2_0.8_0.2	0.088	0.110	0.118	0.128	0.158
0.2_0.8_0.25	0.097	0.125	0.134	0.144	0.181
0.2_0.8_0.3	0.107	0.146	0.157	0.170	0.242
0_0.7_0.2	0.156	0.188	0.200	0.214	0.279
0_0.7_0.25	0.175	0.217	0.233	0.247	0.309
0_0.7_0.3	0.198	0.253	0.270	0.289	0.379
0_0.8_0.2	0.103	0.131	0.139	0.150	0.193
0_0.8_0.25	0.109	0.150	0.160	0.172	0.235
0_0.8_0.3	0.137	0.173	0.187	0.203	0.253

Stock Harvest HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	0.125	0.163	0.176	0.187	0.257
0.075_0.7_0.25	0.145	0.190	0.203	0.221	0.298
0.075_0.7_0.3	0.156	0.224	0.241	0.259	0.343
0.075_0.8_0.2	0.094	0.114	0.122	0.131	0.170
0.075_0.8_0.25	0.102	0.130	0.139	0.150	0.194
0.075_0.8_0.3	0.118	0.150	0.161	0.176	0.251

Gradient CE HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	0.105	0.141	0.154	0.170	0.224
0.075_0.7_0.25	0.129	0.174	0.191	0.208	0.264
0.075_0.7_0.3	0.161	0.211	0.233	0.251	0.334
0.075_0.8_0.2	0.068	0.093	0.100	0.109	0.150
0.075_0.8_0.25	0.081	0.108	0.118	0.128	0.183
0.075_0.8_0.3	0.100	0.132	0.145	0.158	0.219

4.4.5 Spawning Biomass Depletion in 2020 Relative to 2013

For all scenarios, the spawning biomass increases between 2013 and 2020 (Figure 9, Table 10). This relative increase appears less in the case of the 0.2 depletion level for 0.7 viral mortality scenarios (top most boxplot) than for the 0.3_0.7 scenarios (lower most boxplot). The relative improvement is greater for the 0.2 depletion (which sits above the red reference line) than for the 0.3 depletion (which sits below the red reference line). This is because the spawning biomass was lower in the 0.2 scenarios than the 0.3 depletion level. Similarly the starting level of the spawning biomass in 2006 was lower in the 0.8 viral mortality scenarios relative to the 0.7 viral mortality and therefore the (2020/2013) ratio for the 0.8 viral mortality appear higher than 0.7. However in absolute terms spawning biomass improved more for the 0.3 depletion level. The differences exhibited between different harvest rates within a given viral mortality rate are relatively minor (Table 10).

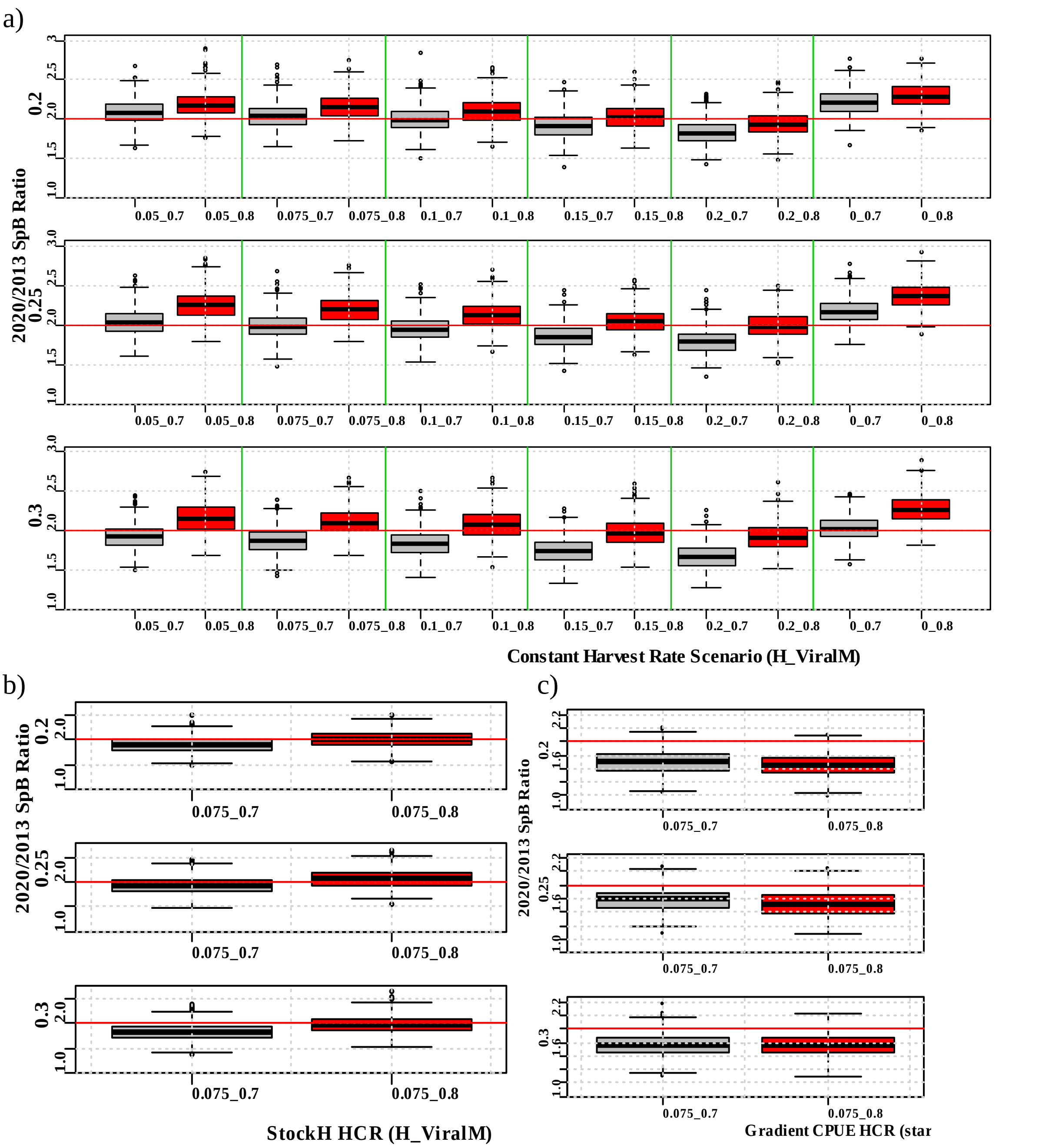


Figure 9. Spawning Biomass Depletion in 2020 relative to that in 2013 for 6 scenarios within the the three HCRs. Three HCRs are presented: a) Constant Harvest HCR, b) Stock Harvest HCR and c) Gradient CE HCR. In each box plot the initial depletion level in 2006 is along the y-axis and the combination of harvest rate and viral mortality rate is along the x-axis. The two colours identify the two viral mortalities (grey = 0.7, red = 0.8).

Table 10. Percent quantiles (0%, 25%, etc) of the distribution of Spawning Biomass Depletion in 2020 relative to that in 2013. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

Constant Harvest

Scenario	0	25	50	75	100
0.05_0.7_0.2	1.627	1.989	2.088	2.203	2.678
0.05_0.7_0.25	1.605	1.931	2.042	2.152	2.636
0.05_0.7_0.3	1.502	1.820	1.934	2.026	2.448
0.05_0.8_0.2	1.757	2.081	2.178	2.286	2.900
0.05_0.8_0.25	1.798	2.124	2.252	2.372	2.857
0.05_0.8_0.3	1.685	2.029	2.158	2.302	2.741
0.075_0.7_0.2	1.661	1.929	2.039	2.136	2.696
0.075_0.7_0.25	1.476	1.882	1.984	2.095	2.684
0.075_0.7_0.3	1.439	1.773	1.874	1.978	2.391
0.075_0.8_0.2	1.734	2.042	2.157	2.269	2.745
0.075_0.8_0.25	1.787	2.076	2.199	2.313	2.765
0.075_0.8_0.3	1.688	2.001	2.107	2.229	2.667
0.1_0.7_0.2	1.511	1.898	1.983	2.098	2.836
0.1_0.7_0.25	1.538	1.841	1.946	2.047	2.522
0.1_0.7_0.3	1.409	1.729	1.833	1.945	2.509
0.1_0.8_0.2	1.656	1.995	2.104	2.218	2.653
0.1_0.8_0.25	1.663	2.010	2.132	2.240	2.704
0.1_0.8_0.3	1.542	1.957	2.071	2.206	2.670
0.15_0.7_0.2	1.390	1.805	1.912	2.031	2.474
0.15_0.7_0.25	1.416	1.748	1.851	1.954	2.438
0.15_0.7_0.3	1.331	1.639	1.743	1.854	2.276
0.15_0.8_0.2	1.639	1.924	2.024	2.131	2.602
0.15_0.8_0.25	1.621	1.942	2.051	2.153	2.574
0.15_0.8_0.3	1.543	1.865	1.974	2.090	2.606
0.2_0.7_0.2	1.440	1.733	1.817	1.927	2.330
0.2_0.7_0.25	1.355	1.689	1.792	1.891	2.444
0.2_0.7_0.3	1.280	1.569	1.672	1.776	2.264
0.2_0.8_0.2	1.489	1.844	1.940	2.050	2.480
0.2_0.8_0.25	1.512	1.878	1.988	2.102	2.495
0.2_0.8_0.3	1.523	1.809	1.920	2.046	2.616
0_0.7_0.2	1.665	2.100	2.203	2.317	2.774
0_0.7_0.25	1.759	2.066	2.173	2.284	2.773
0_0.7_0.3	1.573	1.926	2.021	2.132	2.470
0_0.8_0.2	1.867	2.195	2.292	2.407	2.766
0_0.8_0.25	1.882	2.249	2.374	2.476	2.926
0_0.8_0.3	1.822	2.158	2.272	2.402	2.888

Stock Harvest HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	1.509	1.811	1.908	2.001	2.493
0.075_0.7_0.25	1.465	1.794	1.915	2.021	2.440
0.075_0.7_0.3	1.398	1.715	1.813	1.924	2.401
0.075_0.8_0.2	1.562	1.903	2.018	2.128	2.509
0.075_0.8_0.25	1.553	1.931	2.054	2.168	2.613
0.075_0.8_0.3	1.525	1.850	1.962	2.095	2.644

Gradient CE HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	1.229	1.578	1.692	1.809	2.195
0.075_0.7_0.25	1.269	1.665	1.792	1.893	2.280
0.075_0.7_0.3	1.282	1.649	1.755	1.859	2.352
0.075_0.8_0.2	1.193	1.539	1.642	1.755	2.091
0.075_0.8_0.25	1.287	1.593	1.723	1.846	2.252
0.075_0.8_0.3	1.285	1.639	1.752	1.876	2.229

4.4.6 Exploitable Biomass Depletion in 2020 Relative to 2013

The relative change in exploitable biomass between 2013 and 2020 has a similar pattern to that for the spawning biomass. Once again, the starting level in spawning biomass in 2006 was lower in the 0.8 viral mortality scenarios relative to the 0.7 viral mortality and therefore the ratio for the 0.8 viral mortality appear higher than 0.7 (Figure 10, Table 11). This enabled the ratio between years to be greater in the 0.8 relative to the 0.7 viral mortality scenarios. The change in exploitable biomass is proportionally greater than that which occurred with the spawning biomass.

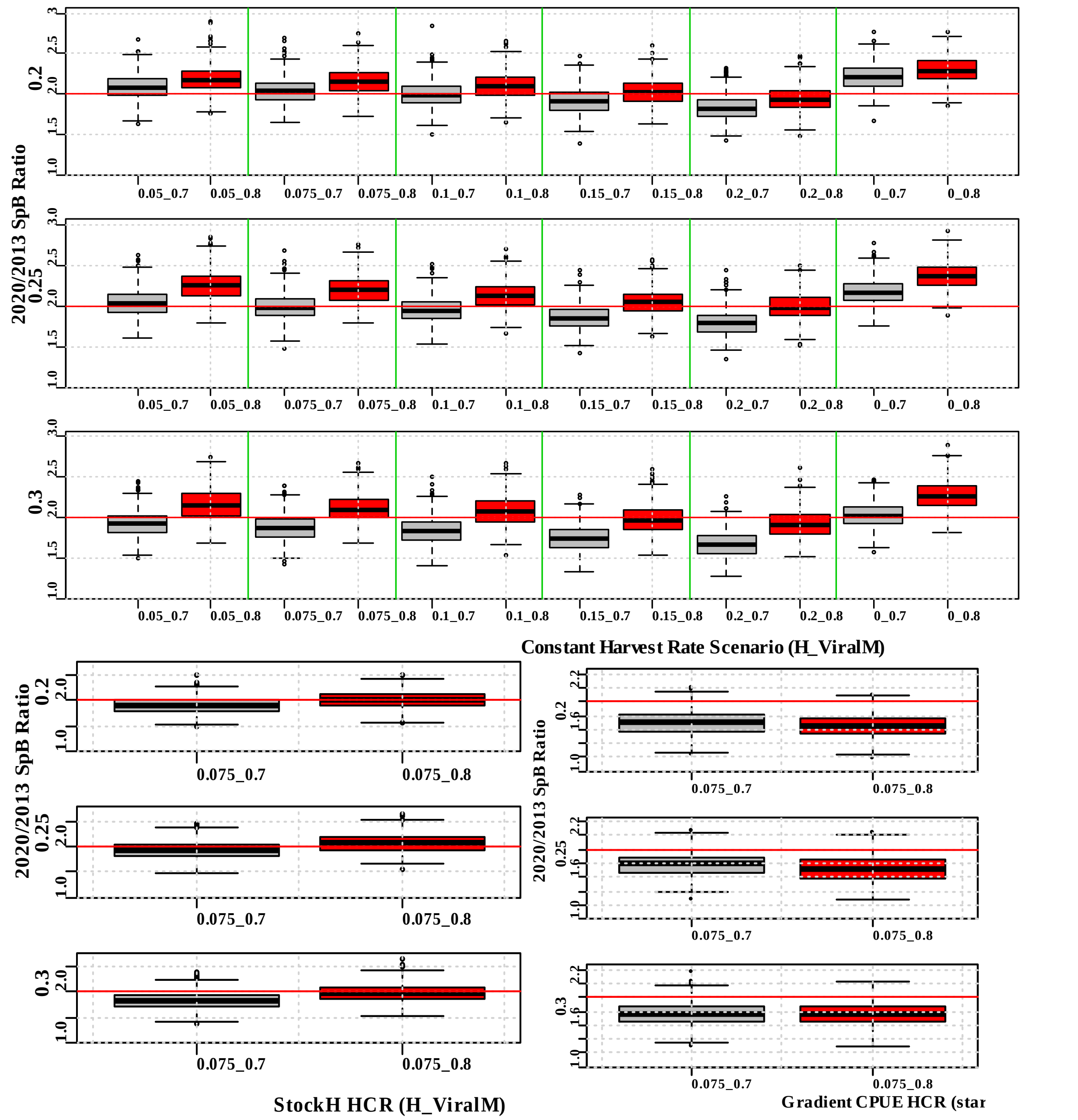


Figure 10. Exploitable Biomass Depletion in 2020 relative to that in 2013 for 6 scenarios within three HCRs: a) Constant Harvest HCR, b) Stock Harvest HCR and c) Gradient CE HCR. In each box plot the initial depletion level in 2006 is along the y-axis and the combination of initial harvest rate and viral mortality rate is along the x-axis. The two colours identify the two viral mortalities (grey = 0.7, red = 0.8).

Table 11. % quantiles (0%, 5%, etc) of the distribution of Exploitable Biomass Depletion in 2020 relative to that in 2013 across replicate runs in each scenario. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

Constant Harvest

Scenario	0	25	50	75	100
0.05_0.7_0.2	3.63	5.10	5.60	6.06	7.45
0.05_0.7_0.25	2.87	3.87	4.29	4.70	6.54
0.05_0.7_0.3	2.42	3.17	3.46	3.79	5.11
0.05_0.8_0.2	5.14	6.21	6.60	7.04	9.75
0.05_0.8_0.25	5.01	6.08	6.48	6.92	8.32
0.05_0.8_0.3	3.82	5.50	6.03	6.66	8.54
0.075_0.7_0.2	3.73	4.83	5.25	5.61	7.32
0.075_0.7_0.25	2.50	3.58	3.99	4.40	6.02
0.075_0.7_0.3	2.16	2.99	3.31	3.63	5.81
0.075_0.8_0.2	4.62	5.94	6.31	6.70	8.17
0.075_0.8_0.25	4.47	5.69	6.13	6.59	8.20
0.075_0.8_0.3	3.54	5.16	5.82	6.34	7.91
0.1_0.7_0.2	3.13	4.52	4.95	5.40	7.09
0.1_0.7_0.25	2.40	3.42	3.80	4.15	5.72
0.1_0.7_0.3	2.09	2.84	3.12	3.41	4.50
0.1_0.8_0.2	4.49	5.59	5.98	6.35	7.82
0.1_0.8_0.25	4.24	5.34	5.72	6.16	7.67
0.1_0.8_0.3	3.16	4.88	5.43	5.92	7.84
0.15_0.7_0.2	2.56	4.05	4.41	4.81	6.17
0.15_0.7_0.25	2.01	3.06	3.35	3.71	5.64
0.15_0.7_0.3	1.80	2.48	2.73	3.05	4.87
0.15_0.8_0.2	3.86	5.01	5.31	5.66	7.25
0.15_0.8_0.25	3.79	4.79	5.20	5.55	6.97
0.15_0.8_0.3	2.76	4.32	4.82	5.34	6.82
0.2_0.7_0.2	2.46	3.55	3.92	4.30	5.91
0.2_0.7_0.25	1.88	2.70	2.99	3.35	4.98
0.2_0.7_0.3	1.53	2.20	2.44	2.70	3.92
0.2_0.8_0.2	3.86	4.44	4.81	5.17	7.29
0.2_0.8_0.25	3.36	4.35	4.67	5.07	6.38
0.2_0.8_0.3	2.43	4.00	4.40	4.84	6.60
0_0.7_0.2	4.28	5.84	6.30	6.76	9.20
0_0.7_0.25	3.36	4.39	4.77	5.21	7.35
0_0.7_0.3	2.71	3.65	3.99	4.31	5.83
0_0.8_0.2	5.76	7.02	7.47	7.96	9.48
0_0.8_0.25	4.95	6.91	7.38	7.87	9.54
0_0.8_0.3	4.19	6.24	6.97	7.53	9.82

Stock Harvest HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	3.08	4.07	4.40	4.73	6.45
0.075_0.7_0.25	2.26	3.25	3.54	3.89	5.23
0.075_0.7_0.3	2.15	2.76	2.99	3.26	5.19
0.075_0.8_0.2	3.79	4.92	5.22	5.53	7.05
0.075_0.8_0.25	3.73	4.85	5.15	5.52	6.70
0.075_0.8_0.3	3.18	4.39	4.80	5.21	6.85

Gradient CE HCR

Scenario	0	25	50	75	100
0.075_0.7_0.2	1.54	2.68	2.98	3.29	4.20
0.075_0.7_0.25	2.11	2.70	2.95	3.20	4.29
0.075_0.7_0.3	2.01	2.58	2.80	3.02	3.85
0.075_0.8_0.2	1.70	2.23	2.51	2.83	4.04
0.075_0.8_0.25	1.75	2.59	2.88	3.24	5.27
0.075_0.8_0.3	2.04	2.97	3.25	3.54	4.91

4.5 Comparison of Harvest Rates in Most Plausible Scenario

In the consideration of the various scenarios the most plausible had the least initial depletion (0.3=30%) and the lowest viral mortality (0.7=70%). In addition, all the HCR performance measures were consistent in their behaviour when the viral mortality was 0.7. Therefore, for clarity the various harvest rates are compared only for the scenario that combined an initial depletion of 0.3 and a viral mortality of 0.7.

4.5.1 Catch Related Performance Measures

There is an obvious and marked increase in the total catch taken between 2014 – 2020 as the harvest rate increases. There is also a slight difference in the relative variability of catches (AAV) between scenarios (Figure 11).

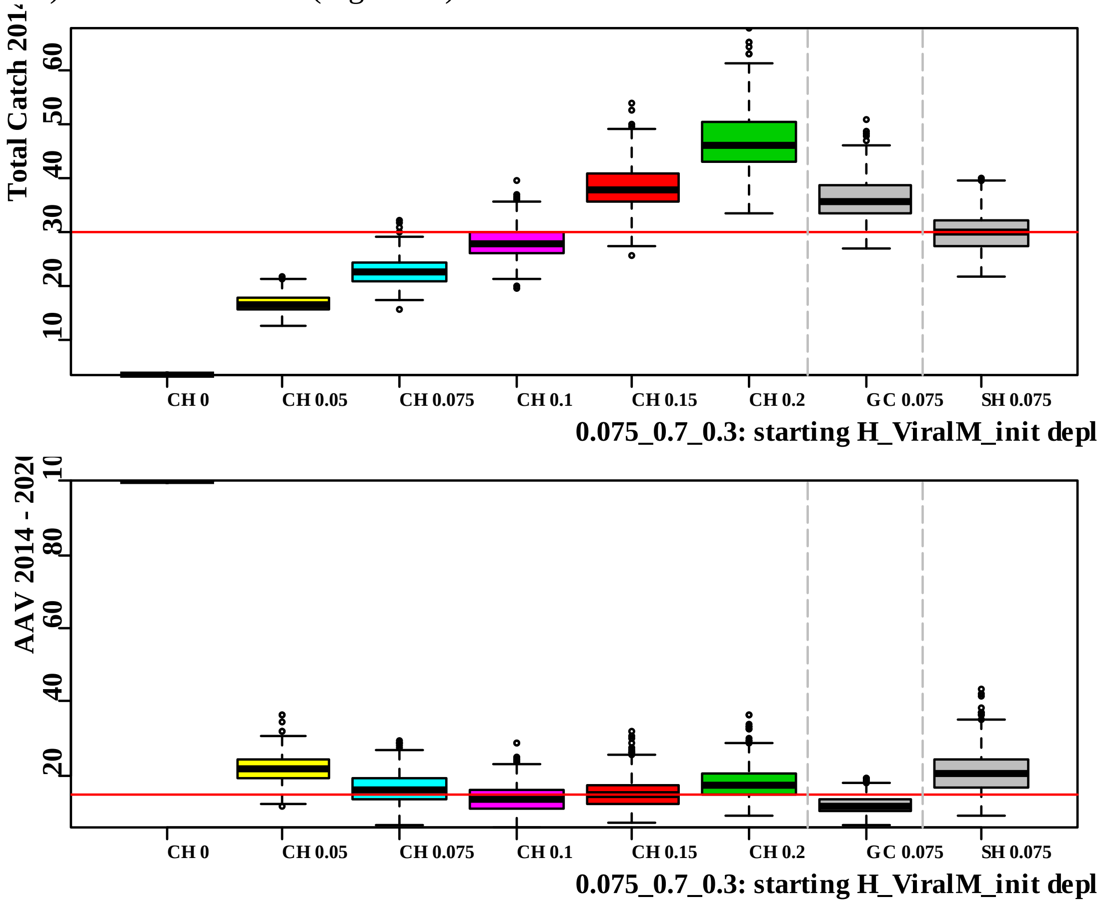


Figure 11. The Total Catch (upper plot) and the Average Annual Variation (lower plot) of the predicted catch taken on the Crags between 2014 – 2020 for the scenario of 0.3 initial depletion and 0.7 viral mortality. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR. The red lines are to simplify comparison between scenarios.

4.5.2 Ratio of Mean Length of Catch of 2020/2013

There is a noticeable difference in the mean length of the catch in 2020 relative to that in 2013 between the harvest rate scenarios. However, the proportional changes are very minor being a maximm of about 1.5% between the smallest and the largest, which would be very difficult to detect in a real fishery. More importantly, harvest rates greater than 0.1 (10%) can further reduce the mean length from 2013 – 2020 (Figure 12).

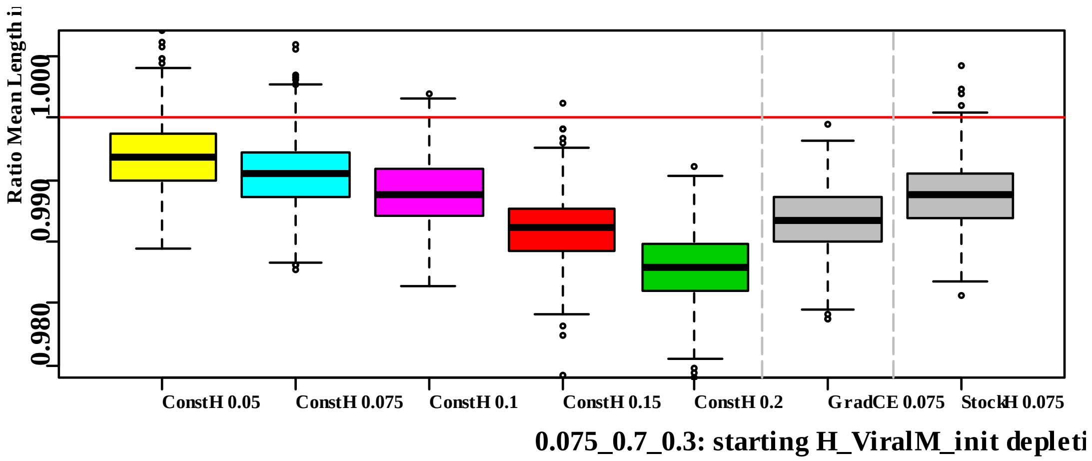


Figure 12. The ratio of the predicted mean length of the commercial catch in 2020 relative to the 2013 for the scenario of 0.3 initial depletion and 0.7 viral mortality. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

4.5.3 Spawning Biomass Depletion in 2020 Relative to B_0

The scale of recovery is, not surprisingly, negatively influenced by increasing the annual harvest rate (Figure 13). All harvest rates lead to a depletion level that is below the maximum producitivity by 2020. Perhaps more importantly, as the stock is assumed to have started in 2006 at 0.3 spawning biomass depletion then the stock should have recovered from the viral mortality by 2020.

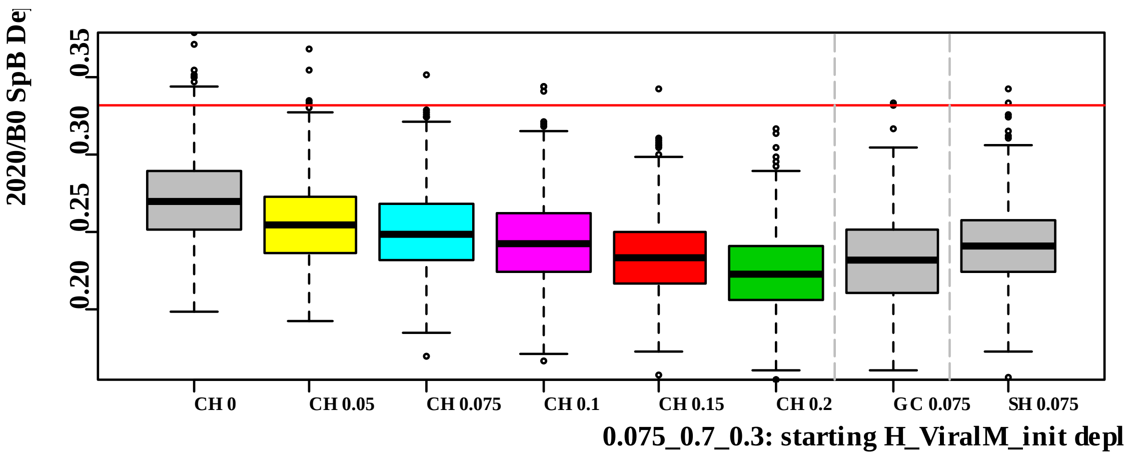


Figure 13. Spawning Biomass Depletion in 2020 relative to the B_0 for the scenario of 0.3 initial depletion and 0.7 viral mortality. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR. The red line is to simplify comparison between scenarios. A depletion level of 0.3 indicates the level above which the maximum productivity is likely to be produced according to (Figure 2).

4.5.4 Spawning Biomass Depletion in 2020 Relative to 2013

As with the spawning biomass recovery, the ratio between 2020 and 2013 was greater as harvest rate decreased (Figure 14).

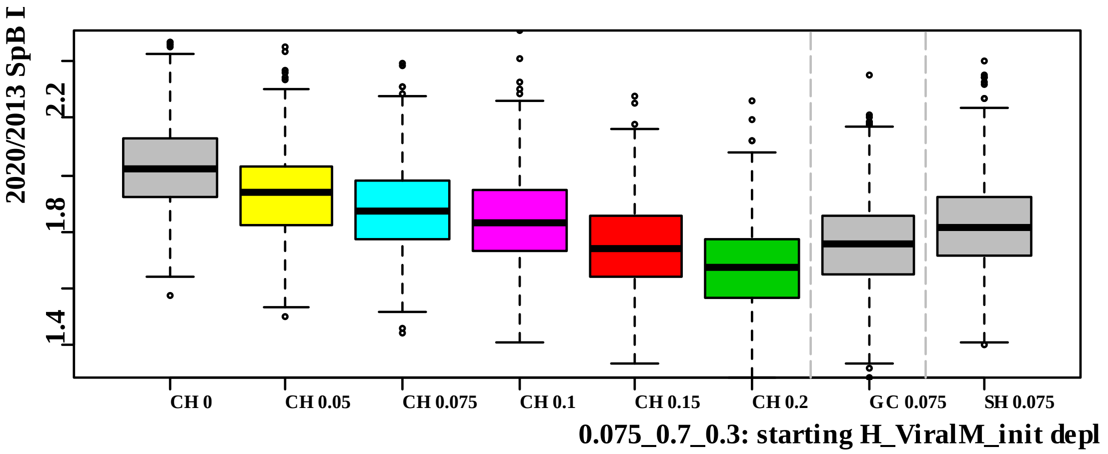


Figure 14. Spawning Biomass Depletion in 2020 relative to that on 2013 for the scenario of 0.3 initial depletion and 0.7 viral mortality. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR. The red line is to simplify comparison between scenarios.

4.5.5 Exploitable Biomass Depletion in 2020 Relative to 2013

As with the spawning biomass recovery, the exploitable biomass ratio between 2020 and 2013 was greater the smaller the catch or harvest rate (Figure 15). Exploitable biomass can be expected to markedly increase by 2020, but by between about 250 - 350 % depending on the harvest rate applied. It should be remembered that the exploitable biomass is greatly influenced by the LML and being set at 135mm will limit the access to fishable biomass.

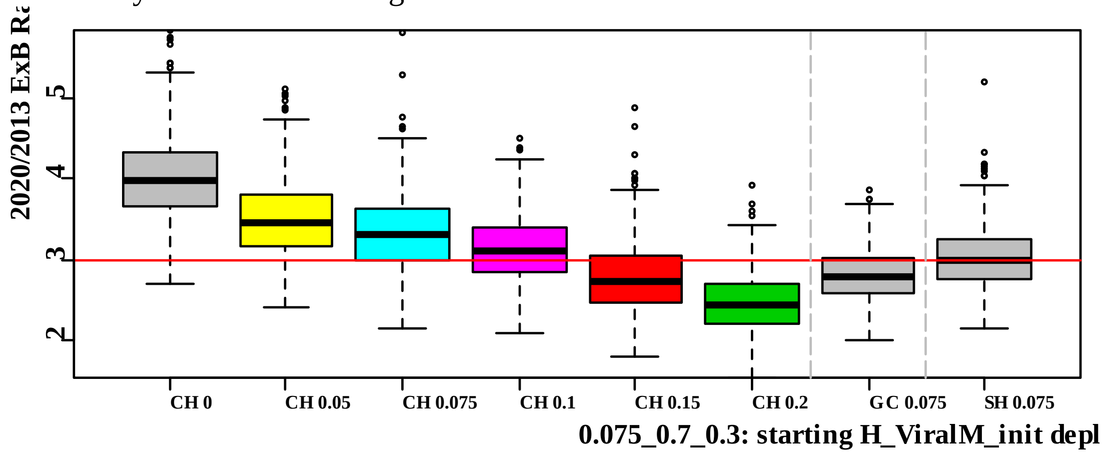
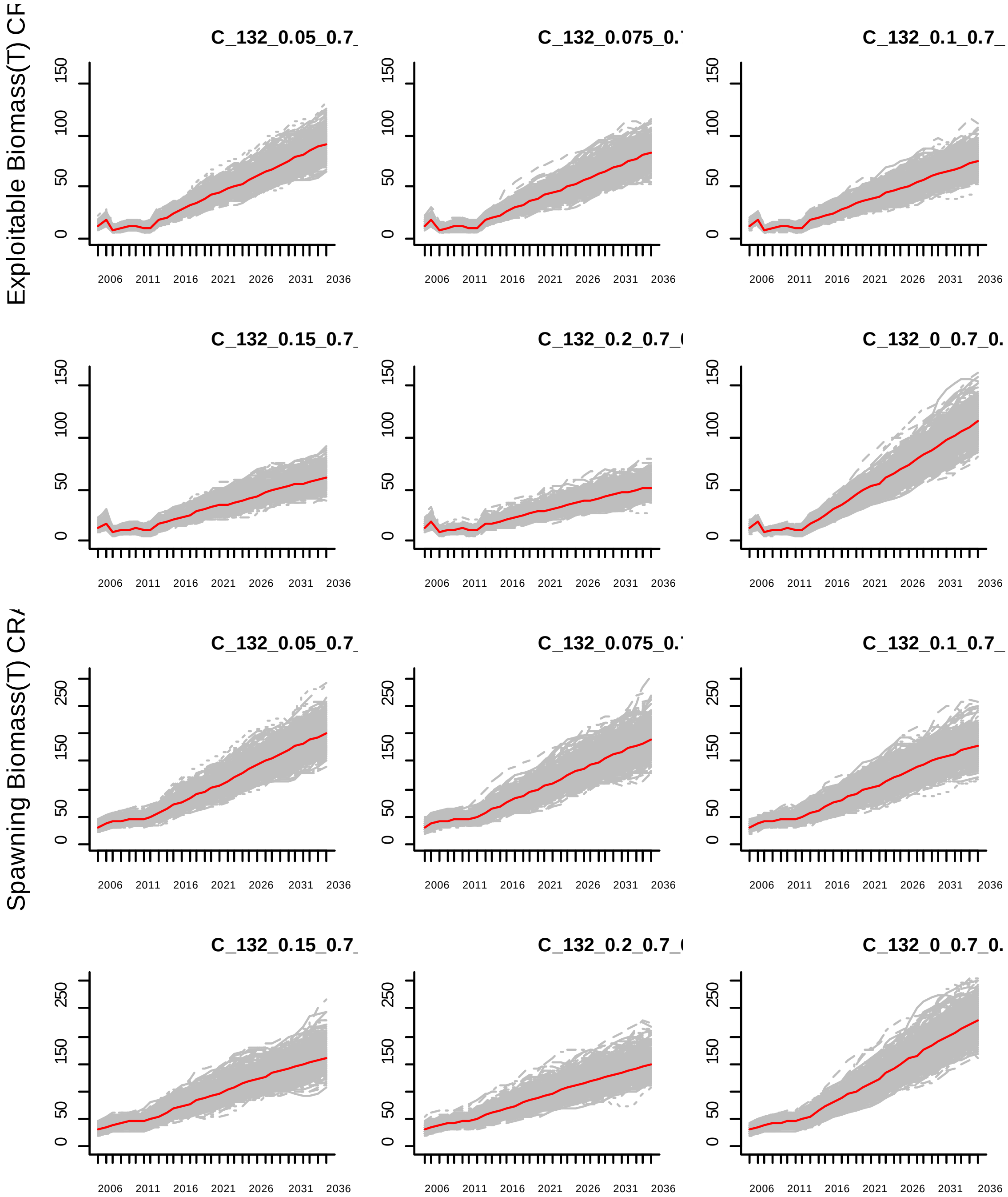


Figure 15. Exploitable Biomass Depletion in 2020 relative to that on 2013 for the scenario of 0.3 initial depletion and 0.7 viral mortality. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR. The red line is to simplify comparison between scenarios.

4.5.6 Trajectories



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6 Appendix: MSE Specification and Conditioning

6.1 Introduction

The MSE framework begins with a model of the biological system which consists of an operating model, which functions as a simplistic interpretation of "how the world works" (Sainsbury and Sumaila, 2003).With respect to abalone stocks, the parameters of the operating model consist of key biological processes including somatic growth, size at maturity, length at weight, mortality and recruitment (and stock productivity). The parameters may be determined from data and/or stakeholder advice. The operating model can include reasonable alternative hypotheses (Sainsbury and Sumaila 2003) and the uncertainties surrounding those hypotheses can be expressed as probability distributions around the parameter values. This section describes the parameters of the operating model and the associated uncertainties and correlation between the life history parameters, for the reef-codes of interest.

Reef-codes of interest in the Western Zone fishery, their identifiers and associated sampling sites:

- Crags (Port Fairy Region): reef-code 3.05 and 3TC (old reef code); consist of 5 sites
    - Inside Crags (old site ID=362, new site ID=129),
    - McKenzie Crags (old site ID=51, new site ID=130),
    - The Crags (old site ID=134, new site ID=131,
    - Outside Crags (old site ID=360, new site ID=132),
    - The Crags inside (old site ID=361, new site ID=133).
- Mills and Killarney

  Killarney (Warnambool): reef code 3.10 and 3KN (old reef code); consist of 2 sites
    - site ID = 123
    - Killarney (site ID = 124)

  Mills: reef code 3.09 consist of 2 sites
    - Mills Reef (site ID = 125)
    - Inside Mills (site ID = 126)
- Watersprings (Portland region): reef code 1.03 and 1WS (old reef code):
    - South West Bridgewater (site ID = 153)
    - Petrified forest (site ID = 154)
    - Watersprings (site ID = 155)

6.2 Previous Modelling

The previous modelling work on the potential for recovery from the viral mortality was described in Gorfine et al., (2008). Most of the modelling in the Gorfine et al., (2008) study was conducted by Bardos, who provided a draft manuscript at the end of Gorfine et al., (2008) that described many of the its details. The model structure is similar in general form to the national abalone model, which is a classically structured size-based population model that has been adapted to abalone through having separate emergent and cryptic components. There are some differences between the Bardos model and the current modelling.
The features of the Bardos model include:

- designed to be applied zone-wide (i.e. as if to a single population).
- initiated by fitting the size-structured population dynamics model to multiple individual reef-codes within the fishery.

- The size transition matrix used a size range from 52 – 162 mm in 2mm increments
- a probabilistic Gompertz model was applied in the size transition matrix to describe the growth of the abalone at a reef-code spatial scale.

6.3 Current Modelling

The current model structure is also similar in general form to the national abalone model, in that it is a classically structured size-based population model with separate emergent and cryptic populations.

The features of the current model include:

- can have a large number of essentially separate populations within a reef code.
- it is not fitted to fishery data
- The size transition matrix used a size range from 2 – 170 mm in 2 mm increments (i.e 85 two mm size classes from 2 – 170 mm)
- uses the inverse logistic model (Haddon et al., 2008) to describe growth at the population level (i.e at a smaller spatial scale than reefcode)

6.4 Information and data available

The first stage in preparing an operating model is to source all available relevant data sources and other information sources such as reports. This was then followed by stakeholder advice. The data files used in the previous modelling (Gorfine et. al. 2008) were made available to aid the transition to the different modelling framework used in the present study. The data for all reefcodes that were considered in the previous modelling includes:

- growth data in the form of tagging data with various times at liberty although only annual data was used
- maturity – data was not available only the parameters were available in Gorfine et. al. (2008)
- length frequency distributions
  - Scientific and
  - commercial
- historical catches
  - Legal
  - illegal – based on anectodal evidence in Gorfine et. al. (2008)
- abundance estimate for determining the percent viral mortality
  - annual estimate
  - month specific estimates

The reefcode identifier was used to isolate and extract the required data from each file.

Table 12. A number of files containing data and previously estimated parameters used in the conditioning of the MSE; much derived from the Gorfine et al, (2008) modelling.

File	Contents
18_Sites.xls	Contains a description of the sites that are used in the files within the WZModelling directory.
Westernzone _Abalone TagReleaseData2013.xls	Data to estimate Weight at Length and Length at Width relationships
Tagging_data.tab	Western zone tag-recapture data used to estimate growth parameters.
LengthFrequency.tab	LF data both commercial and non-commercial survey: re-formatted and the Crags reefcode data extracted
Prerecruits.tab and Recruits.tab	Assumed survey relative abundance indices for two size classes. Not used in current analysis.
Maturity	18_Sites.xls contained details of reef specific maturity used in the Bardos modelling; including the Crags
bardos2\Math to F90\matricesused\TheCraggs.txt	Contains the growth transition matrix used in the Bardos modelling for the Crags

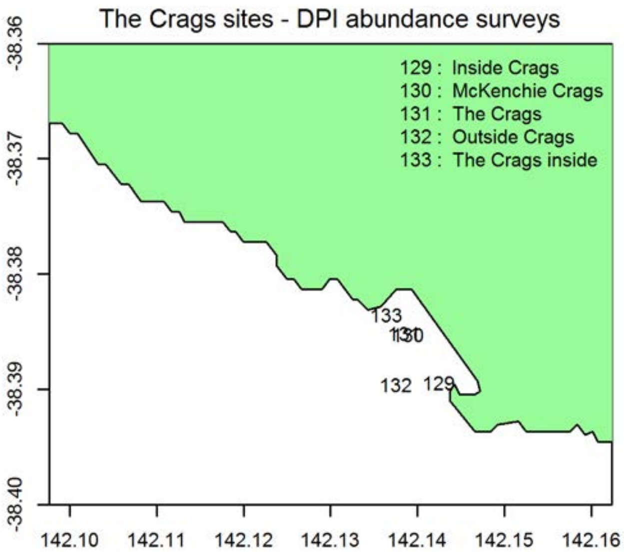

Figure 16. Map showing 5 sites of DPI abundance surveys at the CRAGS

6.5 Characteristics of the fishery

6.5.1 Length frequency

Length frequency data was collected from two types of surveys: scientific and commercial. The two surveys yielded different values in maximum size with the commercial survey returning larger shell length abalone than scientific surveys. A comparison is provided in Figure 17to illustrate the disparity in maximum shell length between the two survey methods

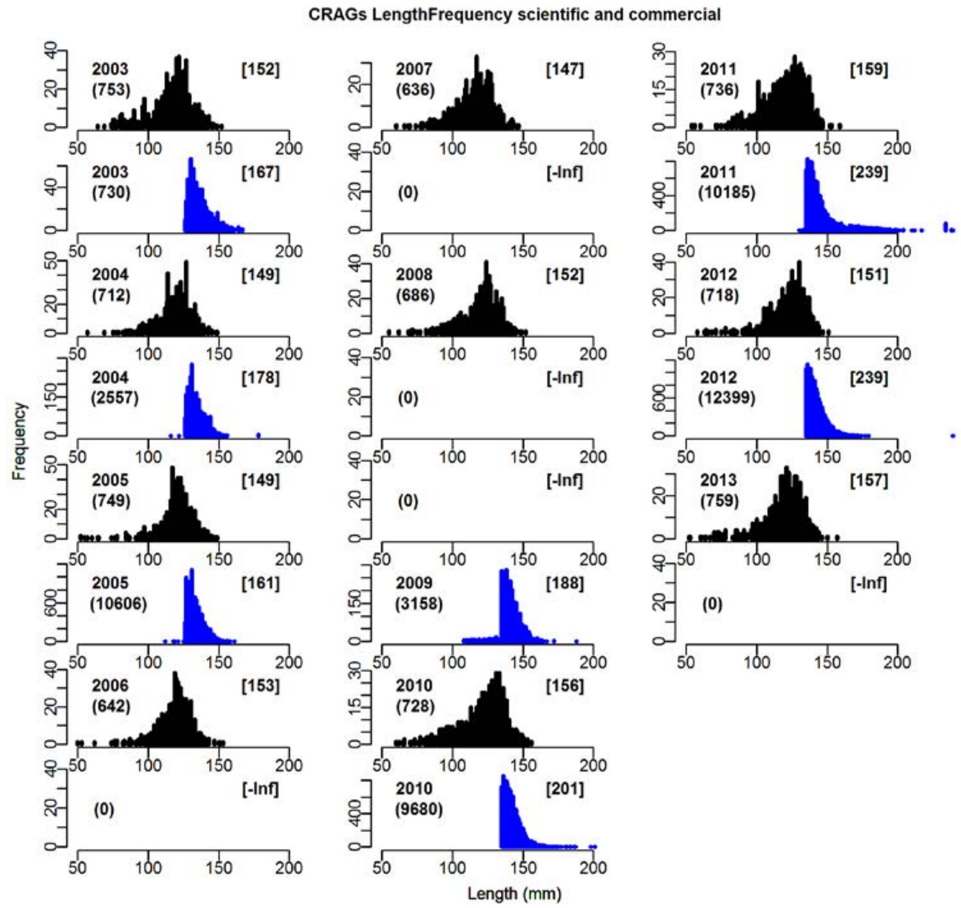

Figure 17. A comparison of the length frequency distribution of blacklip from scientific (black) commercial (blue) catches of abalone from the Crags (ReefCode 3.05); an area of the Western Zone in Victoria. The years are identified in the top left, the sample size is in parentheses and the maximum shell length in square bracket (top right of each plot). The data for years 2006 – 2009 for the commercial catches (blue) is missing because the fishery was closed due to the outbreak of the AVG disease. The Voluntary Minimum Length was increased following the virus outbreak (Table 13).

6.5.2 LML and VML

Table 13. The LML and Voluntary Minimum Length (VML) at the Crags since 2003. The value in square brackets [] were in file “Western Zone Modelling Datasets.xls” provided by DPI. The value in double square brackets [[]] are provided by WADA. It is possible that the VML was issued under permit in which case catching below the VML may be considered illegal.

Year	LML(approx SM_{50})	LML (update-Zac files)	VML
2003	120	120	125
2004	120	120	125
2005	120	120	125/[127]
2006	120		125
2007	120		125
2008	120	130	125
2009	120	130	125/[[135]]
2010	120	130	135
2011	120	135	135
2012	120	135	135
2013		130	[135]

6.5.3 Catch

The catches used in the previous study (Gorfine *et al*. 2008) were provided with eight significant digits, which suggests they were derived from some algorithm rather than from reported catches.

The quota year begins in April of that year i.e. 2006 quota year is 1st April 2006 – 31st March 2007

Table 14. Catch values reported for the Crags, derived from the file: 'catch table.xls' and AbaloneTRF\\analyses\\WZModelling\\Catch_Craggs.txt (for 1978 – 2013).

Year	Catch (t)	Year	Catch (t)	Year	Catch (t)	Year	Catch (t)
1965	3.789	1978	24.445	1991	43.329	2004	26.138
1966	10.283	1979	26.984	1992	34.800	2005	23.607
1967	16.778	1980	40.306	1993	33.785	2006	10.983
1968	39.104	1981	46.091	1994	31.285	2007	0
1969	61.430	1982	27.665	1995	31.844	2008	0
1970	37.551	1983	33.914	1996	43.924	2009	3.368
1971	35.168	1984	38.840	1997	25.615	2010	3.667
1972	52.603	1985	33.745	1998	39.494	2011	4.683
1973	46.886	1986	22.898	1999	30.314	2012	9.857
1974	45.579	1987	42.718	2000	26.313	2013	5.314
1975	45.727	1988	20.812	2001	32.573		
1976	40.992	1989	17.410	2002	20.615		
1977	38.823	1990	26.337	2003	22.930		

6.6 Conditioning the Operating Model

In order for the simulated stock dynamics for the selected reefcodes to be at least consistent with the observed properties of the stock, the operating model needs to be conditioned to reflect the biological properties of the local abalone populations and the productivity of the modelled stock

An important requirement of the operating model is to relate it to incorporate a realistic level of uncertainty to all parameters (for Crags, Mills-Killarney, Watersprings) The main aspect of the operating model include both data and stakeholder advice on the biology of the population and the productivity of the fishery. It was not sufficient to fit the operating model to data since stakeholders may have advised that the data inadequately represented the biology.

The term 'conditioning the model' means to make the model properties consistent with the observed properties of the stock being modelled. This is not the same as fitting the model to the available data in the classical stock assessment approach, although there are similarities. The operating model was therefore conditioned on:

- description of growth, including maximum length of the catch
- maturity at size,
- historical catches
- productivity: useful for estimating recruitment at B_0, that would correspond to a appropriate biomass at B_0 and depletion level in 2006 immediately before the virus.

6.6.1 Growth

Model selection

For a range of reasons the growth model in the transition matrix of the current study differed from the previous modelling. The growth description used in the modelling in Gorfine et al., (2008) was based around a probabilistic Gompertz growth model that was fitted using custom software not freely available. Changing the simulation framework to accept this model would have involved many related changes to the simulation framework and taken much longer than was available so, instead, it was decided to use an inverse logistic model (Haddon et al, 2008). This change was required by the different design of the MSE simulation framework, the need to include the full time lags into the population dynamics of the modelling, and the fact that altering the probabilistic Gompertz curve is not a simple exercise.

Fit to tagging data

Tagging data was available for the Crags reefcode. The previous modelling (Gorfine et al., 2008) stated that the probabilistic Gompertz model was fitted "… against an extensive set of tag-recapture growth datasets for the region." (Gorfine et al., 2008, Appendix p 9). The dataset was subsetted to include sample where the time at liberty was annual. The nearest annual time-at-liberty was a time-at-liberty = 373. This subset of the data only had 19 observations of growth increments from tagged and recaptured animals (although 77 data points were in the data set relating to single year increments, Figure 18).

The inverse logistic (IL) model (Haddon et al, 2008) was fitted to the data using maximum likelihood. This growth model currently provides a good description of abalone growth in Tasmania (Helidoniotis et al, 2011; Helidoniotis and Haddon, 2012, 2013) .

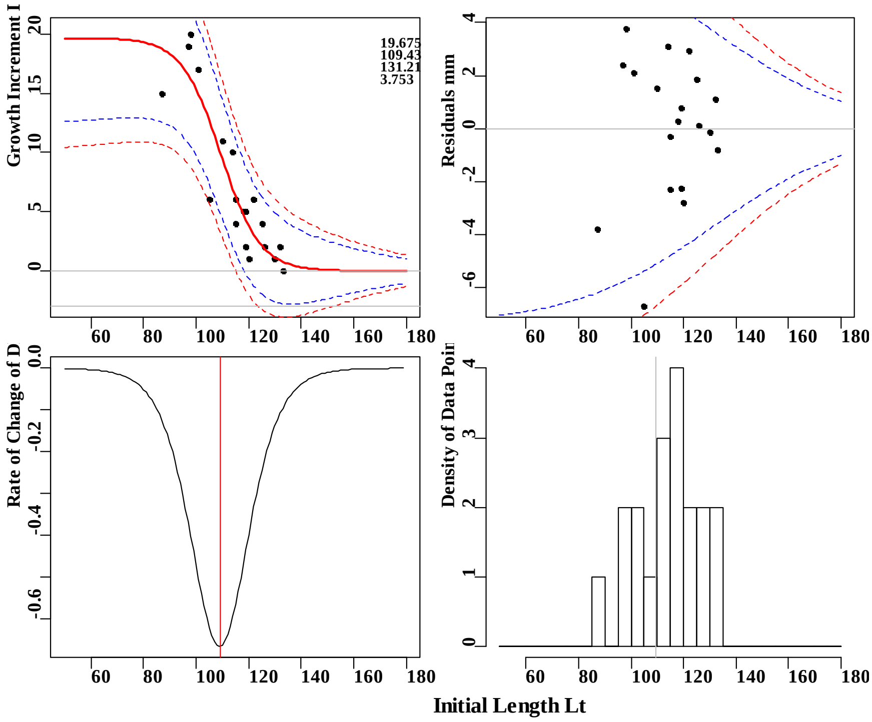

Figure 18. The inverse logistic model fitted to the 19 data points specific to the Crags. The parameter estimates are MaxΔL = 19.6747, L50 = 109.4345, L95 = 131.2185, and MaxSig = 3.7529.

Further development of the growth model was carried out. It was decided early on to generate a growth model that would be consistent to the Gompertz model used in the size transition matrix used in the modelling that formed the basis of the Gorfine et. al. (2005) report, notwithstanding that we used a different growth model (the inverse logistic). The size transition matrix used for growth in the Bardos modelling (which was provided as a file) was used to generate length increments and thereby mimic tagging data. The Gompertz and inverse logistic were then fitted to this simulated tagging data and compared. In total three growth models were compared (Figure 19):

- The Gompertz model fitted to the simulated tagging data of the Bardos matrix
- The inverse logistic fitted to the simulated tagging data of the Bardos matrix
- The inverse logistic fitted to observed tagging data (time at liberty = 373 days)

Even though the tagging data available is limited there were enough from the Crags to gain an estimate of the Inverse Logistic parameters. While these gave a reasonable fit to the available data they were markedly different from the implications of the Gompertz growth transition matrix and its similar IL curve (the solid black line depicted as “IL (98,142)” in the legend of Figure 19). All three curves make sense of the data, although it is possible to argue that the three lowest data points for animals less than 100 mm in initial length appear to be having a great deal of influence.

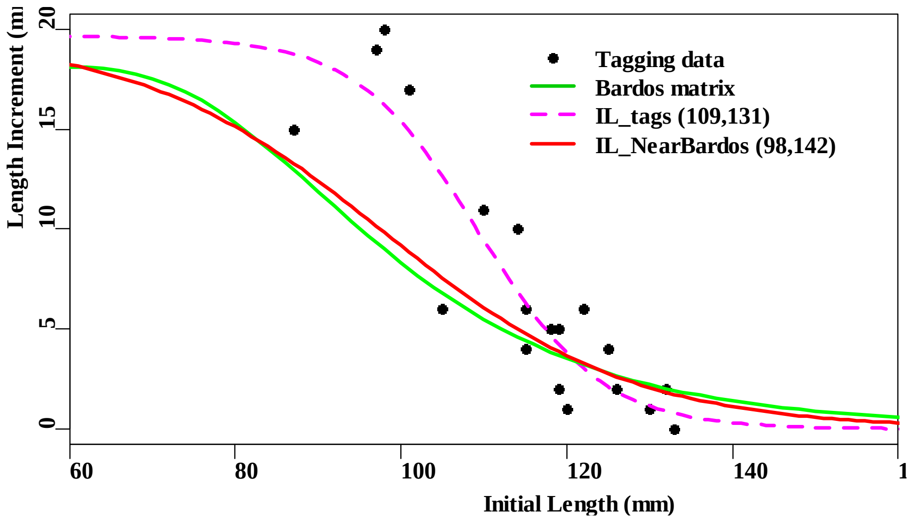

Figure 19. The tagging data points from the Crags reefcode plus the fitted inverse logistic Curve, a fitted probabilistic Gompertz growth curve fitted to increments generated from a Gz -size transition matrix developed by Bardos (Gorfine et al., 2008), and the Inverse Logistic fitted to increments generated from a Gz -size transition matrix developed by Bardos.

However uncertainty remained around the fits of the growth models and they continued to be considered inconclusive. Therefore it was decided to use the entire observed tagging dataset and not just that limited to one year time-at-liberty. Three curves of predicted annual growth increment at a given initial length were then produced:

- the IL curve fitted to all tagging data,
- and the IL curve fitted to tagging data with a time-at-liberty of 373 days (Figure 20).
- the Gompertz model fitted to the Bardos transition matrix,

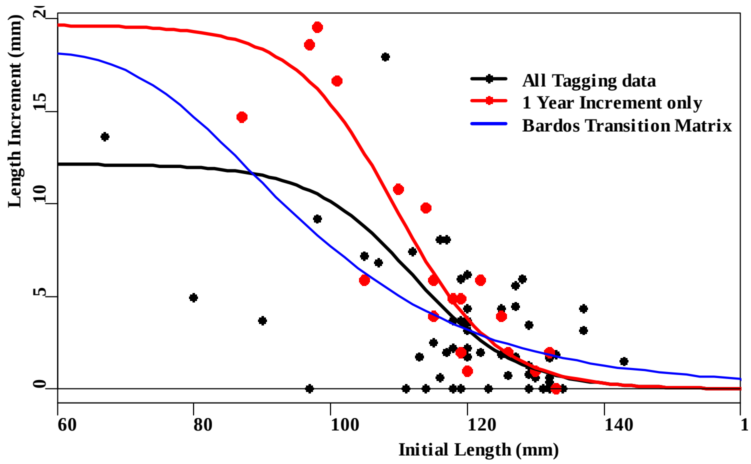

Figure 20. A comparison of an IL curve fitted to all Crag reefcode data (including Old Reef Code 3TC data), another IL curve fitted only to those data with about 1 year (373 days time-at-liberty) between tag and recapture, and finally to the increments implied by the Bardos (Gompertz) transition matrix. All length increments have been divided by the (DaysAtLiberty/365) to relate the data more closely to the fitted curves (which predict annual growth increments). The red line is fitted only to the red points, the black line to both the black and the red points and it is assumed that the blue line is a Gompertz model fitted to all the available data.

Whatever the case, it is clear that parameterisation of the growth models remain uncertain. The variation in the data makes all three curves fail to describe different aspects of the data.

To improve the description of growth it was decided to generate an unfished length frequency distribution from each of these growth models, and compare the outcome to observed length frequency data (obtained from commercial catches and scientific surveys, Figure 17). First, a size transition matrix need to be developed and this is described hereforth.

Developing a size transition matrix

The description of growth is important to the dynamics of any size-structured model such as used in abalone modelling (and in rock lobsters, Tasmanian giant crab, prawns, etc). Size-structured modelling is used because all of these species are very difficult and expensive to age consistently. In the previous modelling (Gorfine et al, 2008) instead of including all size classes from post-larval to the maximum size, abalone growth was modelled from 52 mm up to 162 mm in 2mm steps. This has advantages for computing speed because there are obviously fewer size classes to process in the calculations. However, there is the disadvantage of having to arrange for animals growing from smaller size classes into the start of the modelled size range. The new recruits were distributed into the modelled population by spreading those predicted new animals across a range of size classes in a specific manner: 10% of recruits in each of first five size classes, 52 – 60 mm, accounting for 50%, then 6% for the next 5 size classes, 62 – 70mm, and finally 2% into the next 10 size classes, 72 – 90 mm, thereby summing to 100% of all new recruits. Furthermore a weighting was applied to each size class. This approach would be better than putting them all into the first size class but it does differ from how they would enter into the modelled size classes if they had grown through from the post-larval stages (Figure 21).

In the present modelling we used a size range from 2 – 170 mm in 2 mm size classes. All recruitment was therefore put into the first size class, the lower bound of which was 2mm and the upper was 4mm (the second size class is from 4 – 6 mm, etc). The application of the growth predicted by the annual growth transition matrix spreads out the size distribution of each cohort into widening modes as time passes and such modes grow through the 52mm size class more naturally than imposing a given schedule. The primary advantage of using a full range of sizes (2 – 170 mm) is that any time lags between settlement and recruitment, which are very important in abalone population dynamics, are correctly modelled and automatically incorporated into changes passing through the population (Figure 21).

Updating growth parameters using unfished equilibrium size distribution and length frequency data

By combining the population dynamics, the natural mortality rate, and the size transition matrices used to describe growth, it is possible to grow the modelled populations forward without imposing any fishing mortality and thereby determine the expected numbers at size in the unfished equilibrium population (Haddon, 2011; Haddon and Helidoniotis, 2013; (Figure 21). The key equations are listed in equations (9) to (12).

To ensure that the growth curve itself did not greatly alter the outcomes, it was determined early in the project that the unfished length frequency distribution predicted by the inverse logistic be consistent with the Gompertz model, at least over the range 52 – 162mm.

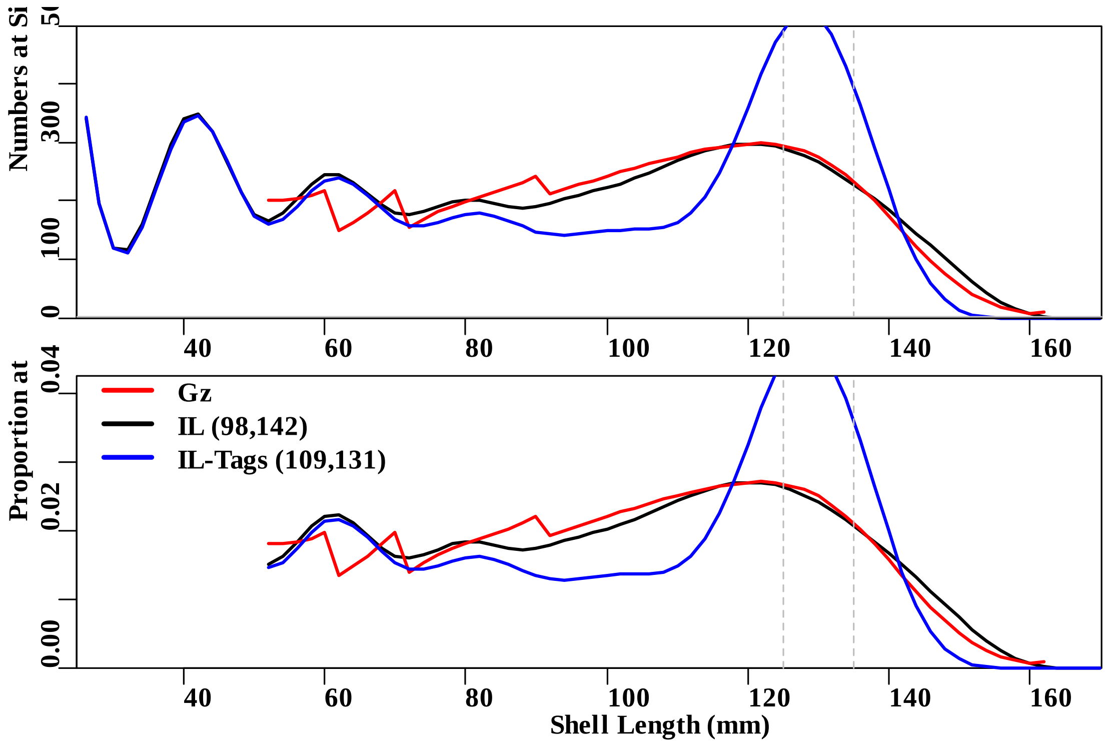

Figure 21. The unfished equilibrium size structure from the Bardos-modelling Gompertz transition matrix (red line), plus an Inverse Logistic model with parameters selected to closely mimic the outcome of the Bardos modelling (black line; MaxΔL = 19.6747, L50 = 98, L95 = 142, and MaxSig = 4). Finally, the IL model derived from fitting to the 19 tagging data points (blue line; MaxΔL = 19.6747, L50 = 109, L95 = 131, and MaxSig = 4. The two vertical dashed lines are at 125 and 135mm to reflect the two recent LMLs. Here the outcome of the Gompertz model does not take into account the correct weighted distribution of new recruits into the 52 mm size class. As such this resulted in the jagged lines for size classes <100m (this was an oversight) however for the remainder of the size classes the Inverse logistic (98, 142) is reasonably consistent with the Gompertz for >100mm size classes

Each size transition matrix resulted in differences in the unfished length frequency distribution. Whether this difference is important will be further explored by comparing to observed length frequency distributions. Nevertheless it does indicate that the average growth described by the two transition matrices does not describe all growth characters expressed at the length frequency data at the Crags reefcode (Figure 17). The length frequency data (between 2009-2011) appears to imply that growth is more rapid that the analyses suggest thus far. By examining the site names in the 'OldReefCode' 3TC, which includes among its locations sites declared as 'The Craggs', the analyses so far) appear to be based upon data from five SiteNames and these may not be fully representative of the fishery at the Crags: Inside Craggs (old site ID=362, new site ID=129), McKenzie Crags (old site ID=51, new site ID=130), Outside Craggs (old site ID=360, new site ID=132), The Craggs (old site ID=134, new site ID=131, and The Craggs inside (old site ID=361, new site ID=133).

It soon became apparent that growth transition matrices based on the inverse logistic model fitted to tagging data predicted an unfished length frequency distribution that was inconsistent with observed length frequencies in the commercial catches taken from 2009 onwards (Figure 9)

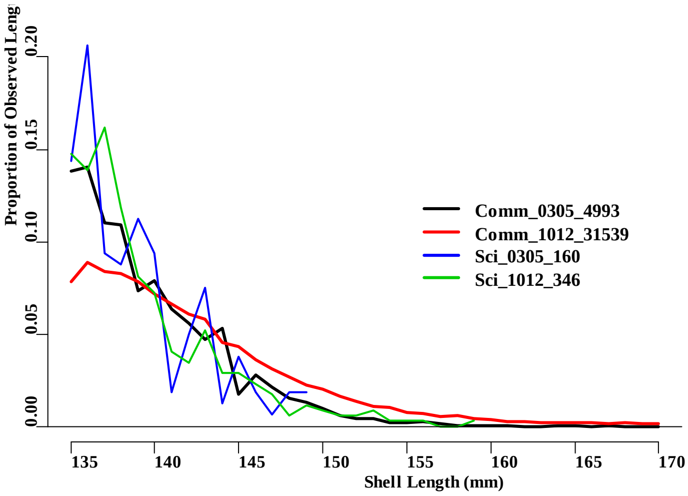

Figure 22. A comparison of the proportional distribution of lengths between 135 – 170 mm in the commercial and scientific samples from 2003 – 2005 and from 2010 – 2012. Each group of three years and scientific or commercial data were combined to form four series. The legend also contains the total sample sizes across each set of three years of data (the commercial samples being much larger than the scientific samples).

Stakeholders advised that the maximum length was still below anecdotal evidence. This meant that some alternative growth description was required. An alternative was then produced by increasing the L95 parameter, while keeping the L50 and MaxΔL stable, until growth sufficient to account for the observed size distributions was obtained.
The final parameters (Table 15) led to a much larger unfished equilibrium size distribution. By distributing plots of the expected unfished size distributions it was possible to exclude growth parameters that led to relatively small maximum sizes and a very low proportion of animals greater than 160mm in the unfished population.

Table 15. The Crags (ReefCode 3.05): Parameters for the length based inverse logistic model with parameters estimated by fitting to tag recapture data using maximum likelihood and the revised parameters following stakeholder review. The initial tagging date was 28/06/1999, the capture date was 05/07/2000 and the time at liberty was 373 days.

Origin of Parameters	MaxDL	L50	L95
Fit to raw data Tagging_data.tab	19.6747	109.4345	131.2182
Closely resembles the Gompertz curve	19.6747	98.0	142.0
Final Revision after stakeholder review	19.6747	109.4345	147.2182

Variation in growth: incorporating population specific variation within a reef code
The operating model includes a spatial scale of the biology of individual populations. A visual inspection of the Crags reefcode area and the sampling locations was provided by WADA and this enabled an approximate identification of eight nominal areas representing different types of virtual populations that, between them, may encompass the variability in the Crags reefcode (Figure 23). The MSE can accommodated any number of populations and does not need to be restricted to eight but within the current model for the Crags, eight was nominated. If the exact number of separate populations is uncertain, as in this case, then the number selected can be considered to represent population types, each with certain

characteristics different from the other types rather than identify specific locations within a reefcode.

Growth variation between populations within the Crags reefcode was incorporated by including variation to the L_{50} and L_{95} parameters of the inverse logistic growth model and having eight separate population descriptions each with somewhat different growth. In this way the operating model can include a spatial scale of the biology of individual populations.

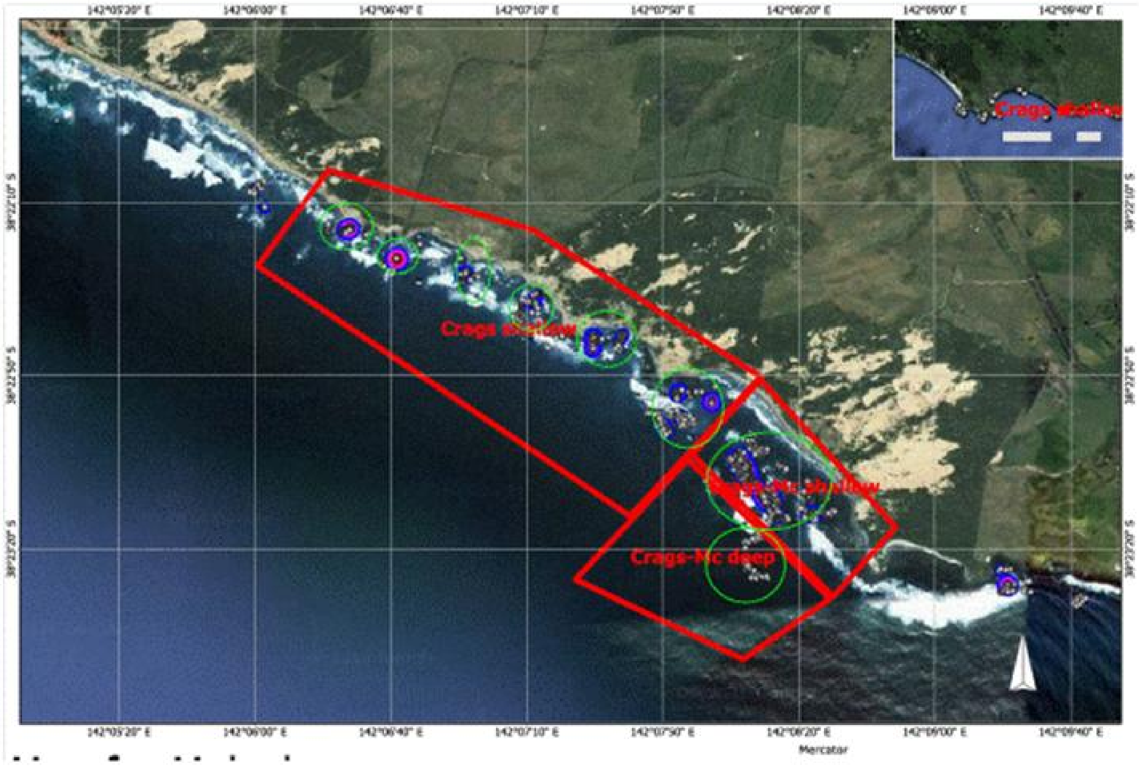

Figure 23. The Crags Reef code and the location of sampling sites (blue circles). Following a visual inpsection of the map, eight population areas were identified for the Crags enabling subdivision of the Crags Reef Code at a fine spatial scale. These eight populations are identified as green circles abd provide the means of including a wide range of variation within the single reefcode.

For each population a set of life history parameters was generated for each of the eight population areas across the reef code. The life history set for each population consisted of:

Required Population Parameters = [$g1$, $g2$, l_m, m, a, R_0]

where: $g1$ and $g2$ = two growth parameters, l_m = maturity, m = natural mortality, a = weight at length parameter, R_0= recruitment. Uncertainty is represented by allowing a range of reasonably alternative models or hypotheses and this can be captured by placing probability distributions and conditional probabilities around parameter estimates.

Variation in growth: unfished equilibrium size distribution

While the growth parameters are consistent with recent observed length frequencies, and also consistent with stakeholder memories of early size distributions from relatively unfished stocks, it has not been fitted to data and so remains uncertain. This is another reason why the observed length frequencies in any catch may provide an indication of how well the stock is recovering. At the same time it should provide an indication of how well (or how poorly) the growth has been described.

Eight populations were used in the simulations of the Crags reefcode and each had a different growth parameters, which when combined led to an unfished equilibrium size distribution which approximated stakeholder intuitions about the historical sizes observed (Figure 24).

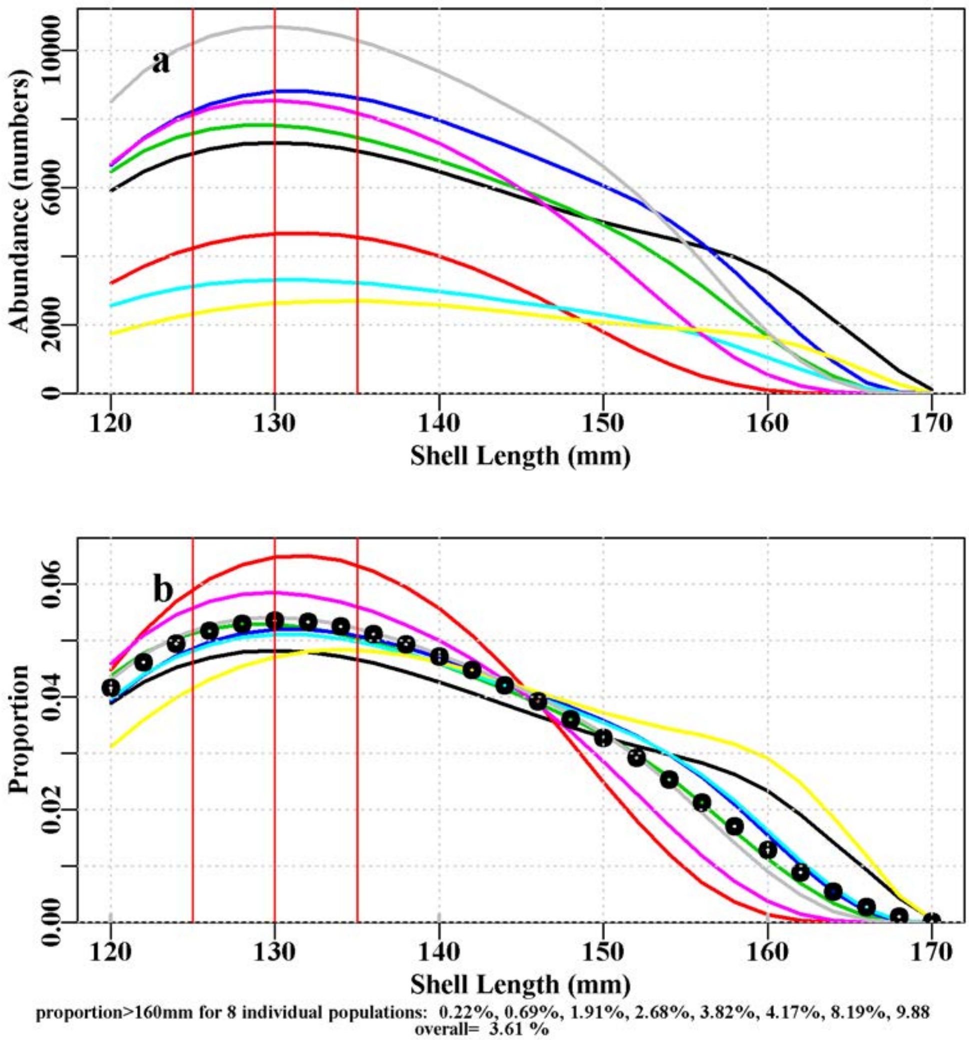

Figure 24. The unfished length frequency distributions of 8 virtual populations that attempt to capture the fine scale variability within the CRAGs (Reef Code 3.05). Plot **a** shows the expected unfished relative abundance by size to illustrate that each population has a different overall abundance and contributed to the total accordingly. In plot **b**, the dotted curve is the unfished size distribution of the 8 populations combined (i.e the sum of the separate abundances in plot **a**). Only the unfished size distributions of emergent abalone above 120mm are shown, which was the LML setting for that region according to data from the years 2003-2006. The vertical red lines at 125 mm and 135 mm indicate the other LML used (125: between 2003 – 2008; 135 mm between 2009 – present). The vertical line at 130mm is approximately the modal size class of the 8 populations combined. The proportion of the abundance above 160mm is calculated for each population because this was one metric that formed part of the basis of stakeholder decisions on the selection of suitable growth curves.

6.6.2 Maturity and Emergence

There were no direct data on size at maturity (the Gorfine et al, 2008 report refers to a survey by 'Dixon, unpublished') and the file 18_Sites.xls contained the maturity ogive parameters for an array of reefcodes. In the Bardos model both size-at-maturity and size-at-emergence are described by equivalent logistic equations:

Maturity:
$$f_L = \left(1 + \exp\left(-\ln\left(19\right)\left(L - L_{50}^{mat}\right) / \phi^{mat}\right)\right)^{-1} \tag{4}$$

Where the parameters are the same except that L_{50}^{mat} is the size at 50% maturity at length L, and ϕ^{mat} is the central 95% spread for the maturity ogive.

Emergence:
$$\alpha_l = \left(1 + \exp\left(-\ln\left(19\right)\left(l - l_{50}\right) / \phi\right)\right)^{-1} \tag{5}$$

Where l is length or size, l_{50} is the size at 50% emergence, and ϕ is the distance between the 2.5th and 97.5th percentiles (the central 95% spread around the l_{50}).

While there are different terms for the 50% size and central 95% spread, and L_{50} is one of the estimated parameters in the Bardos model, under the emergence section it is stated: "It is assumed that emergence typically coincides with maturity …" (Gorfine et al., 2008, p 11). However, under maturity it states that for the centre and width parameters l_{50}^{mat} and ϕ^{mat}: "Values for these parameters employed for each reef were derived from the closest analogous reef examined in the maturity survey data of Dixon (unpublished)." (Gorfine et al., 2008, p 11). This was confusing because although the maturity survey data indicated l_{50}^{mat} and ϕ^{mat} parameters for the Crags of 102.3mm and 27.738mm, in the report the estimate of l_{50} for emergence was given as 117mm for the lower IUU scenario and 118mm for the higher IUU scenario. While there is potential for confusion in practice it would appear that the two l^{50} parameters were not taken to be the same but 102.3 was used for the maturity ogive.

An alternative maturity curve, used in the current modelling is described by:

$$f_L = \frac{\exp(a + bL)}{\left(1 + \exp(a + bL)\right)} e^{N(0,\sigma)} \tag{6}$$

Where a and b are the parameters generating the logistic curve; one advantage of this form is that the size at which 50% of the population are maturity is estimated as $-a/b$.

The data and description of the size at maturity for these abalone stocks is also important as providing a guide as to what would constitute an appropriate Legal Minimum Length (LML). If the size at maturity data mentioned in Gorfine et al. (2008) can be obtained this would continue to be a useful resource for the management of these stocks.

6.6.3 Maturity at Size

In the Bardos modelling (Gorfine et al, 2008) a particular equation was used to describe the proportion of the population at size which would be expected to be mature. To avoid having to change the MSE simulation model, which uses a slightly different formulation, compare equations (4) and (6), new parameters that gave rise to an equivalent curve to that previously defined were identified (**Figure 25**). The parameters that were fitted to equation (4) in the Bardos modelling were $L50^{Mat}$ = 102.3 and ϕ = 27.738, whilst the two alternative parameters were a = -11, and the b = -a/102.3.

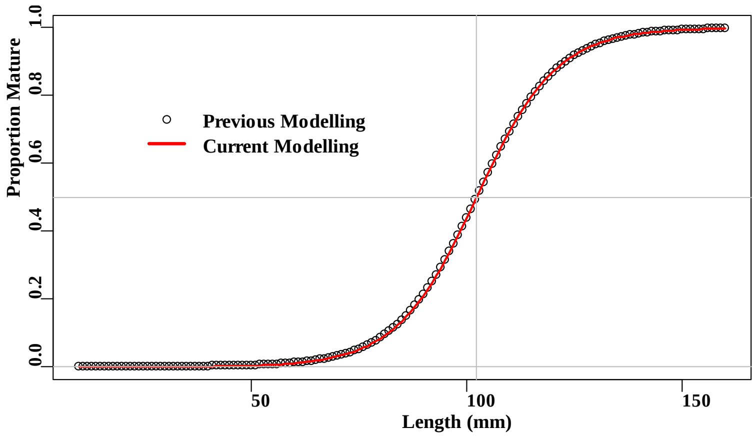

Figure 25. Comparison of the logistic curve used in the Bardos modelling (the open circles; $L50^{Mat}$ = 102.3, ϕ = 27.738) with the equation used in the simulation model, which required different parameters (red line; a = -11, b = -a/102.3). The L_{50} is indicated by the crossed grey lines.

Variation in maturity

The parameters of the western zone were provided by DPI and a plot of these show the variability in the western zone

Table 16. estimated parameters for size at maturity for the western zone provided by DPI in 18_Sites.xls file. The equations used to calculate proportion mature is given in equation (4)

Reefcode	Site.Name	Region	L50	phi
1.02	Whites	Portland	89.9	15.008
1.03	Water Springs	Portland	95.93	15.83
1.05	The Tits	Portland	95.93	15.83
1.07	Seal Caves	Portland	95.93	15.83
1.08	Horseshoe	Portland	95.93	15.83
2.01	Murrells	Portland	92.5	22.512
2.02	Jones Bay	Portland	95.93	15.83
2.04	Devils Kitchen	Portland	95.93	15.83
2.05	Inside Nelson	Portland	95.9	12.328
2.06	Killer Waves	Portland	95.9	12.328
2.09	Passage	Portland	102.3	16.75
3.02	Julia Percy - Northeast Reef	Pt Fairy	90.7	15.41
3.03	Julia Percy - East Side	Pt Fairy	90.7	15.41
3.04	Julia Percy - Prop Bay	Pt Fairy	90.7	15.41
3.05	The Craggs	Pt Fairy	102.3	27.738
3.08	Lighthouse Reef	Pt Fairy	94.4	26.934
3.09	Mills	Pt Fairy	89.5	8.174
3.11	The Cutting	Pt Fairy	95.04	20.368

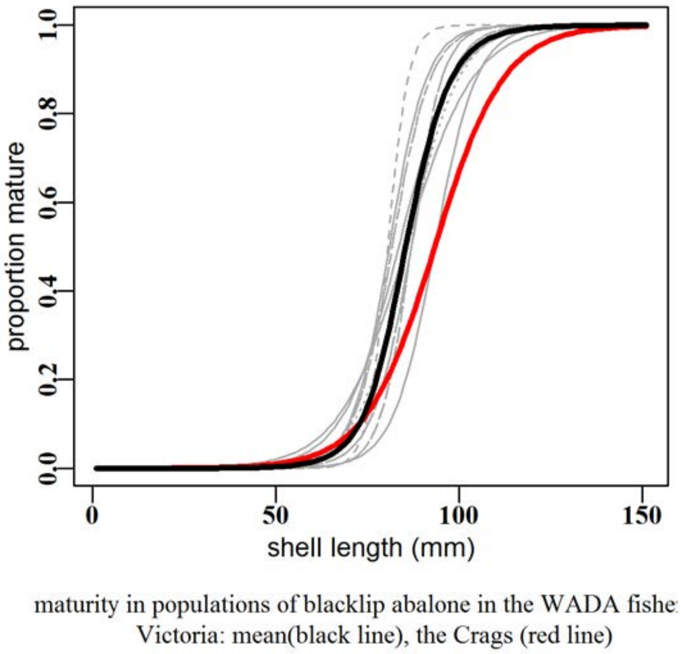

Figure 26. Proportion mature in the western zone showing the total variability in the western zone. The grey lines show the proportion mature for each of the individual 18 sites in the western zone. Parameters are provided in Table 16. The black line is the mean for the western zone and the red line is the Crags.

Variation in the western zone was used to assign variation to the Crags. The suggestion was to add the variation exhibited in the western zone to the Crags reefcode while maintaining the 50% size at maturity specific to the Crags reefcode. By observing the range of uncertainties in Figure 26 it was possible to determine parameter distributions for the Crags
The mean size at 50% maturity (SM_{50}) for the Crags remained at 102 mm which was estimated from Figure 25. In order to account for variability, the parameters from the western zone were used to estimate a similar range of trajectories for the Crags except with an SM_{50} of 102mm and a standard deviation of 2 (normal distribution). Uncertainty was also applied to the slope parameter (a) (mean= -15, standard deviation = 2.3, normal distribution)

In R code:

```
SM50= rnorm(L50a, 2),
 a<- rnorm(-15, 2.3)
 b<--a/L50b
```

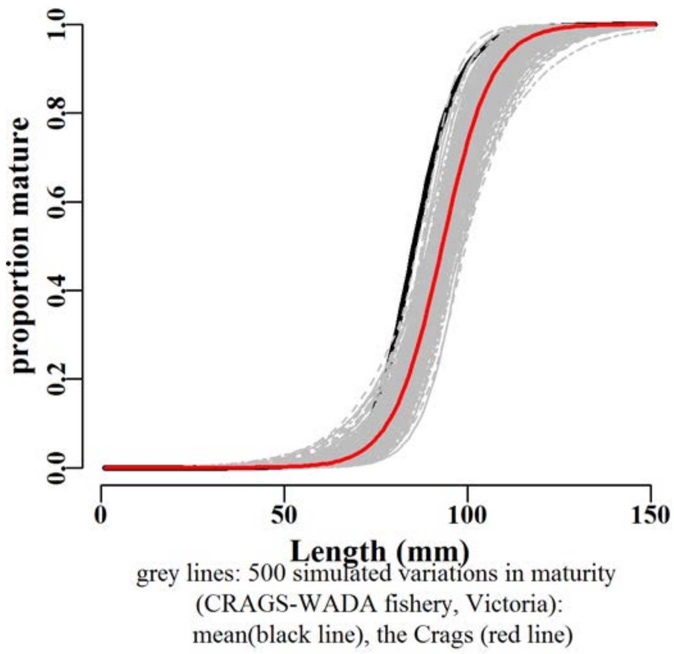

Figure 27. Simulated data in generating trajectories in proportion mature in the Crags. The grey lines show the proportion mature for each run of the simulation. The black line is the mean for the western zone and the red line is the parameters for the Crags provided by DPI.

6.6.4 Weight at Length

In a size-based model, to convert a size distribution to a measure of mass requires a length to whole weight relationship. This typically takes a power relationship of the form:

$$Wt_L = aL^b e^{\varepsilon} \tag{7}$$

Where the two parameters *a* and *b* relate length to weight; the expected residual error structure is log-normal. This means that this relationship can be fitted to log-transformed length and weight data by using simple linear regression (Figure 28).

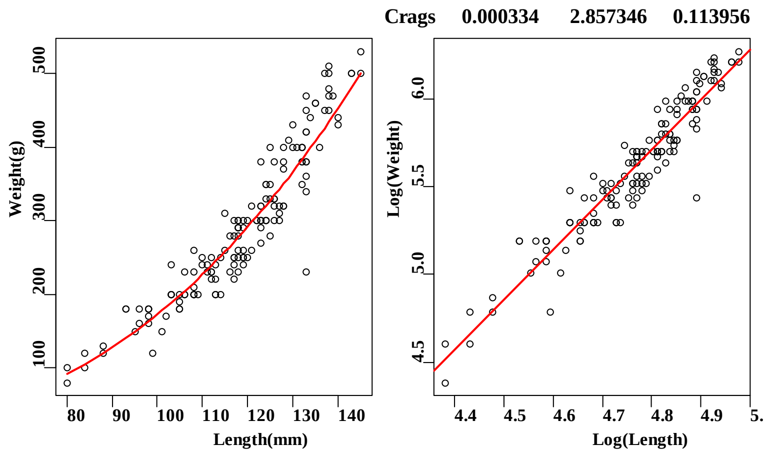

Figure 28. An example of a weight at length relationship; in this case for the Crags reefcode, which has an intercept of 0.00033, a gradient of 2.857, and a standard deviation around those mean values of 0.114.

Table 17. The weight at length relationships for the various reef codes for which data was provided across Western Victoria. The intercept and gradient relate to the *a* and *b* in equation (7)

Site_name	Latitude	Longitude	Intercept(*a*)	Gradient(*b*)	Sigma
Blowholes_Depth	-38.3807	141.3655	0.0000597	3.2073	0.1285
Blowholes_Depth	-38.3842	141.3690	0.0000544	3.2164	0.1106
Murrels	-38.4100	141.5174	0.0000925	3.1186	0.1093
Jones_Bay_Depth	-38.4201	141.5235	0.0000609	3.2053	0.1019
Outside_Nelson	-38.4284	141.5334	0.0000974	3.1044	0.1213
Devils_Kitchen	-38.4274	141.5551	0.0003586	2.8424	0.1480
Julia_Percy_Island_Prop_Bay	-38.4200	141.9944	0.0001967	2.9843	0.1116
Julia_Percy_Island_East_Side	-38.4244	142.0016	0.0001390	3.0459	0.1273
Julia_Percy_Island_North	-38.4113	142.0118	0.0001978	2.9856	0.1422
Crags	-38.3874	142.1393	0.0003338	2.8573	0.1140
Burnet's	-38.3936	142.1498	0.0000724	3.1905	0.1064
Water_Tower_Pig_Smith	-38.3959	142.1919	0.0001125	3.0757	0.0961
Water_Tower_Drain_Bay	-38.3935	142.1832	0.0001057	3.0901	0.1192
Water_Tower	-38.3953	142.2123	0.0000619	3.1957	0.2132
Lighthouse_Reef	-38.3951	142.2517	0.0003701	2.8468	0.1023
Mills	-38.3654	142.2996	0.0000805	3.1510	0.1267
Killarney	-38.3616	142.3271	0.0003168	2.8792	0.1056

To provide variation amongst populations it was found, during the development of the original MSE simulation model framework (Haddon and Helidoniotis, 2013), that there was a relationship between the *a* and the *b* parameters for the weight at length relationship (**Figure 29**).

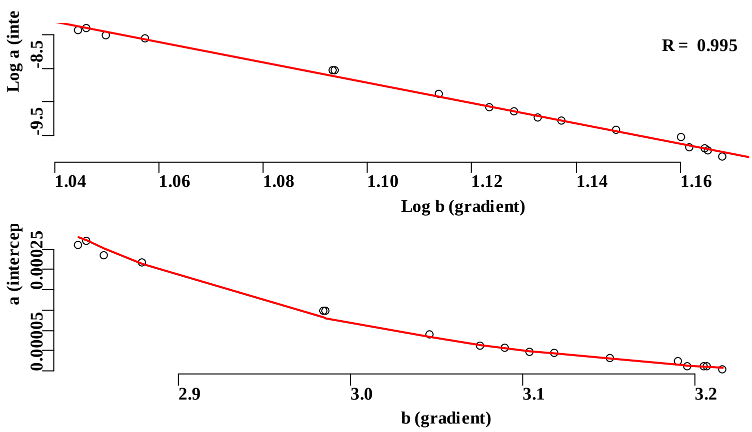

Figure 29. The relationship between the *a* and *b* parameters from the 17 sites from western Victoria with data available. The power function depicted in the lower panel has parameters *a* = 2916.018 and *b* = -15.174. Given a randomly picked value of *b* this relationship can be used to predict the corresponding *a* parameter value.

6.7 Incorporating Uncertainty in the operating model

Using the available empirical data, selections of biological parameters and their probability density distributions were made; in this work, the distributions were characterized as either normal or log-normal.

Simple linear and non-linear relationships between estimated parameters from an array of populations and these relationships can then be used to produce combinations of related parameters in equations describing processes such as growth, size at maturity, and size at emergence. Thus, for example, in Tasmania, it was only necessary to select two out of the three parameters describing growth in each population because there was a tightly fitting linear surface relationship found between the three growth parameters of the inverse logistic model across the 27 populations studied for growth characteristics (Helidoniotis et al 2011). In an analogous fashion, there was a tightly fitting logarithmic relationship between the two parameters describing the weight at length relationship for 17 separate populations (Figure 29), which could be used to simplify the allocation of this biological property to each simulated population.

Not only were there relationships between the parameters of curves describing particular biological properties but there were also relationships between the various biological properties within populations. For example, populations that have a smaller size at maturity also have a smaller maximum length and often a lower weight to shell length relationship (FRDC Project No 2007/020). These variables all have an influence on the relative productivity of different populations. Using these relationships simplified the conditioning of the simulation framework onto a particular quota zone or reefcode using the data available in Western Victoria. The equations describing the dynamics and the supporting equations describing growth, size at maturity, weight at length, selectivity, size at emergence and other processes affecting the biology and fishery for each population are detailed in the Appendix.

1.1.1 Parameters and their probability distributions

Two of the growth parameters of the inverse logistic (i.e the L_{50} and the L_{95}) are sampled from a joint probability distribution where $L_{95} = L_{50}$ +constant each having a normal distribution and an independant standard deviation (s.d). The parameters ($Max\Delta L$ and L_{50}) were determined by fitting an inverse logistic model to the tagging data and a second dataset was generated by estimating the length increments from a previously developed size transition matrix (Gorfine et al. 2008). The *L95* was related to the *L50* using the simple relationship $L95 = L50 + constant + \varepsilon$. The 'constant' was determined using input from stakeholders advice because initially the *L95* obtained from the available tagging data led to an unfished size frequency distribution which was considered to be implausibly small by stakeholders with experience in the fishery in its very early days. After deliberations with stakeholders the growth parameters included in the operating model were:

$Max\Delta L = \mathbf{N}(19.6747, 1.25)$ normal distribution
$L50 = \mathbf{N}(109.4345, 2.0)$ normal distribution
$L95 = L50 + \mathbf{N}(37.7837, 4.0)$ normal distribution
$SigMax = \mathbf{N}(4.75, 0.09)$

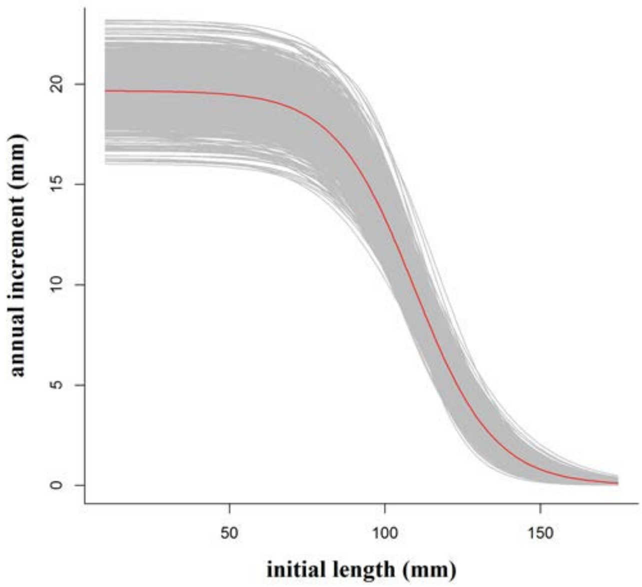

Figure 30. The trajectory of the inverse logistic model for the parameters and their variability [($Max\Delta L$ = **N**(19.6747, 1.25) normal distribution, *L50* = **N** (109.4345, 2.0) normal distribution, *L95* = *L50* + **N** (37.7837, 4.0) normal distribution , *SigMax* = **N**(4.75, 0.09)]. These parameters were used randomly in the size transition matrix within the modelling framework.

The maturity parameter is was similar to that used in the Gorfine (*et al* 2008):

SaMb = -*SaMa*/*Maturity_L50*
SaMa = N(-15.0,2.3) normal distribution
Maturity_L50 = **N**(102.0,2.0) normal distribution

The emergence was considered to coincide with size at which 50% of the population was mature (SM_{50}) and in the previous modelling SM_{50} = 102.5 (Gorfine et al. 2008) therefore the $L50_c$ parmater in emergence = 102.5 and *L95c* = 112.5

Emergence_L50 = **N**(102.5, 0.5) normal distribution
Emergence_L95 = **N**(112.5, 1) normal distribution

Weight to length relationship is independently drawn from a normal distribution

Wt_lgth_b = **N**(2.8573, 0.1140) normal distribution
Wt_lgth_a = *pWtbtoa* x *Wtb*^-15.173802

where *Wtbtoa* = **N**(2916.018,-15.173802) normal distribution.

Recruitment is random recruitment deviate generated from a lognormal distribution. All recrutiment is into the 2mm size class and recruitment is stochastic around a Beverton Holt stock recruitment curve:

Recruitment = **N**(11.11, 0.5) lognormal distribution

Stock recruitment using Beverton Holt function consist of the steepness parameter drawn from a normal distribution

steepness = $\mathbf{N}(0.5, 0.02)$ normal distribution

Natural mortality is constant across all length classes and is similar for both cryptic and emergent abalone. It is sampled from a normal probability distribution independent of any other parameters

Mortality = $\mathbf{N}(0.2, 0.001)$ normal distribution

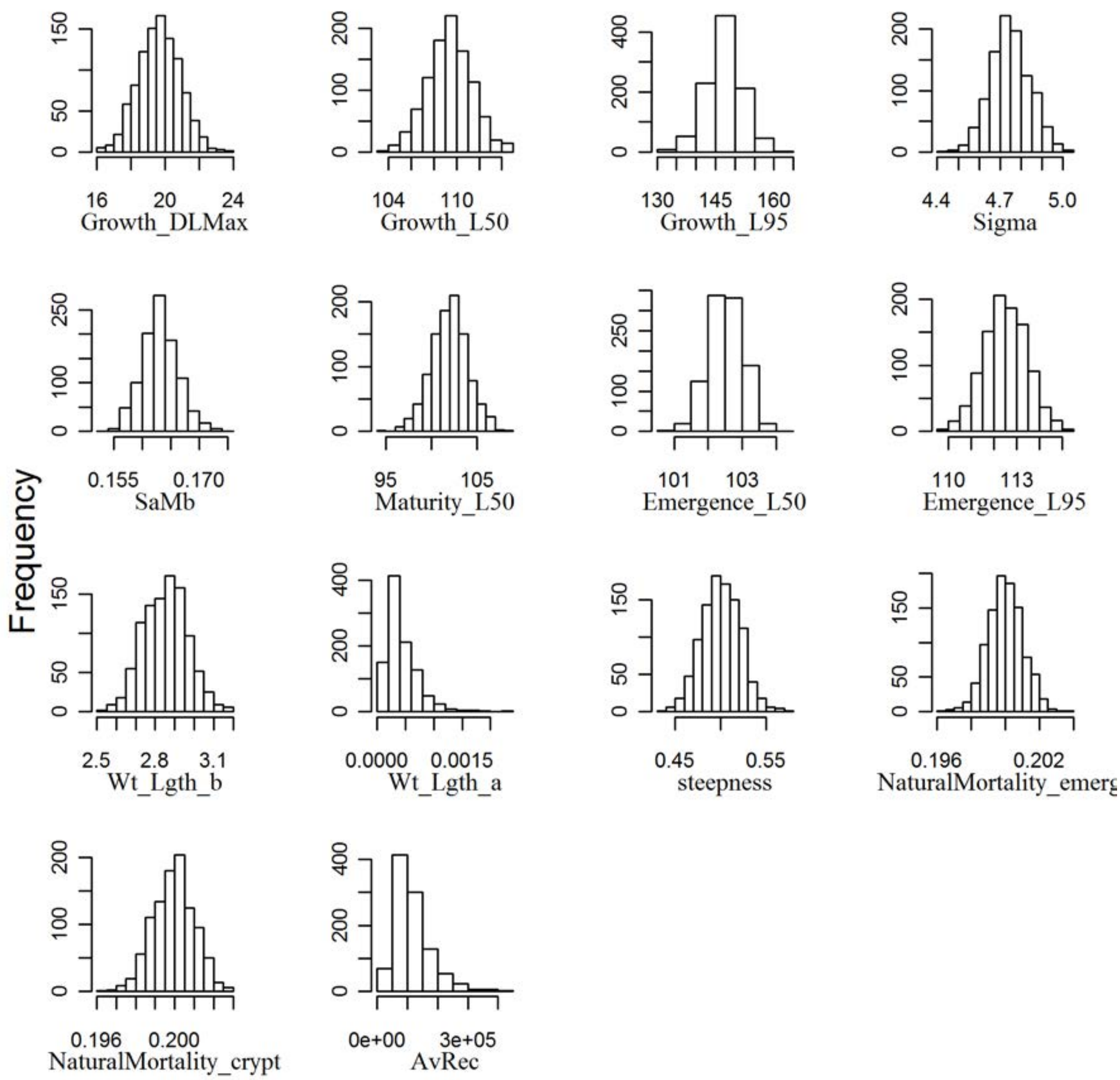

Figure 31. Parameter distributions for 14 different biological properties indicating the range of uncertainty and variation between populations.

6.8 Conditioning on Historical Catches: stock reduction analysis

6.8.1 Introduction

In order for the simulated stock dynamics for the selected reefcodes to be at least consistent with the observed properties of the stock the operating model needs to also be conditioning the productivity of the modelled stock on the historical catches. This means the simulations should at least reflect of the productivity of the reefcode prior to the viral outbreak. As explained below, conditioning the productivity on the historical catches has some similarities to fitting the model to the available data

6.8.2 Using the Historical Catches

The productivity or production of biomass in the simulated reefcode stock is determined by the growth characteristics and natural mortality combined with the levels of recruitment.

$$B_{t+1} = B_t + G - M - C + R \qquad (8)$$

where B_t is the stock biomass at time t, G represents increases in biomass through growth processes, M and C represent losses to biomass through natural mortality events and through fishing mortality or catch. Finally, R represents increases in biomass through the recruitment of new individuals into the population. While this is a gross simplification it does capture the essential processes involved.

In order to condition on the historical catches a so-called stock reduction is used where we assume that before the fishery the stock was in an unfished equilibrium state and we have assumed three potential states of spawning biomass depletion prior to the viral outbreak (20%B_0, 25%B_0, and 30%B_0). Given these assumed 2006 depletion levels, along with assumed characteristics for natural mortality, growth, and recruitment, it is possible to use the operating model dynamics to sequentially remove the time series of total catches (while applying growth, recruitment, and natural mortality, each with their own sources of variation; see the operating model description for details). This allows the appropriate average recruitment level to be selected that leads to the median outcome being the selected depletion level after the full time series of catches from 1965 – 2006 have been removed (Table 18; Figure 32).

Table 18. Historical catches time series from the Crags reefcode along with an estimate of the proportion of IUU catches taken at the same time. These data were developed for the previous modelling work (Gorfine *et al*, 2009). QYear is the abalone quota year (1st April – 31st March), the IUU Low series was used (baseline IUU). The Total column is the Crags catches plus the matched proportion of those catches C * (1+IUU).

QYear	Crags	IUU	Total	QYear	Crags	IUU	Total	QYear	Crags	IUU	Total
1965	3.789	0.8	6.820	1979	26.984	0.18	31.841	1993	33.785	0.05	35.474
1966	10.283	0.8	18.510	1980	40.306	0.17	47.158	1994	31.285	0.05	32.850
1967	16.778	0.8	30.201	1981	46.091	0.16	53.465	1995	31.844	0.05	33.436
1968	39.104	0.8	70.387	1982	27.665	0.15	31.814	1996	43.924	0.05	46.120
1969	61.430	0.8	110.574	1983	33.914	0.14	38.662	1997	25.615	0.05	26.896
1970	37.551	0.75	65.713	1984	38.840	0.13	43.889	1998	39.494	0.05	41.469
1971	35.168	0.5	52.753	1985	33.745	0.12	37.794	1999	30.314	0.05	31.829
1972	52.603	0.25	65.754	1986	22.898	0.11	25.416	2000	26.313	0.05	27.629

1973	46.886	0.24	58.138	1987	42.718	0.1	46.990	2001	32.573	0.05	34.201
1974	45.579	0.23	56.062	1988	20.812	0.09	22.685	2002	20.615	0.05	21.646
1975	45.727	0.22	55.787	1989	17.410	0.08	18.803	2003	22.930	0.05	24.077
1976	40.992	0.21	49.600	1990	26.337	0.07	28.181	2004	26.138	0.05	27.445
1977	38.823	0.2	46.587	1991	43.329	0.06	45.929	2005	23.607	0.05	24.787
1978	24.445	0.19	29.089	1992	34.800	0.05	36.540	2006	10.983	0.05	11.532

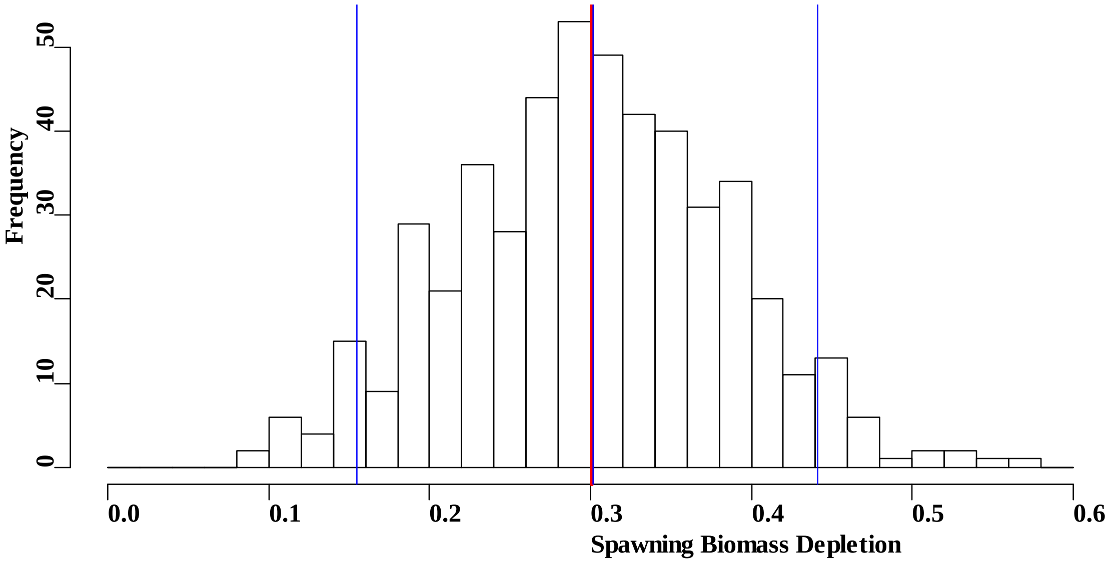

Figure 32. Simulated frequency distribution of the spawning biomass depletion level following a stock reduction analysis using the total catches from the Crags reefcode abalone fishery from an unfished state obtained by applying catches from 1965 – 2006. The average recruitment level was fitted on the criteria that the average and median expected biomass depletion level would approximate 30% of the unfished equilibrium state. The red line is the average (30.012%) while the fine blue lines are the median (30.142%) and 90% intervals (15.5 – 44.1%).

To find the average population recruitment level that leads to the median approximating the required depletion level (e.g. 30% in Figure 32), requires that average level to be searched for numerically. This is why this part of the conditioning is in fact a crude fitting process. Nevertheless, the variation possible due to recruitment and other sources of variation is very high, and the final average depletion is an assumed scenario level, so this should not be confused with formal stock assessment model fitting.

Use of this stock reduction analysis meant that for each scenario of initial depletion selected the appropriate stock productivity could also be used. The average recruitment doesn't alter very much and yet has a large effect on the average depletion level in 2006 (Table 19). This is because the average recruitment is the natural log of average recruitment so small changes can imply large differences. Also, the maximum productivity (Maximum Sustainable Yield) of the populations in the simulated reefcode is at a depletion level somewhere between 31 – 35%, so any value below that level is very prone to rapid reductions in stock size if catches are greater than the surplus production. The productivity of the fishery decline as expected between the years1964 – 2006 (Figure 33).

Table 19. The average recruitment required to generate an average initial depletion.

Initial Depletion	Average Recruitment
20%	11.06
25%	11.11
30%	11.16

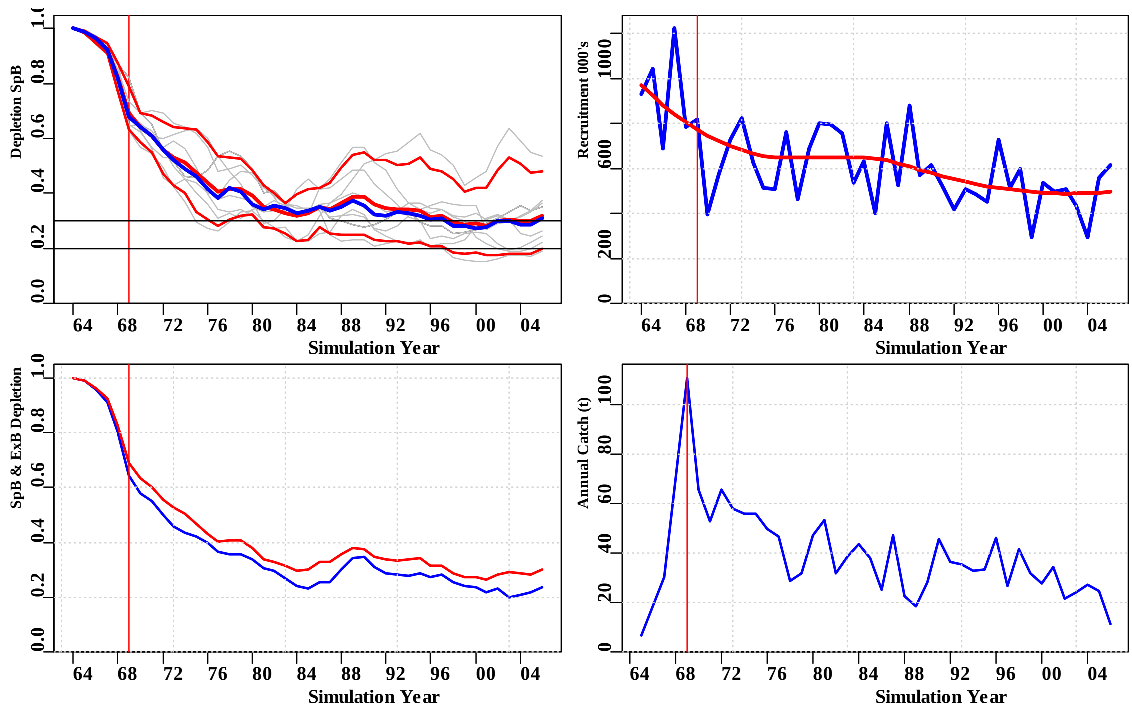

Figure 33. A typical stock reduction using the Crags simulation starting with catches from 1965. Top left is the spawning biomass depletion level of the eight representative populations (grey lines), with their average and the median with 90% intervals. Top right is the recruitment with the long term trend and expected recruitment declines with the decline in spawning biomass. Bottom left is the expected depletion of both the spawning and exploitable biomass relative to an unfished state, and bottom right is the catch history used (from Gorfine et al, 2008)., which includes some IUU catches (see Table 18). The vertical red line identifies the peak catch.

6.9 Unfished equilibrium biomass and numbers at size

When simulating fishing the abundance within each size class for each year of the simulation was estimated using the size transition matrix, adjusted by natural mortality for the cryptic population and then both natural and fishing mortality for the emergent population. For the emergent population, mortality was applied in such a way that half the natural mortality was applied in the first half of the year, followed by growth and then full fishing mortality, finally the other half of the natural mortality is applied. Recruitment was only added to the 2mm size class of the cryptic population. By assuming that the population above the LML of 125 mm and 135 mm is fully selected it is possible to compare the expected proportion at size in the population with the proportion at size in the observed catches.

In each of the populations making up the reefcode, given constant growth, described by a transition matrix, **G**, constant recruitment, **R**, defined as R_0, and constant natural mortality, $\mathbf{C_S}$ and $\mathbf{O_S}$, which are each the survivorship from half the natural mortality for the cryptic and emergent components respectively, and by definition there is no fishing morality, then at equilibrium the cryptic component of an unfished population, $\mathbf{N^{C*}}$, is defined as:

$$\mathbf{N}^{\mathbf{C}*} = \left(\mathbf{I} - \left[\mathbf{C}_{\mathrm{S}}\mathbf{G}\mathbf{C}_{\mathrm{S}}\left(\mathbf{I} - \mathbf{E}\right)\right]\right)^{-1}\mathbf{R} \tag{9}$$

where **I** is a unit matrix and **E** is the logistic description of emergence from crypsis to emergence. Consequently, the equilibrium number of emergent abalone, $\mathbf{N}^{\mathbf{E}*}$, in an unfished population is:

$$\mathbf{N}^{\mathbf{E}*} = \left(\mathbf{I} - \mathbf{O}_{\mathrm{S}}\mathbf{G}\mathbf{O}_{\mathrm{S}}\right)^{-1}\mathbf{O}_{\mathrm{S}}\mathbf{G}\mathbf{O}_{\mathrm{S}}\mathbf{E}\mathbf{N}^{\mathbf{C}*} \tag{10}$$

Recruitment, **R**, is described using a vector with all new recruits allocated to the first size class and all other size classes being set to zero (size classes from 2 – 172 mm in 85 size classes of 2mm). A Beverton-Holt stock recruitment relationship was assumed, whose *a* and *b* parameters were re-structured in terms of steepness, *h*, unfished mature biomass B_0^{Sp} , and the average unfished recruitment level, R_0:

$$a = \frac{4hR_0}{5h-1} \qquad \text{and} \qquad b = \frac{B_0^{Sp}(1-h)}{5h-1} \tag{11}$$

Using this re-parameterization the Beverton-Holt relationship becomes:

$$R_{t+1} = \frac{4hR_0B_t^{Sp}}{\left(1-h\right)B_0^{Sp} + \left(5h-1\right)B_t^{Sp}}e^{\varepsilon - \sigma_R^2/2}, \qquad \varepsilon = N\left(0,\sigma_R^2\right) \tag{12}$$

The residual error distribution around the expected recruitment is log-normal; σ_R is the standard deviation of the natural logarithm of the recruitment residuals, the $-\sigma_R^2/2$ is a bias correction term that ensures that the time series of estimated recruitments relates to the mean rather than the median recruitment level (Hastings & Peacock, 1975). If the σ_R term is set as a very small number the recruitment will be effectively deterministic (Haddon and Helidoniotis, 2013).

Calculating the mature or spawning biomass requires the number at size (from equations (9) and (10), the weight at length, and the size at maturity; equations (5) and (4). The weight at length is described by a power relationship:

$$W_L = aL^b e^{N(0,\sigma)} \tag{13}$$

where W_L is the weight at length *L*, The parameters *a* and *b* describe the power relationships between length and weight, and exp(N(0,σ) is log-normal variation. These are combined to produce the spawning biomass at time *t*:

$$B_t^{Sp} = \sum_{L=2}^{172}\left(N_{t,L}^{E}W_L f_L + N_{t,L}^{C} f_L\right) \tag{14}$$

6.10 Simulations

6.10.1 Conditioning the Simulation Framework

Following is a description of the general characteristics of the model conditioning; the mathematical specification of the model is presented in the Appendix and Haddon and Helidoniotis (2013). The operating model is the part of the simulation framework that attempts to mimic the underlying dynamics of the fished abalone stock that is being examined. There are other parts that mimic the fishery imposed on the stock, and others that generate the simulated data that might typically be gathered from a fishery. For the underlying dynamics to appropriately reflect the fishery or part of a fishery under study the operating model needs to be conditioned on the biological properties of abalone from the area of interest. The simulation model being used was developed mostly using the east coast of Tasmania as an example stock (and the west coast, to a lesser extent). While the underlying equations describing the population dynamics remain the same the description of the size at maturity, growth, weight at length, size at emergence, and related biological properties, especially those that influence the biological productivity, need to be altered to be based on populations found in the vicinity of the Victorian Crags reefcode.

The conditioning involved estimating or searching out previously estimated values for model parameters to describe the growth, the size at maturity, and the productivity of the Crags. Achieving this conditioning in the short time frame available to prepare the model and conduct the simulations was only possible when all available empirical data, whether from commercial or non-commercial sources, was used where necessary to obtain the necessary parameters (Table 20). However, the previous modelling study (Gorfine et al, (2008), had also left an array of data files and model input files, and so in addition to using available empirical data it was possible to search those model related files, using the report as a guide (Gorfine et al (2008), to identify the appropriate parameter estimates that were already available. For example, raw data on maturity at length were not available and estimates reported from a "Dixon (unpublished) study" (Gorfine et al, 2008, Appendix page 11) were used to generate the size at maturity curve instead. This was especially important as the size at maturity is, obviously, very influential on the amount of mature or spawning biomass when combined with numbers at length and the outcome of the modelling is sensitive to these parameter values (if possible, It would be advantageous to future work to source the original raw data and use that to estimate paremters and variability).

Table 20. Parameters of the operating model conditioned on available data sources. The operating model is a four parameter model consisting of MaxDL, L50, L95, σ, B_0, steepness (recruitment excluded), i.e

Symbol	Value	Variation	Description
Indices			
s	1 – 8		Number of populations assumed to represent variation at the Crags
L	2, 4, …, 170 mm		Size classes (85 two mm)
t	1, 2, …, 31=2006 - 2036		simulation year ≡ 1 - 31
c	2, 4, … emergence curve		cryptic population: size classes
e	Emergence curve,…, 170		emergent population: size classes
Parameter			
M	0.2	0.001; N	Natural Mortality (cryptic and emergent)
h	0.5	0.02; N	Steepness (recruitment dynamics)
MaxDL	19.6747	1.25; N	Growth, IL model
L50	109.4345	2.0; N	Growth, IL model
L95	147.2182	4.0; N	Growth, IL model; Base Case
SigMax	4.75	0.09; N	Growth, IL model
SaMa	-15	2.3; N	Size at Maturity
L50mat	102.0	2.0; N	Size at Maturity
SaMb	$-a/L50mat_s$		Size at Maturity (per population
Wtb_L	2.8573	0.114; N	Length to weight
$Wtbtoa_L$:a	2916.018		Translate Wtb_L to *a* intercept
$Wtbtoa_L$:b	-15.173802		Translate Wtb_L to *a* gradient
State Variables			
AvRec	11.06	0.5; LN	Average recruitment; 20% initDepletion
AvRec	11.11	0.5; LN	Average recruitment; 25% initDepletion
AvRec	11.16	0.5; LN	Average recruitment; 30% initDepletion
LML	125		Legal Minimum Length to 2005
LML	135		Between 2009 -2014
	132		From 2014 onwards

There were multiple sources of variation within the simulations. Biological parameters and a sampling distribution were selected that were used to define probability distributions for each biological property needed to define the populations making up a simulated reefcode. By defining a random seed each simulated reefcode could either be repeated as required or be forced to be different.

Replicate scenarios were redrawn 500 times, (1 scenario = 500 replicates)
For each draw

$$N_i / \Sigma N_i = P_i = \text{proportion of each population}$$

The Crags Reef Code was subdivided into eight populations. The biological parameters for each scenario were drawn randomly from probability distributions using traditional Monte Carlo method and each time new parameter values were drawn.

The second source of variation was expressed during the dynamics of the simulations and was related to

1) Variation in Recruitment through time : *SigmaR* = 0.5
2) Variation in estimates of Exploitable biomass used in the Harvest Control Rule: *SigmaCE*=*SigmaB* = 0.11

Given a large enough number of simulations the mean values of the various model output statistics would be expected to converge towards a specific trajectories through the period of the simulations. The mean and spread of these outputs in particular years are presented and compared in the results..

It was found that 200 simulations provided a reasonable balance between the time taken to conduct the simulations and the ability to capture the full ranger= of variation expressed by the ssimulation framework. Fortunately, some input parameters were correlated to each other as listed in setion 8.2 (Conditioning the model: biological functions), in particular the growth parameter *L50* was correlated to *L95* and to size at maturity *Maturity_L50*.

After a simulation has been run, statistics can be easily obtained for all input parameters and outputs. This includes mean value, standard deviation, confidence intervals and sensitivity analysis.

6.10.2 Adding variation between simulated populations

A single rand sees is selected (one rand see for each level of depletion) and is used to simulate a zone. The selection of a single rand seed (for each level of depletion) ensures that the productivity of the simulated zone is identical between zones. The next step is to deplete the stock (initial depletion and viral mortality). Following that recruitment and the CE variation is added as well as exploitable biomass with variation between each of the 500 replicate simulations i.e a different rand-seed for each of the 500 replicates.

6.11 Scenarios Considered

When considering the dynamics of the abalone resources in Western Victoria the initial state of stock depletion on the reef-codes considered and the level of mortality imposed by the viral outbreak remain highly uncertain. To account for these uncertainties a number of scenarios were considered that encompassed the range of variables and value that typically describe stock status (Table 21). Apart from initial depletion and viral mortality these scenarios also included the harvest control rule selected; where the different constant harvest rates are treated as separate HCRs.

A base case is considered where catches are zero against which all the scenarios with positive catches can be compared. The zero catch scenario is the extreme where rebuilding would be expected to be maximized but, obviously, catches would be non-existent. Using this as a base case enables comparisons to illustrate what would be lost in terms of rebuilding time but also what would be gained in terms of catches.

With the ConstH HCR, there are six possible values (including zero), which when combined with the three initial depletion levels and two viral mortality levels lead to 36 different scenarios (Table 21). The selection of the different *H* levels related to current practice. During the May 2012 – May 2013 fishing season the harvest level was set at 0.05. During that year it was considered that the stock had recovered sufficiently to lead to a suggestion of increasing the harvest rate to 0.075, which was therefore included in the simulations. Harvest levels of 0.15 and 0.2 were included to consider the performance of the fishery if it were fished harder than currently suggested.

Table 21. In total 48 scenarios considered within the simulation framework: 1 HCR x 6 harvest rates X 3 initial depletion levels x 2 viral mortality rates (36 scenarios in total) plus 2 HCR x 3 initial depletion levels x 2 viral mortality rates (12 scenarios in total). In the ConstH HCR there were 36 scenarios in total. In the StockHarvest HCR and GradientCE HCR and initial harvest rate of 0.75 was relevant, leading to 6 scenarios, Each scenario had 500 replicates.

Description	Values
(ConstHarvest HCR) Annual harvest rate	0, 0.05, 0.075, 0.1, 0.15, 0.2
(StockHarvest and GradCE HCR) initial harvest rate	0.075
Initial spawning biomass depletion	0.2, 0.25, 0.3
Viral Mortality	0.7, 0.8

6.12 Relative plausibility of the scenario of viral mortality and depletion: Catch success

The management strategy evaluation is based upon a simulation model that has only been conditioned to be consistent with the western zone abalone fishery rather than having been formally fitted to data from that fishery. Despite this it is still possible to determine, to a limited extent, the relative likelihood of the different scenarios by comparing the predicted catches in the years 2009 – 2012 within each scenario with those observed. If the initial depletion is too low or the viral mortality too high then, given the variability included in the simulations to represent uncertainty there will be some combinations of initial depletion and viral mortality that would make obtaining the observed catches highly unlikely. By counting the number of replicates that succeed in meeting the observed catches over the period 2009 – 2012, these can be tabulated and the relative likelihood of each particular scenario being the case in reality can be assessed.

Even if a particular scenario failed to enable the observed catches to be taken in all replicates this would not mean that the particular scenario involved was not possible. Instead it would imply that, given the assumptions of the modelling, it was proportionally less likely than those scenarios (combinations of initial depletion and viral mortality) where the observed catches were possible in more replicates.

Catch Success: In the plausibility test 90% of the Exploitable biomass generated by the model is calculated for each year between 2009 – 2013. This represents the maximum predicted catches for each those years according to the model. We also know the observed catches from industry. If the observed industry catches are higher than the maximum model catches – it is registered as a fail for that modelled scenario. If the observed catches are lower than the estimated catches – it's a pass. If the estimated model generates an extremely high catch (e.g 5 times higher than the observed catches), that becomes a false positive because the biomass is too high and the model is predicting too much biomass. This would raise concerns that the MSE is bullet proof so we need to know when it just stops to fail and therefore scenarios that fail are useful.

6.13 Harvest Control Rules

The harvest cotnrole rules uses are explained in the main body of the report in the methods section

6.14 Characterizing the Performance of the Harvest Control Rules

The primary aims of this study are to examine how well the stock is expected to recover under different harvest levels. Measuring the stock and fishery performance across the various scenarios included characterizing the differences in expected catch, expected spawning biomass depletion level, and expected mean length of catch in 2020, sometimes relative to the situation in a reference year, or relative to the unfished state. The first year modelled was 2006, this meant that 2012 was year 7 and 2020 was year 15.

Aspects of the catch performance through time (the scale of catches and their variability) were characterized along with changes to the spawning biomass and the ratio of exploitable biomass to spawning biomass. The estimate of the spawning biomass through time was included in order to determine when the stock may have returned to more resilient levels. Likely catches set by the Harvest Control Rule in 2020 were examined to allow industry and government to make informed choices when planning and understanding the trade-offs between rebuilding and harvesting during the early years of recovery.
In addition the mean length and its variation were included as a means of exploring whether these might provide a workable performance measure of the initial stock recovery. Therefore, the mean lengths in 2020 relative to those in the reference year (2013) was considered as a potential fishery performance measure. Variation was characterized by tabulating the median and 90% intervals for each HCR performance measure considered.

a) The median and 90% intervals of the total catch from 2014 – 2020:

$$\sum_{y=2014}^{2020} C_y \tag{15}$$

where C_y is the reported landed catch in year y.

b) The median and 90% intervals of the average annual absolute change in catch (Average Annual Variation - AAV) from 2014 - 2020

$$\frac{100 \sum_{y=2015}^{2020} \left| C_y - C_{y-1} \right|}{\sum_{y=2014}^{2020} C_y} \tag{16}$$

c) The median and 90% intervals of the spawning biomass depletion level in 2020 relative to the unfished spawning biomass and the spawning biomass in 2013:

$$\begin{gathered} SpB_{2020} / SpB_0 \\ SpB_{2020} / SpB_{ref} \end{gathered} \tag{17}$$

where SpB_y is the spawning biomass in year y.

d) The median and 90% intervals of the exploitable biomass depletion level in 2020 relative to the exploitable biomass in 2013:

$$ExB_{2020} / ExB_{ref} \tag{18}$$

where ExB_y is the exploitable biomass in year y. Because the LML has a large influence over the exploitable biomass and it has changed from 120mm to 135mm a comparison with the exploitable biomass in the unfished population would have reduced value; especially given the consideration that the LML is likely to be reduced at some stage in the future once rebuilding has come about.

e) The median and 90% intervals of how the ratio of exploitable to spawning biomass changes from a reference year to 2020:

$$\frac{\left(ExB_{ref} / SpB_{ref} \right)}{\left(ExB_{2020} / SpB_{2020} \right)} \tag{19}$$

f) Finally, the mean length of catch in 2020 relative to that in a reference year:

$$\frac{\sum_{L=135}^{172} f_L L_{2020}}{\sum_{L=135}^{172} f_L} \Big/ \frac{\sum_{L=135}^{172} f_L L_{ref}}{\sum_{L=135}^{172} f_L} \tag{20}$$

where f_L is the frequency of length L.

6.15 Simulation Outputs

Single Replicates

The list of scenarios considered attempted to cover the range of the main uncertainties relating to the initial depletion and the viral mortality (Table 21). Each model run retains almost complete information concerning the dynamics and details of the component populations, including the numbers at size of the animals for each of the eight populations in the cryptic and emergent classes, as well as in the catch (if any). In addition, a large array of other statistics, derived constants, and outputs for each component population within each zone (reefcode) are stored ready for analysis once the simulations have run their course. Generally the variation inherent in the recruitment dynamics will drive much of the variation in fishery performance, however, a single replicate may contain idiosyncracies simply because the random sequence of variation is reflect in the output. A deterministic simulation projection for a given scenario demonstrated the expected response of the stock assuming that the initial conditions being expressed in the stock meet the scenario situation (Figure 34).

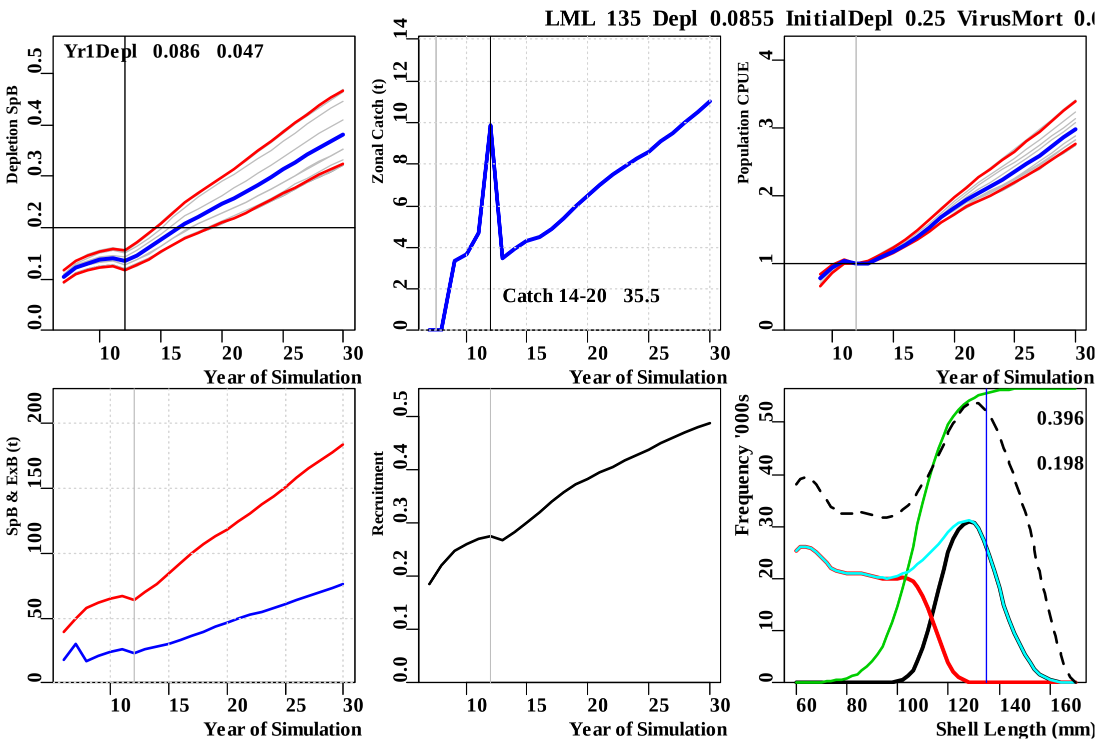

Figure 34. Example of a single replicate scenario run for an initial depletion level prior to the viral outbreak of 25%B_0, a viral mortality of 65%, and an annual harvest rate of 15 % (variation in the combination of the initial depletion led, in this case, to a 2006 depletion level of 8.55% rather than 8.75% = 0.25 * 0.35). In this case variation in the dynamics of the fishery and recruitment has been reduced to trivial levels so these plots are effectively deterministic dynamics. Outputs include the depletion state of spawning biomass, the expected catches, the expected average CPUE, the average state of depletion of the spawning and exploitable biomass, the expected relative recruitment levels, and the size distributions of the cryptic and emergent populations in the final year (in 2030) relative to the expected unfished size distribution and maturity ogive.

If variation is included in the recruitment dynamics, in the perceived CPUE, and in the perceived exploitable biomass used to set the following years TAC (15% observed exploitable biomass + noise), then the smooth trajectories exhibited by the deterministic projection are altered (Figure 35). Despite these simulations starting off identically, the mean end result of the deterministic run is that it achieves a depletion level of about 39%B_0 in 2030, and the run with variation achieve about 38%B_0 (chance has led to a similar outcome in this particular case).

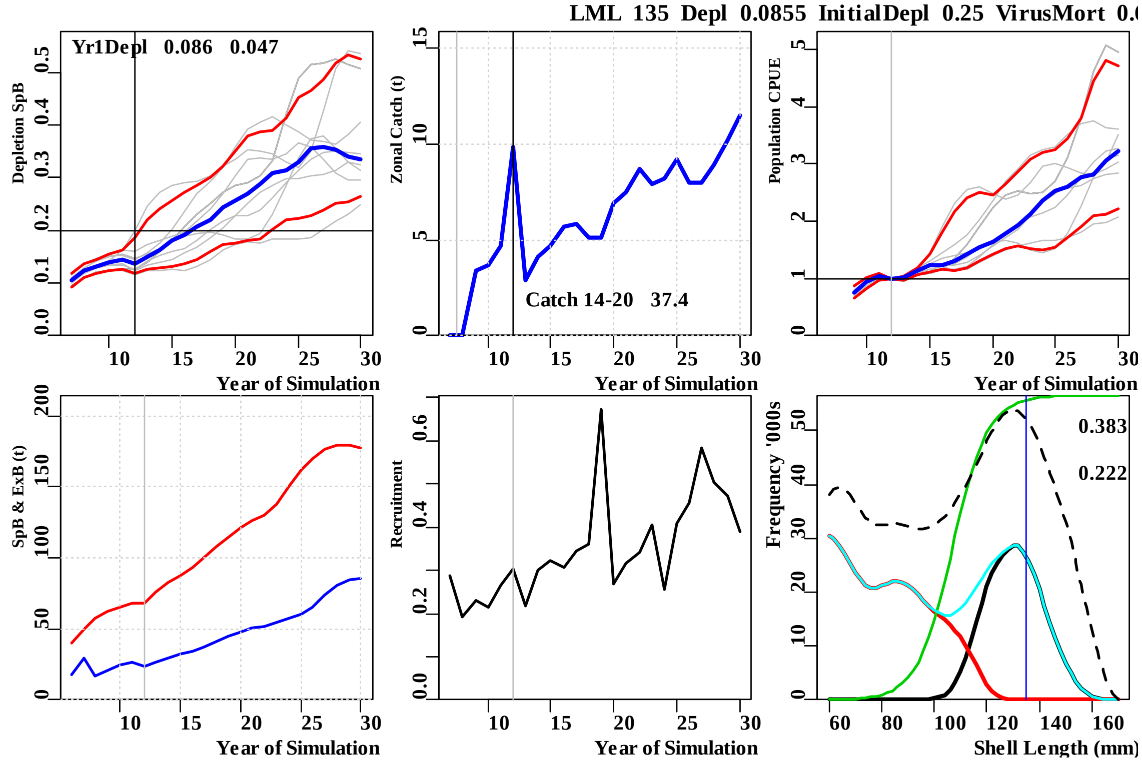

Figure 35. The same scenario as expressed in Figure 34 except random variation has been added to the predicted recruitment levels, the perceived CPUE, and the perceived exploitable biomass levels each year. The grey lines in two of the graphs relate to individual populations, the blue lines in the top three graphs are the medians, while the red lines are the central 90% intervals. The numbers in the top left graph are the depletion levels of spawning and exploitable biomass in 2006 while those in the bottom right graph are the same for 2030. The numbers in the middle top graph are the total reefcode catches between 2014 and 2020. In the length frequency graph the green line is the maturity ogive, the dotted line is the unfished equilibrium size distribution, the red line the cryptic stock and the black line the emergent stock, finally the pale blue line is the predicted combined size distribution in 2030.

Given the reported size at maturity at the Crags (~107 mm), it is possible that the LML of 135mm may be very conservative. While the stock is highly depleted, then the 135 mm LML appears to be a sensible rebuilding strategy. However, if the stock begins to recover to acceptable levels it may be a reasonable option to reduce the LML to some degree, and possibly increase the harvest rate. With constant harvest rates at or below 15% the stock rebuilds in the future to levels above the stock's most productive, which reflects the relatively high LML. At some stage in the recovery, it should be possible to increase the harvest rate and or decrease the LML at which the abalone are taken. Before this stage is reached, however, assuming that large changes in the recruitment dynamics have not occurred and that rebuilding does occur, it might be best to have developed a harvest strategy that was agreed to by all stakeholders that would permit a staged transition back to the fishery at its most productive.

A single replicate with variation provides an impression of how the dynamics may develop but only becomes useful for identifying likely outcomes when the simulation is replicated a large number of times. As a trade-off between the time taken to run the simulation and the number of replicates, 200 appears to provide a reasonable estimate of the expected variation across all the sources of variation built into the model. Once these have been run for all 36 scenarios within the HCR then the outcomes can be summarized across replicates and the variation across replicates can be used to estimate the degree of variability that may occur in the outcomes (Table 21).

Multiple Replicates (500)

Each of the 36 scenarios (Table 21) had 200 replicates, which could all be achieved, usually between 4.5 – 5 hours of computer time. The scenarios encompassed a relatively wide range of outcomes but of course, attempting to synthesize such an amount of information, along with estimates of the variation inherent in the system being simulated can be difficult. Single scenarios are a simpler place to begin to introduce the types of outcome exhibited (Figure 36).

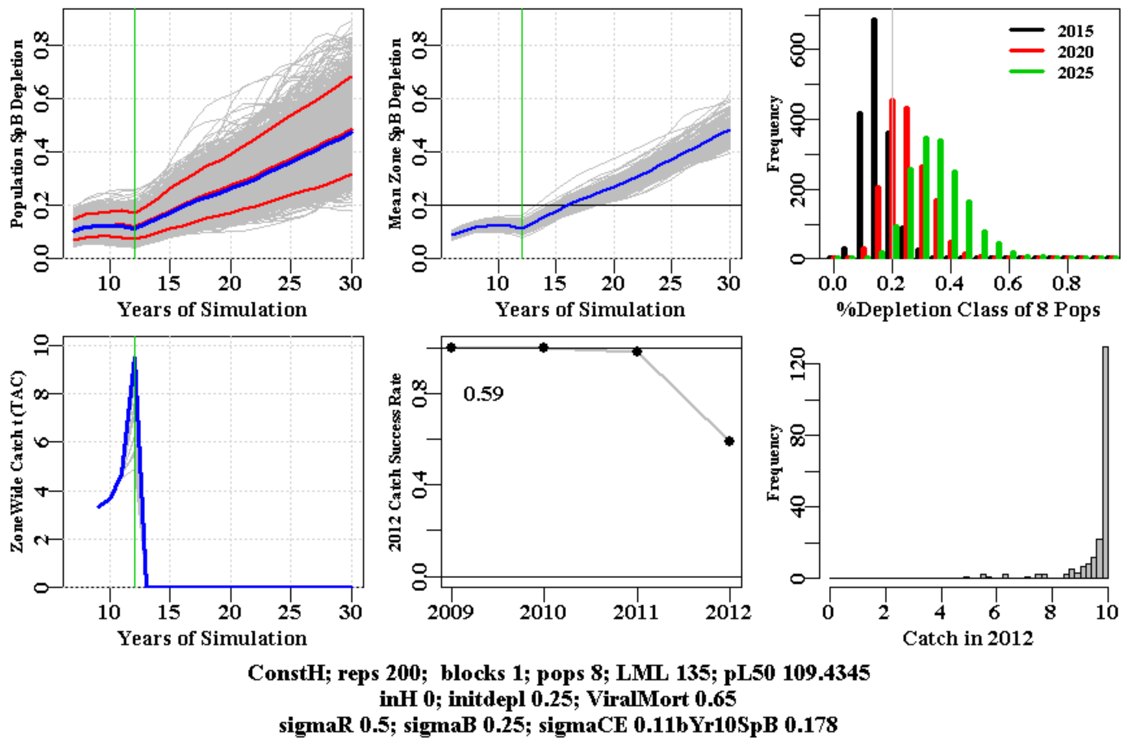

Figure 36. An example of the simulation outputs using 200 replicates of the scenario involving an initial depletion level of 25%B_0, a viral mortality of 65% and zero commercial catch (inH = 0). The panel on the left illustrates the state of depletion of each of the 200 x 8 populations across the replicate reefcode simulations, with the median and the 90% percentiles of the distribution of depletion levels. The central panel is the one that represents the depletion level of the reefcode and illustrates the 200 replicates as the grey lines and the median. The right hand panel illustrates the distribution of depletions across the 8 populations in 2015, 2020, and 2025. Catches are limited to 2009 – 2012 and not all replicates achieved the observed catches, which lowers the credibility of the scenario. Details of this credibility are depicted in the bottom right hand two graphs. The catch in 2012 should be 9.856t.

The primary objective or question being asked relates to whether a commercial fishery now will have an overly negative impact on recovery times, and if not how large a fishery is possible. The reference for each scenario will be the no fishing version of each set of initial depletions and viral mortality rates (Figure 36).

Even with no fishing, given the viral mortality (0.65) and initial depletion (0.25) the catches taken already prevented any recovery until about year 8 or 9 (2013 or 2014), although, in fact, commercial fishing has been occurring in the 2013 season, but only about 4.5 tonnes have come off the Crags so far into the season (according to data available in the reef reports cards in January 2014). With such depletion levels the low catches taken so far are indicative of the likely range of catches possible in the near future; although, depending on how high they are, they may adversely affect recovery.

The same scenario as the previous single replicate zone analyses can be considered (Figure 37); the estimation of the annual TAC will only be possible with error as the information regarding relative abundance remains uncertain.

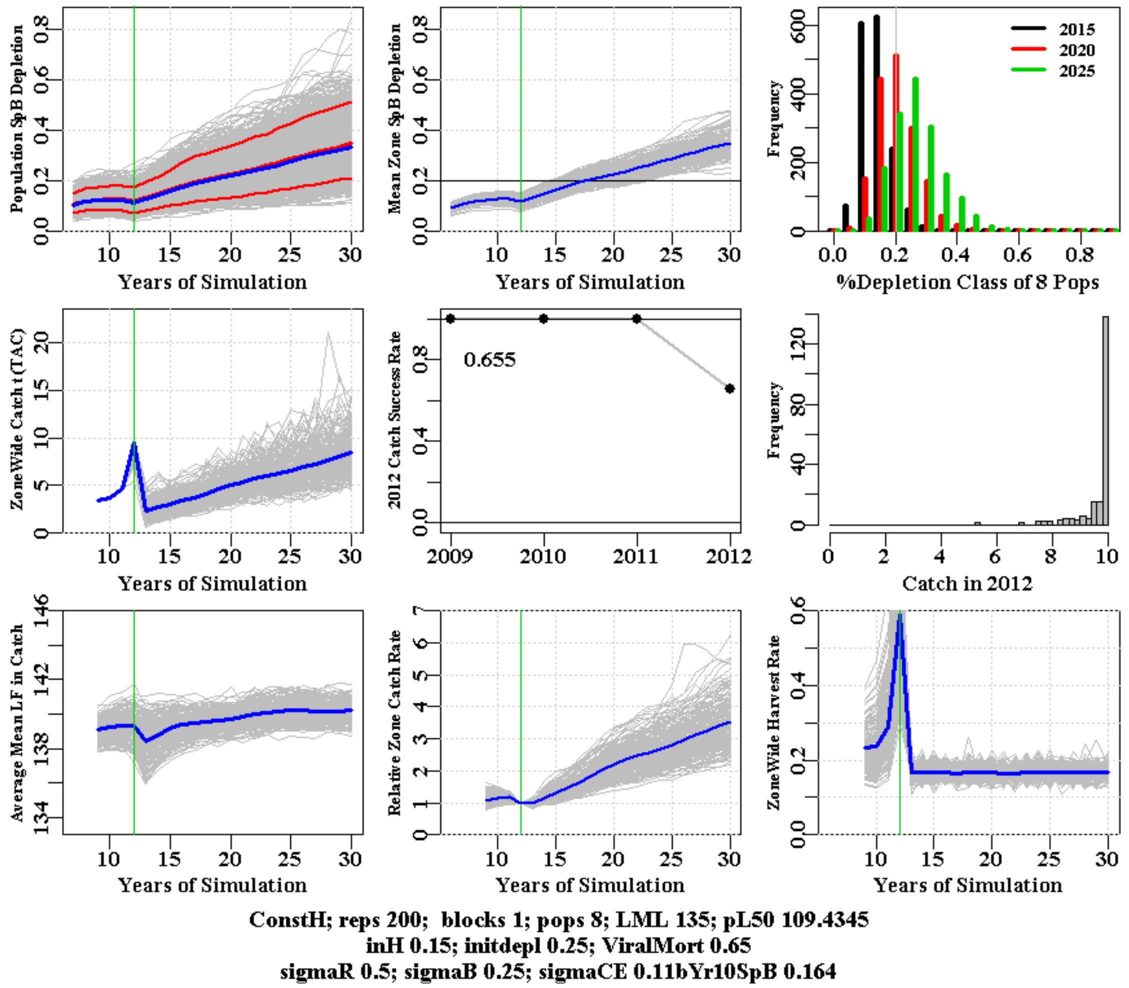

Figure 37. 200 replicates of the scenario with an initial depletion of 25%B_0, a viral mortality of 65%, and an annual harvest rate of 15%. The top six graphs have the same structure as in Figure 36. The bottom left illustrates the predicted changes in the mean shell length, the expected changes in CPUE relative to that in 2012, and the predicted actual harvest rate. The extent of variation is apparent. The catch success rate in this example is higher than the example without variation (Figure 13), which is a reflection of that variation.

The predicted catch series (Figure 36 and Figure 37) can sometimes imply that it would not have been possible to catch the 9.856 tonnes taken in 2012. Clearly that is inconsistent with the observed facts, which suggests that either the initial depletion or the viral mortality assumed may be too great. This provides a means for determining the relative plausibility or credibility of particular scenarios. It is possible that this peak of catches in 2012 may only have been possible through the re-aggregation of survivors of the viral outbreak making them very simple to deplete in early fishing. The mean length of the catch remains mostly flat over the period when exploitation occurs (2009 – 2012) except for a dip related to the 9.8 t catch. The mean length recovers rapidly following the large reduction in fishing. Once the stock recovers to about 15%B_0 in about 2015, the mean length in the catch stops rising so rapidly and only increases by a further 1mm over a period of 15 years. The amount of available biomass for exploitation and the mean length of the catch when the stock is badly depleted appear to be potential performance measures that could be used in the future to provide an indication of the current stock status, if only on the Crags reefcode. If these potential performance indicators are going to be effective, this will only be able to be properly distinguished, from the fishery performance, over the next few years. If a scenario is considered that is identical to this one except that the viral mortality is only 50% the outcome differs (Figure 38).

With a viral mortality of only 50% the simulation dynamics are rather different from the 65% scenario. The 9 tonnes catch in 2012 appears possible in 96% of replicates rather than only 65.5%, although catches would have been well above the 5 or 7.5% harvest rate that was desired at that time. This can be inferred from the still dramatic drop in predicted catches in all scenarios. Nevertheless, whereas with an 65% viral mortality a 15% harvest rate can still permit a recovery to about 34.6%B_0 by 2030 (25 years), with a viral mortality of 50% this recovery reaches about 40.7%B_0 in the same time. For comparison the simulations where catches were cut to zero from 2013 onwards led to a recovery to about 48.1% in 2030. Given that the reefcode is predicted to be at its most productive at a depletion level of about 35%B_0 then other management changes, such as a change in LML, before then would have been appropriate.

The mean length of the catch with the 50% viral mortality exhibits a slow increase with only a minor reduction in mean lenth resulting from the 2012 catches, which differs from the 65% viral mortality scenario. Both scenarios stabilize at about the same mean length.

The plausibility of the different scenarios differs markedly. With an initial depletion of 25% and a viral mortality of 50% almost all replicates (96%) were able to generate the observed catches without the harvest rate becoming impossibly high, which is not the case with the 65% viral mortality case.

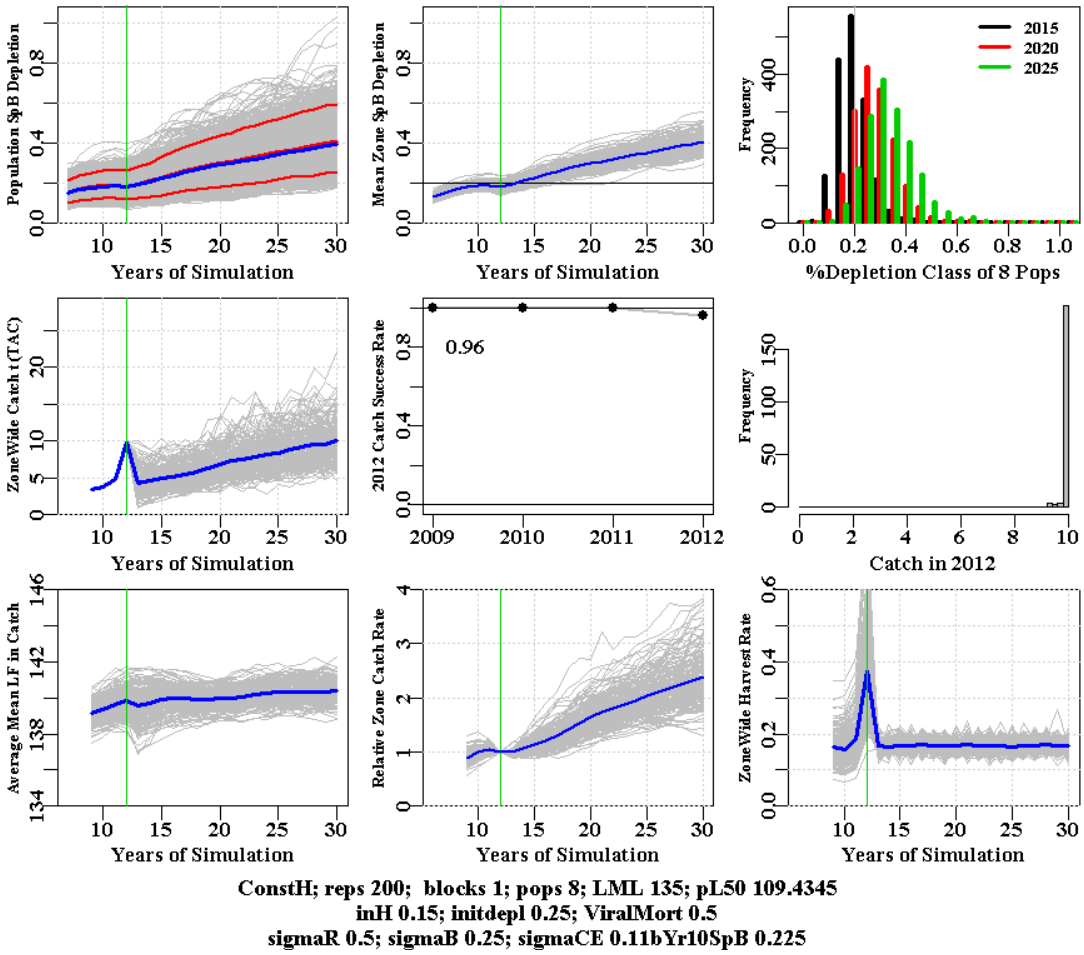

Figure 38. 200 replicates of the scenario with an initial depletion of 25%B_0, a viral mortality of 50%, and an annual harvest rate of 15%. See **Figure 36** and **Figure 37** for an explanation of what each graph represents. The scenario here differs from the one previously considered in having a less severe viral impact.

Visualizing Differences between Scenarios and HCR

The graphs of the full dynamics of the simulation (e.g. Figure 38) are useful for illustrating the trends through time of the various model outputs but given there are 36 scenarios spread across the HCR, comparions would become confusing and difficult. The strategy used was to select a given year, in this case 2020, and consider the mean and spread of the various HCR performance measures during that year (Figure 39).

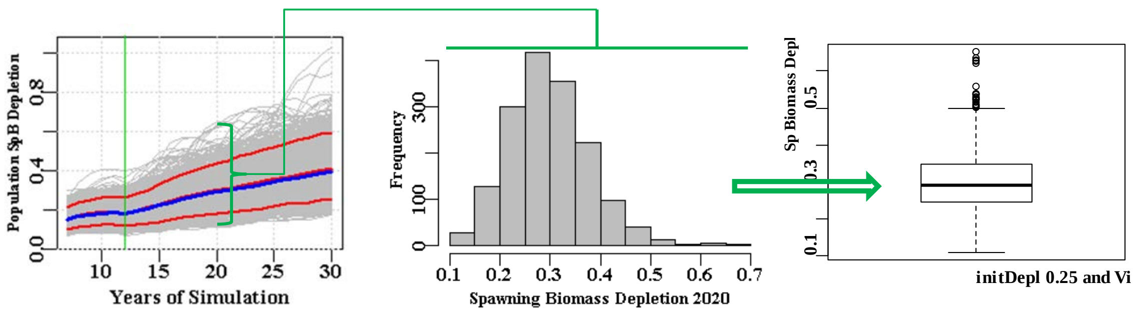

Figure 39. Extraction of the distribution of replicate HCR performance measures for a given combination of HCR and scenario. The outcomes are slices through the time series of the history of the dynamics.

Such boxplots can be used to summarize the effects of the various scenarios within the Constant H HCR on the HCR performance measures this can be done separately for the plausibility of the various scenarios.

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Report 2: Modelling the Potential for Recovery of Western Victorian Abalone Stocks: Mills Killarney, and Watersprings

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Modelling the Potential for Recovery of Western Victorian Abalone Stocks: Mills Killarney, and Watersprings

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November 2014

1 MSE results of Watersprings and Mills-Killarney reefcodes.

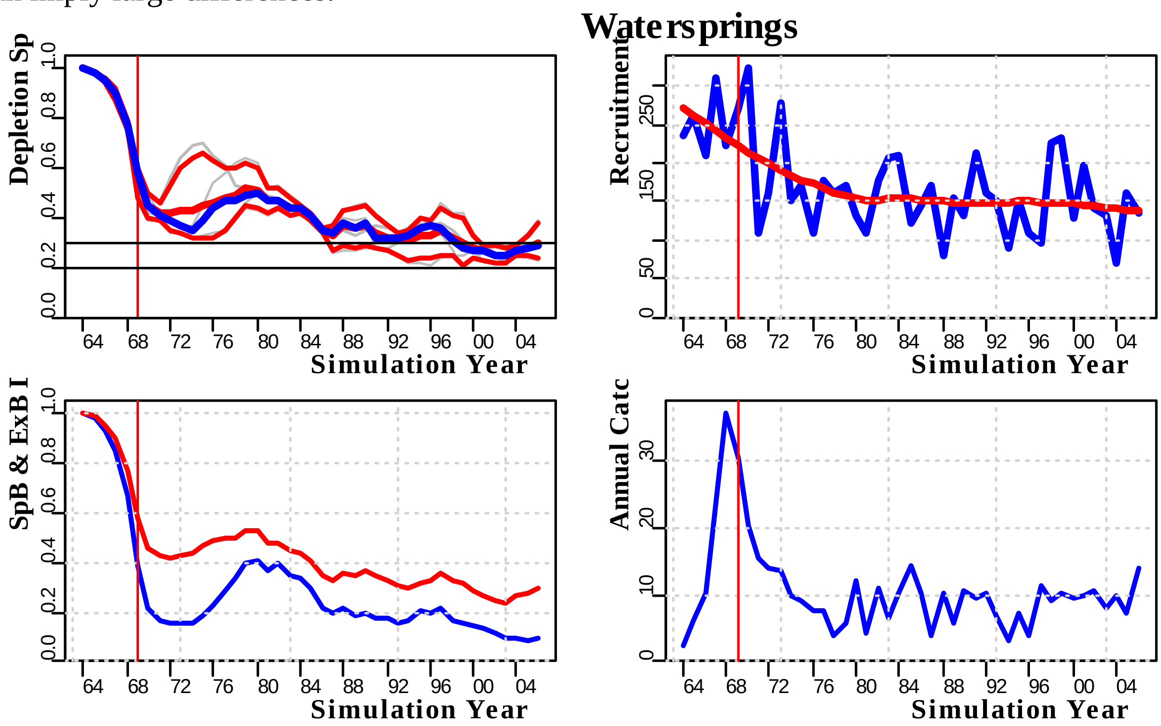
1.1 Fishery

Table A 1. Commercial catches

qyear	Crags(3.05)	Watersprings (1.03)	Mills-Killarney
2006	10.98285	6.84036	10.91364
2007	0	14.145	0
2008	0	0	0
2009	3.368	0	0
2010	3.667	0	0
2011	4.683	0	1.83389
2012	9.857	2.132	3.45546
2013	5.314	7.114	8.10437

1.2 Stock reduction analysis

A stock reduction analysis was carried out for each reefcode. This enabled the selection of appropriate parameters for each scenario of initial depletion so that the appropriate stock productivity could be used. This involved conducting a grid search to select the required level of spawning biomass depletion. The R_0 recruitment parameter therefore changes slightly depending on the depletion level used however because this is a natural log small changes can imply large differences.



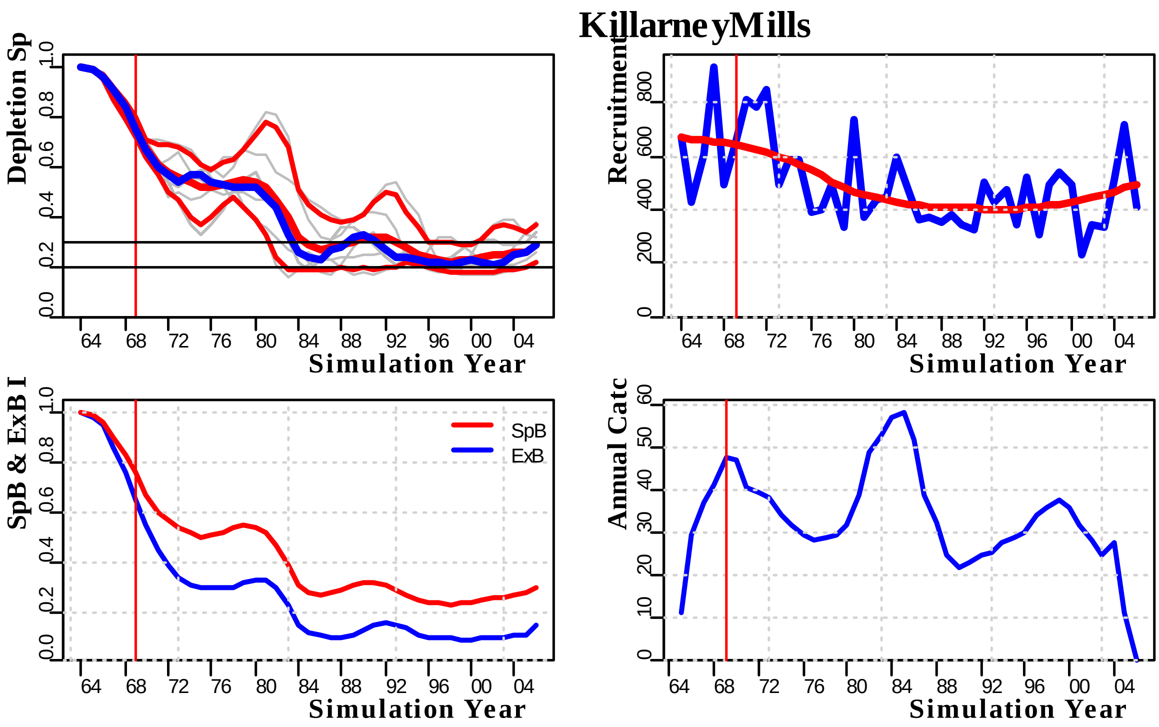


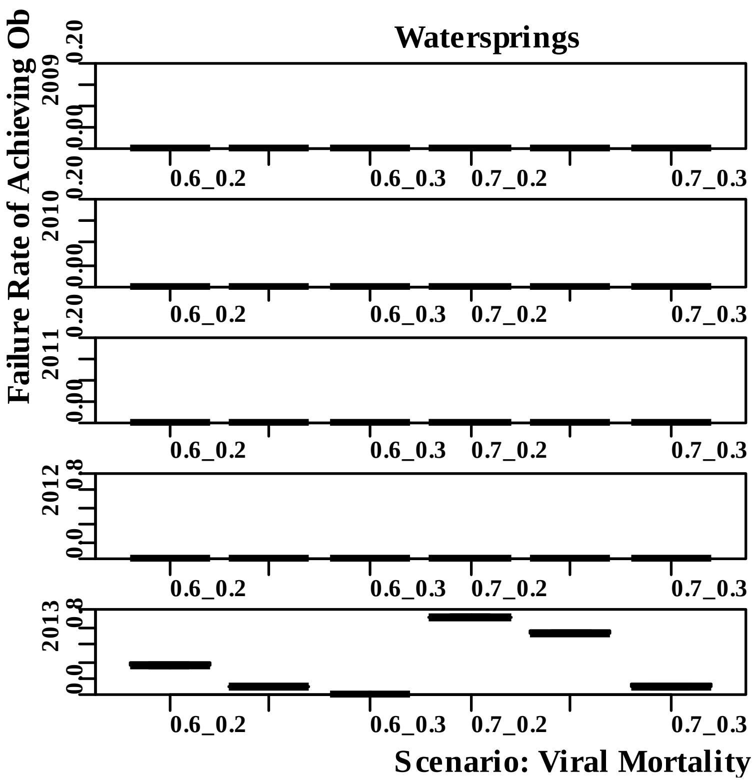
Figure 40. A typical stock reduction using the starting with catches from 1964. Top left is the spawning biomass depletion level of the representative populations (grey lines, 4 populations for Watersprings and 6 for Mills-Killarney), with their average and the median with 90% intervals. Top right is the recruitment with the long term trend and expected recruitment declines with the decline in spawning biomass. Bottom left is the expected depletion of both the spawning (red line) and exploitable biomass (blue line) relative to an unfished state, and bottom right is the catch history used (from Gorfine et al, 2008)., which includes some IUU catches (see Table A 14). The vertical red line identifies the peak catch.

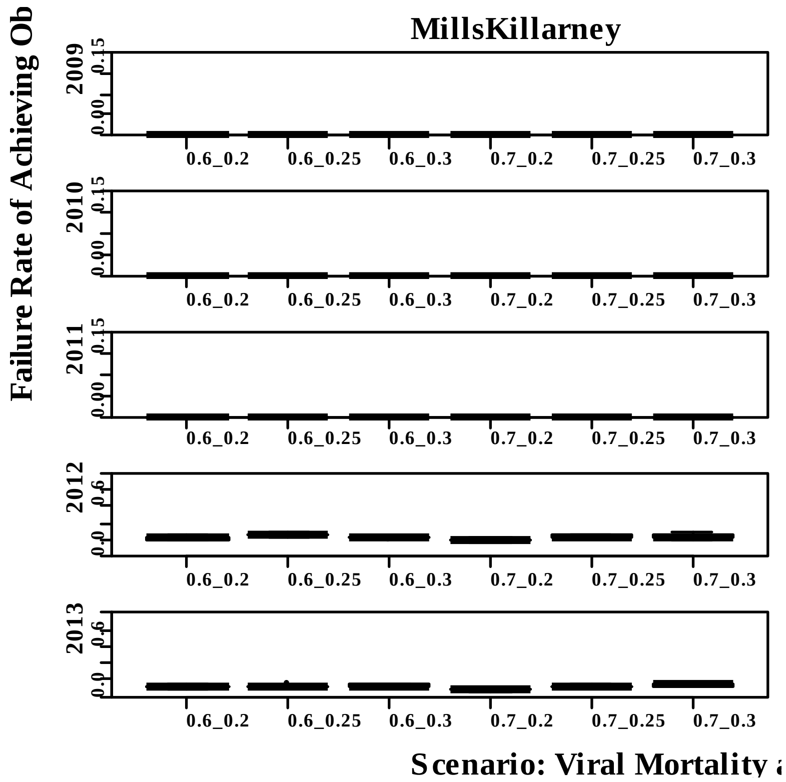
1.3 HCR and Scenario Results

1.3.1 Scenario Plausibility

Between 2009 and 2013 the observed catches (**Table A 1**) can be compared to the predicted exploitable biomass to determine the relative plausibility of the harvest rate with that which was predicted to have occurred. This is during the period when the intention was to apply an annual harvest rate of 0.05; that is before the alternative HCR described here were considered in the simulation. Up to 2013 there is no change in harvest rate or HCR and the scenarios assumed for the initial depletion and the viral mortality are based upon previous industry advice. The plausibility analysis is therefore focussed on six combinations of viral mortality and initial depletion. Furthermore there are 6 replicate groups (representing the 6 harvest rates tested) of 500 replicate zones for each of the six combinations of initial depletion and viral mortality (6 x 6 = 36), and therefore there are 6 estimates of failure rate for each scenario (for the Constant H harvest Control rule). These estimates provide a mean value of the relative plausibility of the catches with a spread about that mean.

For Watersprings the most plausible scenario was a depletion level of 0.3 and a Viral Mortality of 0.6 (Figure 41). For Mills and Killarney the result were clear but remained perplexing – a viral mortality of 0.8 clearly resulted in implausible outcomes however reducing it to 0.7 resulted in more plausible outcome for all depletion levels. Usually a reduction in viral mortality would result in more plausible outcome but not for all depletion levels.





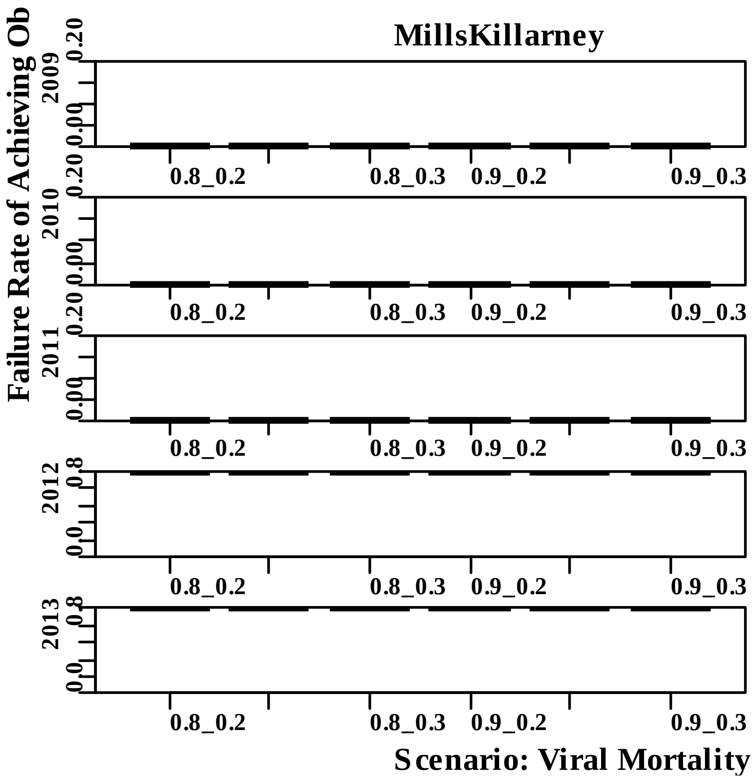


Figure 41. The relative failure rate of the different scenario combinations of viral mortality and initial depletion for Watersprings and Mills-Killarney. Four scenarios of viral mortality are considered for Mills-Killarney (0.6, 0.7, 0.8, 0.9). The smaller the value the greater the plausibility.

Table A 2. Catch failure rates across observed catches in 2009 – 2013 across 6 replicates for each scenario of viral mortality and initial depletion. Each of the 6 replicates consists of 500 replicate simulations. A value of 0 indicates a zero failure rate and 1 indicates 100% failure rate. The Group is the combination of viral mortality (0.7 and 0.8) and initial depletion level (0.2, 0.25, 0.3) against which the rates were assessed.

Waterspring						Mills Killarney					
Group	Y200	Y201	Y201	Y201	2013	Group	Y200	Y201	Y201	Y201	2013
0.6_0.2	0	0	0	0	0.36	0.6_0.2	0	0	0	0.202	0.15
0.6_0.2	0	0	0	0	0.35	0.6_0.2	0	0	0	0.234	0.11
0.6_0.2	0	0	0	0	0.39	0.6_0.2	0	0	0	0.258	0.13
0.6_0.2	0	0	0	0	0.37	0.6_0.2	0	0	0	0.204	0.12
0.6_0.2	0	0	0	0	0.38	0.6_0.2	0	0	0	0.238	0.11
0.6_0.2	0	0	0	0	0.33	0.6_0.2	0	0	0	0.206	0.10
0.6_0.25	0	0	0	0	0.11	0.6_0.2	0	0	0	0.250	0.12
0.6_0.25	0	0	0	0	0.10	0.6_0.2	0	0	0	0.254	0.13
0.6_0.25	0	0	0	0	0.12	0.6_0.2	0	0	0	0.282	0.13
0.6_0.25	0	0	0	0	0.09	0.6_0.2	0	0	0	0.236	0.14
0.6_0.25	0	0	0	0	0.10	0.6_0.2	0	0	0	0.272	0.11
0.6_0.25	0	0	0	0	0.10	0.6_0.2	0	0	0	0.252	0.13
0.6_0.3	0	0	0	0	0.00	0.6_0.3	0	0	0	0.224	0.13
0.6_0.3	0	0	0	0	0.00	0.6_0.3	0	0	0	0.232	0.12
0.6_0.3	0	0	0	0	0.00	0.6_0.3	0	0	0	0.222	0.12
0.6_0.3	0	0	0	0	0.00	0.6_0.3	0	0	0	0.232	0.10
0.6_0.3	0	0	0	0	0.00	0.6_0.3	0	0	0	0.232	0.10
0.6_0.3	0	0	0	0	0	0.6_0.3	0	0	0	0.200	0.13
0.7_0.2	0	0	0	0	0.93	0.7_0.2	0	0	0	0.206	0.10
0.7_0.2	0	0	0	0	0.92	0.7_0.2	0	0	0	0.210	0.09
0.7_0.2	0	0	0	0	0.92	0.7_0.2	0	0	0	0.192	0.07
0.7_0.2	0	0	0	0	0.92	0.7_0.2	0	0	0	0.166	0.09
0.7_0.2	0	0	0	0	0.92	0.7_0.2	0	0	0	0.188	0.07
0.7_0.2	0	0	0	0	0.94	0.7_0.2	0	0	0	0.220	0.09
0.7_0.25	0	0	0	0	0.77	0.7_0.2	0	0	0	0.258	0.12
0.7_0.25	0	0	0	0	0.73	0.7_0.2	0	0	0	0.240	0.12
0.7_0.25	0	0	0	0	0.73	0.7_0.2	0	0	0	0.228	0.13
0.7_0.25	0	0	0	0	0.77	0.7_0.2	0	0	0	0.264	0.11
0.7_0.25	0	0	0	0	0.72	0.7_0.2	0	0	0	0.228	0.10
0.7_0.25	0	0	0	0	0.73	0.7_0.2	0	0	0	0.234	0.15
0.7_0.3	0	0	0	0	0.13	0.7_0.3	0	0	0	0.220	0.14
0.7_0.3	0	0	0	0	0.09	0.7_0.3	0	0	0	0.226	0.14
0.7_0.3	0	0	0	0	0.13	0.7_0.3	0	0	0	0.260	0.15
0.7_0.3	0	0	0	0	0.11	0.7_0.3	0	0	0	0.224	0.13
0.7_0.3	0	0	0	0	0.11	0.7_0.3	0	0	0	0.194	0.15
0.7_0.3	0	0	0	0	0.11	0.7_0.3	0	0	0	0.276	0.13

1.4 Performance indicators

Six performance indicators were formulated. Each scenario for the constant HCR control rule was evaluated against each of the performance indicator: 1) Total Catch between 2014 – 2020, 2) Variability in Catch between 2014 – 2020 (AAV), 3) Mean length of catch, 4) Spawning stock depletion in 2020 (relative to B_0), 5) Spawning stock depletion in 2020 relative to 2013, 6) Exploitable Biomass depletion 2020 relative to 2013.

1.4.1 Total Catch 2014 – 2020

The smaller the viral mortality the larger the total catch between 2014 and 2020 (**Figure 5**, Table 6 regardless of initial depletion. Similarly a stock depleted down to 0.3 of the initial biomass results in higher total catch than stock depleted down to 0.25 and 0.2. Each boxplot for the total catch demonstrates the variation between replicates. The variation (range of catches between the 6 replicates) appears to be greater in the 0.6 (60%) viral mortality scenarios relative to their equivalents at 0.7 viral mortality (compare the range of the whiskers in the boxplot). Not surprisingly, the higher the harvest rate selected the larger the total catch, irrespective of with scenario was considered.

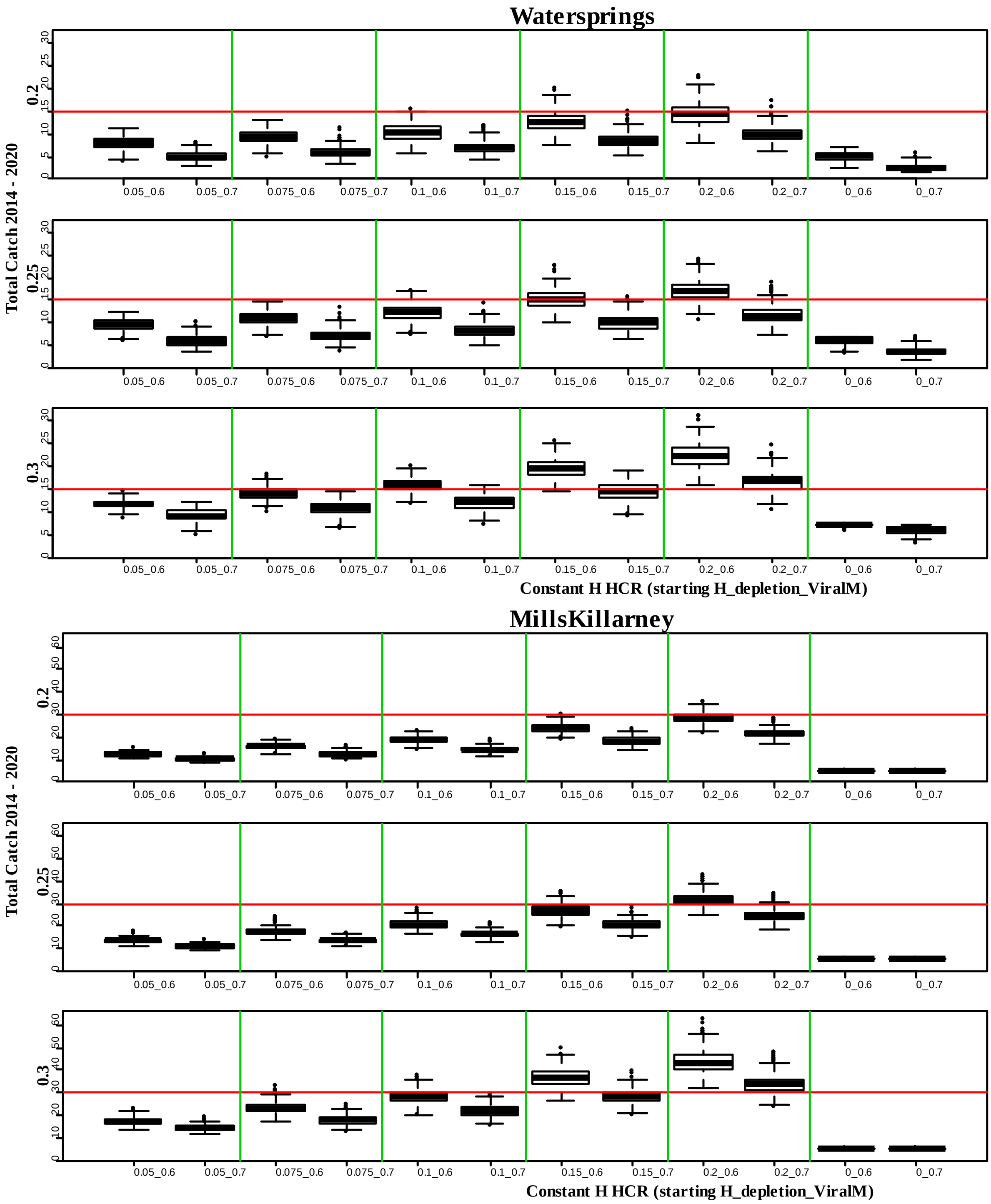


Figure 42. Sum of the predicted catch taken on the Crags between 2014 – 2020. In each set of boxplots consists of a different pre-viral 2006 depletion level (20%, 25%, and 30%). The red line at (Watersrpings -15 tonnes, Mills Killarney - 30 tonnes) is there to simplify comparison between scenarios.

Table A 3. Quantiles of total cummulative catch (2014:2020) across replicate runs in each scenario for the Constant H harvest control rule.

Watersprings: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	3.584	6.444	7.320	8.279	10.512
0.05 0.6 0.25	5.657	8.193	9.012	9.736	11.638
0.05 0.6 0.3	7.894	10.486	11.000	11.441	13.470
0.05 0.7 0.2	2.585	3.904	4.426	5.111	7.684
0.05 0.7 0.25	3.264	4.774	5.542	6.241	9.514
0.05 0.7 0.3	4.469	7.841	8.602	9.528	11.323
0.075 0.6 0.2	4.371	7.515	8.571	9.603	12.139
0.075 0.6 0.25	6.268	9.252	10.176	10.979	13.367
0.075 0.6 0.3	9.252	12.144	12.753	13.446	16.183
0.075 0.7 0.2	3.256	4.727	5.206	5.900	10.322
0.075 0.7 0.25	3.410	5.711	6.410	7.273	12.003
0.075 0.7 0.3	5.854	8.988	9.900	10.749	13.074
0.1 0.6 0.2	5.100	8.213	9.269	10.487	14.023
0.1 0.6 0.25	6.440	10.116	11.229	12.274	15.442
0.1 0.6 0.3	10.943	13.553	14.312	15.186	17.668
0.1 0.7 0.2	3.957	5.357	6.062	6.889	10.501
0.1 0.7 0.25	4.598	6.613	7.422	8.265	12.813
0.1 0.7 0.3	6.375	9.873	11.037	11.994	14.348
0.15 0.6 0.2	6.453	9.874	11.232	12.585	17.753
0.15 0.6 0.25	9.081	12.223	13.353	14.612	20.053
0.15 0.6 0.3	13.229	16.070	17.349	18.516	22.740
0.15 0.7 0.2	4.701	6.578	7.395	8.321	13.313
0.15 0.7 0.25	5.494	7.806	8.751	9.917	13.931
0.15 0.7 0.3	8.065	11.873	12.923	14.084	17.051
0.2 0.6 0.2	6.967	11.062	12.601	14.152	20.034
0.2 0.6 0.25	9.234	13.931	15.321	16.435	20.892
0.2 0.6 0.3	14.195	18.341	19.725	21.093	27.158
0.2 0.7 0.2	5.370	7.612	8.386	9.477	15.013
0.2 0.7 0.25	6.218	9.177	10.190	11.234	16.311
0.2 0.7 0.3	8.972	13.385	14.660	15.793	21.277
0 0.6 0.2	2.299	4.151	5.068	5.870	7.110
0 0.6 0.25	3.222	5.607	6.334	6.868	7.110
0 0.6 0.3	5.805	7.110	7.110	7.110	7.110
0 0.7 0.2	1.610	2.202	2.563	3.158	5.677
0 0.7 0.25	2.007	3.009	3.538	4.267	6.839
0 0.7 0.3	3.207	5.379	6.038	6.599	7.110

Table 3 (cont...) Quantiles of total cummulative catch (2014:2020) across replicate runs in Mill Killarney: Constant Harvest HCR

Scenario	0	25	50	75	100
0.05 0.6 0.2	9.539	10.748	11.197	11.633	13.368
0.05 0.6 0.25	10.058	11.563	12.102	12.645	15.580
0.05 0.6 0.3	11.994	14.490	15.274	16.195	19.515
0.05 0.7 0.2	7.960	9.017	9.359	9.736	11.049
0.05 0.7 0.25	8.312	9.633	10.042	10.540	12.495
0.05 0.7 0.3	10.103	11.943	12.543	13.209	16.598
0.075 0.6 0.2	11.371	13.290	13.879	14.555	16.514
0.075 0.6 0.25	12.280	14.399	15.174	16.024	20.942
0.075 0.6 0.3	15.368	18.851	20.005	21.463	28.169
0.075 0.7 0.2	9.167	10.686	11.216	11.703	13.993
0.075 0.7 0.25	9.758	11.582	12.198	12.685	14.871
0.075 0.7 0.3	10.968	14.726	15.671	16.719	20.826
0.1 0.6 0.2	13.059	15.649	16.414	17.129	19.830
0.1 0.6 0.25	14.627	17.013	18.144	19.212	24.063
0.1 0.6 0.3	17.476	22.550	24.195	25.718	32.441
0.1 0.7 0.2	10.448	12.346	12.923	13.574	16.495
0.1 0.7 0.25	11.452	13.506	14.279	15.076	18.557
0.1 0.7 0.3	13.780	17.777	18.812	20.407	25.139
0.15 0.6 0.2	16.419	19.922	20.827	21.895	25.857
0.15 0.6 0.25	16.777	21.821	23.321	24.680	30.772
0.15 0.6 0.3	22.747	29.183	31.380	33.624	42.616
0.15 0.7 0.2	12.583	15.169	16.132	16.949	20.489
0.15 0.7 0.25	13.029	16.885	17.934	19.014	24.476
0.15 0.7 0.3	17.894	23.024	24.605	26.263	33.617
0.2 0.6 0.2	19.120	23.293	24.743	26.146	31.035
0.2 0.6 0.25	21.558	25.721	27.415	29.020	36.561
0.2 0.6 0.3	27.907	34.676	37.319	40.006	53.495
0.2 0.7 0.2	14.949	17.754	18.791	19.744	24.570
0.2 0.7 0.25	16.078	19.842	21.026	22.318	29.531
0.2 0.7 0.3	20.325	26.796	28.835	30.837	40.803
0 0.6 0.2	5.100	5.100	5.100	5.100	5.100
0 0.6 0.25	5.100	5.100	5.100	5.100	5.100
0 0.6 0.3	5.100	5.100	5.100	5.100	5.100
0 0.7 0.2	4.528	5.100	5.100	5.100	5.100
0 0.7 0.25	5.086	5.100	5.100	5.100	5.100
0 0.7 0.3	5.100	5.100	5.100	5.100	5.100

1.4.2 Variation of Catches between Years Across All Scenarios

The AAV (Average Anual Variation) is the year-to-year variation within replicates or in other words the stability of catches for each scenario. This statistic is somewhat distorted because the Average Annual Variation (AAV) is more useful as an index for a developed fishery rather than one that is recovering. If the average trajectory of the 500 replicate runs are considered for any scenario a large part of the variation in catches is derived from the increase in catches as the stock recovers.

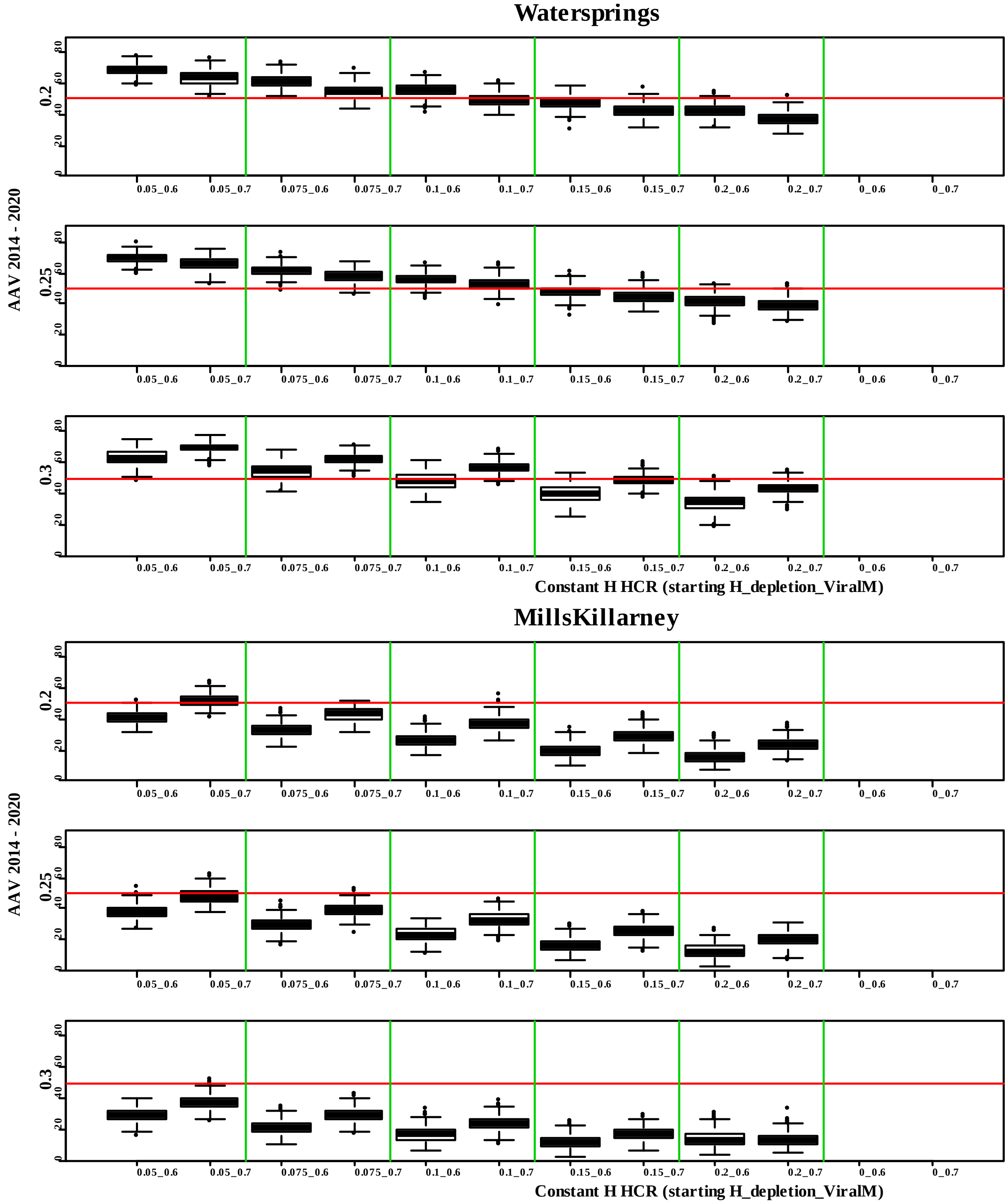


Figure 43. Average Annual Variation of the predicted catch taken between 2014 – 2020. The Constant Harvest HCR is presented, Each set of boxplots represents a different pre-viral 2006 depletion level (20%, 25%, and 30%). The red lines is there to simplify comparison between scenarios.

Table A **4.** Percent quantiles (0%, 5%, etc) of the AAV across replicate runs in each scenario between 2014 – 2020 For the Constant Harvest HCR

Waterspings: Constant Harvest HCR

Scenario	0	25	50	75	100
0.05 0.6 0.2	58.15	66.90	69.34	71.33	78.19
0.05 0.6 0.25	59.20	67.66	69.84	71.63	79.08
0.05 0.6 0.3	47.65	59.56	63.06	66.41	75.74
0.05 0.7 0.2	50.37	60.57	63.45	66.17	76.43
0.05 0.7 0.25	53.31	62.99	66.20	68.77	75.74
0.05 0.7 0.3	58.01	67.78	69.80	71.60	77.23
0.075 0.6 0.2	50.64	59.29	61.79	64.38	73.57
0.075 0.6 0.25	48.29	59.34	61.55	63.85	72.85
0.075 0.6 0.3	40.64	51.05	54.26	57.86	67.65
0.075 0.7 0.2	43.70	51.12	53.98	57.43	69.16
0.075 0.7 0.25	45.70	54.85	57.66	60.87	67.78
0.075 0.7 0.3	50.42	60.45	62.54	64.72	71.28
0.1 0.6 0.2	40.98	52.87	55.71	58.17	66.29
0.1 0.6 0.25	43.06	53.86	56.03	58.51	66.30
0.1 0.6 0.3	34.63	44.39	48.11	51.69	61.30
0.1 0.7 0.2	40.13	46.61	49.54	52.13	61.45
0.1 0.7 0.25	38.89	50.13	52.80	55.52	66.64
0.1 0.7 0.3	45.78	54.40	56.62	58.78	68.27
0.15 0.6 0.2	29.83	45.67	48.25	51.05	58.51
0.15 0.6 0.25	31.75	45.59	48.00	50.54	61.08
0.15 0.6 0.3	24.81	35.36	39.29	43.42	53.47
0.15 0.7 0.2	31.16	39.65	42.40	45.38	56.66
0.15 0.7 0.25	35.29	41.88	44.77	47.56	59.37
0.15 0.7 0.3	36.85	46.43	48.59	50.86	60.44
0.2 0.6 0.2	31.15	39.32	41.96	44.65	55.06
0.2 0.6 0.25	26.97	39.65	42.48	44.96	53.14
0.2 0.6 0.3	18.78	30.52	33.90	37.72	51.26
0.2 0.7 0.2	27.97	34.60	37.27	40.07	51.87
0.2 0.7 0.25	28.56	37.01	39.83	42.34	52.23
0.2 0.7 0.3	29.16	40.82	43.56	45.84	55.42
0 0.6 0.2	100	100	100	100	100
0 0.6 0.25	100	100	100	100	100
0 0.6 0.3	100	100	100	100	100
0 0.7 0.2	100	100	100	100	100
0 0.7 0.25	100	100	100	100	100
0 0.7 0.3	100	100	100	100	100

Table 4 (cont…). Percent quantiles (0%, 5%, etc) of the AAV across replicate runs in each scenario between 2014 – 2020 For the Constant Harvest HCR

Mills Killarney: Constant Harvest HCR

Scenario	0	25	50	75	100
0.05 0.6 0.2	31.47	39.02	41.49	44.17	52.38
0.05 0.6 0.25	26.88	35.04	37.64	40.36	54.33
0.05 0.6 0.3	16.20	26.20	29.27	31.64	39.73
0.05 0.7 0.2	41.23	49.50	52.04	54.48	63.92
0.05 0.7 0.25	38.28	44.95	47.75	50.91	62.50
0.05 0.7 0.3	24.69	34.50	36.97	39.86	52.46
0.075 0.6 0.2	22.41	29.88	32.50	35.12	46.88
0.075 0.6 0.25	16.84	26.40	29.17	31.80	44.74
0.075 0.6 0.3	10.77	18.21	20.78	23.74	34.50
0.075 0.7 0.2	31.85	40.30	43.31	45.92	52.54
0.075 0.7 0.25	24.84	36.41	39.27	41.68	53.23
0.075 0.7 0.3	16.46	26.15	28.89	31.82	42.62
0.1 0.6 0.2	17.31	23.87	26.71	29.46	40.99
0.1 0.6 0.25	11.15	20.39	23.45	26.35	34.08
0.1 0.6 0.3	5.70	13.56	16.46	19.44	32.70
0.1 0.7 0.2	26.19	34.13	36.82	39.59	55.95
0.1 0.7 0.25	19.14	30.22	32.94	35.87	45.95
0.1 0.7 0.3	9.73	20.73	23.48	26.46	38.55
0.15 0.6 0.2	9.34	16.73	19.48	22.52	33.85
0.15 0.6 0.25	6.75	13.70	16.54	19.45	30.18
0.15 0.6 0.3	2.62	9.27	11.60	14.54	25.71
0.15 0.7 0.2	18.43	26.13	28.65	31.51	43.88
0.15 0.7 0.25	12.65	22.33	25.16	28.02	38.10
0.15 0.7 0.3	6.67	13.85	16.73	19.26	28.64
0.2 0.6 0.2	6.62	12.30	15.00	18.53	30.61
0.2 0.6 0.25	2.11	10.06	12.74	16.07	27.14
0.2 0.6 0.3	3.30	10.36	13.48	16.60	30.52
0.2 0.7 0.2	12.30	21.28	24.10	26.42	36.60
0.2 0.7 0.25	6.60	17.14	19.84	23.09	31.43
0.2 0.7 0.3	5.20	10.47	13.10	15.77	33.21
0 0.6 0.2	100	100	100	100	100
0 0.6 0.25	100	100	100	100	100
0 0.6 0.3	100	100	100	100	100
0 0.7 0.2	100	100	100	100	100
0 0.7 0.25	100	100	100	100	100
0 0.7 0.3	100	100	100	100	100

1.4.3 Ratio of Mean Length of Catch of 2020/2013

Using Mean length as a performance measure is not very sensitive to and difficult to interpret. It should be noted that the mean length may not neccessarily increase if the numbers of animals above the LML size increase. The reason for this is that although the numbers at larger sizes may increase so do those at the smaller size classes; and if the smaller size classes increase more than the larger sizes the mean size may decline. This is not necessarily a bad outcome however this performance measure needs further consideration as the dynamics associated with the mean length become better known. If the proportion at length changes very little during large change in relative abundance then no length based measure will be useful as an index of recovery. It is possible, given the simulation outputs, that there can be a small amount of contrast in mean length when the stock is very badly depleted. Thus, mean length might be used as a warning sign and confirmation that a stock is seriously depleted, but diver awareness of underwater conditions should already have identified this. Although there is an increase in total catches for a stock that is depleted to 0.3 the mean length in catch is lowest in the 0.3 depleted stock because its possibly an indication that a greater proportion of new recruits (i.e smaller size classes closer to the LML) are contributing to the overall biomass thereby causing the mean length to decrease.

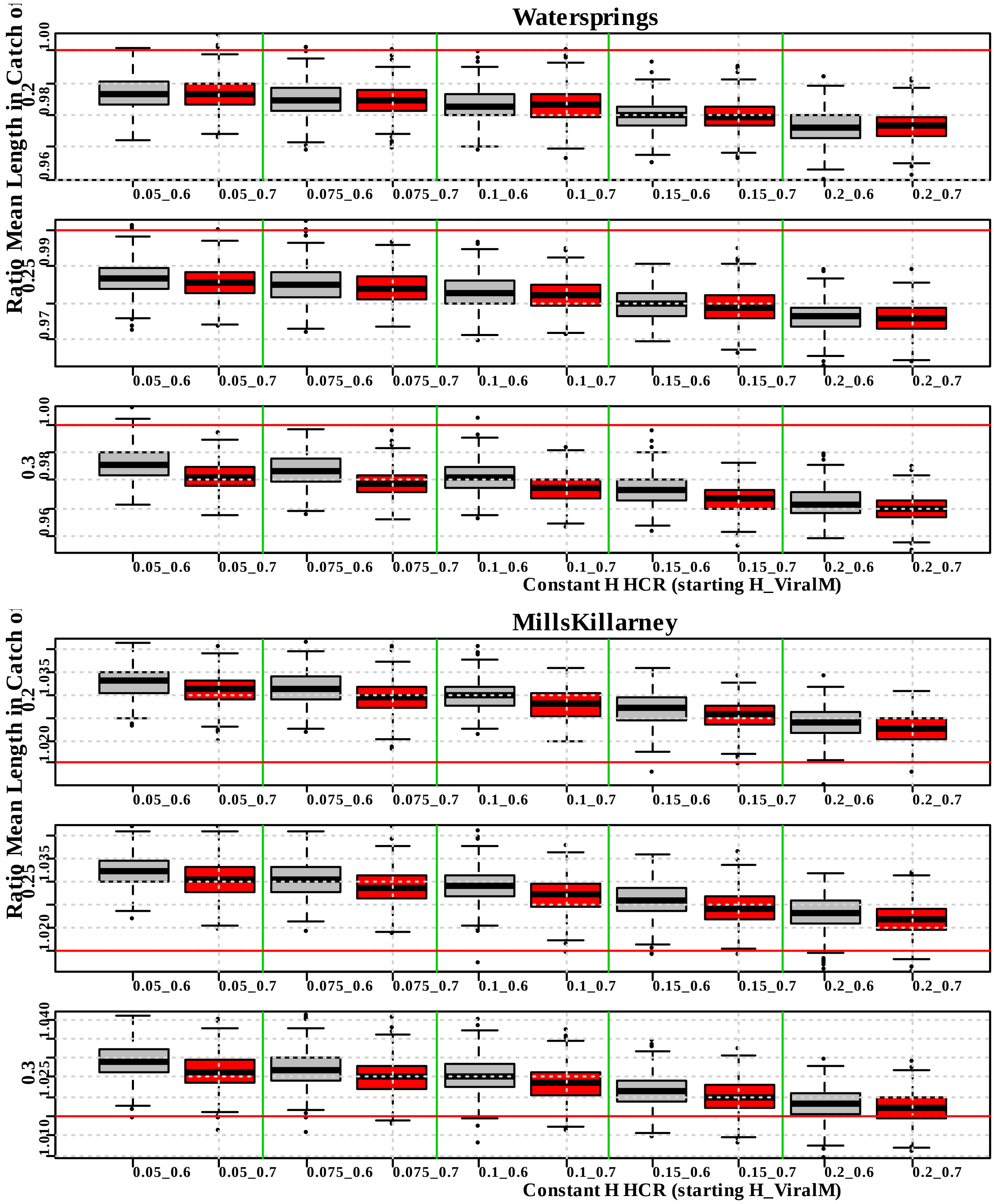


Figure 44. The ratio of the mean length in the commercial catch between 2020 and 2013 (2020/2013). The Constant Harvest HCR is presented. The initial depletion level in 2006 is the annotation to the left of each set of boxplots and each combination of initial H and viral mortality rate is listed under each separate boxplot. The horizontal red line is to aid identification of scenarios that lead to a decline in mean length.

Table A 5. Percent quantiles (0%, 5%, etc) of the distribution of the ratio of mean length in 2020/2013 in catches across replicate runs in each scenario from 2013 – 2020 for the Constant Harvest HCR.

Waterspring: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	0.9721	0.9830	0.9867	0.9905	1.0056
0.05 0.6 0.25	0.9728	0.9839	0.9870	0.9898	1.0010
0.05 0.6 0.3	0.9717	0.9819	0.9857	0.9901	1.0066
0.05 0.7 0.2	0.9727	0.9833	0.9866	0.9897	1.0046
0.05 0.7 0.25	0.9737	0.9827	0.9857	0.9887	0.9998
0.05 0.7 0.3	0.9678	0.9780	0.9813	0.9852	0.9970
0.075 0.6 0.2	0.9686	0.9813	0.9848	0.9886	1.0010
0.075 0.6 0.25	0.9721	0.9819	0.9850	0.9882	1.0023
0.075 0.6 0.3	0.9676	0.9800	0.9832	0.9880	0.9985
0.075 0.7 0.2	0.9696	0.9816	0.9846	0.9876	1.0005
0.075 0.7 0.25	0.9736	0.9812	0.9841	0.9871	0.9963
0.075 0.7 0.3	0.9658	0.9756	0.9788	0.9821	0.9980
0.1 0.6 0.2	0.9686	0.9800	0.9828	0.9865	0.9996
0.1 0.6 0.25	0.9695	0.9801	0.9830	0.9860	1.0027
0.1 0.6 0.3	0.9661	0.9776	0.9814	0.9850	1.0025
0.1 0.7 0.2	0.9663	0.9796	0.9830	0.9867	1.0000
0.1 0.7 0.25	0.9713	0.9797	0.9824	0.9850	0.9946
0.1 0.7 0.3	0.9628	0.9738	0.9776	0.9807	0.9915
0.15 0.6 0.2	0.9652	0.9765	0.9797	0.9828	0.9961
0.15 0.6 0.25	0.9696	0.9767	0.9798	0.9828	0.9910
0.15 0.6 0.3	0.9619	0.9729	0.9766	0.9802	0.9975
0.15 0.7 0.2	0.9663	0.9765	0.9793	0.9825	0.9952
0.15 0.7 0.25	0.9664	0.9760	0.9791	0.9822	0.9948
0.15 0.7 0.3	0.9561	0.9699	0.9732	0.9764	0.9861
0.2 0.6 0.2	0.9598	0.9731	0.9763	0.9799	0.9919
0.2 0.6 0.25	0.9629	0.9735	0.9764	0.9790	0.9890
0.2 0.6 0.3	0.9591	0.9687	0.9717	0.9757	0.9896
0.2 0.7 0.2	0.9607	0.9732	0.9764	0.9795	0.9911
0.2 0.7 0.25	0.9638	0.9730	0.9761	0.9788	0.9892
0.2 0.7 0.3	0.9540	0.9667	0.9701	0.9729	0.9848

Table 5 (cont…). Percent quantiles (0%, 5%, etc) of the distribution of the ratio of mean length in 2020/2013 in catches across replicate runs in each scenario from 2013 – 2020 for the Constant Harvest HCR.

Watersprings: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	1.0281	1.0356	1.0382	1.0403	1.0468
0.05 0.6 0.25	1.0266	1.0348	1.0371	1.0395	1.0471
0.05 0.6 0.3	1.0197	1.0313	1.0342	1.0372	1.0469
0.05 0.7 0.2	1.0249	1.0340	1.0363	1.0382	1.0455
0.05 0.7 0.25	1.0244	1.0328	1.0352	1.0379	1.0471
0.05 0.7 0.3	1.0162	1.0288	1.0314	1.0347	1.0445
0.075 0.6 0.2	1.0266	1.0343	1.0365	1.0392	1.0468
0.075 0.6 0.25	1.0242	1.0328	1.0355	1.0382	1.0456
0.075 0.6 0.3	1.0156	1.0294	1.0321	1.0350	1.0459
0.075 0.7 0.2	1.0231	1.0321	1.0344	1.0368	1.0476
0.075 0.7 0.25	1.0234	1.0312	1.0336	1.0362	1.0465
0.075 0.7 0.3	1.0177	1.0272	1.0302	1.0327	1.0451
0.1 0.6 0.2	1.0260	1.0328	1.0348	1.0371	1.0456
0.1 0.6 0.25	1.0171	1.0317	1.0338	1.0362	1.0458
0.1 0.6 0.3	1.0132	1.0273	1.0300	1.0333	1.0449
0.1 0.7 0.2	1.0248	1.0305	1.0331	1.0355	1.0411
0.1 0.7 0.25	1.0196	1.0295	1.0322	1.0345	1.0427
0.1 0.7 0.3	1.0161	1.0255	1.0285	1.0311	1.0423
0.15 0.6 0.2	1.0179	1.0295	1.0320	1.0344	1.0412
0.15 0.6 0.25	1.0190	1.0286	1.0309	1.0337	1.0407
0.15 0.6 0.3	1.0146	1.0237	1.0264	1.0291	1.0391
0.15 0.7 0.2	1.0199	1.0285	1.0307	1.0328	1.0393
0.15 0.7 0.25	1.0193	1.0270	1.0292	1.0317	1.0414
0.15 0.7 0.3	1.0129	1.0224	1.0250	1.0280	1.0373
0.2 0.6 0.2	1.0151	1.0268	1.0290	1.0312	1.0394
0.2 0.6 0.25	1.0160	1.0259	1.0282	1.0307	1.0368
0.2 0.6 0.3	1.0092	1.0205	1.0234	1.0259	1.0347
0.2 0.7 0.2	1.0179	1.0255	1.0275	1.0298	1.0359
0.2 0.7 0.25	1.0155	1.0243	1.0267	1.0291	1.0368
0.2 0.7 0.3	1.0093	1.0195	1.0220	1.0246	1.0340

1.4.4 Spawning Biomass Depletion in 2020 Relative to B0

The total spawning biomass remaining in 2006 following both initial depletion and viral mortality as a fraction of the B_0 is as follows (initial dep_viral mortality): 0.3_0.6 = 0.12 (12%), 0.3_0.7 = 0.09 (9%), 0.25_0.6 = 0.1 (10%), 0.2_0.7 = 0.06 (6%), 0.2_0.6 = 0.08 (8%), 0.25_0.7 = 0.075 (7.5%). All the scenarios are greater than these values for total spawning biomass depletion (Figure 8, Table 9) which indicates a rebuilding of stock at all scenarios.

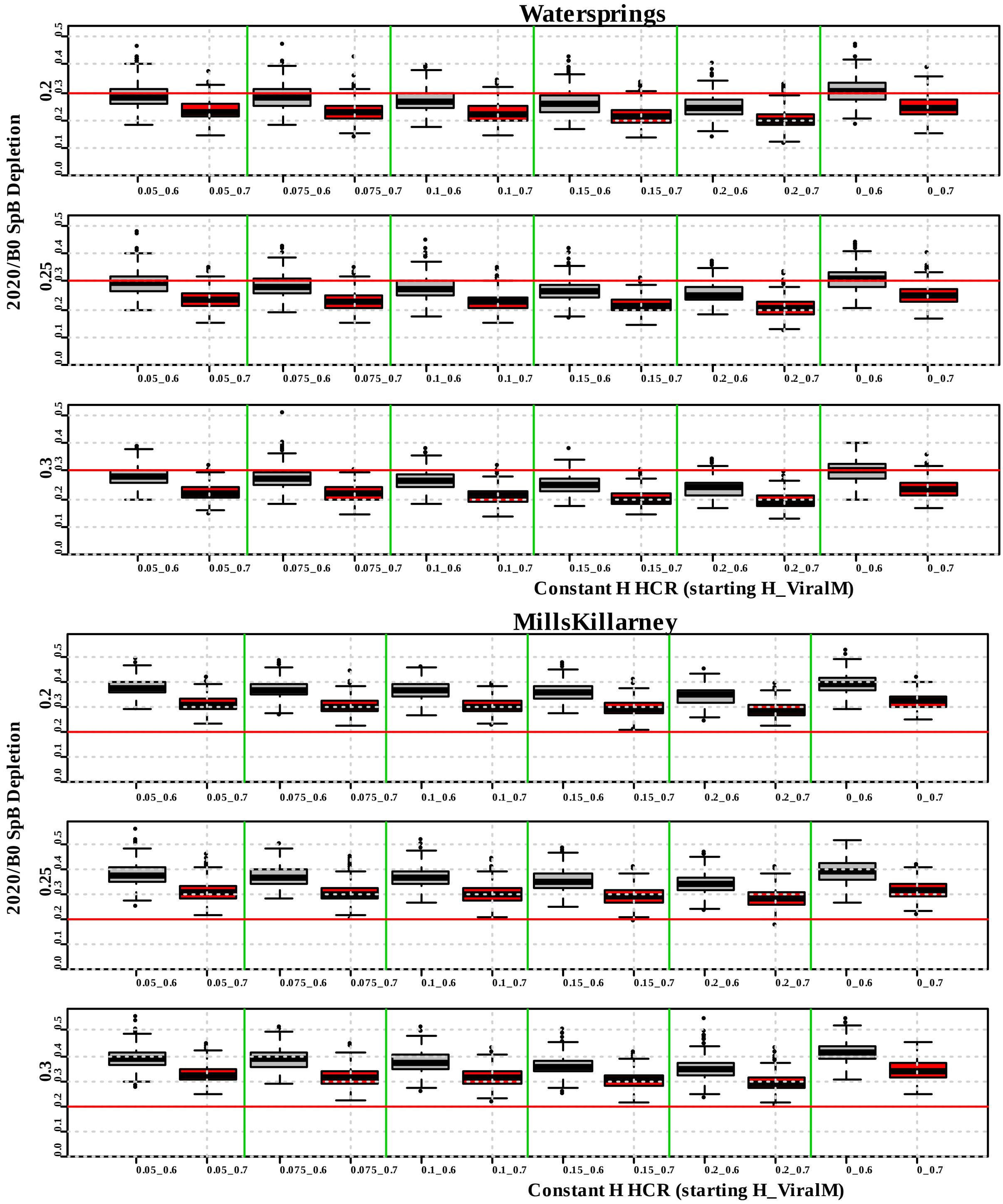


Figure 45. Spawning Biomass Depletion in 2020 relative to the B_0 for 6 scenarios within each of the HCRs. The Constant Harvest HCR is presented. The initial depletion level in

2006 is the annotation to the left of each set of boxplots and each combination of initial H and viral mortality rate is listed under each separate boxplot.

Table A 6. Percent quantiles (0%, 5%, etc) of Spawning Biomass Depletion in 2020 relative to B_0. For the Constant Harvest HCR.

Watersprings: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	0.183	0.257	0.285	0.316	0.466
0.05 0.6 0.25	0.198	0.269	0.294	0.323	0.481
0.05 0.6 0.3	0.197	0.255	0.279	0.305	0.388
0.05 0.7 0.2	0.148	0.211	0.232	0.257	0.372
0.05 0.7 0.25	0.153	0.211	0.232	0.256	0.349
0.05 0.7 0.3	0.146	0.204	0.220	0.242	0.318
0.075 0.6 0.2	0.182	0.255	0.284	0.313	0.473
0.075 0.6 0.25	0.192	0.259	0.283	0.311	0.424
0.075 0.6 0.3	0.180	0.250	0.273	0.297	0.511
0.075 0.7 0.2	0.138	0.206	0.227	0.248	0.424
0.075 0.7 0.25	0.154	0.206	0.228	0.253	0.348
0.075 0.7 0.3	0.143	0.197	0.216	0.239	0.303
0.1 0.6 0.2	0.179	0.244	0.268	0.299	0.398
0.1 0.6 0.25	0.177	0.252	0.277	0.305	0.451
0.1 0.6 0.3	0.178	0.239	0.261	0.287	0.378
0.1 0.7 0.2	0.142	0.198	0.222	0.248	0.344
0.1 0.7 0.25	0.151	0.206	0.225	0.245	0.350
0.1 0.7 0.3	0.137	0.192	0.209	0.229	0.321
0.15 0.6 0.2	0.166	0.233	0.257	0.286	0.425
0.15 0.6 0.25	0.166	0.241	0.264	0.288	0.419
0.15 0.6 0.3	0.175	0.226	0.251	0.274	0.377
0.15 0.7 0.2	0.137	0.191	0.212	0.236	0.333
0.15 0.7 0.25	0.141	0.194	0.213	0.233	0.312
0.15 0.7 0.3	0.141	0.183	0.199	0.219	0.300
0.2 0.6 0.2	0.137	0.224	0.247	0.273	0.403
0.2 0.6 0.25	0.180	0.234	0.252	0.280	0.369
0.2 0.6 0.3	0.165	0.215	0.239	0.256	0.340
0.2 0.7 0.2	0.114	0.180	0.200	0.223	0.329
0.2 0.7 0.25	0.122	0.185	0.203	0.225	0.333
0.2 0.7 0.3	0.129	0.172	0.190	0.209	0.297
0 0.6 0.2	0.181	0.275	0.303	0.333	0.471
0 0.6 0.25	0.207	0.282	0.308	0.335	0.439
0 0.6 0.3	0.199	0.272	0.299	0.323	0.400
0 0.7 0.2	0.155	0.218	0.246	0.277	0.391
0 0.7 0.25	0.164	0.225	0.248	0.271	0.403
0 0.7 0.3	0.162	0.213	0.235	0.255	0.353

Table 6 (cont...) Percent quantiles (0%, 5%, etc) of Spawning Biomass Depletion in 2020 relative to B_0. For the Constant Harvest HCR.

Mills Killarney: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	0.289	0.356	0.377	0.399	0.493
0.05 0.6 0.25	0.248	0.346	0.371	0.403	0.557
0.05 0.6 0.3	0.273	0.361	0.385	0.412	0.551
0.05 0.7 0.2	0.235	0.288	0.311	0.331	0.415
0.05 0.7 0.25	0.214	0.283	0.308	0.330	0.456
0.05 0.7 0.3	0.244	0.303	0.326	0.350	0.442
0.075 0.6 0.2	0.264	0.345	0.369	0.392	0.479
0.075 0.6 0.25	0.278	0.340	0.367	0.397	0.500
0.075 0.6 0.3	0.288	0.359	0.386	0.415	0.511
0.075 0.7 0.2	0.225	0.283	0.300	0.326	0.436
0.075 0.7 0.25	0.202	0.277	0.297	0.323	0.447
0.075 0.7 0.3	0.225	0.290	0.314	0.342	0.448
0.1 0.6 0.2	0.270	0.339	0.363	0.387	0.460
0.1 0.6 0.25	0.266	0.337	0.361	0.392	0.516
0.1 0.6 0.3	0.253	0.345	0.373	0.402	0.514
0.1 0.7 0.2	0.222	0.282	0.299	0.321	0.390
0.1 0.7 0.25	0.208	0.276	0.295	0.322	0.439
0.1 0.7 0.3	0.211	0.287	0.311	0.335	0.426
0.15 0.6 0.2	0.275	0.334	0.353	0.378	0.469
0.15 0.6 0.25	0.248	0.326	0.348	0.380	0.484
0.15 0.6 0.3	0.247	0.335	0.357	0.382	0.505
0.15 0.7 0.2	0.205	0.271	0.294	0.315	0.407
0.15 0.7 0.25	0.194	0.265	0.287	0.311	0.407
0.15 0.7 0.3	0.216	0.279	0.301	0.322	0.414
0.2 0.6 0.2	0.244	0.319	0.346	0.368	0.451
0.2 0.6 0.25	0.229	0.312	0.339	0.367	0.460
0.2 0.6 0.3	0.233	0.319	0.343	0.368	0.541
0.2 0.7 0.2	0.223	0.269	0.286	0.307	0.388
0.2 0.7 0.25	0.174	0.260	0.280	0.307	0.407
0.2 0.7 0.3	0.198	0.268	0.290	0.310	0.430
0 0.6 0.2	0.291	0.366	0.391	0.418	0.522
0 0.6 0.25	0.264	0.358	0.389	0.423	0.514
0 0.6 0.3	0.305	0.384	0.412	0.441	0.545
0 0.7 0.2	0.247	0.302	0.320	0.341	0.412
0 0.7 0.25	0.219	0.291	0.313	0.338	0.415
0 0.7 0.3	0.246	0.313	0.338	0.368	0.450

1.4.5 Spawning Biomass Depletion in 2020 Relative to 2013

For all scenarios, the spawning biomass increases between 2013 and 2020 (Figure 9,Table 10). This relative increase appears less in the case of the 0.2 depletion level (top most boxplot) than for the 0.3 depletion level (lower most boxplot). The relative improvement is greater for the 0.2 depletion (which sits above the red reference line) than for the 0.3 depletion (which sits below the red reference line). This is because the spawning biomass was lower in the 0.2 scenarios than the 0.3 depletion level. Similarly the starting level of the spawning biomass in 2006 was lower in the 0.7 viral mortality scenarios relative to the 0.6 viral mortality and therefore the (2020/2013) ratio for the 0.7 viral mortality appear higher than 0.6. However in absolute terms spawning biomass improved more for the 0.3 depletion level. The differences exhibited between different harvest rates within a given viral mortality rate are relatively minor (Table 10).

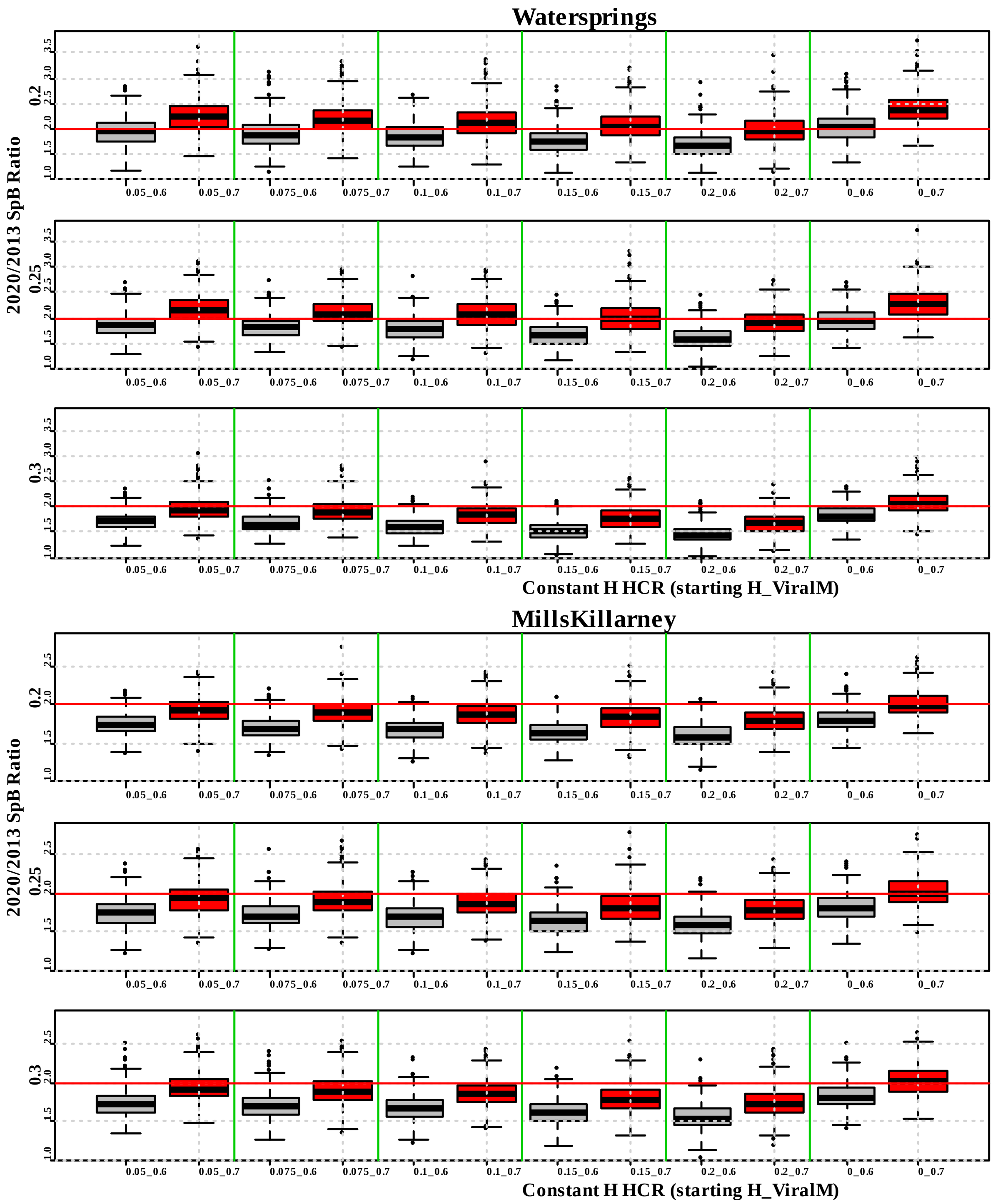


Figure 46. Spawning Biomass Depletion in 2020 relative to that in 2013 for 6 scenarios for the Constant Harvest HCR. In each box plot the initial depletion level in 2006 is along the y-axis and the combination of harvest rate and viral mortality rate is along the x-axis. The two colours identify the two viral mortalities (grey = 0.6, red = 0.7).

Table A 7. Percent quantiles (0%, 25%, etc) of the distribution of Spawning Biomass Depletion in 2020 relative to that in 2013. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

Watersprings: Constant Harvest HCR

Scenario	0	25	50	75	100
0.05 0.6 0.2	1.1974	1.7633	1.9431	2.1426	2.8104
0.05 0.6 0.25	1.2765	1.6862	1.8421	1.9978	2.6831
0.05 0.6 0.3	1.2369	1.5890	1.7095	1.8222	2.3402
0.05 0.7 0.2	1.4549	2.0325	2.2443	2.4467	3.5814
0.05 0.7 0.25	1.4267	1.9830	2.1583	2.3393	3.0728
0.05 0.7 0.3	1.3697	1.8049	1.9363	2.0857	3.0473
0.075 0.6 0.2	1.1475	1.7136	1.8814	2.0744	3.0937
0.075 0.6 0.25	1.3198	1.6601	1.7998	1.9464	2.7060
0.075 0.6 0.3	1.2547	1.5435	1.6555	1.7954	2.5116
0.075 0.7 0.2	1.4201	1.9909	2.1755	2.3818	3.3340
0.075 0.7 0.25	1.4123	1.9429	2.0785	2.2717	2.9701
0.075 0.7 0.3	1.3975	1.7670	1.9034	2.0673	2.7948
0.1 0.6 0.2	1.2587	1.6720	1.8460	2.0549	2.6774
0.1 0.6 0.25	1.1521	1.6231	1.7675	1.9289	2.7857
0.1 0.6 0.3	1.2189	1.4847	1.6047	1.7198	2.1595
0.1 0.7 0.2	1.3150	1.9180	2.1246	2.3301	3.3416
0.1 0.7 0.25	1.2821	1.8739	2.0642	2.2508	2.9374
0.1 0.7 0.3	1.3133	1.6930	1.8230	1.9720	2.8771
0.15 0.6 0.2	1.1198	1.5871	1.7344	1.9265	2.8220
0.15 0.6 0.25	1.1568	1.5123	1.6554	1.8089	2.4335
0.15 0.6 0.3	1.0303	1.3998	1.5156	1.6410	2.0715
0.15 0.7 0.2	1.3598	1.8694	2.0488	2.2485	3.2094
0.15 0.7 0.25	1.3211	1.7883	1.9665	2.1726	3.3092
0.15 0.7 0.3	1.2560	1.6150	1.7549	1.9093	2.5307
0.2 0.6 0.2	1.1220	1.4998	1.6653	1.8349	2.9191
0.2 0.6 0.25	1.0555	1.4595	1.5878	1.7406	2.4518
0.2 0.6 0.3	0.9756	1.3373	1.4411	1.5537	2.0970
0.2 0.7 0.2	1.1339	1.7874	1.9768	2.1802	3.4320
0.2 0.7 0.25	1.2437	1.7266	1.8827	2.0704	2.7298
0.2 0.7 0.3	1.1231	1.5339	1.6660	1.8024	2.4189
0 0.6 0.2	1.3446	1.8430	2.0313	2.2167	3.0750
0 0.6 0.25	1.3947	1.7875	1.9385	2.1078	2.6993
0 0.6 0.3	1.3397	1.7039	1.8184	1.9518	2.3647
0 0.7 0.2	1.6857	2.1972	2.3623	2.5754	3.7420
0 0.7 0.25	1.6293	2.0828	2.2740	2.4623	3.7240
0 0.7 0.3	1.4282	1.9132	2.0531	2.2052	2.9469

Table 7 (cont....) Percent quantiles (0%, 25%, etc) of the distribution of Spawning Biomass Depletion in 2020 relative to that in 2013. Three HCRs are presented: Constant Harvest HCR, Stock Harvest HCR and Gradient CE HCR.

Mills Killarney: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	1.3520	1.6534	1.7322	1.8410	2.1810
0.05 0.6 0.25	1.2228	1.6314	1.7546	1.8739	2.3742
0.05 0.6 0.3	1.3290	1.5960	1.7188	1.8279	2.4898
0.05 0.7 0.2	1.3962	1.8192	1.9332	2.0486	2.4118
0.05 0.7 0.25	1.3486	1.7885	1.9322	2.0579	2.5663
0.05 0.7 0.3	1.4797	1.8156	1.9173	2.0458	2.6208
0.075 0.6 0.2	1.3302	1.6112	1.6940	1.7894	2.1939
0.075 0.6 0.25	1.2616	1.6135	1.7065	1.8290	2.5559
0.075 0.6 0.3	1.2685	1.5751	1.6978	1.7997	2.4025
0.075 0.7 0.2	1.4042	1.7827	1.8993	2.0070	2.7315
0.075 0.7 0.25	1.3373	1.7734	1.8856	2.0247	2.6701
0.075 0.7 0.3	1.3254	1.7698	1.8830	2.0235	2.5237
0.1 0.6 0.2	1.2448	1.5825	1.6735	1.7732	2.0927
0.1 0.6 0.25	1.2218	1.5793	1.6913	1.8136	2.2723
0.1 0.6 0.3	1.1958	1.5567	1.6614	1.7667	2.3108
0.1 0.7 0.2	1.3490	1.7721	1.8839	1.9962	2.4133
0.1 0.7 0.25	1.3776	1.7532	1.8689	1.9867	2.4191
0.1 0.7 0.3	1.3931	1.7369	1.8549	1.9553	2.4260
0.15 0.6 0.2	1.2811	1.5380	1.6346	1.7319	2.0797
0.15 0.6 0.25	1.2454	1.5228	1.6371	1.7540	2.3389
0.15 0.6 0.3	1.1741	1.4926	1.6008	1.7210	2.1782
0.15 0.7 0.2	1.3179	1.7153	1.8380	1.9567	2.5038
0.15 0.7 0.25	1.3684	1.6759	1.8137	1.9599	2.7886
0.15 0.7 0.3	1.3186	1.6530	1.7792	1.9041	2.5399
0.2 0.6 0.2	1.1409	1.4882	1.5852	1.7079	2.0616
0.2 0.6 0.25	1.1603	1.4849	1.5943	1.7018	2.1880
0.2 0.6 0.3	1.0272	1.4358	1.5381	1.6521	2.2962
0.2 0.7 0.2	1.3852	1.6812	1.7972	1.9075	2.4226
0.2 0.7 0.25	1.3062	1.6660	1.7876	1.9106	2.4177
0.2 0.7 0.3	1.1837	1.6216	1.7284	1.8516	2.4227
0 0.6 0.2	1.4503	1.7117	1.8011	1.8959	2.3751
0 0.6 0.25	1.3519	1.7030	1.8075	1.9396	2.3977
0 0.6 0.3	1.3885	1.7175	1.8098	1.9353	2.4905
0 0.7 0.2	1.6241	1.8960	1.9965	2.1060	2.5951
0 0.7 0.25	1.4784	1.8922	2.0089	2.1510	2.7587
0 0.7 0.3	1.5218	1.8836	2.0027	2.1429	2.6436

1.4.6 Exploitable Biomass Depletion in 2020 Relative to 2013

The relative change in exploitable biomass between 2013 and 2020 has a similar pattern to that for the spawning biomass. Once again, the starting level in spawning biomass in 2006 was lower in the 0.7 viral mortality scenarios relative to the 0.6 viral mortality and therefore the ratio for the 0.7 viral mortality appear higher than 0.6 (Figure 10, Table 11). This enabled the ratio between years to be greater in the 0.8 relative to the 0.7 viral mortality scenarios. The change in exploitable biomass is proportionally greater than that which occurred with the spawning biomass.

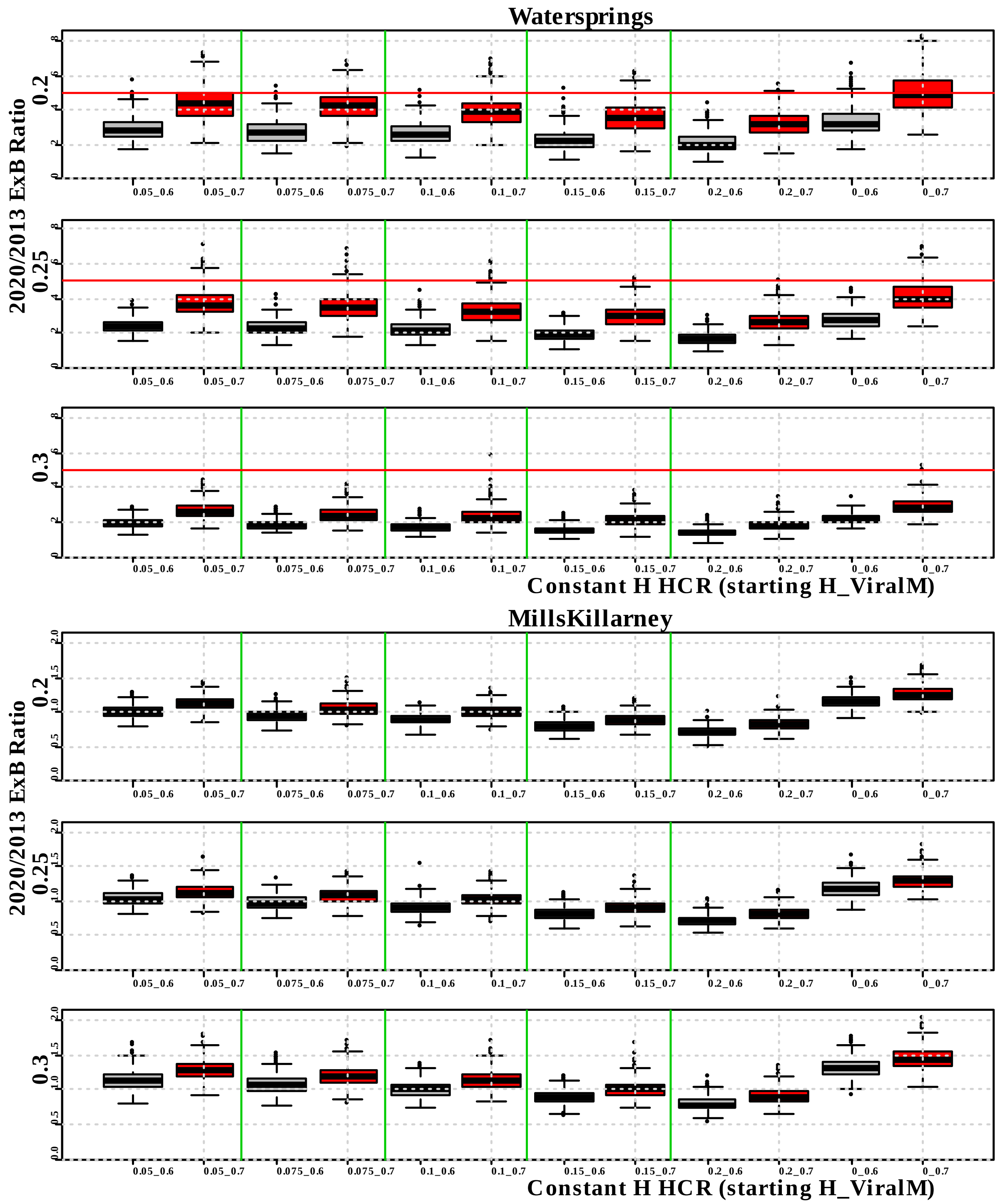


Figure 47. Exploitable Biomass Depletion in 2020 relative to that in 2013 for 6 scenarios for the Constant Harvest HCR. In each box plot the initial depletion level in 2006 is along the y-axis and the combination of initial harvest rate and viral mortality rate is along the x-axis. The two colours identify the two viral mortalities (grey = 0.6, red = 0.7).

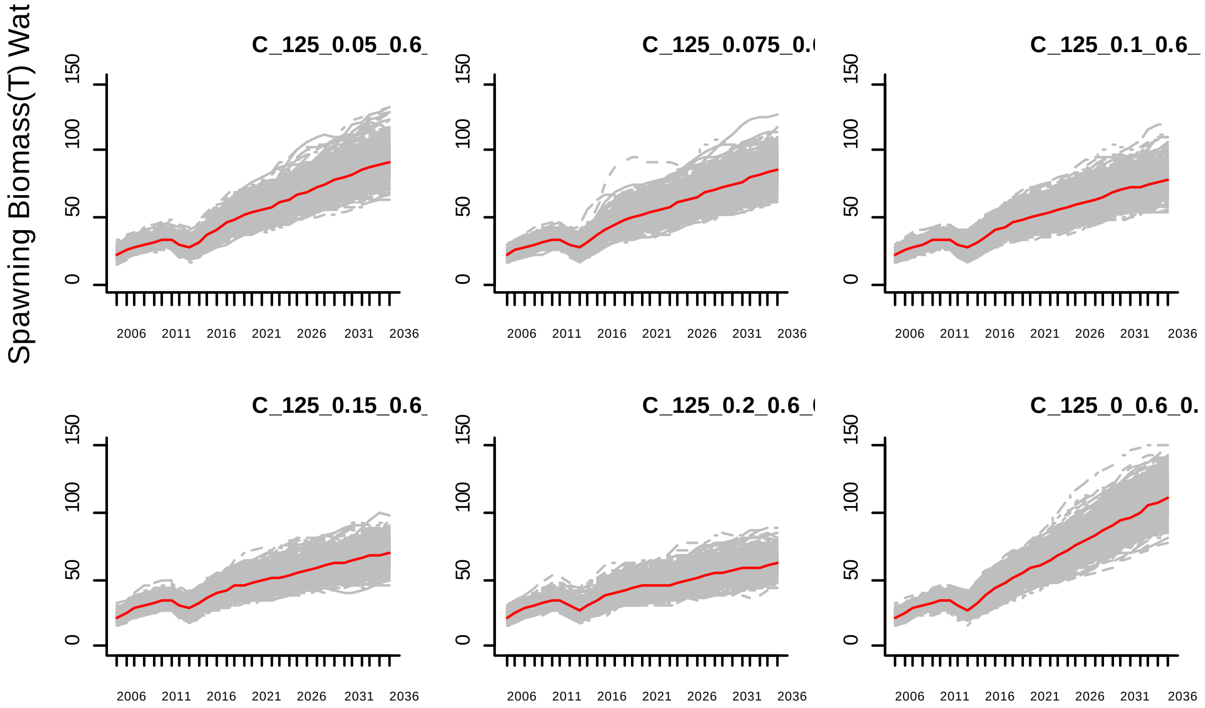
Table A 8. % quantiles (0%, 5%, etc) of the distribution of Exploitable Biomass Depletion in 2020 relative to that in 2013 across replicate runs in each scenario. The Constant Harvest HCR.

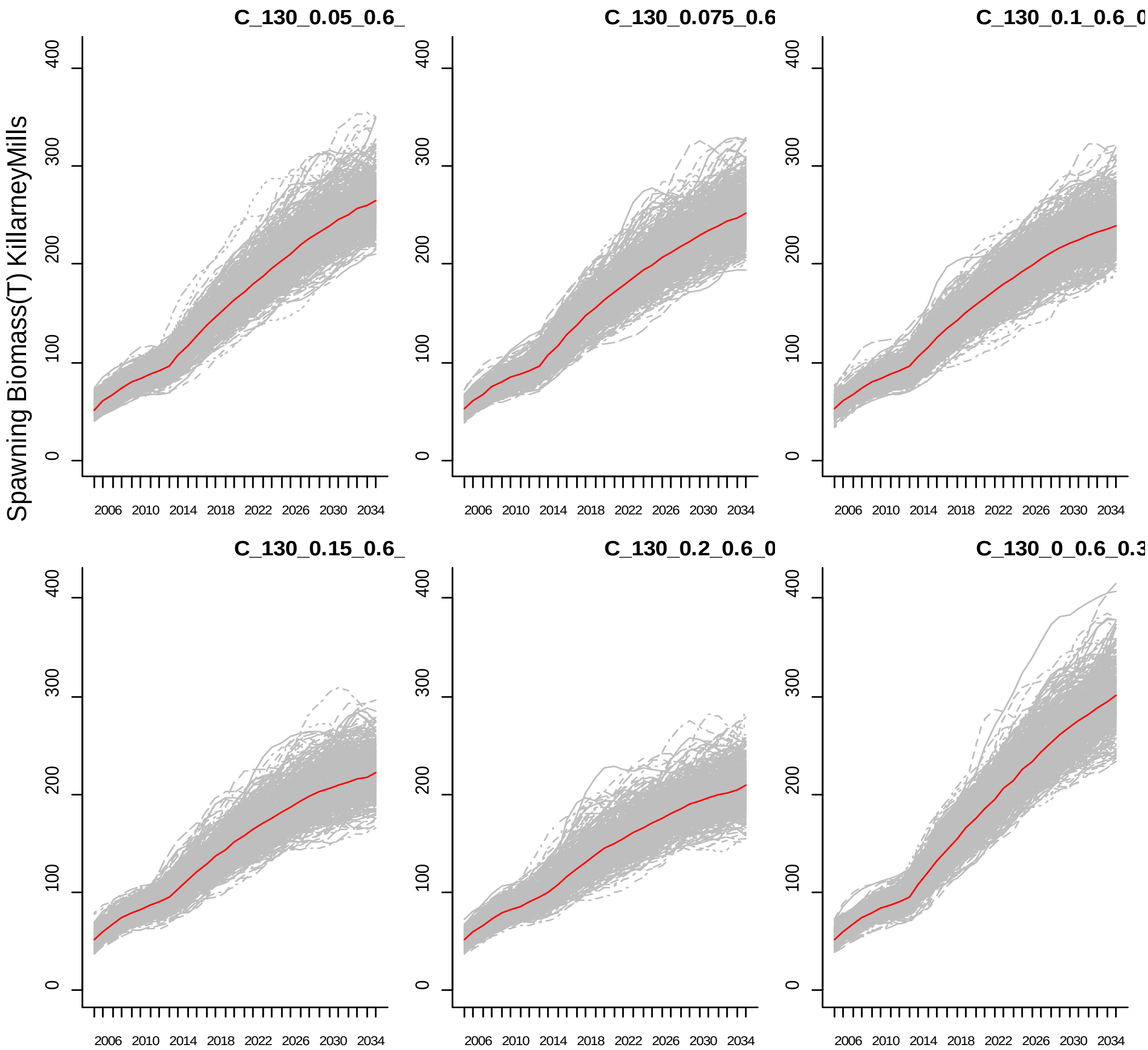
Watersprings: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	1.711	2.481	2.794	3.328	5.705
0.05 0.6 0.25	1.537	2.135	2.415	2.691	3.882
0.05 0.6 0.3	1.301	1.757	1.941	2.131	2.839
0.05 0.7 0.2	2.049	3.683	4.368	4.981	7.220
0.05 0.7 0.25	2.019	3.207	3.655	4.218	7.146
0.05 0.7 0.3	1.588	2.297	2.568	2.939	4.364
0.075 0.6 0.2	1.527	2.244	2.636	3.135	5.316
0.075 0.6 0.25	1.342	2.059	2.286	2.608	4.249
0.075 0.6 0.3	1.332	1.666	1.820	2.002	2.857
0.075 0.7 0.2	1.899	3.651	4.209	4.788	6.830
0.075 0.7 0.25	1.860	3.020	3.463	3.990	6.865
0.075 0.7 0.3	1.473	2.158	2.399	2.674	4.216
0.1 0.6 0.2	1.260	2.169	2.552	3.029	5.075
0.1 0.6 0.25	1.297	1.937	2.163	2.511	4.402
0.1 0.6 0.3	1.177	1.548	1.697	1.862	2.668
0.1 0.7 0.2	1.946	3.330	3.853	4.411	6.885
0.1 0.7 0.25	1.613	2.784	3.191	3.691	6.079
0.1 0.7 0.3	1.373	2.025	2.255	2.559	5.868
0.15 0.6 0.2	1.099	1.904	2.204	2.605	5.231
0.15 0.6 0.25	1.062	1.674	1.902	2.188	3.182
0.15 0.6 0.3	1.040	1.373	1.523	1.669	2.463
0.15 0.7 0.2	1.553	2.970	3.504	4.100	6.151
0.15 0.7 0.25	1.578	2.545	2.958	3.411	5.112
0.15 0.7 0.3	1.113	1.817	2.077	2.349	3.782
0.2 0.6 0.2	1.012	1.709	2.022	2.415	4.323
0.2 0.6 0.25	0.945	1.475	1.703	1.950	2.995
0.2 0.6 0.3	0.820	1.227	1.356	1.502	2.381
0.2 0.7 0.2	1.468	2.706	3.175	3.653	5.521
0.2 0.7 0.25	1.295	2.296	2.628	3.042	5.070
0.2 0.7 0.3	1.056	1.636	1.793	2.042	3.407
0 0.6 0.2	1.782	2.775	3.208	3.764	6.680
0 0.6 0.25	1.724	2.389	2.705	3.069	4.607
0 0.6 0.3	1.610	2.012	2.213	2.405	3.378
0 0.7 0.2	2.531	4.178	4.905	5.718	8.180
0 0.7 0.25	2.364	3.488	4.014	4.689	6.925
0 0.7 0.3	1.910	2.582	2.887	3.223	5.299

Table (8 cont...) % quantiles (0%, 5%, etc) of the distribution of Exploitable Biomass Depletion in 2020 relative to that in 2013 across replicate runs in each scenario. The Constant Harvest HCR.

Mills Killarney: Constant Harvest HCR					
Scenario	0	25	50	75	100
0.05 0.6 0.2	0.805	0.956	1.005	1.065	1.285
0.05 0.6 0.25	0.804	0.961	1.028	1.101	1.366
0.05 0.6 0.3	0.802	1.045	1.132	1.221	1.666
0.05 0.7 0.2	0.842	1.057	1.121	1.188	1.440
0.05 0.7 0.25	0.823	1.063	1.127	1.218	1.625
0.05 0.7 0.3	0.915	1.183	1.270	1.379	1.802
0.075 0.6 0.2	0.740	0.888	0.941	0.999	1.259
0.075 0.6 0.25	0.751	0.898	0.959	1.045	1.339
0.075 0.6 0.3	0.761	0.990	1.063	1.147	1.512
0.075 0.7 0.2	0.788	0.986	1.048	1.116	1.487
0.075 0.7 0.25	0.792	1.005	1.071	1.149	1.424
0.075 0.7 0.3	0.802	1.109	1.186	1.283	1.716
0.1 0.6 0.2	0.687	0.842	0.892	0.946	1.122
0.1 0.6 0.25	0.630	0.843	0.908	0.975	1.524
0.1 0.6 0.3	0.742	0.925	0.998	1.081	1.379
0.1 0.7 0.2	0.744	0.944	0.998	1.065	1.338
0.1 0.7 0.25	0.705	0.950	1.018	1.085	1.419
0.1 0.7 0.3	0.844	1.040	1.128	1.228	1.714
0.15 0.6 0.2	0.602	0.748	0.795	0.852	1.060
0.15 0.6 0.25	0.593	0.752	0.802	0.861	1.127
0.15 0.6 0.3	0.616	0.831	0.887	0.951	1.190
0.15 0.7 0.2	0.661	0.827	0.889	0.944	1.193
0.15 0.7 0.25	0.643	0.838	0.906	0.978	1.344
0.15 0.7 0.3	0.742	0.929	0.999	1.083	1.671
0.2 0.6 0.2	0.488	0.661	0.709	0.757	0.999
0.2 0.6 0.25	0.538	0.668	0.718	0.767	1.028
0.2 0.6 0.3	0.528	0.728	0.782	0.850	1.196
0.2 0.7 0.2	0.610	0.766	0.819	0.878	1.223
0.2 0.7 0.25	0.613	0.751	0.821	0.887	1.137
0.2 0.7 0.3	0.652	0.828	0.899	0.974	1.342
0 0.6 0.2	0.926	1.095	1.149	1.215	1.492
0 0.6 0.25	0.888	1.094	1.176	1.251	1.646
0 0.6 0.3	0.927	1.220	1.311	1.394	1.753
0 0.7 0.2	0.984	1.196	1.263	1.335	1.680
0 0.7 0.25	1.032	1.214	1.292	1.366	1.802
0 0.7 0.3	1.036	1.333	1.435	1.547	2.050

1.4.7 Trajectories of spawning biomass

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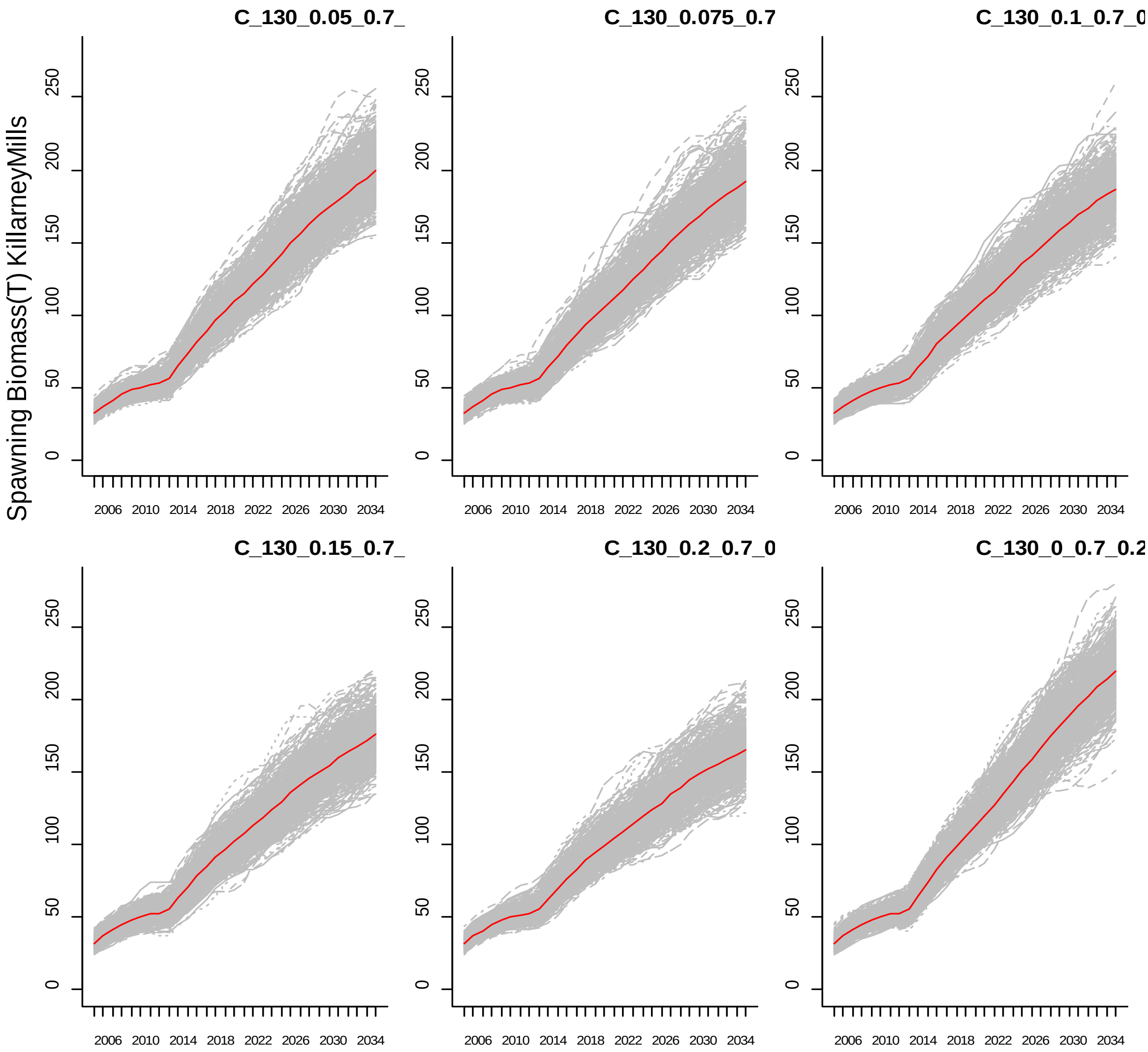
C_130_0.075_0.6
C_130_0.1_0.6_0
C_130_0.15_0.6_
C_130_0.2_0.6_0
C_130_0_0.6_0.3
Spawning Biomass(T) KillarneyMills
0
100
200
300
400
2006 2010 2014 2018 2022 2026 2030 2034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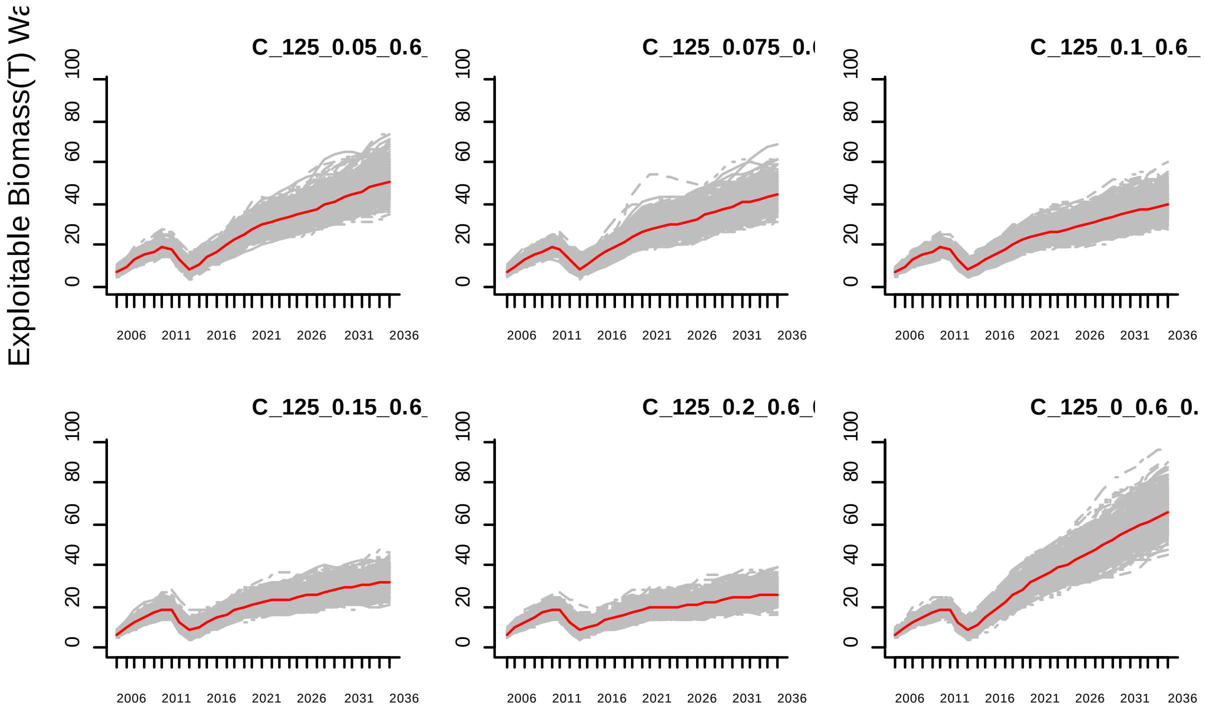
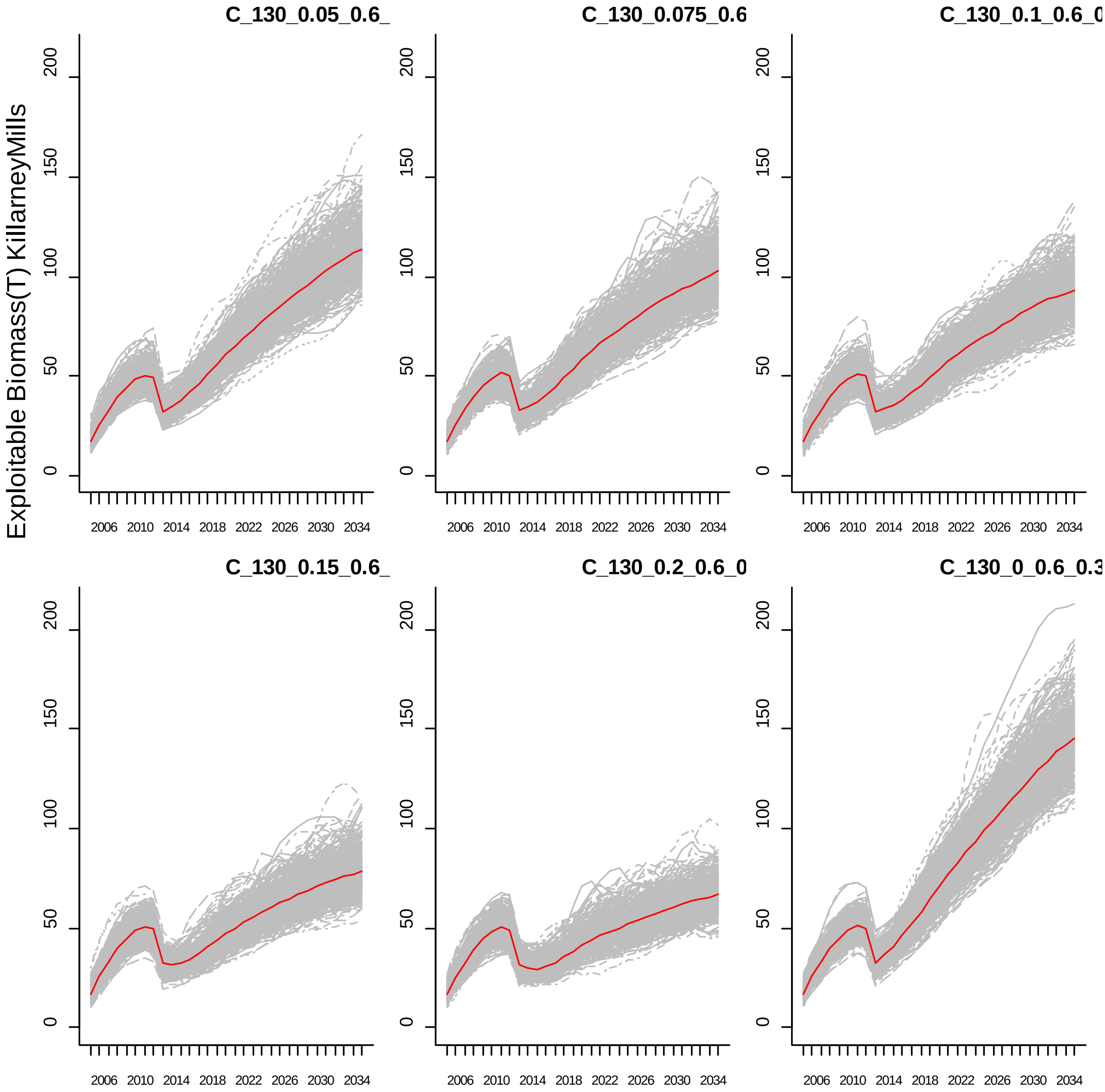
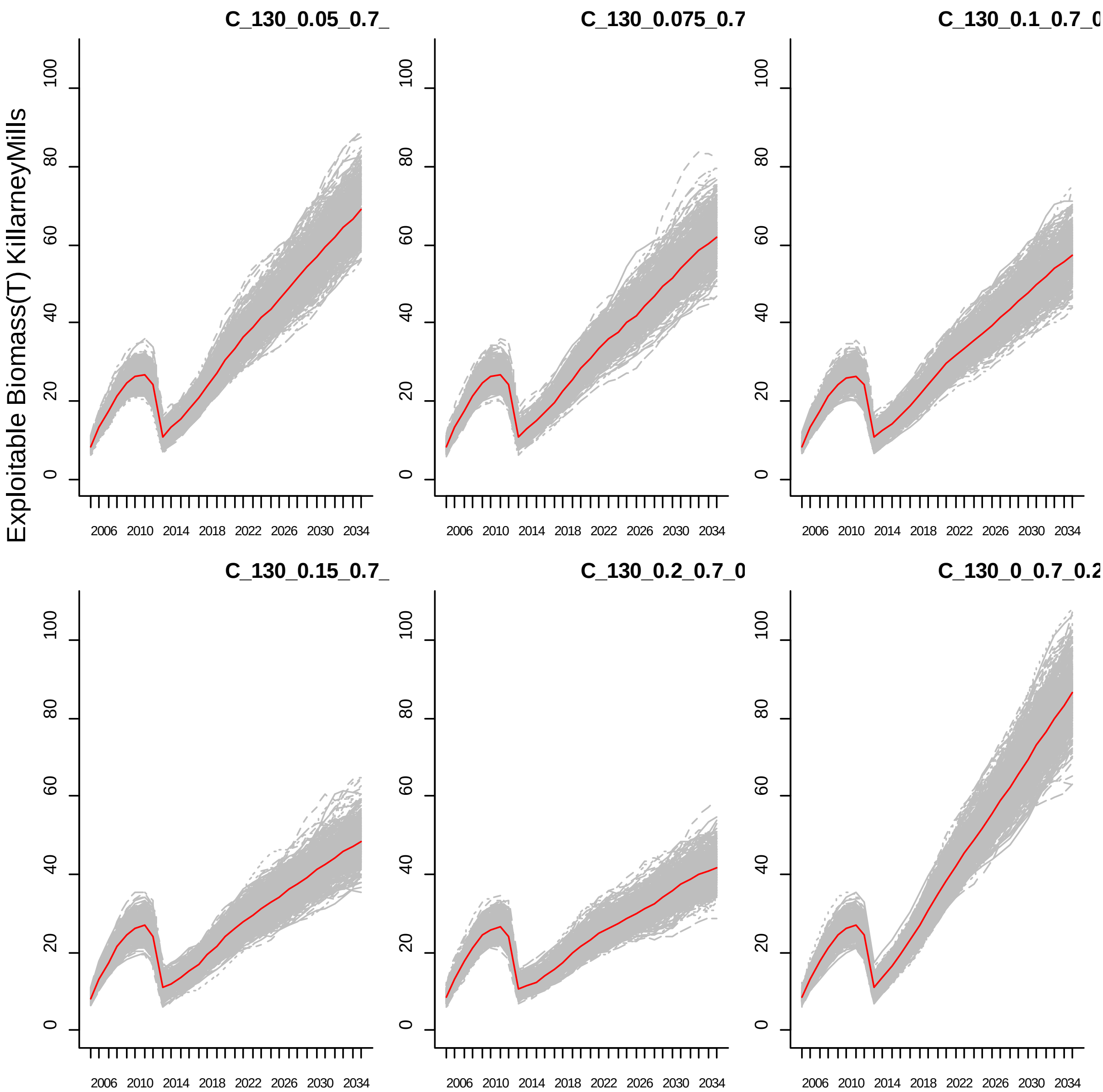
C_130_0.075_0.7
C_130_0.1_0.7_0
C_130_0.15_0.7_
C_130_0.2_0.7_0
C_130_0_0.7_0.2
Spawning Biomass(T) KillarneyMills
0
50
100
150
200
250
2006
2010
2014
2018
2022
2026
2030
2034

1.4.8 Trajectories of exploitable biomass





C_130_0.05_0.6_
C_130_0.075_0.6
C_130_0.1_0.6_0
C_130_0.15_0.6_
C_130_0.2_0.6_0
C_130_0_0.6_0.3
Exploitable Biomass(T) KillarneyMills
0
50
100
150
200
2006
2010
2014
2018
2022
2026
2030
2034



C_130_0.05_0.7_
C_130_0.075_0.7
C_130_0.1_0.7_0
C_130_0.15_0.7_
C_130_0.2_0.7_0
C_130_0_0.7_0.2
Exploitable Biomass(T) KillarneyMills
0
20
40
60
80
100
2006 2010 2014 2018 2022 2026 2030 2034

1.5 Estimating parameters for Mills-Killarney and Watersprings to develop an operating model

1.5.1 Sites

- Watersprings (Portland region): reef code 1.03 and 1WS (old reef code): has the highest catches in the Portland Region, consist of 3 sites in the DPI survey data
- Killarney (Warnambool): reef code 3.10 and 3KN (old reef code); consist of 2 sites in the DPI survey data. Has the highest catches in the Warrnambool region, consist of 2 sites in the DPI survey data.
- Mills (Warnambool): reef code 3.09 consist of 2 sites in the DPI survey data.
- Included as a reference Crags (Port Fairy Region): reef-code 3.05 and 3TC (old reef code); consist of 5 sites. Crags has the highest catches in the Port Fairy Region

Within their respective regions each of the above reefcodes have the highest catches.
[file C:\A_CSIRO\AB_VIC\AbaloneTRF\New files 30 March\Attachment 7]

1.5.2 Growth parameters (MaxDL, L50, L95)

Watersprings had virtually no annual increment data, only the closest was 144 days at liberty (2 data points) and 486 (3 data points). Killarney had only 8 data points at an annual time at liberty. Mills Reef had only 8 data point at a time-at-liberty of 352 days.
Due to insufficient growth tagging data, with annual increments, for Watersprings and Killarney it was necessary to rely on the length frequency distribution to infer growth. Therefore the growth parameters for Watersprings and Killarney, were based on the Crags but with the L95 adjusted according to the max length of the length frequency data. Killarney had the lowest maximum shell length and therefore it was determined that it had the slowest growth of all reef codes. This was consistent with stakeholder's perceptions and reports (see appendix).
The MaxDL was obtained by using the MaxDL for the Crags (19.6747) with a bit of an adjustment for each reef-code depending on the maximum shell length for each reef-code (see length frequency distributions): a higher maximum shell length meant that MaxDL was slightly increased (i.e higher than the Crags which was 19.6747) and a lower maximum shell length (Killarney) meant the maxDL was slightly decreased (i.e lower than the Crags which was 19.6747).

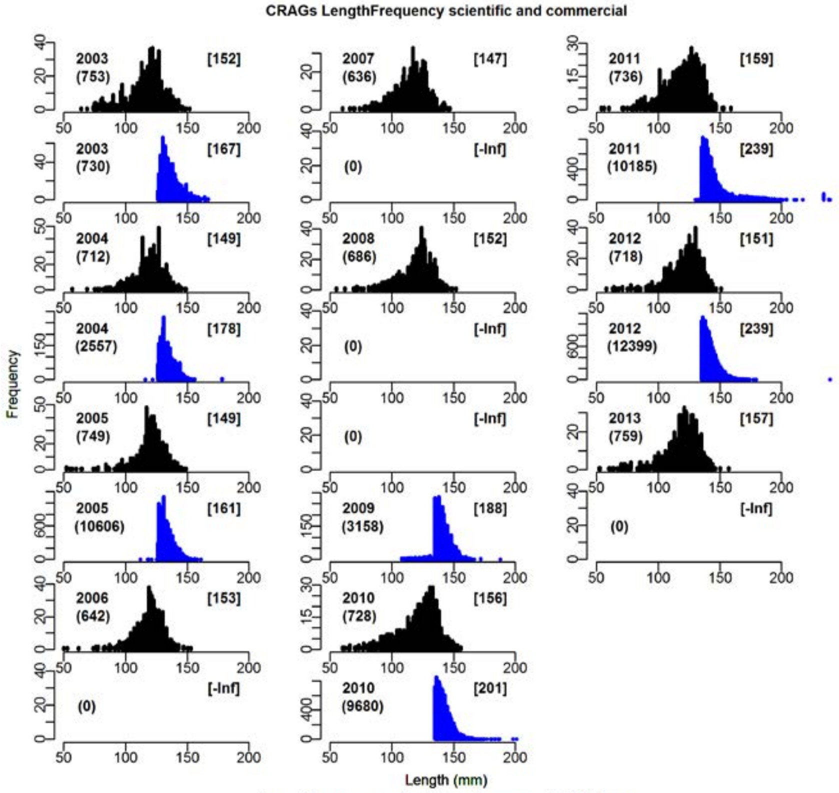
The L50 was based on size at maturity data (SM50) plus 5mm i.e size at 50% of population is mature (SM50) + 5 mm. The 5 mm came from observing the difference between the SM50 and the L50 of the CRAGS which did have both growth and maturity data.

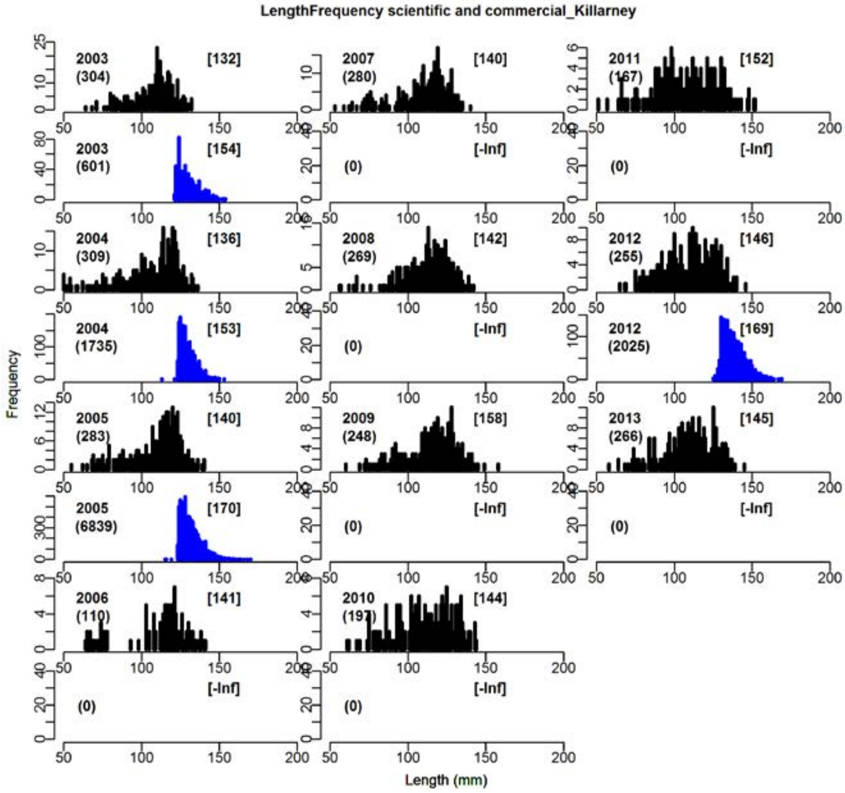
The L95 was determined by visual inspection of the length frequency distributions taking the maximum shell size observed (approximately).

Table A 9. The growth parameters for the inverse logistic operation model for three reefcodes – Crags and the additional reefcodes Watersprings (reef code 1.03 and 1WS old reef code) and Mills/Killarney (Killarney reef code 3.10 and 3KN old reef code). CRAGS parameters Final Revision after stakeholder review for (ReefCode 3.05): Parameters for the length based inverse logistic model with parameters estimated by fitting to tag recapture data using maximum likelihood and the revised parameters following stakeholder review.

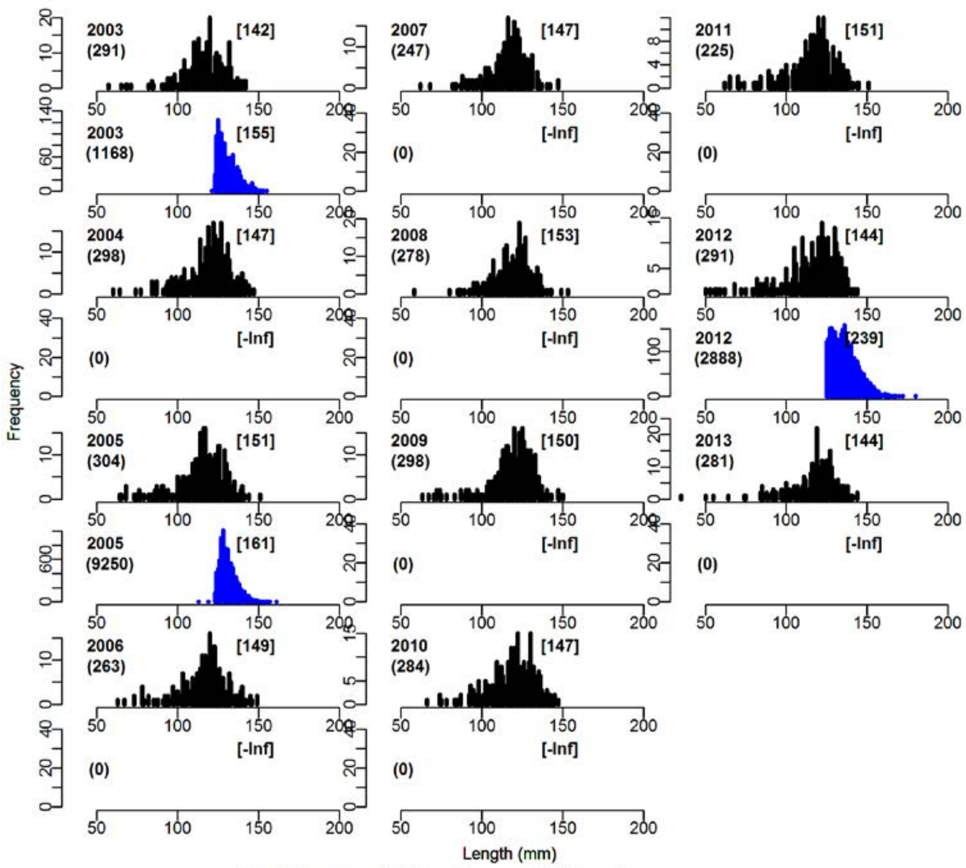
Reefcode	Name	(MaxDL) Juvenile growth rate (mm/yr)	(L50) akin to size at maturity, (mm)	(L95) Mean maximum shell length (mm)
1.03	Watersprings	20	100	160
3.05	Crags	19.6747	109.4345	147.2182
3.09	Mills (combine with Killarney)			
3.10	Killarney	18	105	142.5

1.5.3 Length Frequency

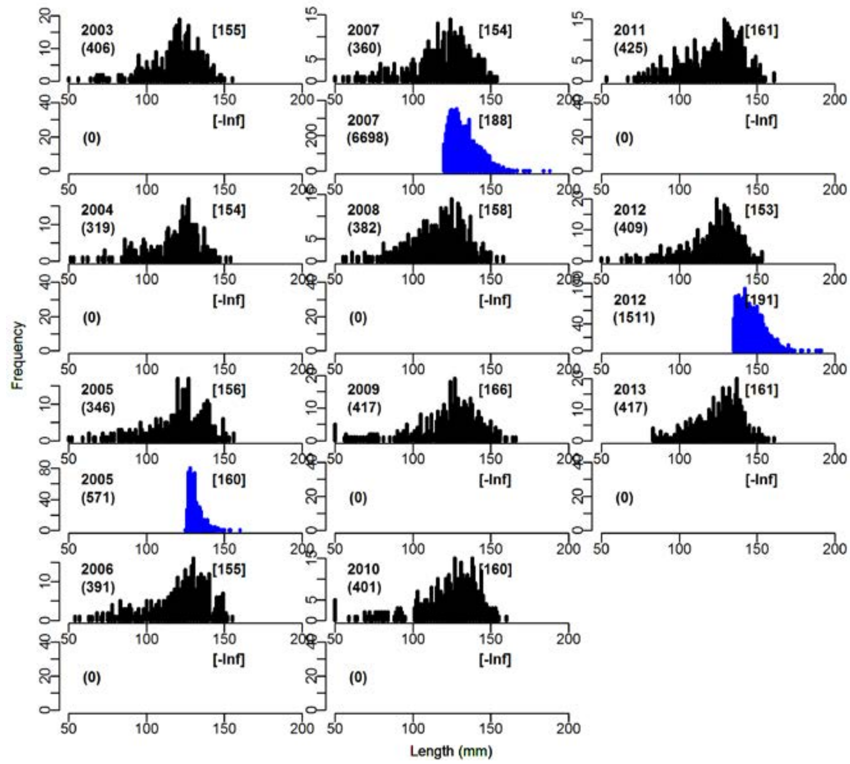




LengthFrequency scientific and commercial_Mills



LengthFrequency scientific and commercial_Watersprings.



1.5.4 Size at maturity

For the Crags the L50 parameter (of the maturity ogive) was provided in the following file (file: C:\A_CSIRO\AB_VIC\AbaloneTRF\analyses\bardos2\Math to F90\ Reefcodematurity.txt)
A table of that file is presented in Table 2. The corresponding L50 parameter for Watersrpings and Killarney presented in table2 were used for those reeefcodes.

Table A 10. The maturity parameters used in the Bardos model for three reefcodes – Crags and two/three additional reef codes Watersprings (reef code 1.03 and 1WS old reef code) Mills (reefcode 3.09) and Killarney (reef code 3.10 and 3KN old reef code). The L50 parameter for the CRAGS (as presented in this table was used in the current MSE.

Reefcode	Name	L50 (Size at 50% maturity)	Phi (from bardos model)
1.03	Watersprings	95.93	15.0
3.05	Crags	102.3	27.738
3.09	Mills	89.5	8.174
3.10	Killarney	98.3	23.584
	Mills_Killarney	100	15.0

1.5.5 Length to weight

Length to weight parameters were developed for all avilable reefcodes and presented are the values for the reefcodes included in the curent simulation (Table A 11). There did not appear to be any length to weight data for Watersprings specifically but other nearby reefcoes were provided (1.02 and 1.06). Mills and Killarney are presented and the Crags is included for comparison purposes.

Table A 11. The parameters of 3 reef-codes in western Victoria (Crags, Mills, Killarney) with weight at length relationships. The weight to length relationship can clearly influence the total weight of animals. Reef code 3.05 is the Crags and Reef code 3.1 is Killarney. There was no data directly from Watersprings.

Zone	Site	ReefCode	Region	latitude	longitude	*a*	*b*	Sigma
Western	Crags	3.05	Port Fairy	-38.3874	142.1393	3.34E-04	2.8573	0.1140
Western	Killarney	3.1	Warnambool	-38.3616	142.3271	3.17E-04	2.8792	0.1056
	Mills	3.09	Warnambool	-38.3654	142.2996	8.05E-05	3.1510	0.1266

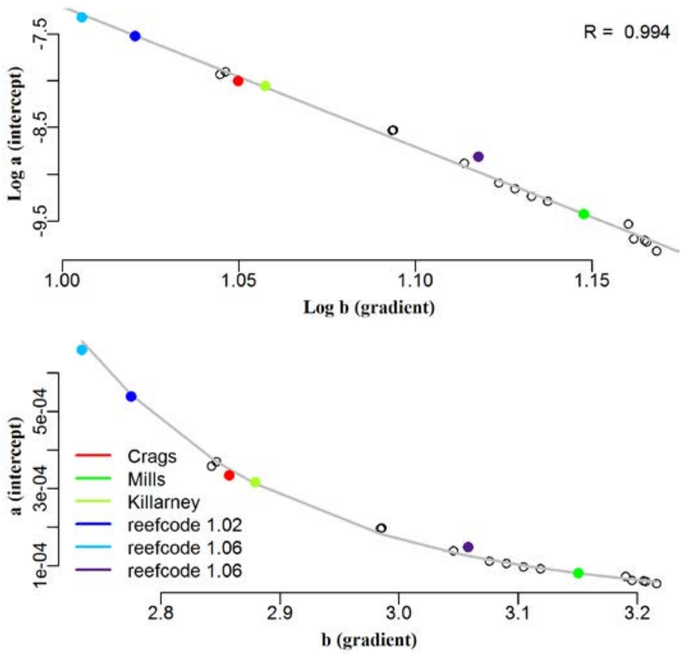


Figure 48. Relationship between the a and b parameters of the Weight at Length relationships for 34 sites around Western Victoria. The relationship is a = 2916.018 x b^-15.173802. The 0.995 is the R^2 for the linear regression of the log transformed data. **With the exception of Watersprings, all the reef codes included in the MSE were included in the analysis. There was no data directly from Watersprings however additional data from nearby reef codes was included (1.02, and two at 1.06) .**

The b parameter is converted to an a parameter using

$$a = 2916.018 \times b^{-15.173802} \tag{21}$$

Where the two parameters *a* and *b* relate length to weight; *a* correspond to the intercept and *b* the gradient.

1.5.6 Viral mortality: Recruits and prerecruits

A fuller description is presented with analyses from DPI diver abundacne survey. A summary of findings is as follows:

- 60 – 70 % for Watersprings (patchy mortality) viral impact was not until late 2007 (Ducan suggests 70 – 80% for some sites in Watersprings and 30 -40% for others)
- 80 – 90 % Killarney (Ducan suggests 70 – 80% make it same as for Crags)
- 70 – 80 % Crags

At waterspings the mortality commenced in 2007 but continued until 2009. The watersrpings kill was patchy (pers comm Duncan Worthington) see appendix

The percent mortality on recruits (size class = > 120 mm) is based on the difference between the mean abundance of 2003-2006, and the mean abundace of 2007. For waterspring viral mortality occurred after 2007 therefore previral (2005-2007) and postvital (2008-2010) (Table A **12**).

Percent mortality preecruits (size class < 120mm) is estimated based on the difference between the mean abundance of 2003-2006, and the mean abundance of 2007 (Table A **13**).

Table A 12 Abundance estimate of recruits (size class = > 120 mm) based on DPI diver surveys.

Reef Code	Site	postvirus	previrus	percent_mort2007
Killarney	123	3.166667	4	20.8
Killarney	124	6.333333	15.68	59.6
Mills	125	3.166667	10.2	69
Mills	126	7.666667	15.6	51
Watersprings	153	8.6	10.8	20.6
Watersprings	154	6.1	3.5	-75.9
Watersprings	155	10.7	14.6	26.8
Crags	129	10.333333	24	57.0
Crags	130	3.666667	14.84	75.3
Crags	131	3.666667	19.0417	80.7
Crags	132	5.166667	23.875	78.4
Crags	133	4.166667	16.8	75.2

Table A 13 Abundance estimate of pre-recruits (size class < 120mm) based on DPI diver surveys.

Reef Code	Site	postvirus	previrus	percent_mort2007
Killarney	123	17.333333	28.2	38.5
Killarney	124	7.833333	48.6	83.9
Mills	125	5.833	15.6	62.6
Mills	126	13.166	42.8	69.2
Watersprings	153	7.1	9.1	22.0
Watersprings	154	4.3	6.1	29.0
Watersprings	155	6.5	19.7	67.1
Crags	129	24.666667	70.2	64.9
Crags	130	4.5	16.16	72.2
Crags	131	6	22	72.7
Crags	132	19.5	83.375	76.6

Figure 49 Estimating percent mortality following viral outbreak based on DPI abundance survey for four reefcodes (Crags, Killarney, Mills and Watersprings)

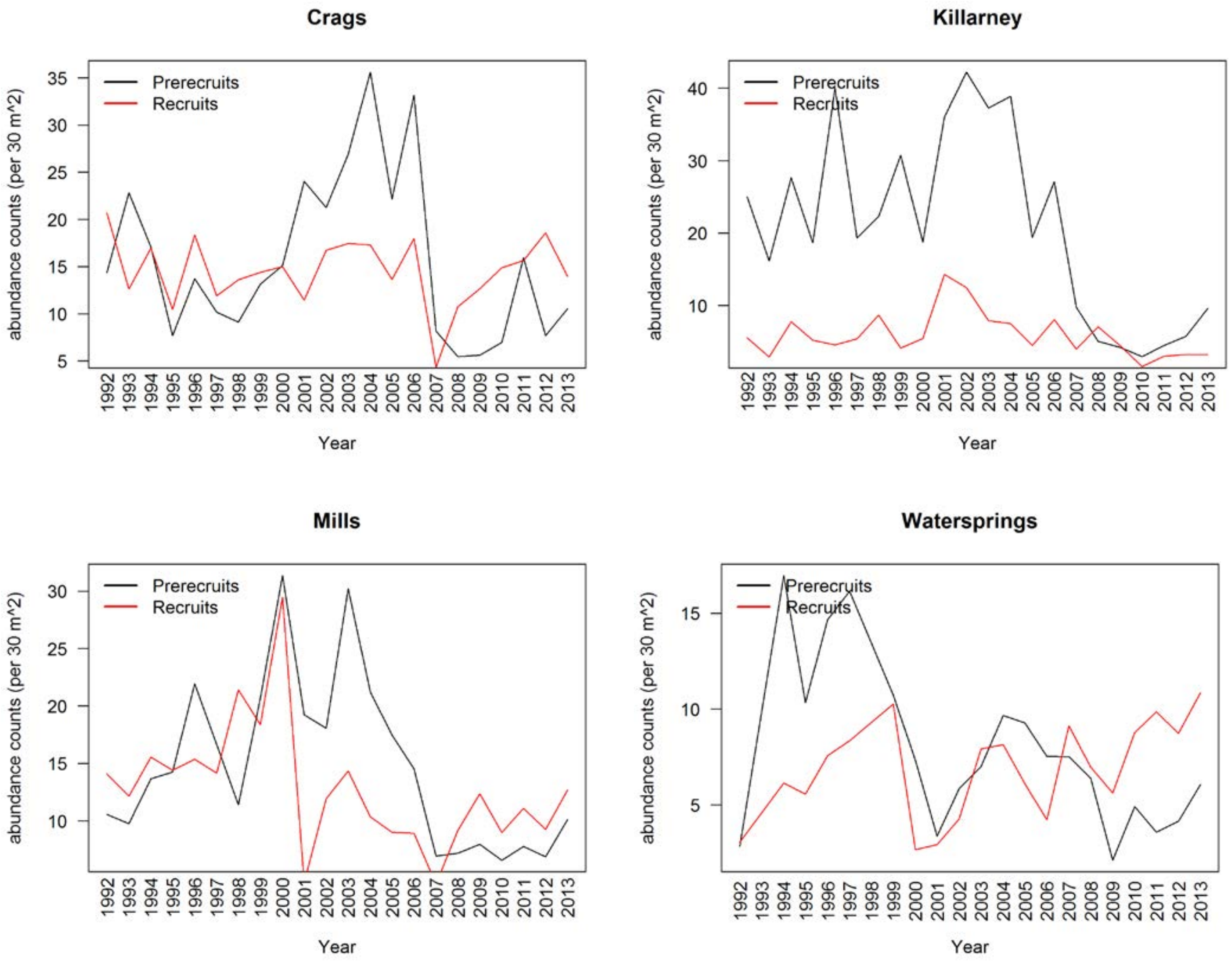


Figure 50. Estimating abundance estimates in multiple sites within each of the four reef-codes using DPI abundance surveys: two sites within the Crags reefcode

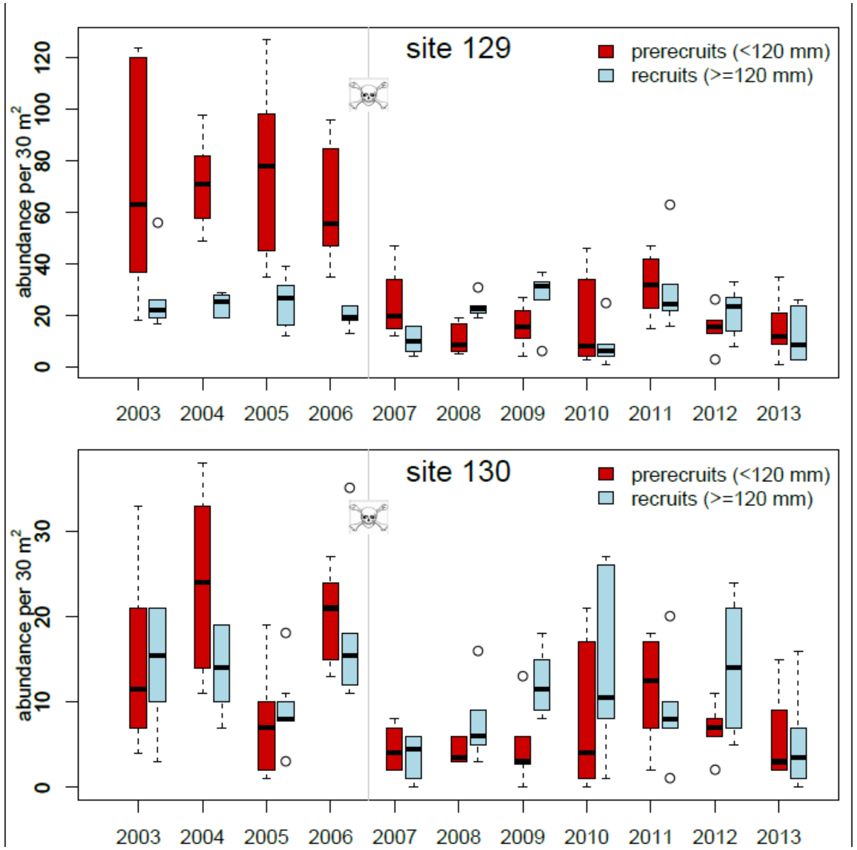


Figure 50 (cont….) Estimating abundance estimates in multiple sites within each of the four reef-codes using DPI abundance surveys: two sites each within the Mills and Killarney reefcodes

Killarney **Mills**

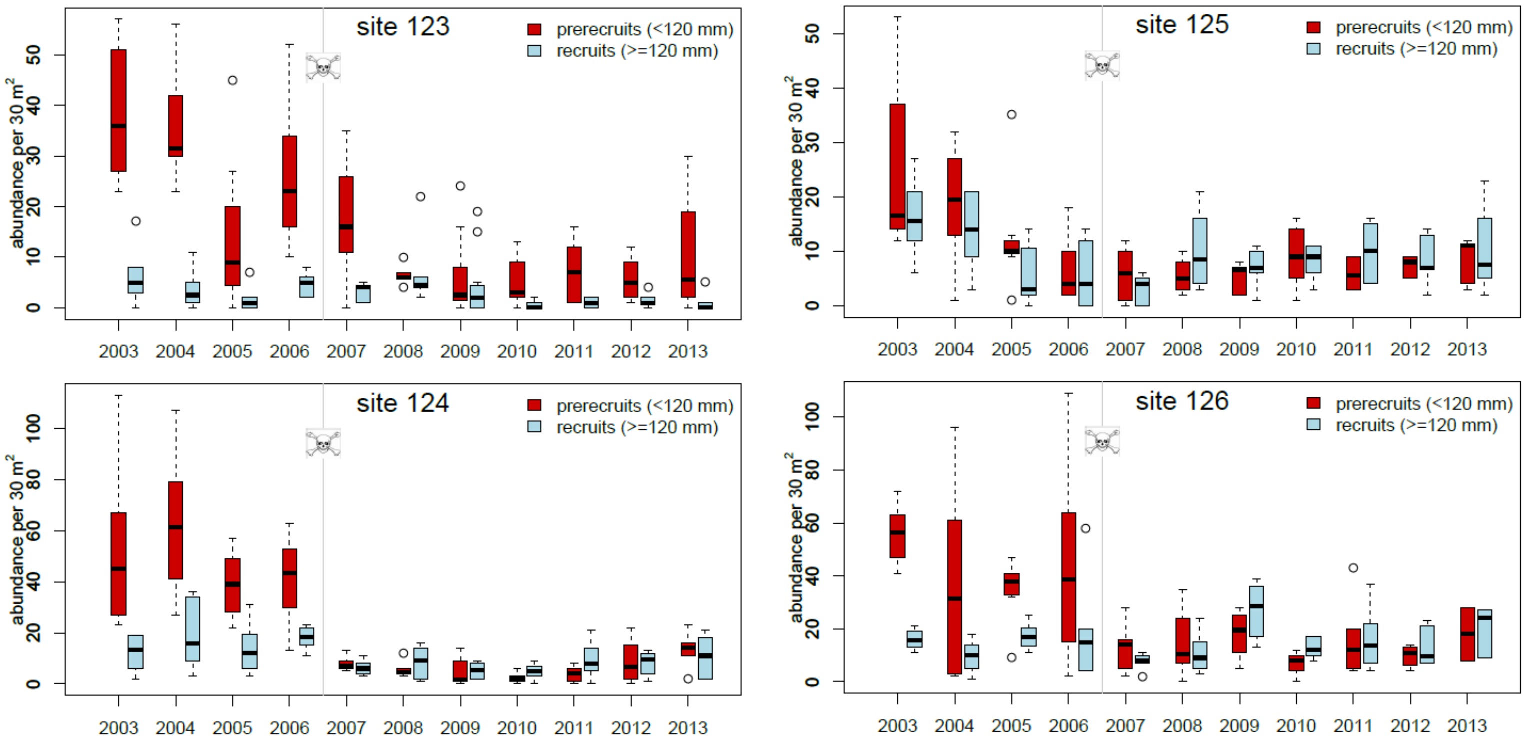
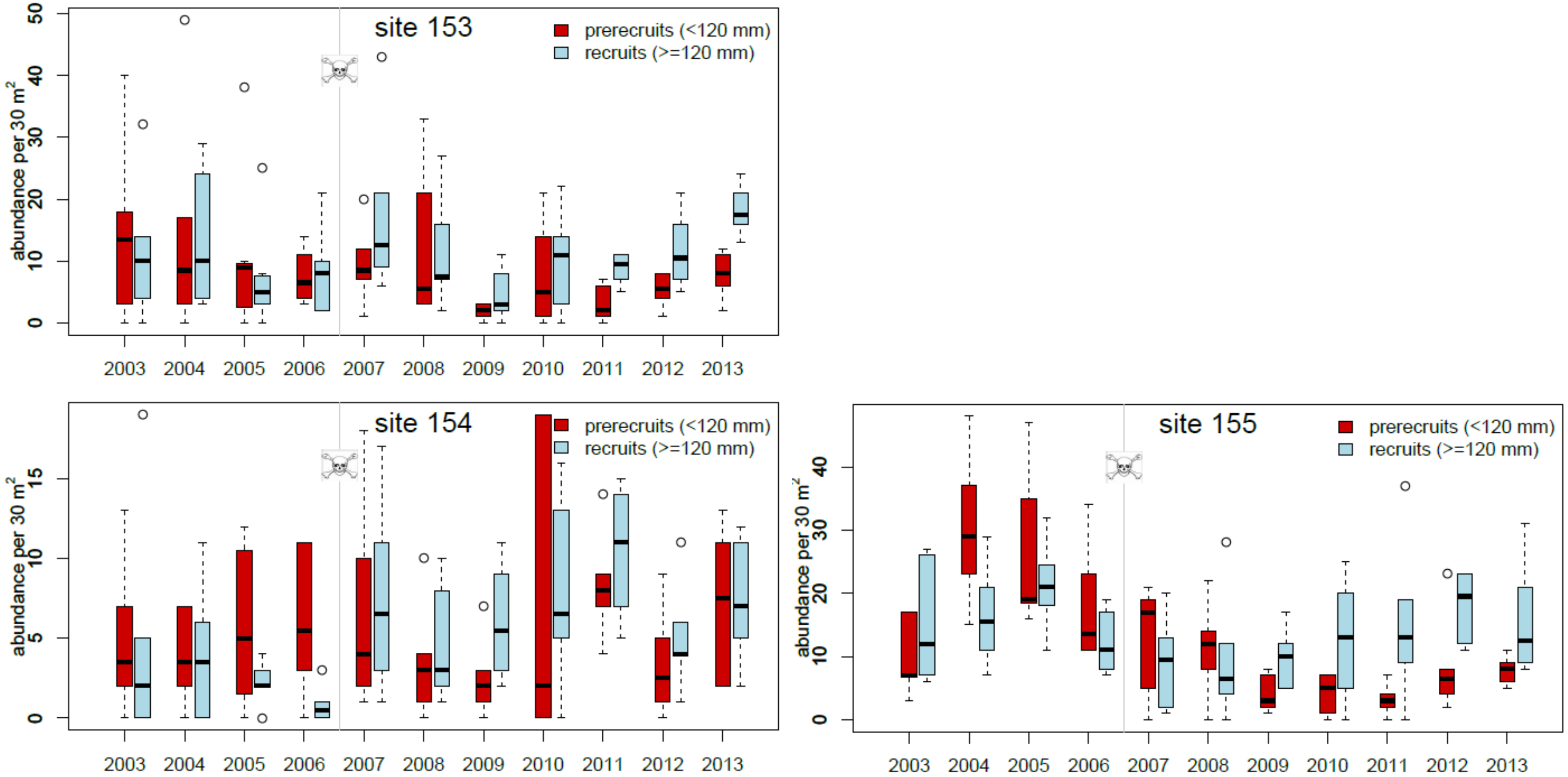


Figure 50 (cont….) Estimating abundance estimates in multiple sites within each of the four reef-codes using DPI abundance surveys: three sites each within the Waterspings reefcode.



1.5.7 Catches and IUU fishing

A low IUU schedule was applied to both Mills, Killarney and the Crags in Gorfine *et. al.* (2008). Following stakeholder advice it was considered that more accessible places such as Mills and Killarney will have higher IUU (pers. Comm. Duncan Worthington).

For Mills and Killarney the IUU was considered to have been higher than that for Crags or Watersprings therefore a separate IUU schedule was developed (Table A **14**). This involved calculating a medium IUU, being average of the low and high IUU schedules that was presented in Gorfine et al (2008). This ‘medium IUU’ proportion was added to the catches this resulted in a spike of catches in some year. Thererefore in order to smooth out the catches (that included IUU) a 5 year moving average was estimated and used in the stock reduction analysis

The Watersprings reefcode was not included in Gorfine *et al* (2008) and therefore the IUU was developed from stakeholder advice. The IUU for Watersprings was considered negligible (10-15 kg, pers comm. Harry Gorfine) and it was suggested to include IUU in the early years (pers. Comm. Duncan Worthington). Therefore a second low IUU schedule was developed specifically for Watersprings (Table A **14**). Historically, commercial misreporting of catches was considered likely at Watersprings as it is a less visible area and therefore even though the IUU schedule was considered lower than the Crags the IUU was equal to the Crags in the early years (1965 - 1980) to take into consideration some underreporting of commercial catches (Table A **14**).

Table A 14. IUU schedules used in the current modelling and the total historical catch with IUU included. Also shown is the commercial catch for the Crags, Watersprings, Mills and Killarney derived from the file: 'catch table.xls' 1965 – 2006. Commercial catches for Mill and Killarney because these were combined in the simulation modelling. For more recent catches refer to AbaloneTRF\\analyses\\WZModelling\\) and C:\A_CSIRO\AB_VIC\AbaloneTRF\New_files_24_Jan\ReefcodeTargetsDec2013update.docx.

qyear	IUU low	IUU low.2	IUU med	IUU high	Crags(3.05)	Crags +IUU low	Watersprings	Waterspring +IUU low.2	Mills (3.09)	Killarney (3.10)	Mills-Killarney	Mills-Killarney +IUU.med	Mills-Killarney +IUU.med (5 yr av)
1965	0.8	0.8	1.15	1.5	3.78863	6.819534	1.276842	2.298316	0.416726	1.27217	1.688896	3.6311264	3.631126
1966	0.8	0.8	1.15	1.5	10.28342	18.51016	3.465713	6.238283	1.131112	3.453032	4.584144	9.8559096	9.85591
1967	0.8	0.8	1.15	1.5	16.77821	30.20078	5.654585	10.17825	1.845499	5.633895	7.479394	16.0806971	25.18444
1968	0.8	0.8	1.15	1.5	39.10406	70.38731	13.17883	23.72189	4.301203	13.13061	17.431813	37.47839795	31.57241
1969	0.8	0.8	1.15	1.5	61.4299	110.5738	20.70308	37.26554	6.756907	20.62732	27.384227	58.87608805	35.40186
1970	0.75	0.75	1.125	1.5	37.55053	65.71343	17.53505	30.68634	4.130325	12.60896	16.739285	35.57098063	39.99442
1971	0.5	0.5	0.85	1.2	35.16841	52.75262	13.60686	20.41029	3.868306	11.80907	15.677376	29.0031456	39.18697
1972	0.25	0.25	0.665	1.08	52.60334	65.75418	12.38316	15.47895	5.786041	17.66349	23.449531	39.04346912	33.64938
1973	0.24	0.24	0.6	0.96	46.88571	58.13828	11.35896	14.08511	5.157137	15.74358	20.900717	33.4411472	32.5281
1974	0.23	0.23	0.535	0.84	45.57853	56.06159	11.26502	13.85598	5.013355	15.30465	20.318005	31.18813768	31.86226
1975	0.22	0.22	0.47	0.72	45.72676	55.78665	8.205602	10.01083	5.02966	15.35442	20.38408	29.9645976	28.95127
1976	0.21	0.21	0.405	0.6	40.99166	49.59991	7.435349	8.996772	4.508827	13.76444	18.273267	25.67394014	27.11751
1977	0.2	0.2	0.415	0.63	38.82265	46.58718	6.366703	7.640044	4.270251	13.03612	17.306371	24.48851497	25.30709
1978	0.19	0.19	0.43	0.67	24.44467	29.08916	6.314539	7.514301	4.188314	12.78538	16.973694	24.27238242	24.06867
1979	0.18	0.18	0.44	0.7	26.98417	31.84132	3.375785	3.983426	3.793148	11.57908	15.372228	22.13600832	24.58036
1980	0.17	0.17	0.45	0.73	40.306	47.15802	5.009	5.86053	4.04548	12.34936	16.39484	23.772518	24.63189
1981	0.16	0.05	0.465	0.77	46.09069	53.4652	11.507	12.08235	4.755246	14.51601	19.271256	28.23239004	26.33762
1982	0.15	0.05	0.475	0.8	27.66462	31.81431	4.162637	4.370769	4.139795	12.63727	16.777065	24.74617088	31.56183
1983	0.14	0.05	0.485	0.83	33.914	38.66196	10.61931	11.15028	5.45034	16.63788	22.08822	32.8010067	39.50668
1984	0.13	0.05	0.5	0.87	38.84	43.8892	6.336	6.6528	7.93839	24.23298	32.17137	48.257055	42.15694
1985	0.12	0.05	0.51	0.9	33.745	37.7944	9.711396	10.19697	10.37619	31.67467	42.05086	63.4967986	45.33744
1986	0.11	0.05	0.52	0.93	22.8977	25.41645	13.81437	14.50509	6.73436	20.55752	27.29188	41.4836576	45.76003
1987	0.1	0.05	0.535	0.97	42.7182	46.99002	9.872	10.3656	6.534328	19.9469	26.481228	40.64868498	40.81225
1988	0.09	0.05	0.545	1	20.812	22.68508	3.815	4.00575	5.576139	17.0219	22.598039	34.91397026	31.18998
1989	0.08	0.05	0.33	0.58	17.4102	18.80302	9.708	10.1934	4.363293	13.31953	17.682823	23.51815459	26.6325
1990	0.07	0.05	0.11	0.15	26.3372	28.1808	5.6279	5.909295	3.42019	10.44058	13.86077	15.3854547	21.73768
1991	0.06	0.05	0.105	0.15	43.3291	45.92885	10.1604	10.66842	4.174984	12.74469	16.919674	18.69623977	20.31612
1992	0.05	0.05	0.1	0.15	34.7996	36.53958	9.167	9.62535	3.628297	11.07585	14.704147	16.1745617	22.0787

1993	0.05	0.05	0.1	0.15	33.7848	35.47404	9.72132	10.20739	6.011125	19.26724	25.278365	27.8062015	23.63418
1994	0.05	0.05	0.1	0.15	31.28549	32.84976	6.562815	6.890956	6.989302	22.40255	29.391852	32.3310372	24.32867
1995	0.05	0.05	0.1	0.15	31.84388	33.43607	3.07272	3.226356	5.007336	16.04983	21.057166	23.1628826	26.28686
1996	0.05	0.05	0.1	0.15	43.92413	46.12034	6.973155	7.321813	4.792408	15.36093	20.153338	22.1686718	27.68664
1997	0.05	0.05	0.1	0.15	25.61538	26.89615	3.67458	3.858309	5.613208	17.99181	23.605018	25.9655198	29.38095
1998	0.05	0.05	0.075	0.1	39.49449	41.46921	10.76828	11.30669	7.699123	24.67772	32.376843	34.80510623	33.46708
1999	0.05	0.05	0.05	0.05	30.31371	31.8294	8.583645	9.012827	9.240707	29.6189	38.859607	40.80258735	35.24292
2000	0.05	0.05	0.05	0.05	26.31342	27.62909	9.6747	10.15844	9.87278	31.64486	41.51764	43.593522	37.57186
2001	0.05	0.05	0.05	0.05	32.57268	34.20131	9.116205	9.572015	7.03152	22.53787	29.56939	31.0478595	36.13587
2002	0.05	0.05	0.05	0.05	20.61497	21.64572	9.43299	9.90464	10.37601	25.44327	35.81928	37.610244	31.73588
2003	0.05	0.05	0.05	0.05	22.9303	24.07682	10.2787	10.79264	11.33815	14.9715	26.30965	27.6251325	28.54848
2004	0.05	0.05	0.05	0.05	26.1384	27.44532	7.6209	8.001945	7.7929	10.11439	17.90729	18.8026545	24.63077
2005	0.05	0.05	0.05	0.05	23.60685	24.78719	9.36475	9.832988	11.37205	14.96747	26.33952	27.656496	17.10872
2006	0.05	0.05	0.05	0.05	10.98285	11.53199	6.84036	7.182378	2.45657	8.45707	10.91364	11.459322	11.58369
2007	0	0	0	0	0	0	14.145	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	3.368	3.368	0	0	0	0	0	0	0
2010	0	0	0	0	3.667	3.667	0	0	0	0	0	0	0
2011	0	0	0	0	4.683	4.683	0	0	0.70089	1.133	1.83389	1.83389	2.678744
2012	0	0	0	0	9.857	9.857	2.132	2.132	1.50546	1.95	3.45546	3.45546	3.34843
2013	0	0	0	0	5.314	5.314	7.114	7.114	2.99437	5.11	8.10437	8.10437	4.464573

1.5.8 LML and VML

Although Mills and Killarney had different LMLs, due to them being managed as separate reef-codes, only one set could be applied in the simulations.

Table A 15. LML and VML for the reef-codes used in the simulation modelling

Mills/Killarney (3.10)				Watersprings (1.03)			
Year	ReefCode	LML	VML	Year	ReefCode	LML	VML
2000	3.10	120		2000	1.03	120	
2001	3.10	120		2001	1.03	120	
2002	3.10	120		2002	1.03	120	
2003	3.10	120	123	2003	1.03	120	125
2004	3.10	120	123	2004	1.03	120	125
2005	3.10	120	123	2005	1.03	120	125
2006				2006	1.03	120	125
2007				2007	1.03	120	
2008	3.10	130		2008	1.03	130	
2009	3.10	130/130		2009	1.03	130	
2010	3.10	130/130		2010	1.03	130	
2011	3.10	130/130	125	2011	1.03	130	
2012	3.10	125/130	130	2012	1.03	135	
2013	3.10	130/130	130	2013	1.03	130	

Report 3: Draft harvest strategy for Western Zone blacklip abalone 2016-2020 based on results of FRDC Project 2012/236 and recent practice

Keith Sainsbury
November 2016

Introduction

The Victorian Wild Harvest Abalone Fishery Management Plan envisages development of a Harvest Strategy, and a process by Government and industry is underway to develop and agree that strategy. The draft harvest strategy here is an input to that process for the Western Zone (WZ) and is a deliverable from FRDC project 2012/236. It is based on a combination of practice about how recommendations for the WZ total allowable catch (TAC) have been developed and made in recent years, plus the Management Strategy Evaluation (MSE) results for FRDC project 2012/236 (Helidoniotis et al. 2015). Recent practice for recommending the WZ TAC has considered several indicators of stock status together with catch limits that are derived from estimates of exploitable biomass and a harvest fraction. FRDC project 2012/236 (Helidoniotis et al. 2015) both calculated maximum sustainable yield and used MSE methods to test the performance of catch control rules for the WZ that are based on various harvest fractions. Performance in relation to achieving stock recovery while maintaining catches was tested across uncertainties in stock dynamics and exploitable biomass estimation.

This draft harvest strategy is based on the two-tiered approach that has been applied for several years in the WZ. That is elaborated further in the decision rules of the draft harvest strategy, but broadly the approach is (i) a TAC is calculated for each of the four Spatial Management Units (SMUs) from an estimate of the exploitable biomass and a desired harvest fraction, with the desired harvest fraction and overall consistency judged by consideration of a range of SMU-wide indicators, and (ii) catch targets/limits are determined for the reefcode groups comprising the SMU based on a range of evidence and consistent with the SMU TAC. The evidence for reefcode recommendations is more qualitative than for SMU recommendations because of the difficulty of adequately monitoring and quantitatively assessing stock status at fine-scales. The Victorian Wild Harvest Abalone Management Plan identifies the SMU as being the unit at which catches, targets and limits will be formally set and regulated. The reefcode catch targets/limits are implemented by co-management arrangements rather than by regulation. This approach recognises the administrative difficulty of managing spatially fine-scale catch limits, the scientific difficulty of assessing stock status and predicting productivity at fine-scales, and the importance of fine-scale catch management to appropriately 'spread the catch' and avoid sequential localised depletion.

The unique context for management of WZ abalone stocks is the outbreak of Abalone Viral Ganglioneuritis (AVG) disease in late 2005 that resulted in significant and spatially variable mortality during 2006 and 2007 (e.g. Gorfine et al 2007). The modelling and analysis from Helidoniotis et al. (2015) concluded that overall:

- Prior to the AVG outbreak the mature biomass had been reduced by fishing to about 30% of the unfished level, which is slightly below the biomass expected to give Maximum Sustainable Yield.
- The AVG mortality was about 70% and it impacted all sizes of abalone.
- In combination the depletion of the mature biomass immediately post-AVG was to about 6-12% of the unfished level, which is below the level at which recruitment is expected to be significantly reduced.

Fishing ceased for 3-5y, depending on reefcode, post-AVG. When fishing resumed low catches and a large minimum legal size were applied to both protect the remaining mature biomass and to allow increase the mature biomass through somatic growth of the survivors. By 2010-11 the mature biomass nearly doubled compared to the lowest level post-AVG, but this was still to a very low level of mature biomass (i.e. depletion in 2011 probably more than 10% but less than 20% of the unfished mature biomass). All immature year classes existing at the time of the AVG were depleted. In addition, the mature biomass in the 2y post-AVG was very depleted and so weak year-classes are expected to have been produced in those years. With the increase in mature biomass by 2010/11 some stronger year-classes are expected to have then been produced. However, about 6y is required for year-classes to grow from settlement to about 100-120mm when they can be reliably detected in the scientific surveys, and about 7y until they substantially contribute to the mature biomass. So the year-class produced in 2010/11 can be reliably detectable from about 2016/17 and would significantly contribute to the mature biomass from about 2017/18. The expectation that stronger year-classes will settle post-2010 assume that AVG impacts and the period of very low mature biomass did not fundamentally disrupt the breeding and recruitment processes. The simulation testing by Helidoniotis et al. (2015) included uncertainties in the relationship between the mature biomass and the breeding success each year but assumed that there has been no fundamental disruption of that relationship. Year-class strength is expected to vary between years because of to fluctuating environmental conditions, and this will be superimposed on any patterns related to AVG impacts and the status of the mature stock (e.g. favourable environmental conditions would could result in strong year-classes on the timeframe expected but unfavourable conditions could result in continued weak year-classes).

While weak year-classes continue to join the mature biomass there is very limited scope for further increase of the mature biomass beyond what can be achieved by somatic growth of the AVG survivors. Without significant recruitment of juvenile abalone the mature biomass is expected to be stable at about the current level for some years, with the duration effected by the fishery harvest, and then to deplete as the current abalone age and die. Because immature abalone are not reliably detected in surveys there is little evidence or warning about the strength of year-classes until they are close to the age of maturity. From this combination of circumstances it is important that there are mechanisms for timely management intervention if the expected stronger yearclasses do not materialise or if the mature biomass begins to decline from its recent level, and both of these are addressed through 'breakout rules' in this draft harvest strategy.

This draft harvest strategy is proposed to operate until 2020. This is because most harvest fraction options and stock projections in Helidoniotis et al. (2015) were evaluated to 2020, though some consequences were calculated to 2036. Consequently, it would be appropriate to review and as necessary revise the harvest strategy in 2020. Further, there are many uncertainties about the stock and the effects of AVG that could cause the harvest strategy to not perform as intended, and so 'break-out rules' are linked to limit reference points that are intended to detect serious departure from the expected recovery trajectory. The draft harvest strategy also includes recommendations for ongoing research and development of the WZ Harvest Strategy.

Objectives

Objectives of the Victorian Fisheries Act (1995) are:
(a) to provide for the management, development and use of Victoria's fisheries, aquaculture industries and associated aquatic biological resources in an efficient, effective and ecologically sustainable manner;
(b) to protect and conserve fisheries resources, habitats and ecosystems including the maintenance of aquatic ecological processes and genetic diversity;
(c) to promote sustainable commercial fishing and viable aquaculture industries and quality recreational fishing opportunities for the benefit of present and future generations;
(d) to facilitate access to fisheries resources for commercial, recreational, traditional and non-consumptive uses;
(e) to promote the commercial fishing industry and to facilitate the rationalisation and restructuring of the industry; and
(f) to encourage the participation of resource users and the community in fisheries management.

The Victorian Wild Harvest Abalone Fishery Management Plan (2014) has an overarching objective to "optimise the commercial, social and cultural value to Victoria derived from the use of fisheries resources and associated ecosystems", and has specific objectives to
(1) rebuild or maintain abalone stocks;
(2) secure access to the resource for commercial and recreational fishing;
(3) enable improvements in economic productivity;
(4) empower effective industry representation, organisation and funding;
(5) ensure fisheries compliance; and
(6) target monitoring and research.

Operational Objectives

The operational objectives of this draft harvest strategy are to:

(i) *rebuild, and then maintain, the mature biomass to levels giving maximum economic yield (MEY), and*
(ii) *avoid recruitment overfishing with high probability.*

These operational objectives combine aspects of objectives a, b and c of the Act and objectives 1 and 3 of the Management Plan. Consequently, the draft harvest strategy focuses on indicators, targets, limits and decision rules for management of the commercial fishery, and on the monitoring and research needed to support the management decision process. It does not address the broader objectives of the Act or Management Plan, such as cross-sectoral resource sharing and management, compliance, representation and participation, funding or restructuring. These broader objectives can be included as appropriate during further development of the Harvest Strategy.

Elaborating these operational objectives:

(i) Rebuild, and then maintain, the mature biomass to levels giving maximum economic yield (MEY).

The Commonwealth Harvest Strategy Policy draws on numerous studies to provide the default recommendation that the stock biomass giving MEY is 1.2 times the biomass giving maximum sustainable yield (MSY). This recommendation is used here.

The mature biomass depletion giving MSY was estimated by Helidoniotis et al. (2015) for three reefcodes selected to span the range of productivity expected among reefcodes in the WZ. The mature biomass depletion, from the unfished level, giving MSY for these reefcodes ranged from 0.34 to 0.37. So the depletion giving maximum economic yield is expected to range from 0.41 to 0.44 among reefcodes. Helidoniotis et al. (2015) also show that the yield-fishing mortality curves for WZ abalone are relatively 'flat topped'. Consequently, the yield is not very sensitive to depletion in the vicinity of MEY, although higher values (i.e. less depletion) will give a higher commercial catch rate and provide greater protection for less productive reefs.

From this the *long-term operational objective* is to recover the mature biomass to 0.43 of the unexploited level, which is the approximate mid-point for MEY depletion across reefcodes modelled.

The modelling by Helidoniotis et al. (2015) indicates that it is not biologically possible to rebuild the mature biomass to 0.43 of the unexploited level by 2020, even in the absence of fishing. However, under a harvest fraction of 0.1 the mature biomass is expected to rebuild to a depletion of 0.24-0.37 by 2020, which represents rebuilding to 54% to 84% of full recovery. This harvest fraction is accepted here as giving an appropriate balance between catch and recovery.

From this the *short-term operational objective* for this harvest strategy is to recover the mature biomass to 0.3 of the unexploited level by 2020, the approximate midpoint of the expected recovery by 2020 with a harvest fraction of 0.1

(ii) Avoid recruitment overfishing with high probability.

Depletion of mature biomass to below 0.2 of the unfished mature biomass is a commonly used threshold for recruitment overfishing and as a limit reference point. In the absence of specific estimation of this threshold for the WZ abalone populations this value is used here. The Commonwealth Harvest Strategy Policy requires that this limit reference point be avoided with 90% probability, and this is also applied here.

The *long-term operational objective* is to maintain the mature biomass above 0.2 of the unexploited level with at least 90% probability.

The *short-term operational objective* for this harvest strategy is to recover the mature biomass to greater than 0.2 of the unexploited level by 2020. The modelling by Helidoniotis et al. (2015) indicates a very high probability that this will be achieved with a harvest fraction of 0.1.

Indicators

This draft harvest strategy uses two level of indicator - primary and secondary. Primary indicators are those for which reference points (and consequently performance measures) can be provided and/or that are input to specified decision rules. In this draft harvest strategy these are typically used at SMU scales and are inputs to the harvest fraction decision rule or 'break-out' rules. Secondary indicators are those that are used in a weight of evidence assessment of stock status, both as a consistency check on the primary indicators and for assessment at reefcode or finer spatial scales.

The primary indicators are the exploitable biomass, the mature biomass, and the number of abalone recruiting to the mature biomass.

The Operational Objectives relate to depletion from the unfished biomass but there is not an annual quantitative assessment to provide that indicator directly. Consequently, there is reliance on the combined interpretation of less direct measures of status and the expected adequacy of the decision rule based on biomass and a harvest fraction. The ratios of current mature biomass to mature biomass in 2013, a time when biomass estimates are available and that included the MSE modelling, provides an indicator of stock status that can be related to the expected recovery under the decision rule based on biomass and a harvest fraction. Also, these primary indicators are considered and interpreted through 'weight of evidence' evaluation of consistency across the secondary indicators at both SMU and reefcode levels.

The estimates of both mature biomass and exploitable biomass are described here as being calculated from the density measured from scientific surveys. In the course of application of this harvest strategy methods to estimate density of exploitable biomass from GPS logger data should be developed, evaluated and, as appropriate, included as a primary indicator. Further, the calculation of biomass from density requires an estimate of the relevant area of abalone habitat. The accumulating GPS logger data, along with information from LIDAR observations and habitat modelling, can provide information to update this estimated habitat area. In the course of this harvest strategy methods to update the relevant habitat area for use in biomass calculation should be developed, evaluated and, as appropriate, included in the biomass calculation methodology.

Primary indicators by SMU

1) Mature stock biomass estimated from the scientific surveys, and the ratio of mature biomass in the current year (y) to that in 2013 ($MB_{y:2013}$).
2) Exploitable biomass estimated from the scientific surveys.

3) Standardised numbers of ‘pre-recruits’ (i.e. less than 120mm, and mostly 100-120mm) estimated from scientific surveys, and a pre-recruit indicator each year (PR_y) that is a two-year running average of the standardized pre-recruit numbers in years y and y-1.

Secondary indicators by SMU

1) Commercial catch and size composition
2) Commercial catch per unit effort, nominal and standardised
3) Numbers of ‘recruits’ (larger than 120mm) estimated from the scientific surveys
4) Recreational fishing catch
5) Indigenous fishing catch

Secondary indicators by reefcode or finer scale

1) Commercial catch and size composition
2) Commercial catch per unit effort, nominal and standardised
3) Numbers of ‘pre-recruits’ (less than 120mm) estimated from scientific surveys
4) Numbers of ‘recruits’ (larger than 120mm) estimated from the scientific surveys
5) Commercial diver qualitative observations
6) Recreational fishing catch and qualitative observations
7) Indigenous fishing catch and qualitative observations

Reference points

The reference points for depletion of the mature biomass from the unfished level are clear from the Operational Objectives, and if depletion estimates are available then they can be inreroreted directly in relation to the reference points implied by the Operational Objectives. However, it is not expected that depletion estimates will be routinely available in the next few years because it is not intended to conduct formal stock assessments every year. Instead the reference points must be based on relative change of empirically measured indicators – specifically the ratio of mature stock biomass in the current year to that in 2013 and the ratio of current ‘pre-recruits’ to those pre-AVG (i.e. standardised pre-recruit numbers for 2003-2006 inclusive). These reference points are intended to track and recognise whether recovery is occurring as expected for the harvest fraction that is applied by the strategy. The ratio of mature stock biomass in the current year to that in 2013 allows comparison of actual recovery of the mature stock with that expected on the basis of the MSE modelling. The ratio of current ‘pre-recruits’ to those in 2003-2006 relates to critical expectations about recovery in the numbers of juvenile abalone post-AVG that, if incorrect, would require a major reconsideration of the harvest strategy through triggering of ‘break out rules’.

There are three reference points:

1. *Target reference point for the ratio of mature stock biomass in the current year to that in 2013*.

The modelling shows that achieving the operational objective for mature stock recovery to the range 0.24-0.37 relative to the unfished level by 2020 is equivalent to an increase in the spawning biomass relative to 2013 in the range 1.60-1.88 over the same period. The ratio of the mature biomass (MB) indicator for any year (y) to that in 2013 is $MB_{y:2013}$. The target is to achieve a mature stock increase relative to 2013 levels in the range 1.60-1.88 by 2020, and the midpoint of this range is approximately 1.7.

- the *target reference point* for $MB_{y:2013}$ by the end of the period to 2020 is 1.7.

2. *Limit reference point for the ratio of mature stock biomass in the current year to that in 2013.*

The current mature stock biomass comprises the survivors of the AVG mortality. In the absence of the expected increase in recruitment of young abalone this biomass will ultimately decline rather than recover as intended. The limit reference point for the ratio of mature stock biomass in the current year to that in 2013 identifies a point beyond which it is prudent to further protect the remaining mature stock. This reference point for the mature stock biomass is approximately the lowest level observed post-AVG.

- the *limit reference point* for $MB_{y:2013}$ is 0.5. This limit reference point is applicable each year throughout the period of the draft harvest strategy.

3. *Limit reference point for the standardised number of ‘pre-recruits’ (i.e. less than 120mm and mostly 100-120mm) compared to the number prior to AVG mortality.*

Modelling indicates that a harvest fraction of about 0.1 allows both good stock recovery and ongoing moderate fishery yields, but this assumes that the fundamental breeding and juvenile recruitment processes are not disrupted. A limit reference point for the number of ‘pre-recruits’ estimated from scientific surveys relative to the average number pre-AVG is used here to identify a point beyond which it is prudent to conclude that unanticipated disruption or delay to recruitment processes has occurred and that the remaining mature stock biomass needs additional protection. For this the pre-AVG reference period is 2003-2006 inclusive; pre-recruit numbers from earlier years were not included because standardised numbers are not currently available. Modelling predicts that the expected stock recovery is associated with pre-recruit numbers in scientific surveys increasing to 0.44 of the pre-AVG numbers by 2020, with this increase starting in 2017 (see Appendix 3). Pre-recruit numbers in scientific surveys are expected to remain about constant (at approximately 0.3 of the pre-AVG numbers) between 2007 and 2016. The pre-recruit indicator is a 2 year running average of the standardised numbers in the scientific surveys, and so this limit reference point relating to pre-recruit recovery should be applied only in 2018 and later years.

- the *limit reference point for the standardised number of 'pre-recruits' is 0.44 times the standardized average pre-recruit numbers in the years 2003-2006 inclusive. This Limit Reference point is applied in 2018, 2019 and 2020 only*.

Decision Rules

TAC setting

The draft harvest strategy would be applied through an annual TAC recommendation workshop that includes at least government and industry, with complete written inputs provided at least 2 weeks prior to the workshop. The workshop would then proceed by the following steps.

For each SMU and the harvest fraction decision rule:

1. Calculate the maximum TAC for that SMU by multiplying the default harvest fraction (Appendix 1) by the estimated exploitable biomass.
2. Review all indicators at the SMU scale. Apply a 'weight of evidence' approach (Appendix 2) to identify the consistency and likely robustness of the TAC estimate determined by the harvest fraction approach. This could include analysis to support a change of the harvest fraction applied to that SMU, up or down, and recalculation of the maximum TAC for that SMU. However, the default harvest fractions are as in Appendix 1, the maximum harvest fraction is 0.15, and any change in the harvest fraction from those in Appendix 1 must be by agreement by all parties and by evidence that the Operational Objectives will be achieved.

For each Reefcode:

3. For each reefcode within the SMU review the information available for that reefcode. The information reviewed includes at least the secondary indicators by reefcode. Where adequate data exists also include the primary indicators. Consider and as necessary reconcile any differences between indicators.
4. For each reefcode within the SMU use a 'weight of evidence' approach to determine the workshop view about the appropriate next year's catch. Add these catches together to give a total SMU catch based on workshop views from reefcode based considerations.

Reconciling SMU and reefcode interpretations:

5. Review the recommended SMU catch from the workshop views based on reefcode considerations (i.e. step 4) and from the harvest fraction based decision rule applied at the SMU level (i.e. step 2).
6. If the recommended catch from the workshop reefcode view is less than the catch from the harvest fraction decision rule, then the workshop view will be accepted. If the catch from the workshop reefcode views is greater than that from the decision rule, then the reasons for the difference are examined and the reefcode catches are reconciled to sum to the decision rule catch, and the decision rule catch is accepted as a total SMU catch limit. In this latter circumstance a review of the appropriateness of the harvest fraction should be conducted and input to the workshop process in the following year.
7. The reefcode specific catches, as reconciled to sum to the accepted SMU catch, will be taken to be the catch targets for those reefcodes so as to help prevent localised depletion.

Breakout rules if limit reference points are violated

Breakout rules are included in a harvest strategy to identify situations where the real-world outcomes may be outside the range of processes and uncertainties that were considered in selection of the harvest strategy. Triggering a breakout rule always results in review of the situation to determine what caused the unexpected result and an appropriate subsequent course of action. Depending on the severity and apparent risks, the management actions while the review is conducted can range from applying the harvest strategy as planned through to ad-hoc modification based on a judgement of risk.

In this draft harvest strategy there are two limit reference points. One relates to possible future decline in the mature biomass and the other to possible failure of the numbers of pre-recruits to show the expected increase. Violation of either would be a significant indication that recovery under the harvest fraction strategy was not occurring as predicted and assumed in the selection of the harvest fractions given in Appendix 1. If either limit reference point is violated the current harvest strategy should be urgently reviewed while the fishery catch is significantly constrained.

There are several features of the indicators and reference points that imply a graduated response is appropriate. Specifically, if the limit reference for the pre-recruit indicator is triggered early in the 2017-2020 period then more latitude should be given to the severity of the management response compared to what would be appropriate if it was still being triggered later in that period. This could be reflected, for example, by early violations triggering reduction in the applied harvest fraction for that SMU by half while more persistent violations resulted in stronger constraints. Ultimately, a lack of evidence for recovery of the pre-recruit numbers after about 2017 is counter to the expectations and assumptions that the harvest strategy is predicated upon. So if during the 2017-2020 period evidence mounts that pre-recruit numbers have not increased consistent with the assumptions underpinning the harvest fraction strategy then that strategy should be terminated and any catches should be extremely precautionary while alternative strategies based on the additional information are developed and tested.

References.

Gorfine, H., R. Day, D. Bardos, B. Taylor, J. Prince, K. Sainsbury and C. Dichmont (2007) Rapid response to abalone virus depletion in western Victoria: information acquisition and reefcode assessment. FRDC Project No. 07/066.

Helidoniotis, F., M. Haddon, K. Sainsbury and H. Peeters (2015) Developing the decision process for setting the TAC for abalone in Victoria, particularly with reference to recovery of AVG-impacted reefs, using Management Strategy Evaluation. FRDC Project No 2012/236.

Appendix 1. Spatial Management Units (SMU) and the suggested constant harvest fractions.

The harvest fraction could be varied, up or down, but the maximum harvest fraction is 0.15 and the default starting values are as below. The basis for any such a change must relate to achieving all operational objectives (for example new evidence, including the progress achieved in rebuilding, indicates that a lower harvest fraction is required to meet the operational objectives or that the operational objectives will all be achieved with a higher harvest fraction).

Western Zone			
Spatial Management Unit (SMU)	**Reefcode**	**Comments**	**Maximum Harvest Fraction (HF)**
Julia Percy Island	3.01	JP North	0.1
	3.02	JP Northeast	
	3.03	JP East	
	3.04	JP Prop bay	
Marine Park	1.025		0
	3.125		
Port Fairy	2.15	Yambuk	0.1
	2.16	Minerva; closed	
	3.05	Crags	
	3.06	Burnets	
	3.07	Water tower	
	3.08	Lighthouse	
Portland	1.01	Discovery Bay; closed	0.1
	1.02	Whites Beach	
	2.01	Murrels	
	2.02	Jones Bay	
	2.03	Outside Nelson	
	2.04	Devils Kitchen; closed	
	2.05	Inside Nelson; closed	
	2.06	Killer Waves; closed	
	2.07	Yellow Rock; closed	
	2.08	Cape grant; closed	
	2.09	the Passage; closed	
	2.10	Lawrence Rocks	
	2.11	Blacknose; closed	
	2.12	Hospital reef; closed	
	2.13	Dutton way; closed	
	2.14	Julia Bank; closed	
	1.03	Water Springs	
	1.04	Blowholes	
	1.05	the Tits	
	1.06	Bully Cove/South Bridgewater	
	1.07	Seal Caves	
	1.08	Horseshoe; closed	
Warrnambool	3.13	Lady Bay; closed	0.075
	3.14	Levys Point; closed	
	3.09	Mills	
	3.10	Killarney	
	3.11	The Cutting	
	3.12	Thunder Point; closed	

Appendix 2. Weight of Evidence approach

A weight-of-evidence approach is used to establish an evidentiary base in support a stock status determination from multiple sources of information, no one of which may be definitive but that together can provide a justifiable interpretation. This is achieved by systematically considering the range of information. Expert judgment can play an important role in the weight-of-evidence approach, but it is necessary to document the key evidence and rationale for decisions. Lines of evidence that can be used in the weight-of-evidence approach can include:

- fishery indicators, including catch, effort, catch rate, size- or age-based indicators, and spatial and temporal distribution of the fishery
- observations and qualitative judgements from divers, scientists and processors.
- risk assessments
- observations from scientifically designed and implemented surveys, including ‘citizen science’ and structured fishing observations
- quantitative stock assessment models

The key attributes of a weight of evidence approach are (i) that all lines of evidence are systematically considered both individually and together, rather than just some evidence being selectively considered; and (ii) the rational for the conclusions is documented.

Weight of evidence approaches can include formal methods to provide the statistical weight on each line of evidence and to statistically update the relative credibility of alternative interpretations. Or they can rely exclusively on qualitative expert judgement. But for both quantitative or qualitative applications specific criteria are usually used to assess the lines of evidence. Commonly these criteria relate to strength (e.g. accuracy/precision or closeness of relationships), consistency, plausibility, coherence, direct versus by analogy, and reliability of the methodology. Application of the weight of evidence approaches in this harvest strategy would benefit from development of agreed assessment criteria.

Appendix 3: Background to pre-recruit indicator and reference point

The intention is to have an indicator that tracks the pre-recruit numbers expected under the recovery scenario in the CSIRO analysis, and a limit reference point that is triggered if the expected increase is not seen in a reasonable time. Stock recovery with fishing at a harvest fraction of about 0.1 is entirely dependent on the expected increase in recruitment occurring.

The CSIRO analysis (FRDC project 2012/236) is for recruitment (settlement) at size 2mm. It takes about 6y to grow from settlement to reasonable representation in the pre-recruit index of the scientific surveys (i.e. mostly 100-120mm), and about 7y to grow to significant maturity (Annex 1). The CSIRO modelling for the most credible AVG mortality, 70%, gave the following depletion in recruitment (R/R0) at different periods (Annex 2):

R/R0 2006 (immediately prior to AVG)	R/R0 2007-2011/12	R/R0 2011/12-2020
0.63	0.19	0.28

The R/R0 measures are based on simulations of the Spawning Stock Biomass (SSB) and a Beverton and Holt (B-H) stock recruitment relationship with steepness=0.5. The simulations use a harvest fraction of 0.075. The simulations incorporate the reduced catches and increased size limit applied immediately post-AVG, and they predict an about doubling (to half the pre-AVG level) of the SSB between 2007 and 2010. This about doubling of the SSB also results from calculation of the SSB from scientific survey data alone (Annex 3), and as the simulations did not use the survey data this provides independent support for the simulation interpretations.

The periods examined by CSIRO are aggregated and do not exactly match the sequence of important events from other observations, and the available results do not reflect the variability expected, but a summary of SSB depletion and the expected pre-recruits (PRs) is approximately:

Settlement yr	R/R0 then	Detectable as PRs	Relative PR numbers observable (%)	
1997	0.63	2003	0.63 (100%)	[pre-AVG]
1998	0.63	2004	0.63 (100%)	
1999	0.63	2005	0.63 (100%)	
2000	0.63	2006	0.63 (100%)	
2001	0.63	2007	0.18 (28%)	[Fully AVG impacted
2002	0.63	2008	0.18 (28%)	yearclasses born in 6y
2001-				
2003	0.63	2009	0.18 (28%)	2006. Survivors 0.63*0.3 =
2004	0.63	2010	0.18 (28%)	0.18]
2005	0.63	2011	0.18 (28%)	
2006	0.63	2012	0.18 (28%)	
2007	0.19	2013	0.19 (30%)	[Very low SSB yearclasses
2008	0.19	2014	0.19 (30%)	born 2007-2010, R/R0 =
2009	0.19	2015	0.19 (30%)	0.19]
2010	0.19	2016	0.19 (30%)	
2011	0.28	2017	0.28 (44%)	[SSB increased to about
half				
2012	0.28	2018	0.28 (44%)	pre-AVG from about 2011,
2013	0.28	2019	0.28 (44%)	R/R0=0.28]
2014	0.28	2020	0.28 (44%)	

Two broad options for indicators and reference point for pre-recruit numbers are:

1. Indicator based on pre-AVG pre-recruit numbers e.g. (current pre-recruits)/(pre-recruits 2003-2006). Given that standardized pre-recruit values are only available from 2003 this limits the standardized pre-AVG time series to 2003-2006, though the full unstandardised time series back to 1992 is available for general comparison. The CSIRO analysis indicates that for observations made 2017-2020 the expected value of this indicator is 0.28/0.63=.44.
2. Indicator based on post-AVG pre-recruit numbers e.g. (current pre-recruits)/(pre-recruits 2007-2012). This potentially allows use of a greater range of years of standardized pre-recruit numbers in the indicator, which potentially reduces any bias caused by inter-annual variability. But it is greatly complicated by the rapid changes that have occurred post-AVG, the dependence of an appropriate reference point on the assumed AVG mortality (in comparison using pre-AVG observations requires no such assumption), and the effects of the lags between SSB and observable pre-recruits (which are not known accurately and may well vary through time). The CSIRO analysis indicates that for observations made 2017-2020, and a reference period 2007-2012 (the time when AVG impacted yearclasses were in the pre-recruits but before yearclasses from the increased SSB could contribute) the expected value of this indicator is 0.28/0.18= 1.5.

Considering the choice of whether to use a pre- or post-AVG reference period:

- Pre-recruit numbers in the period 2003-2006 do not seem unusually high compared to the full time series of survey observations; indeed, for most reef codes it is lower (Annex 5). It is lower than the longer-term average pre-AVG counts for reef codes 1.02, 1.03, 1.05, 1.08, 2.01, 204, 2.05, 2.06, 2.09, 3.02, 3.08. It is about the same for reef codes 2.02, 3.03, 3.10 and 3.11. It is higher for reef codes 3.04, 3.05 and 3.09. So period 2003-2006 seems reasonably reflective of the longer-term pre-AVG pre-recruit observations, though in comparison with the full time series it gives a 'lower bar' for recovery for most reefs and a 'higher bar' for some important reefs (i.e. Prop Bay 3.04, Crags 3.05 and Mills 3.09.

- The following table gives the approximate average standardized pre-recruit counts by area and period. In brackets are the expected counts between 2017 and 2020 implied for each (i.e. multiplier of 0.44 for the pre-AVG indicators and 1.5 for the post-AVG indicators).

	2003-2005	2003-2006	2013	2007-2012	2008-2012	2008-2013
WZ total	27 (11.8)	25 (11)	8 (12)	11 (16.5)	8 (12)	8 (12)
Portland	27 (11.8)	24 (10.5)	7 (10.5)	13 (19.5)	8 (12)	8 (12)
Pt Fairy	35 (15.4)	34 (14.9)	10 (15)	8 (12)	9 (13.5)	9 (13.5)
JPI	30 (13.2)	31 (13.6)	7 (10.5)	13 (19.5)	12 (18)	11 (16.5)
Warrnambool	27 (11.9)	25 (11)	9 (13.5)	7 (10.5)	7 (10.5)	8 (12)

Overall there is not a great deal of difference in the expected counts between 2017 and 2020 depending on whether the reference period is pre- or post-AVG, although there are systematic SMUs differences (e.g. the post-AVG indicator for Pt Fairy is lower than the pre-AVG indicator, while the reverse is the case for JPI and to a lesser extent Portland). The expected 2017-2020 counts for each SMU based on post-AVG reference years are strongly influenced by the reference years that are included (i.e. including 2007 and/or 2013); many rapid changes were occurring in this period and small uncertainties in their timing effect the representativeness of each year. Using just a single post-AVG reference year (e.g. 2013 shown here) gives highly variable results across SMUs, as would be expected because a single year does not provide any averaging across inter-annual variability. The expected 2017-2020 counts based on pre-AVG both reference periods examined are relatively consistent for each SMU.

- For all SMU's except JPI the standardized count in 2015 (the most recent estimates available) are below the implied LRP, whether calculated from pre- or post-AVG reference years. The standardized pre-recruit count for JPI was about 15 in 2015, which is about the LRP calculated from the pre-AVG period but below the LRP calculated from the post-AVG period.

Indicators and related reference points calculated from either the pre- and post-AVG suffer from the same problem that only a short time series (3-4y) that is available; the pre-AVG series is short because the standardized counts are not calculated for the data from 1992-2002 and the post-AVG series is short because of the combined effects of the various time lags and rapid changes in stock status. A short time series makes the reference point vulnerable to short term fluctuations in year-class strength due to environmental effects. While both reference periods suffer from this problem, use of an indicator and related reference point calculated from post-AVG observations also involves additional assumptions that are uncertain and some of which may be time varying (e.g. AVG mortality, age when reasonably detectable in the scientific surveys, the form of the stock-recruitment curve). Consequently, an indicator and related reference point based on pre-AVG observations is preferred.

The reference period 2003-2006 inclusive is taken to give the most consistent and reasonable interpretations, while making use of as many years of observations as possible. Using this reference period may set the limit reference slightly too high for Pt Fairy and slightly too low for Julia Percy Island and to a lesser extent Portland. This possibility should be born in mind when the limit reference point is applied through the harvest strategy. It is recognized that pre-recruit counts are variable, both because of sampling variability and natural inter-annual variability in recruitment processes, so the indicator can be a running 2-year average of the observed pre-recruit numbers.

In summary, the recommended pre-recruit indicator, recommended limit reference point and technical considerations for their application in possible future scenarios are:

The recommended pre-recruit indicator, $\mathbf{Pr_y}$, is:
PR_y = average standardized pre-recruit number across years y and y-1

The corresponding limit reference point for $\mathbf{Pr_y}$ is:
LRP for PR_y = 0.44* average standardized pre-recruit number 2003-2006

As above, the observed pre-recruit numbers are expected to remain about constant at low levels between 2006 and 2016. This is a result of the effects of AVG on recruiting year-classes that existed during 2006/7, and on the SSB in the years 2006/7 to 2010/11, combined with the time lags in measuring year-class strength. Consequently, the expected increase in pre-recruits that the limit reference point is predicated upon occurs, on average, over the period 2017-2020. The indicator Pr_y is a 2y running average. It is recommended that the LRP for Pr_y is applied through the Harvest Strategy from 2018 (i.e. with Pr_y based on pre-recruit the observations in 2017 and 2018) through to 2020. Violation of the LRP in the period 2018-2020 is an indication that the expected recruitment is not occurring and that ongoing fishery catches would be eroding the SSB based primarily on survivors of AVG, and implies the need for urgent measures to protect the remaining SSB to give the greatest chance of ultimately achieving recruitment increase and stock recovery.

The **recommended technical considerations for application of the pre-recruit indicator and limit reference point**, including in some possible future scenarios are:

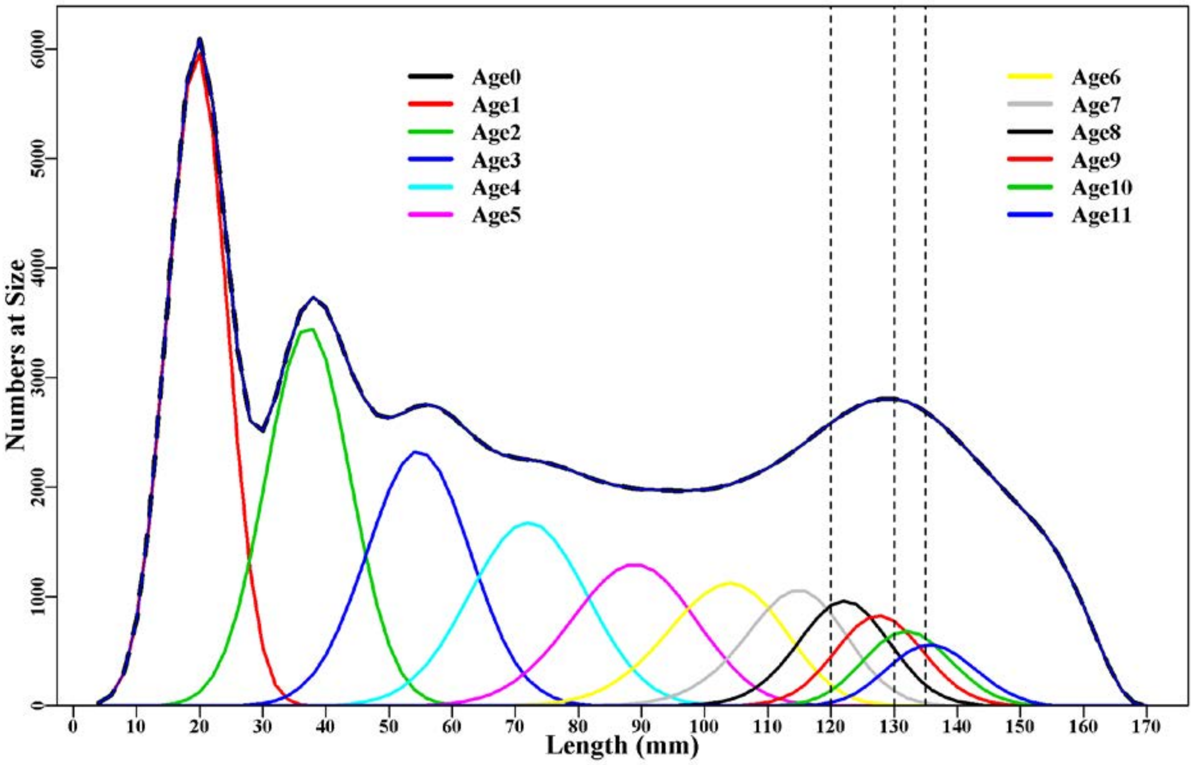
1. The indicator Pr_y is based on the numbers from the scientific surveys as standardized in recent years, and that is the default definition of the indicator for this harvest strategy. However, in recent years there has been dispute about both the rigor of the surveys (e.g. consistency of implementation and data recording, representativeness of the survey sites, interpretation of trends in relation to possible density dependent habitat selection by abalone) and the methods of standardization. It is expected that there will be further examination of these matters. It is possible that this will lead to new/different practices for the future and interpretations of past surveys, and it is possible that a range of plausible interpretations of past survey counts may emerge rather than just one interpretation. Such developments could raise the need to redefine how the pre-recruit indicator is calculated and defined. There are several criteria that should be applied to any proposed change in the pre-recruit indicator. These are;
   - (i) the indicator should have a statically sound, biologically logical, operationally logical (in terms of the survey process) and objective basis for being considered representative of pre-recruit numbers from at least 2003 to 2020;
   - (ii) if the basis in (i) can be established for years prior to 2003 then the indicator for earlier years should be calculated and included (with corresponding change in the limit reference point described below); and
   - (iii) if there are multiple interpretations of the survey counts that all meet (i) then multiple pre-recruit indicators based on the scientific surveys would be acceptable, all such interpretations should be considered with either equal or agreed statistical weighting, and Pr_y should be calculated as a composite index using that weighting.

2. If the indicator Pr_y is changed then the limit reference point for the new Pr_y should be calculated on the same basis as previously (i.e. the pre-AVG average of the new pre-recruit indicator multiplied by 0.44). The pre-AVG average of the new indicator may include years before 2003 if inclusion of earlier years has been adequately justified using the criteria above. Similarly, the pre-AVG average of the new indicator may be a composite of several plausible interpretations of the survey data.

3. There are two technical issues that should be considered during application, and in deciding the appropriate management actions if the limit is triggered.
   - (i) The limit reference point is the ratio of R/R0 in two periods – pre-AVG and 2011/12-2020 – and it is applied as a constant in the period 2017-2020. However, R/R0 is expected to increase systematically during 2017-2020 if/as recovery occurs, rather than as a 'step change' in 2017 as reflected in the constant limit reference point. The consequence is that pre-recruit numbers are expected to be lower in 2017 than 2020, even if recovery is occurring as predicted, giving more chance of incorrectly triggering the limit early in that period compared to later.
   - (ii) There is variability in the predicted trajectories of both R/R0 and recruitment as the stock recovers. So by chance the pre-recruit numbers seen in the real world may be lower than the predicted average. The consequence is that by chance the limit reference point may be triggered falsely at any time in its application, including being triggered in some years but not triggered in adjacent years (or vice versa). However, mitigating against a more relaxed application of the reference point is that if the recruitment is not rebuilding as assumed then, especially given the catch already taken from the AVG survivors since 2006, there would be an urgent need to protect the remaining spawning stock.

These two issues highlight the need for practical application of the harvest strategy to objectively evaluate the evidence as it becomes available through the period of the harvest strategy. If the limit reference is triggered early in the 2017-2020 period, then more latitude should be given to the severity of the management response compared to what would be appropriate if it was still being triggered later in that period. This could be reflected, for example, in early violations triggering reduction in the applied harvest fraction by half while more persistent violations resulted in stronger constraints. Ultimately, a lack of evidence for recovery of the pre-recruit numbers after about 2017 is counter to the expectations and assumptions that the harvest strategy is predicated upon. So if during the 2017-2020 period evidence mounts that pre-recruit numbers have not increased consistent with the assumptions underpinning the harvest fraction strategy, then that strategy should be terminated and any catches should be extremely precautionary while alternative strategies based on the additional information are developed and tested.

Annex 1: Growth model used in CSIRO modelling.



<u>Age length key</u>
Age estimates based on the length increment of one cohort through annual time steps using the inverse logistic model. Parameters estimated after fitting to tag recapture data.

Length (mm)	Age
24	1
44	2
64	3
84	4
102	5
114	6
122	7
128	8
132	9
136	10
140	11

Annex 2: Spawning biomass and recruitment for two scenarios of viral mortality. From Report 12C from Fay Helidoniotis as part of the CSIRO project.

In conjunction with the size composition from the DPI surveys it is possible to distinguish the 0.7 viral mortality and 0.7 viral mortality you should ideally run the model and predict the expected size composition from a few years pre-virus through to about 2020. Of course in the short term we will only be able to make comparison with the data we have (ie to 2013 at present) to judge credibility, but it will be very useful to see how the different viral mortality scenarios play out in the next few years.
Using the Beaverton Holt stock recruitment relationship with known steepness and known spawning stock depletion, calculate to depletion in recruitment i.e (R/R0) . The Beverton Holt stock recruitment equation can be reformulated to the equation below (see Annex for derivation)

$$\frac{R}{R_0} = \frac{4h \times d}{1 - h + 5hd - d}$$

(1)

Where *h* is steepness, and *d* is depletion level. Using a spawning stock depletion level of 0.3 and an associated steepness of each reefcode it is possible to obtain values for (R/R0) (table 1) using equation(1)

Table 22. The depletion in recruitment (R/R0) for each reefcode in 2006 immediately prior to the viral outbreak for a given steepness used in the MSE modelling and using equation (1) to obtain (R/R0).

reefcode	steepness	Recruitment (R/R0)
Crags	0.5	0.63
Watersprings	0.5	0.63
Mills- Killarney	0.55	0.67

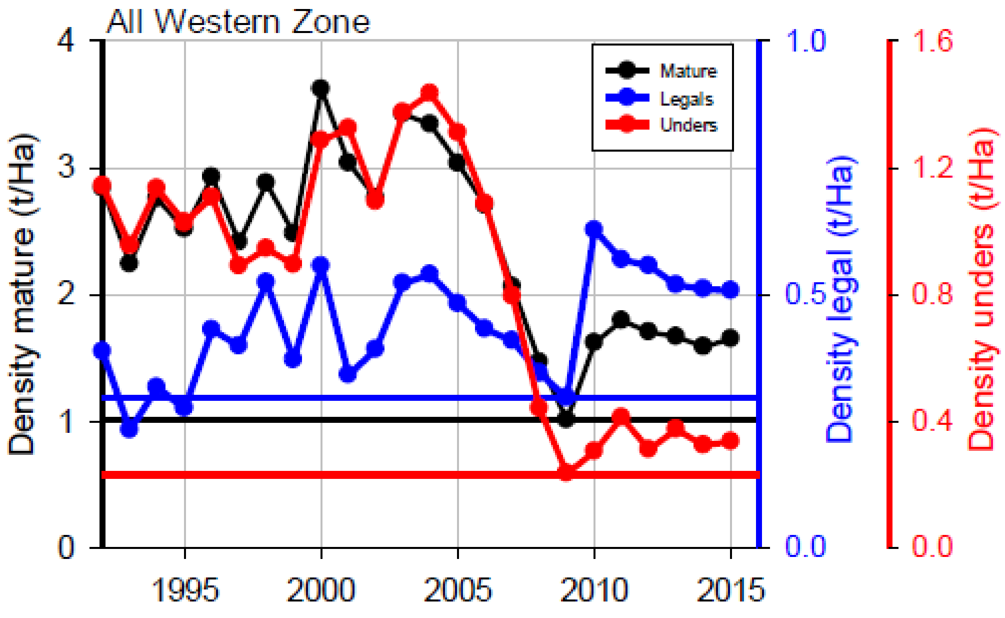
The directly virus effected recruitments (ie recruits already born and growing at the time of the virus) were of year class strength = R/R0 (0.63*virus mortality- if linearity is assumed). (Table 2). It takes 5-6y to grow from settlement to the size range 100-110mm where reasonable detection is possible. Therefore recruitment strength in the 5-6 years after the virus i.e from 2007 -2011/12 will be affected by viral mortality.
Using a starting depletion level of 0.3, it is possible to obtain the (R/R0) for the years where recruitment depletion is largely due to viral mortality i.e 2007 to 2011/12
2007 to 2011/12 (R/R0) = Pre 2006 (R/R0)*survivorship after viral M
or
2007 to 2011/12 (R/R0) = Pre 2006 (R/R0)*(100%-viral M)
From 2011/12 to say 2020, recruitment depletion is mainly driven by Beverton Holt stock recruitment relationship. During these years the population is indirectly effected by viral mortality ie recruits were born of the depleted survivors of the virus but they themselves were not subject to viral mortality. Here equation 1 is applied to calculate (R/R0) (Table 23).

Table 23. The depletion in recruitment (R/R0) (or year class strength) in 2006 immediately after the viral outbreak. A steepness of 0.5 is used for Crags and Watersprings only. The steepness for Mills Killarney was slightly higher at 0.55 and results for that steepness are presented in square brackets []). The 2007 - 2011/12 (R/R0) was calculated using the formula 0.63x100%-virus mortality (if linearity is assumed). Equation 1 was used to calculate (R/R0) for 2011/12 to 2020. Recruitment is the numbers/abundance recruiting into the 2mm size class (i.e. R or R0 is expressed in terms of abundance not biomass)

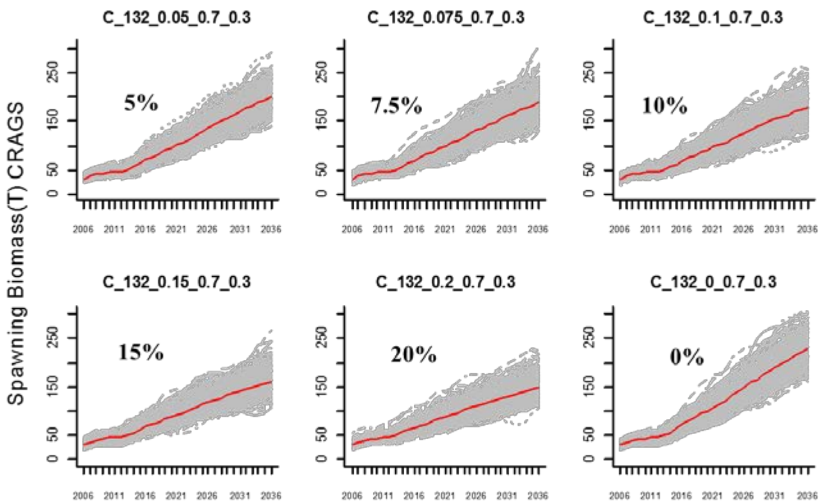
Situation	Biomass (B/B0) depletion	2007 - 2011/12 Recruitment (R/R0)	2011/12 to 2020 Recruitment (R/R0)
Pre-virus	0.3	0.63 [0.68]	0.63 [0.68]
Post virus 50% mort	0.15	0.31 [0.34]	0.41 [0.46]
Post virus 60% mort	0.12	0.252 [0.27]	0.35 [0.4]
Post virus 70% mort	0.09	0.189 [0.20]	0.28 [0.33]
Post virus 80% mort	0.06	0.126 [0.13]	0.2 [0.24]

Annex 3: Spawning biomass estimates post-AVG

Relative biomass calculated by WADA from scientific survey observations alone.
Estimates of the density of legal biomass (>130 mm, blue line), spawning biomass (>102 mm, black line) and undersize biomass (110-130 mm, red line) from sites in abundance surveys since 1992. Horizontal reference lines in each color show the density for each index in 2009. From the WADA documents provided for the 2015/16 quota year assessment.



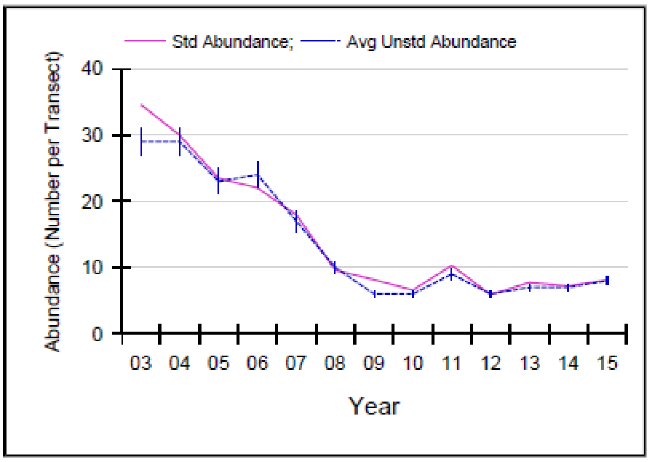
Relative biomass calculated by CSIRO from catches and population parameters alone.
The spawning biomass trajectory to 2036 for these different constant harvest fractions are:



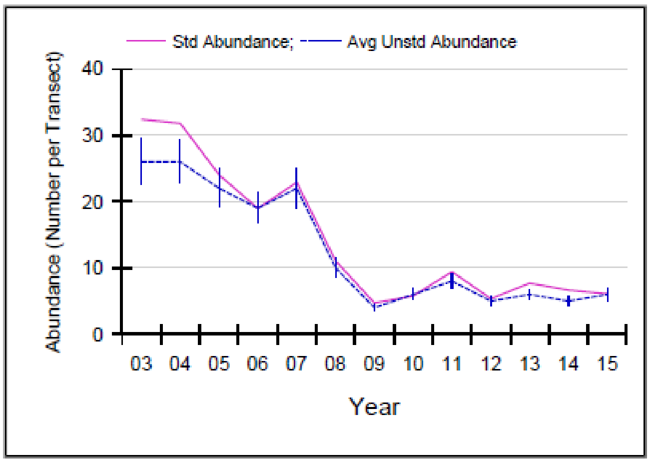
The recovery trajectories all show a slow increase of spawning biomass during 2006-2014/15, which is an about doubling from the low base immediately post-AVG. This is a result of the low catches and large size limit in the fishery post AVG.

Annex 4: Pre-recruit (i.e. <120mm) counts, standardized and unstandardised for the WZ in total and the four Spatial Management Units as given in Reef Assessment Report Card for 2015/16 quota year assessment.

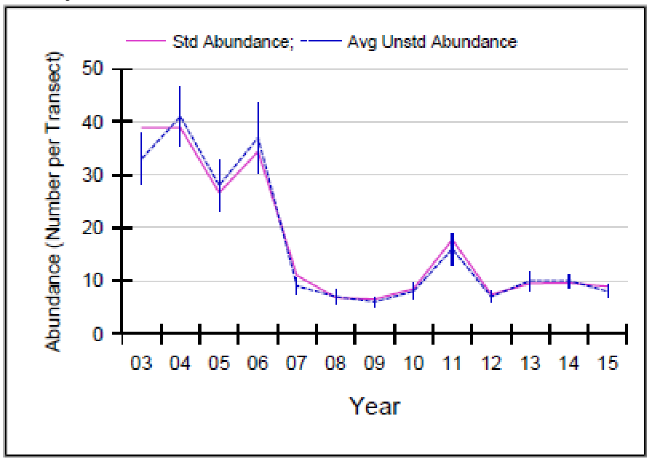
Whole Western Zone



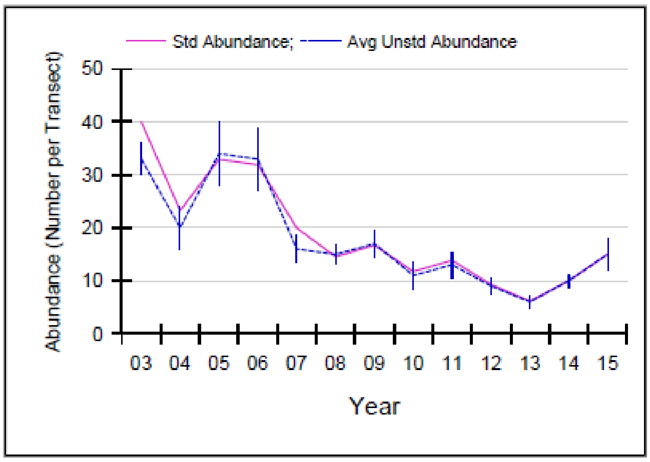
Portland SMU



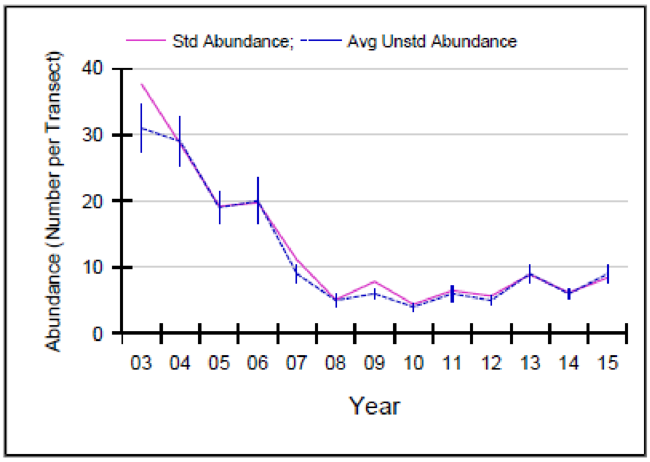
Pt Fairy SMU



Julia Percy Island SMU

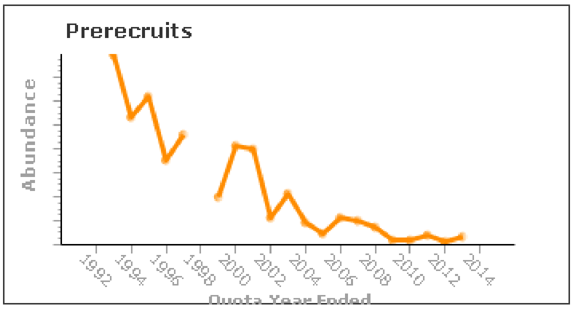


Warrnambool SMU

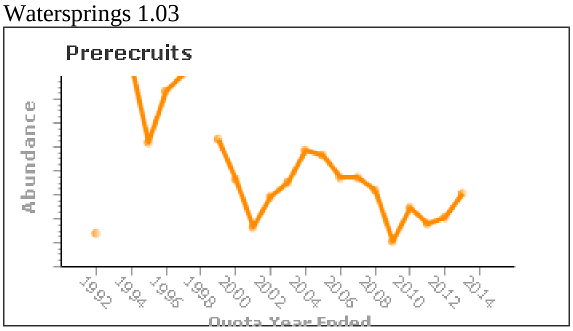


Annex 5: Pre-recruit (i.e. <120mm) counts from the scientific surveys by Reef-Code as given in Reef Assessment Report Card for 2013/14 quota year assessment.

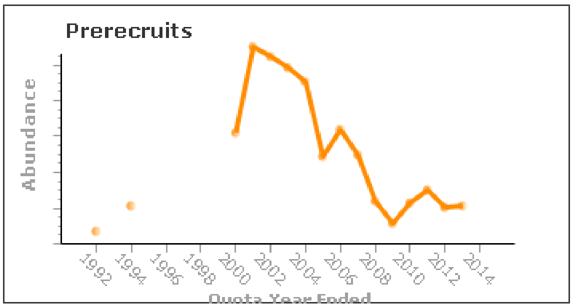
Whites 1.02



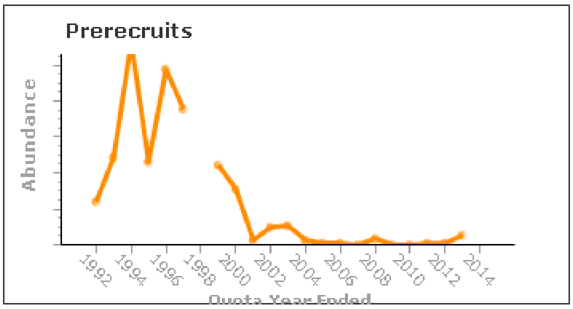
Watersprings 1.03



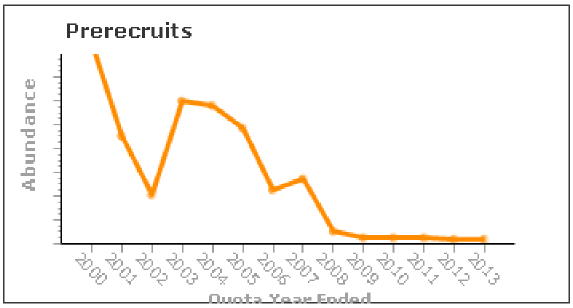
The Tits 1.05



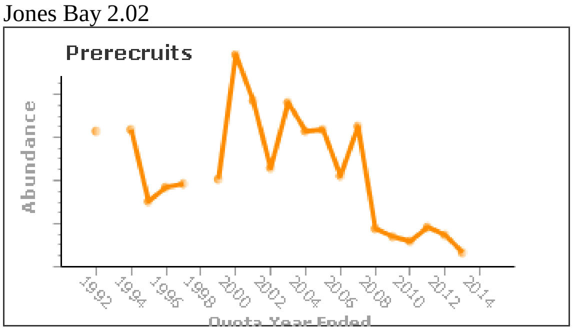
Horseshoe 1.08



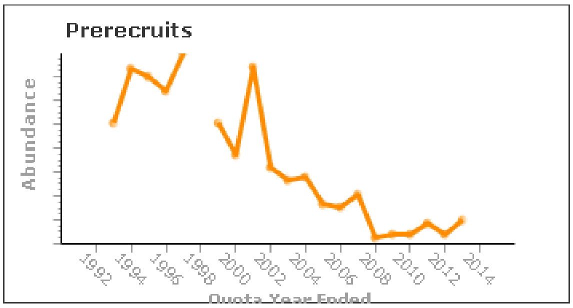
Murrells 2.01



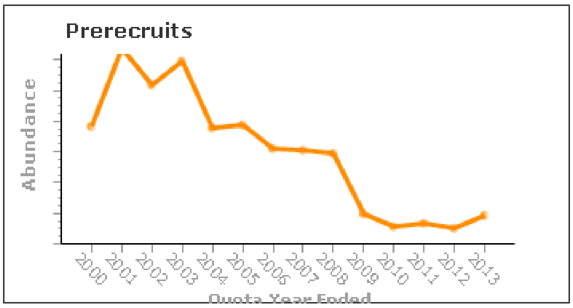
Jones Bay 2.02



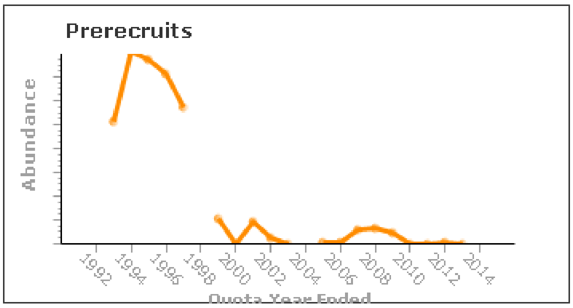
Devils Kitchen



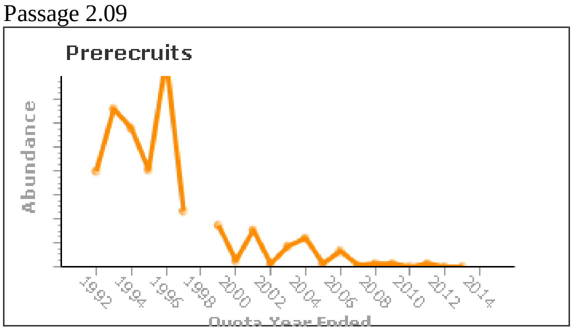
Inside Nelson 2.05



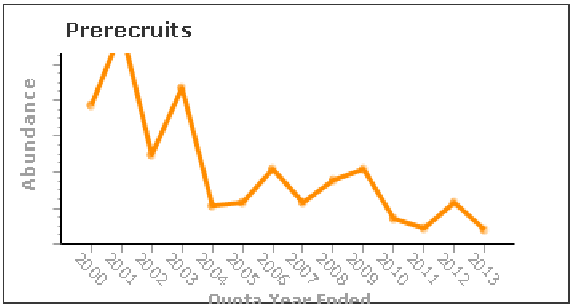
Killer Waves 2.06



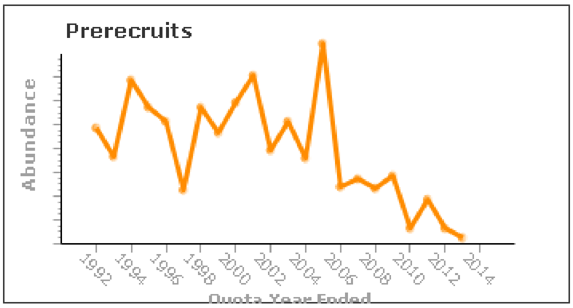
Passage 2.09



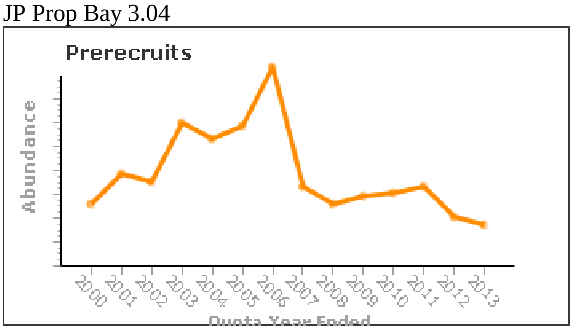
JP North East Reef 3.02



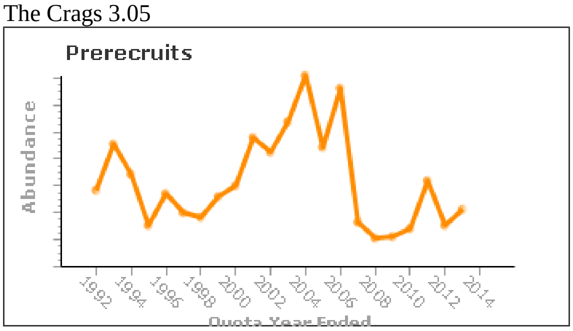
JP East Side 3.03



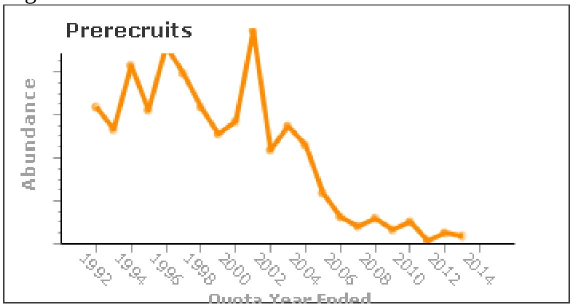
JP Prop Bay 3.04



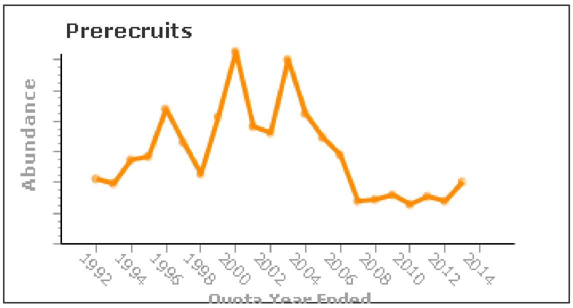
The Crags 3.05



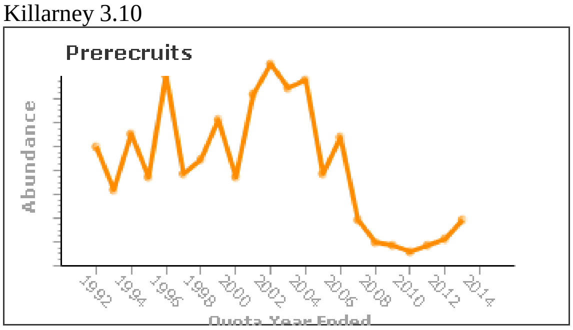
Lighthouse 3.08



Mills 3.09



Killarney 3.10



The Cutting 3.11