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Tini a Tangaroa

Model-based reference levels for New Zealand red rock lobster (*Jasus edwardsii*)

New Zealand Fisheries Assessment Report 2021/81

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This document describes the development and application of a model-based approach to determine reference levels for New Zealand red rock lobster (*Jasus edwardsii*). The approach has currently been applied to five rock lobster Quota Management Areas and the results are reported.

The New Zealand Harvest Strategy Standard requires a specified target biomass about which stocks should fluctuate, a soft limit that triggers a formal, time-constrained rebuilding plan, and a hard limit that triggers a fishery closure. The soft and hard limits are defined in terms of spawning stock biomass (SSB) to safeguard stock sustainability. The target is typically defined as a maximum sustainable yield (MSY)-related reference point or better, which comes down to a decision for managers and stakeholders. This study defines reference levels for red rock lobster in terms of the vulnerable biomass associated with the maximum catch from projected harvest control rules that also meet a risk constraint of keeping the SSB above the soft limit (20% SSB_0^{data}).

We calculated reference levels for five stocks by projecting suites of fixed catch and fixed fishing mortality rate (F) rules 30 years into the future (representing a reasonable time-frame relevant to management), using samples from the posterior distribution of the base case stock assessment for each stock. Fixed catch rules that met the risk constraint, and a catch constraint requiring 99% of the fixed catch to be taken for 95% of projection years be realised, resulted in low average annual catches because the rules could not be adjusted in response to changing stock size over the 30-year projection. Fixed F rules were able to maximise annual average catch because this harvest strategy automatically adjusts to biomass variations, although such a policy is practically unrealistic because it is not possible to accurately know the size of the contributing biomass or respond to changes in estimated biomass in a timely way. However, such rules more closely resemble actual rock lobster management practices than fixed catch rules because the annual catch for these fisheries have been adjusted frequently in the past based on estimated stock status or harvest control rules driven by catch per unit effort. To keep reference level development simple, the Rock Lobster Working Group agreed that the average vulnerable biomass calculated from the biomass levels resulting from maximum constrained fixed catch and constrained fixed F rules balanced the trade-off between maximising catch and keeping catch variability minimised while meeting risk constraints. The reference level projection procedure is capable of being carried out for each annual stock assessment to derive reference level vulnerable biomass. This procedure is especially powerful because it integrates across fishery and ecological goals and is sufficiently flexible to incorporate additional goals specified by stakeholders.

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1. INTRODUCTION

A widely accepted objective of fisheries management is to "*ensure the sustainable production over time from fish stocks… that promotes economic and social well-being of the fishermen and industries that use the production*" (Hilborn & Walters 1992). To meet these ecological, economic, and societal goals, countries and international management agencies worldwide typically assess stock status relative to target and limit reference points. However, the definition of reference points is subjective, and a fishery would need to experimentally exceed theoretical reference points to objectively determine if they were appropriate or not. With the associated impacts on ecosystem health and the economic and social well-being of fishers and industry, such an approach is not likely to be undertaken nor would it yield unequivocal outcomes.

Target and limit reference points are generally defined in terms of spawning stock biomass (*SSB*) and the fishing mortality rate expected to achieve the target or limit *SSB*. *SSB* holds ecological significance because maintaining the spawning stock implies recruitment and ecosystem functioning, while allowing for the sustainable exploitation of the harvested stock. The concept of *SSB* associated with maximum sustainable yield (SSB_{MSY}) is now generally considered a lower limit rather than a target (Caddy & McGarvey 1996, Holt & Talbot 1978, Larkin 1977, Punt & Smith 2001). Target and limit reference points are often explored via the associated fishing mortality rate (*F*), because this is what can be adjusted using catch or effort constraints to meet the target or remain above the limit. Mace (1994) used population models to simulate various commonly used *F* strategies associated with reference points such as the constant *F* associated with maximum sustainable yield (F_{MSY}), the *F* at 10% of the slope at the origin of the yield-per-recruit curve ($F_{0.1}$), and the *F* that reduces the *SSB* per recruit to 40% of unfished levels ($F_{40\%}$). Mace (1994) recommended using $F_{40\%}$ when the stock-recruit relationship is unknown. Thorson et al. (2012) used a meta-analysis of stock assessments of marine fish worldwide to determine that the average estimated ratio of *SSB* at *MSY* to unfished *SSB* is 40%, given variability by life history type. While these general rules are useful starting points and demonstrate the variation in fisheries management needs by species, they are not necessarily helpful for defining reference points for specific stocks or invertebrate fisheries (Hilborn 2002).

The New Zealand Harvest Strategy Standard (HSS, Ministry of Fisheries 2008) requires a specified target about which stocks should fluctuate, a soft limit that triggers a formal, time-constrained rebuilding plan, a hard limit that triggers a fishery closure, and that overfishing is occurring if F_{MSY} is exceeded on average. The HSS defines the soft and hard limits in terms of the *SSB* to safeguard stock sustainability. The target is defined as the biomass (the type of biomass is undefined and not limited to *SSB*) producing the *MSY*-compatible reference points or better. After New Zealand stock assessments determine that the status meets the *SSB*-related risk constraints, removals are generally set at a level below *MSY*. Some stocks have used harvest control rules based on catch per unit effort (CPUE) to set removals each year (e.g., Webber & Starr 2020a, 2020b). The catch limit, determined either by constant catch or control rule, is reassessed with each stock assessment, but the frequency of stock assessments varies by species.

Red rock lobster (*Jasus edwardsii*, hereafter referred to as 'rock lobster') are among the highest value commercial fisheries in New Zealand, consisting of ten management units treated as if they were independent stocks (Figure 1). Eight of the ten rock lobster stocks are each assessed approximately every five years. Until a change in catch and effort data collection procedure was implemented in late 2019, six of these stocks were managed with CPUE-based harvest control rules, developed as part of thoroughly explored management procedures (MPs). Three stocks were managed using constant catch rules often based on the historical catch (Webber & Starr 2020a, 2020b); the tenth rock lobster stock is not fished.

To improve the understanding of setting harvest control rules in New Zealand, Francis & Mace (2005) conducted simulation experiments to find the harvest levels and strategies that maximised long-term mean catch under various scenarios of harvest strategy and environmental variability for several commercially-important finfish species. However, these results are not directly transferable to an invertebrate fishery such as rock lobster.

The objective of this work was to develop a method to identify reference levels in terms of vulnerable biomass, the biomass of importance to stakeholders, applied to each rock lobster stock. These reference levels can be interpreted as proxies for B_{MSY} and represent a lower bound for a management target, since they address both the ecological and fishery objectives of the HSS by maximising catch while meeting specified risk constraints. In this report, 'vulnerable biomass' refers to the start-of-year vulnerable biomass, historically adjusted based on the selectivity, the minimum legal size (MLS) regulations, and the non-retention of ovigerous females active in the final year of the stock reconstruction. We note that target reference points internationally are typically related to *SSB*, including the New Zealand HSS. However, we are defining the rock lobster reference levels in terms of vulnerable biomass because this is the biomass experienced by rock lobster fishers. Because some rock lobster stocks have considerable numbers of mature females below the MLS, *SSB* target levels for these populations will satisfy the sustainability requirements of the HSS but can result in populations with an unacceptably low incidence of harvestable lobsters. A reference level defined in terms of the vulnerable biomass will be more appropriate and usable for stakeholders than one defined by the *SSB,* while still meeting the HSS sustainability requirements. We have applied the procedure presented in this paper to CRA 1 (Rudd et al. 2020), CRA 2 (Webber et al. 2018a), CRA 3 (Webber et al. 2020), CRA 4 (Rudd et al. 2021), and CRA 5 (Webber et al. 2021).

2. METHODS

The approach to calculating reference levels by stock requires an up-to-date stock assessment. New Zealand rock lobster are assessed using the length-based 'lobster stock dynamics' (LSD) model (Webber et al. 2018b), which is custom-built software coded using the Stan programming language (Stan Development Team 2016). One or two rock lobster stocks are assessed annually, rotating such that each of the eight assessed stocks is updated at least every five years.

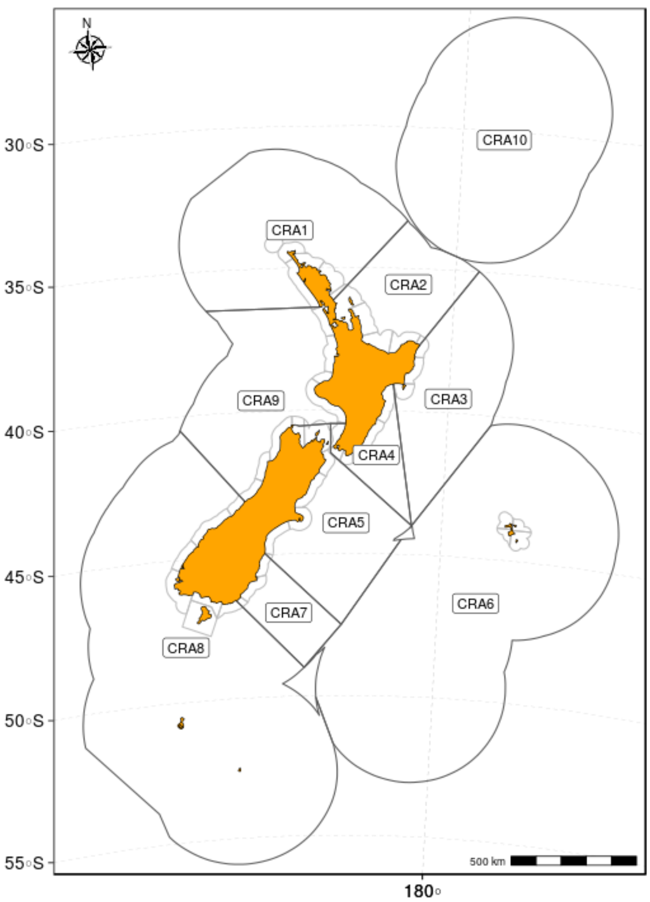

Figure 1: Map of New Zealand red rock lobster Quota Management Areas (QMAs). Reference levels are presented in this report for CRA 1, 2, 3, 4, and 5.

We applied the approach developed in this paper to estimate reference levels for five recently assessed stocks: CRA 1 (Rudd et al. 2020), CRA 2 (Webber et al. 2018b), CRA 3 (Webber et al. 2020), CRA 4 (Rudd et al. 2021), and CRA 5 (Webber et al. 2021; Figure 1). CRA 1, 2, and 4 were treated as single-region stock assessments while CRA 3 and CRA 5 were treated as two-region stock assessments. The CRA 3 stock assessment included two base case models with alternative growth assumptions (either keeping or removing tags at liberty less than one year). Reference levels were calculated for each Quota Management Area (QMA), for each region if there were more than one, and in the case of CRA 3, for each base model. Reference levels are in terms of the adjusted vulnerable biomass, the vulnerable biomass subject to the final model year's selectivity and minimum legal size.

2.1 Projection methods

Key model parameters of interest and probabilities relating to stock status are based on samples from the posterior distribution which were acquired as part of the stock assessment using the Markov chain Monte Carlo (MCMC) algorithm implemented in Stan. Starting with the full set of 1000 draws from the posterior distribution, we projected rock lobster stock dynamics 30 years into the future. Each of the 1000 samples from the posterior distribution represented a 'simulation replicate'. This allowed the uncertainty in population parameter estimates to propagate through the simulations. For each simulation replicate, recruitment deviates were drawn from a lognormal distribution based on the mean (R_{data}), and autocorrelation (ρ_{data}) of model-estimated recruitment deviates beginning in the first year with both length and CPUE data, ending two years before the final reconstruction year, and using the recruitment standard deviation (σ_R) assumed during the stock assessment.

Equation 1
$$\boldsymbol{R_y = R_{\text{data}} e^{\delta_y - 0.5\sigma_R^2}}$$
$$\delta_y \sim N\left(r_{y-1} + R_{\text{data}}\sqrt{1-\rho^2}, \sigma_R^2\right)$$

where R_y is the number of recruits in year y, and δ_y is the recruitment deviation in year y.

A 30-year projection period was chosen because it was long enough to account for recruitment variation but short enough to represent a period without an expectation of major regime shifts. Although long-term projections (e.g., 100–200 years) would ensure the fishery state is far removed from the current levels, they tend to result in overly conservative targets by including rules where the management is left unchanged over unrealistically long periods. Rock lobster populations experience periods of higher and lower recruitment, which would not be adequately represented in long-term stock projections. Shorter term projections, with the expectation that they will be updated after each full stock assessment, are more likely to reflect recent productivity when establishing reference levels that are representative of the current stock.

2.2 Harvest control rules

We projected two types of harvest control rule to explore the trade-off between the amount and variability of catch over time under risk constraints: fixed catch rules and fixed harvest rate (F) rules. Fixed catch rules represent a lower bound on maximum yield because there is no variation in catch over time. Fixed catch rules result in lower maximum catch due to the inability to adjust the catch when there are declines in vulnerable biomass or CPUE, leading to a higher probability of breaching the risk constraints. Fixed F rules represent an upper bound on maximum yield because catch is allowed to vary over time. Fixed F rules also result in higher maximum catches than other rule types because the amount of fishing pressure is automatically adjusted to changes in the vulnerable biomass, given the assumption of perfect knowledge of stock size. Fixed F rules cannot be executed in practice because it is not possible to accurately know the size of the contributing population and the responsiveness of fisheries management actions is not perfect. However, fixed F rules represent a theoretical maximum catch and are more in keeping with the management of New Zealand rock lobster stocks because catch limits have been frequently adjusted based on updated stock assessments or CPUE-based MPs.

Early iterations of the reference level development explored CPUE-based MPs as a set of rules which were intermediate between maximising catch via fixed F rules and minimising variability via fixed catch rules. The Rock Lobster Working Group (RLWG) decided against moving forward with this option for several reasons:

1. the selected rule which met the objectives of high catch and intermediate variability would be sensitive to the suite of MP rules tested, and, with ten parameters governing the MP rules (Webber & Starr 2020b), the search for an optimal rule required a lot of computational time with subjectivity as to whether the candidate suite of rules adequately explored all options;
2. determining what is an acceptable amount of variation in catch is highly subjective and likely variable across QMAs, thus reducing the objective application and generality of the procedure for calculating reference levels;
3. it was unlikely that a CPUE-based MPs selected through this procedure would match the rule previously chosen to manage the fishery; and
4. the CPUE on which the previous MPs were based is no longer considered reliable due to a lack of continuity in the reporting of catch and effort data resulting from a shift to electronic data collection.

Therefore, the approach outlined below seeks to find a reference level that is intermediate between the maximum constrained fixed catch and fixed F rules by applying a more straightforward approach that is not dependent on the use of CPUE.

Suites of fixed catch and fixed F rules projected by stock were chosen using an iterative process. The first step was to project a wide range of rules that overlapped the current catch for each stock and the estimated F. We examined the relationship between vulnerable biomass and average annual catch to ensure a maximum was found for both the fixed catch and fixed F rule types. We then adjusted the range and increments of fixed catch and F rules to find the maximum for each.

The fixed catch and fixed F rules were based only on the size-limited (SL) catch, which includes both the commercial and recreational sectors. Non-size-limited (NSL) catch, the sum of illegal and customary catch, was fixed at the values assumed for the final year of the stock assessment in all simulations.

2.3 Performance

We assessed the performance of each projected harvest control rule based on the final 20 years of the 30-year projection period. The first ten simulation years were removed to reduce the impact of current stock status on the simulated reference point. For each projected rule, we calculated several metrics across years over all simulation replicates, including i) average annual catch, ii) coefficient of variation (CV) of catch, iii) average vulnerable biomass (B), and iv) the probability of falling below the soft limit of 20% equilibrium SSB using mean recruitment from the years of estimated recruitment deviates beginning with the first year with both length and CPUE data (SSB_0^{data}) and ending two years before the end of the reconstruction.

2.4 Finding the reference level

Both the fixed catch and fixed F rules were subject to a risk constraint, which required that selected rules have a probability of less than 0.05 that SSB would fall below the soft limit of 20% SSB_0^{data}. Probability was calculated as the number of years falling below the soft limit (N_{below}) divided by the total number of years (Y) over all samples from the posterior distribution (I), where $N = Y \times I$:

Equation 2 $$\boldsymbol{P}_{\textbf{risk}} = \frac{\boldsymbol{N}_{\textbf{below}}}{\boldsymbol{N}}$$

In this study, N equals 20 000 (Y = 20 years and I = 1000 samples from the posterior distribution) for all reference level calculations. Fixed catch rules were subject to an additional catch constraint, which required the full fixed catch amount to be harvestable from the vulnerable biomass for most years over all simulation replicates. If the full fixed catch amount could not be taken regularly (i.e., if the vulnerable biomass dropped so low that the catch could not be taken, given natural mortality and a cap that no more than 95% of vulnerable biomass could be taken), the rule would be rejected. This additional constraint was set below 100% because requiring a rule to provide 100% of the fixed catch for 100% of years over all simulation replicates would lead to a very conservative reference level, given minor computational differences between expected and observed fixed catch. The LSD model uses the Newton-Raphson algorithm to calculate the *F* associated with the input catch to implement removals from the population, and this approximation sometimes results in very small differences between the input fixed catch and the model predicted catch that was taken from the population. Therefore, we used a fixed catch constraint that required at least 99% of the fixed catch rule to be taken for 95% of years over all simulation replicates. This rule ensured that the 90th quantile of average annual catch over the 20 000 years and simulation replicate strata was within a tolerance of 1–2 tonnes and limited the number of years that failed the fixed catch rule.

We identified the fixed catch and fixed *F* rules that maximised the average annual catch while meeting the risk and catch constraints. The RLWG agreed that the vulnerable biomass level associated with the maximum constrained fixed catch rule would be unrealistically high given that the rule assumed that the simulation catch limit would be left unattended for 30 years without management intervention. The RLWG also agreed that the vulnerable biomass associated with the maximum constrained fixed *F* rule would be unrealistically low given that fixed *F* rules cannot be accurately implemented in practice. To account for this trade-off between the high catch associated with fixed *F* rules and the low variation in catch associated with the fixed catch policy, the RLWG agreed that the reference level would be the average of the two vulnerable biomass levels associated with the maximum fixed catch and fixed *F* rules. This was calculated by taking the mean of each sample from the posterior distribution between the maximum constrained fixed catch and fixed *F* vulnerable biomasses, then taking the average of the resulting distribution. Because fixed *F* distributions were often much lower and had less uncertainty than the fixed catch distributions, taking the median instead of the mean of the resulting distribution would have kept the reference level lower, closer to the fixed *F* distribution. Taking the mean instead of the median of the posterior distributions ensured the final reference level fell more evenly between the fixed catch and fixed *F* distributions of vulnerable biomass.

For the multi-area assessments for CRA 3 and CRA 5, we identified the fixed catch and fixed *F* rules that maximised the average annual catch while meeting risk and catch constraints for each region separately. These were used to define a reference level for each region. We then added together the full distribution of vulnerable biomass (over all year/simulation replicate strata) of the two regions and took the average of the resulting distribution to calculate the overall reference level for CRA 3 and CRA 5, respectively. This procedure was repeated for each of the two CRA 3 stock assessment base models (with and without tag recoveries at liberty for less than one year).

3. RESULTS

For each assessment, we determined that an adequate number of rules across appropriate intervals were projected by finding the inflection points in the relationship between vulnerable biomass and average annual catch (Figure 2, Figure 3). For both fixed catch and fixed *F*, we identified the vulnerable biomass at which average annual catch began to decline, thus representing the theoretical *MSY*. Of the projected rules, we filtered out the rules that did not meet risk and catch constraints. We checked to make sure that fixed catch and fixed *F* rules were run at small enough increments to detect these inflection points. In CRA 3 and CRA 4, none of the rules came close to breaching the risk constraint due to a high incidence of mature females below the minimum legal size. For these assessments, we projected a wide range of fixed catch rules to identify where fixed catch began to fail the catch constraints.

3.1 CRA 1

CRA 1 is the northernmost rock lobster stock in New Zealand (Figure 1, Figure 2). It extends from Kaipara Harbour on the west coast to the Waipu River, south of Bream Bay and Whangarei on the east coast. This QMA includes the Three Kings Islands, designated by a separate statistical area (901).

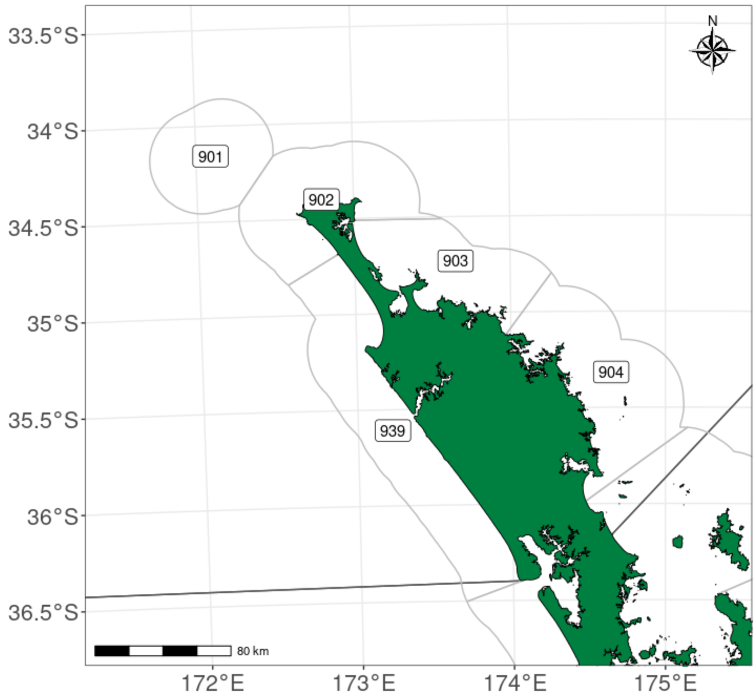

Figure 2; CRA 1 QMA and its statistical areas.

The last year of the 2019 CRA 1 stock assessment was the 2018–19 fishing year, where recruitment deviates were estimated for 1945–2016. In CRA 1, both length and CPUE data were available from 1994 to present. To calculate the reference levels, 30-year projections and SSB_0^{data} used for the risk constraint were based on estimated recruitment deviates for 23 years, from 1994 to 2016 (Figure 3).

CRA 1 projections identified that a fixed F of 0.45 maximised the average annual catch while meeting the risk constraints; this fixed F rule was associated with an average of 345 tonnes of vulnerable biomass, 213 tonnes of annual total catch (166 tonnes of annual SL catch), and a catch CV of 0.144 over time and simulation replicates. A fixed F of 0.46 or greater failed the risk constraint (Table 1, Figure 4, Figure 5, Figure 6).

A total fixed catch of 198 tonnes (150 tonnes of SL catch with the remainder fixed NSL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 563 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.031. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 0.9% of years and simulation replicates. A fixed SL catch of 151 tonnes or greater failed the risk constraint and 170 tonnes or greater failed both the risk and catch constraint (Table 1, Figure 4, Figure 5, Figure 6).

The average vulnerable biomass between the distributions associated with each maximum constrained rule was 454 tonnes (Table 1, Figure 7). Since this was based on the 2019 stock assessment, CRA 1 would have had a probability of 0.737 of being above the reference level in the last modelled fishing year, 2018–19. CRA 1 would have had a probability of 0.210 of being above the vulnerable biomass associated with the maximum constrained fixed catch harvest rule, and a probability of 0.995 of being above the vulnerable biomass associated with the maximum constrained fixed F harvest rule at the start of the 2018–19 fishing year (Table 1, Figure 7).

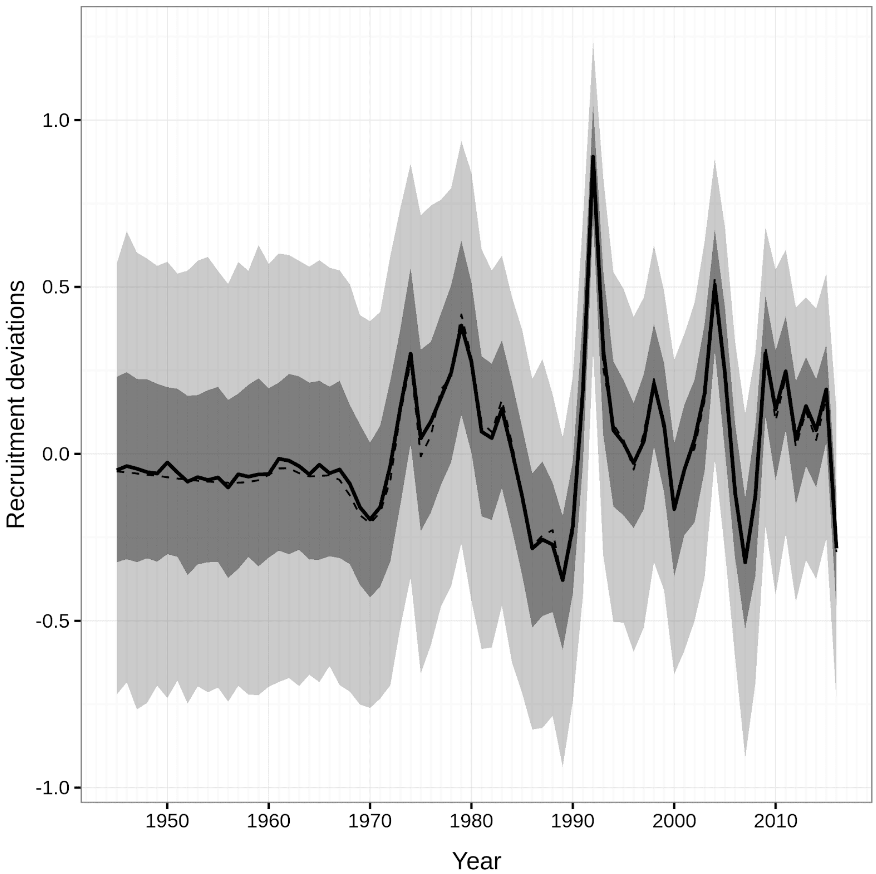

Figure 3: CRA 1 recruitment deviates: Estimated recruitment deviates from the 2019 CRA 1 stock assessment. Recruitment deviates from 1994 to 2016 were used for the 30-year projections and to calculate SSB_0^{data} for use in the risk constraint. The dashed line shows the maximum *a posteriori* (MAP) estimates, the solid line shows the median of the posterior distribution, and shading shows the 50% and 90% credible intervals.

Table 1: CRA 1 fixed catch, fixed F, and averages: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints for CRA 1, as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2019 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

Value	Status from 2018–19 fishing year
Total catch	210 tonnes (131 commercial, 31 recreational, 48 NSL)
Vulnerable biomass	498 tonnes (5th percentile = 398 tonnes, 95th percentile = 646 tonnes)

Value	Fixed catch	Fixed F	Average
Average annual catch	197 (197–198)	213 (167–267)	205 (174–253)
Vulnerable biomass (B_R)	563 (203–961)	345 (249–462)	454 (237–863)
Relative vulnerable biomass (B/B_0)	0.177 (0.061–0.308)	0.108 (0.074–0.150)	0.142 (0.071–0.276)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.285 (0.137–0.444)	0.197 (0.141–0.263)	0.241 (0.140–0.407)
Relative spawning biomass (SSB/SSB_0^{data})	0.428 (0.200–0.650)	0.284 (0.203–0.381)	0.356 (0.202–0.601)
Catch CV	0.031	0.144	–
Probability below soft limit	0.050	0.043	–
Probability 2018 vulnerable biomass was above reference level	0.210	0.995	0.737

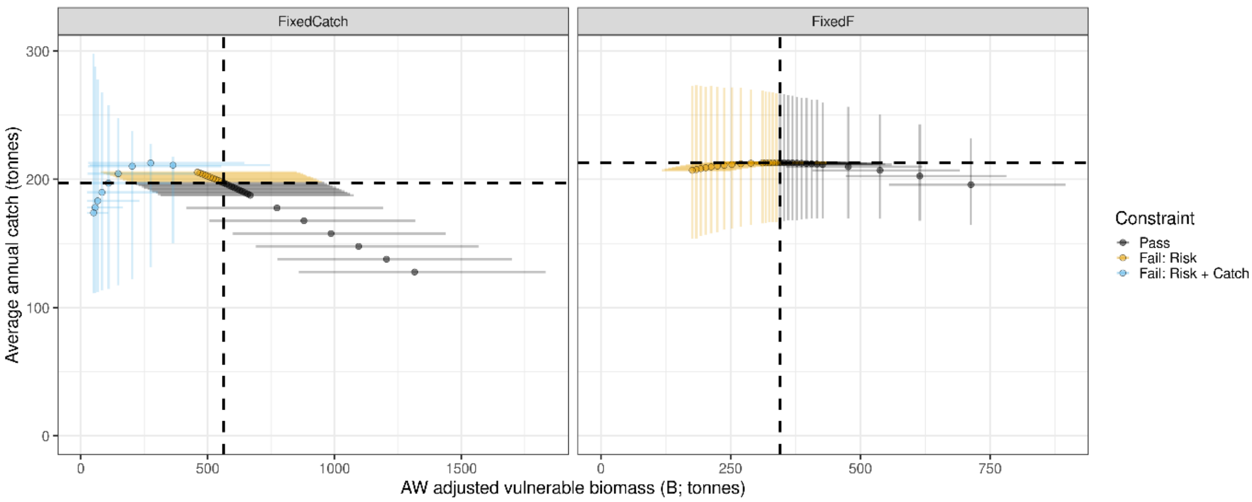

Figure 4: CRA 1 vulnerable biomass vs. catch: adjusted vulnerable biomass (B) compared with average annual catch for fixed catch and fixed F rules. Points show the average autumn-winter (AW) adjusted vulnerable biomass and annual catch by harvest control rule, segments show the 90th percentiles of B (horizontal) and catch (vertical) by rule. The dashed line shows the rule that maximises catch and meets the risk constraints.

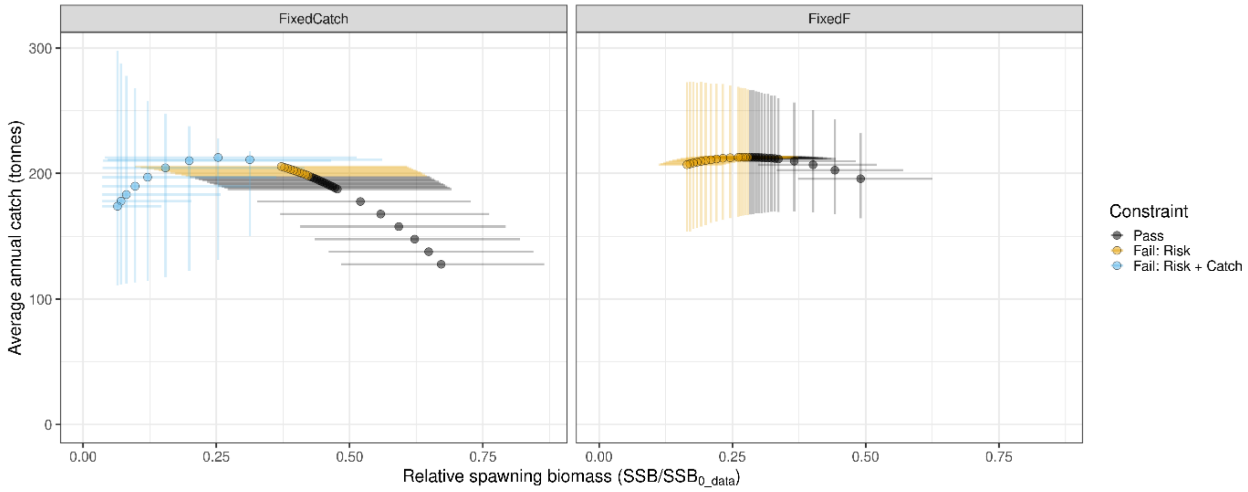

Figure 5: CRA 1 relative spawning biomass vs. catch: relative spawning biomass ($SSB/SSB_0^{\mathrm{data}}$) compared with average annual catch for fixed catch and fixed *F* rules. Points show the average $SSB/SSB_0^{\mathrm{data}}$ and annual catch by harvest control rule and segments show the 90th percentiles of *B* (horizontal) and catch (vertical) by rule.

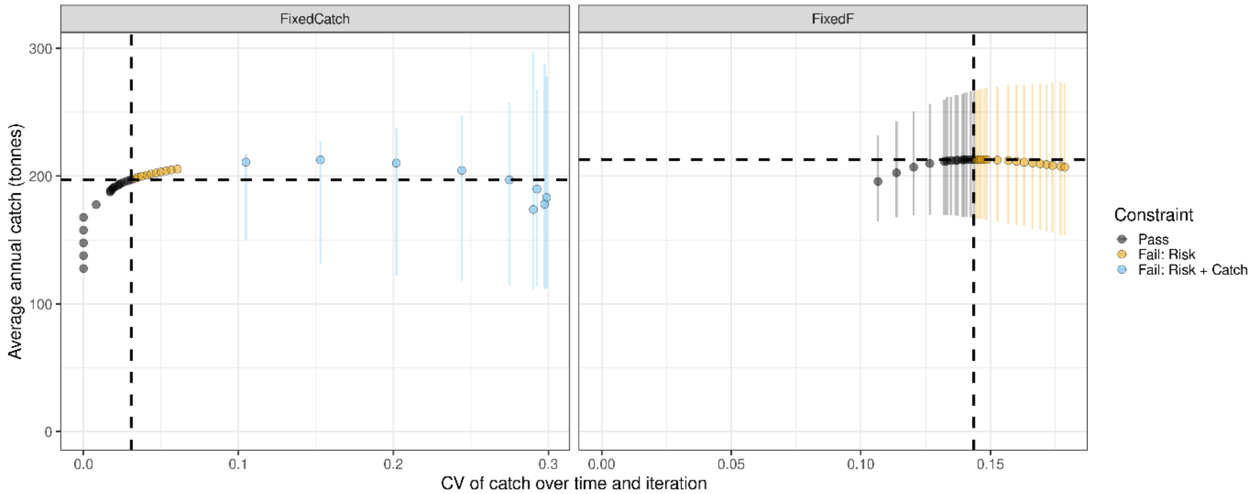

Figure 6: CRA 1 CV vs. catch: CV of catch over time and iteration compared with the average annual catch for fixed catch and fixed *F* rules. Points show the average CV and annual catch by harvest control rule, segments show the 90th percentiles of catch by rule, and the dashed line shows the rule that maximises catch and meets risk constraints.

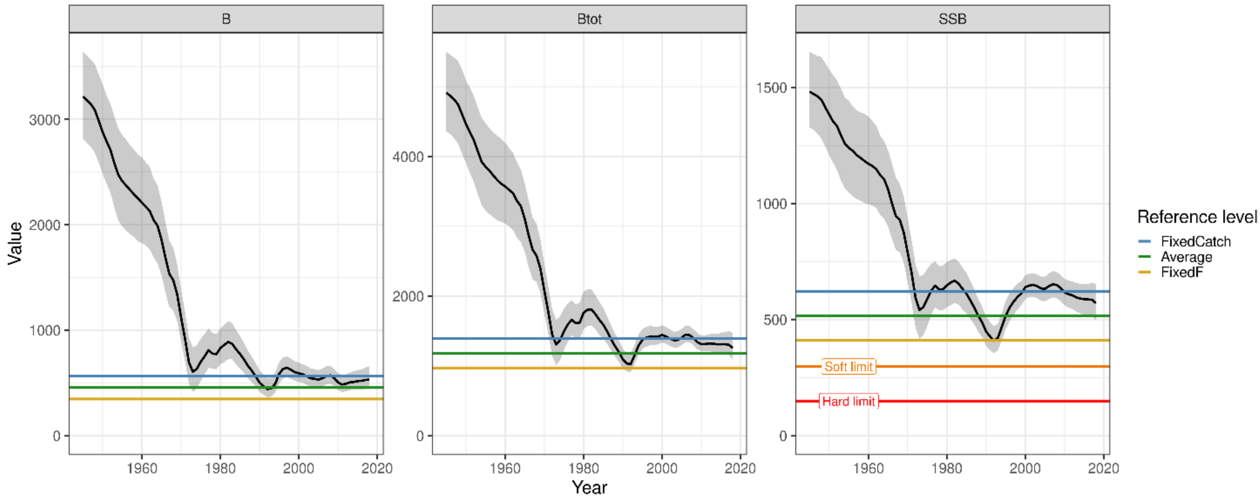

Figure 7: CRA 1 reference level: CRA 1 autumn-winter (AW) adjusted vulnerable biomass (*B*), total biomass (B^{tot}), and spawning stock biomass (*SSB*) median and 90th credible intervals from the 2019 stock assessment compared with the average of the distributions of vulnerable biomass associated with the maximum constrained fixed catch and fixed *F* rules and the average of the latter two distributions, also compared with the soft and hard limits for *SSB*. The 'average' adjusted vulnerable biomass *B* is the reference level B_R.

3.2 CRA 2

The CRA 2 fishery extends from Te Arai Point, south of Whangarei, to East Cape at the easternmost end of the Bay of Plenty (Figure 1, Figure 8). This QMA includes the Hauraki Gulf, both sides of the Coromandel Peninsula, and all of the Bay of Plenty up to East Cape.

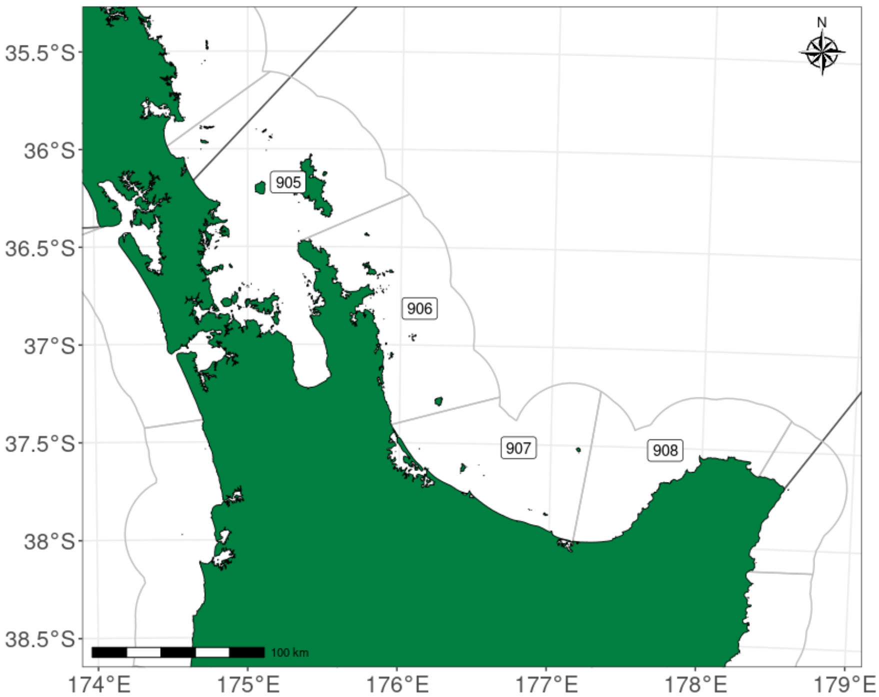

Figure 8: CRA 2 QMA and its statistical areas.

The last year of the 2017 CRA 2 stock assessment was the 2016–17 fishing year, where recruitment deviates were estimated for 1979–-2014. In CRA 2, both length and CPUE data were available from 1986 onwards. To calculate the reference levels, 30-year projections and SSB_0^{data} used for the risk constraint were based on estimated recruitment deviates for 29 years, from 1986 to 2014 (Figure 9).

CRA 2 projections identified that a fixed F of 1.15 maximised the average annual catch while meeting the risk constraints; this fixed F rule was associated with an average of 281 tonnes of vulnerable biomass, 326 tonnes of annual total catch (286 tonnes of annual SL catch), and a catch CV of 0.177 over time and simulation replicates. A fixed F of 1.20 and greater failed the risk constraint (Table 2, Figure 10, Figure 11, Figure 12).

A total fixed catch of 275 tonnes (230 tonnes of SL catch with the remainder fixed NSL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 595 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.02. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 1.1% of years and simulation replicates. A fixed SL catch of 235 tonnes or greater failed the risk constraint and 250 tonnes or greater failed both the risk and catch constraint (Table 2, Figure 10, Figure 11, Figure 12).

The average vulnerable biomass between the distributions associated with each maximum constrained rule was 438 tonnes (Table 2, Figure 13). Since this was based on the 2017 stock assessment, CRA 2 would have had a negligible probability of being above the reference level in 2016, and a negligible probability of being above the vulnerable biomass associated with the maximum constrained fixed catch rule. CRA 2 would have had a probability of 0.001 of being above the vulnerable biomass associated with the maximum constrained fixed F harvest rule start of the 2016–17 fishing year (Table 2, Figure 13).

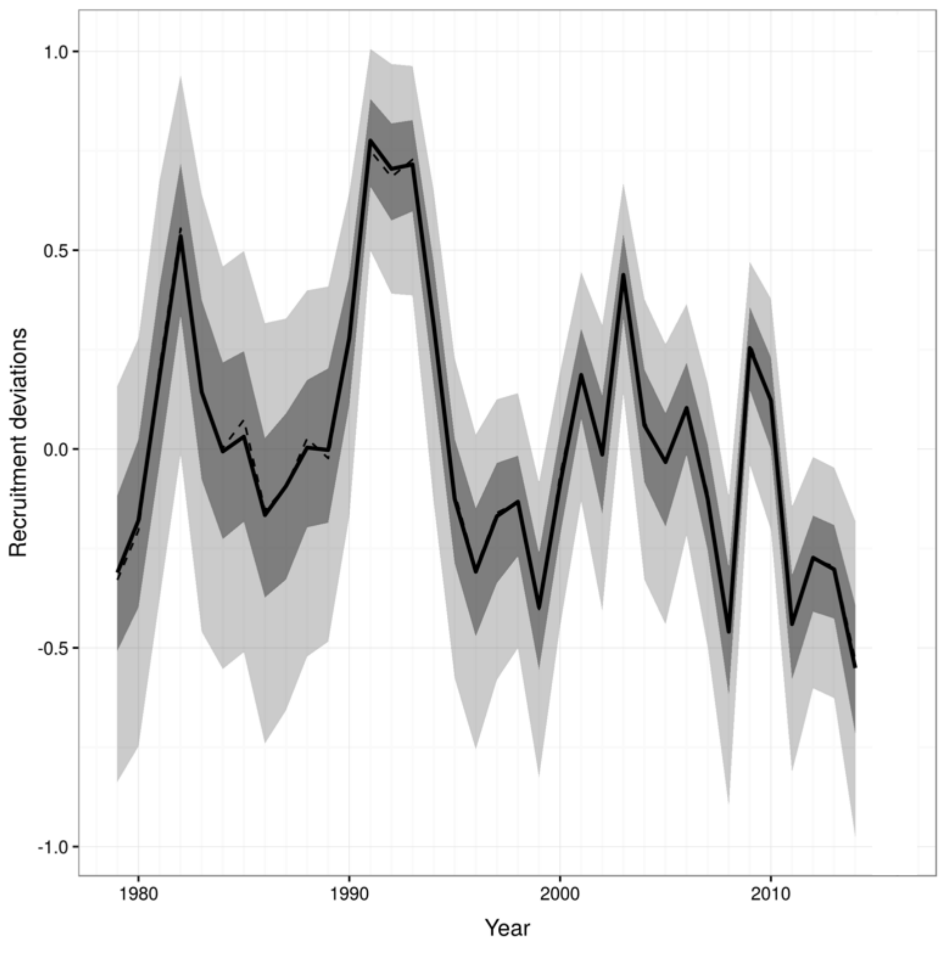

Figure 9: CRA 2 recruitment deviates: Estimated recruitment deviates from the 2017 CRA 2 stock assessment. Recruitment deviates from 1986 to 2014 were used for the 30-year projections and to calculate SSB_0^{data} for use in the risk constraint. The dashed line shows the MAP estimates, the solid line shows the median of the posterior distribution, and shading shows the 50% and 90% credible intervals.

Table 2: CRA 2 fixed catch, fixed F, and averages: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints for CRA 2, as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2017 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

Value	Status from 2016–17 fishing year		
Total catch	222 tonnes (142 commercial, 34 recreational, 45 NSL)		
Vulnerable biomass	203 tonnes (5th percentile = 173 tonnes, 95th percentile = 242 tonnes)		
Value	**Fixed catch**	**Fixed F**	**Average**
Average annual catch	275 (275, 275)	326 (243, 429)	300 (255, 402)
Vulnerable biomass	595 (191, 1058)	281 (189, 399)	438 (190, 938)
Relative vulnerable biomass (B/B_0)	0.156 (0.050, 0.280)	0.074 (0.049, 0.106)	0.115 (0.049, 0.247)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.300 (0.153, 0.465)	0.195 (0.137, 0.265)	0.248 (0.141, 0.425)
Relative spawning biomass (SSB/SSB_0^{data})	0.503 (0.208, 0.810)	0.284 (0.200, 0.388)	0.393 (0.202, 0.747)
Catch CV	0.022	0.177	–
Probability below soft limit	0.045	0.0496	–
Probability 2016 vulnerable biomass was above reference level	0.000	0.000	0.000

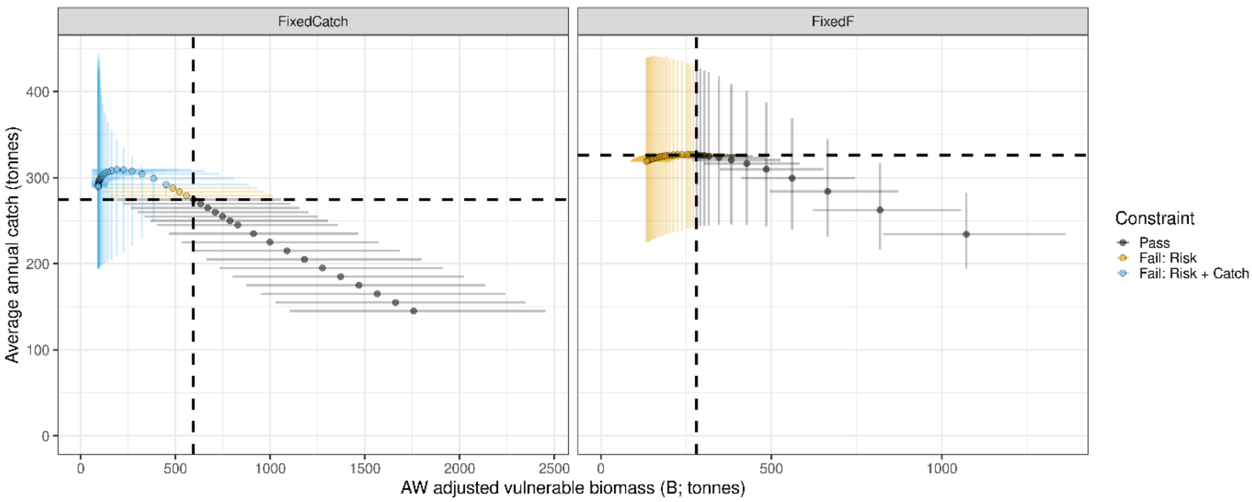

Figure 10: CRA 2 vulnerable biomass vs. catch: adjusted vulnerable biomass (B) compared with average annual catch for fixed catch and fixed F rules. Points show the average autumn-winter (AW) adjusted vulnerable biomass and annual catch by harvest control rule, segments show the 90th percentiles of B (horizontal) and catch (vertical) by rule. The dashed line shows the rule that maximises catch and meets the risk constraints.

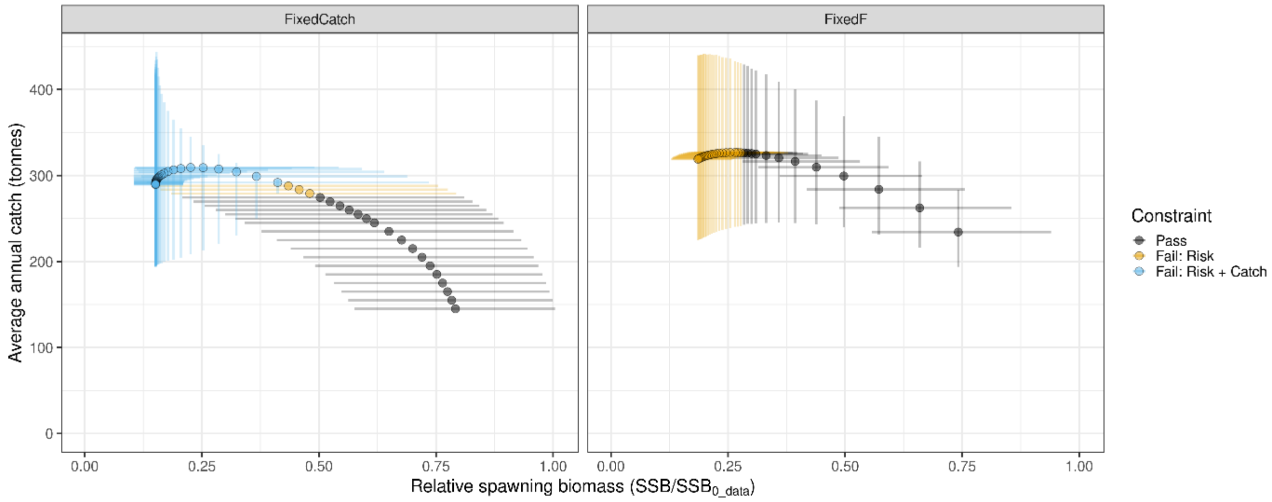

Figure 11: CRA 2 relative spawning biomass vs. catch: relative spawning biomass (SSB/SSB_0^{data}) compared with average annual catch for fixed catch and fixed F rules. Points show the average SSB/SSB_0^{data} and annual catch by harvest control rule and segments show the 90th percentiles of B (horizontal) and catch (vertical) by rule.

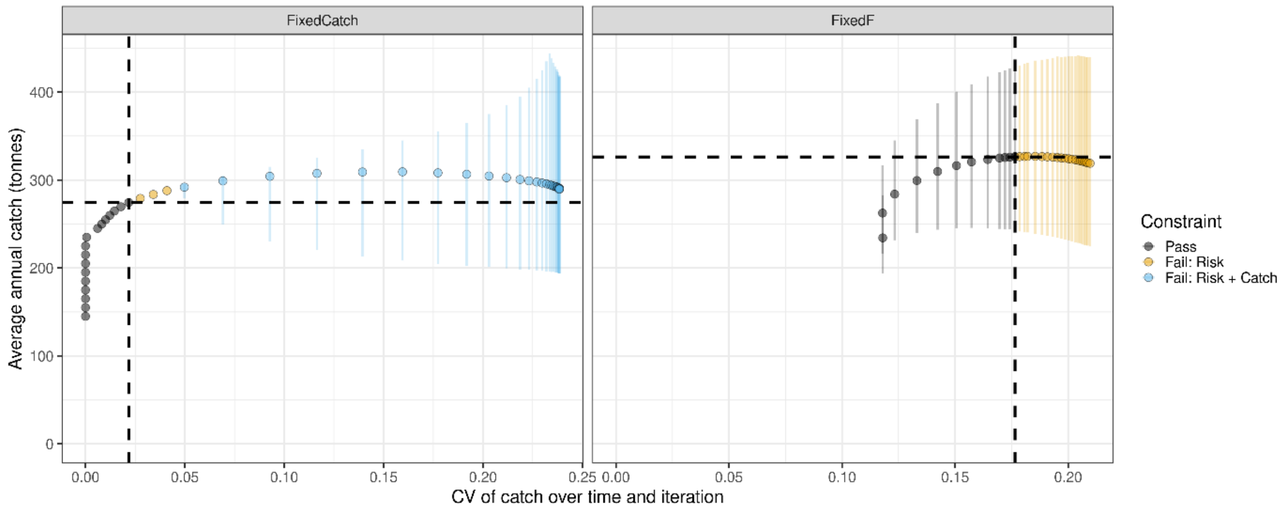

Figure 12: CRA 2 CV vs. catch: CV of catch over time and iteration compared with the average annual catch for fixed catch and fixed F rules. Points show the average CV and annual catch by harvest control rule, segments show the 90th percentiles of catch by rule, and the dashed line shows the rule that maximises catch and meets risk constraints.

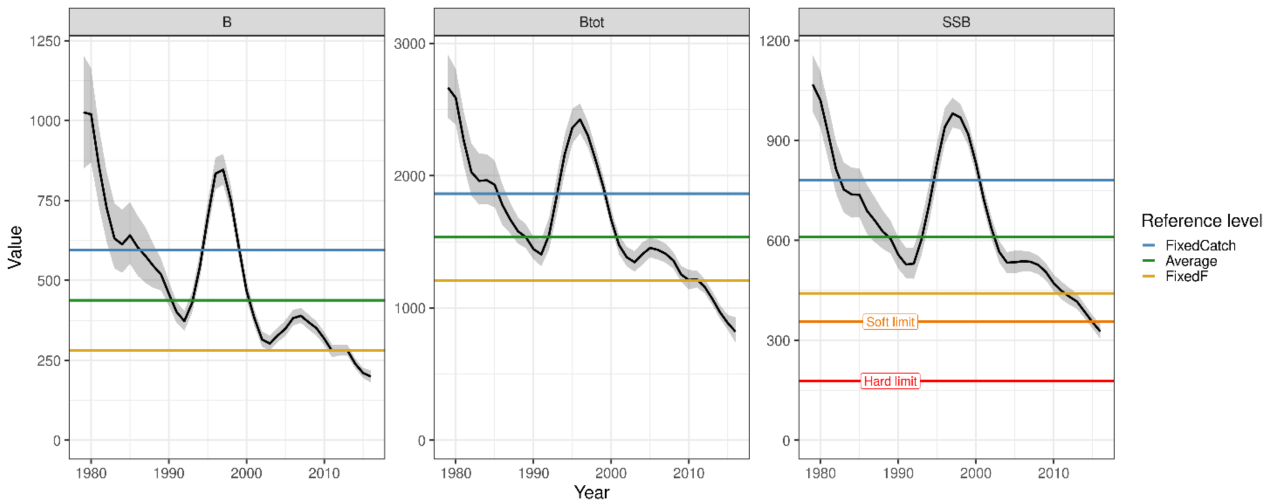

Figure 13: CRA 2 reference level: CRA 2 autumn-winter (AW) adjusted vulnerable biomass (*B*), total biomass (B^{tot}), and spawning stock biomass (*SSB*) median and 90th credible intervals from the 2017 stock assessment compared with the average of the distributions of vulnerable biomass associated with the maximum constrained fixed catch and fixed *F* rules and the average of the latter two distributions, also compared with the soft and hard limits for *SSB*. The 'average' adjusted vulnerable biomass *B* is the reference level B_R.

3.3 CRA 3

The CRA 3 fishery extends from East Cape south to the Wairoa River (Figure 1, Figure 14) and includes Gisborne (910) and Mahia Peninsula (911).

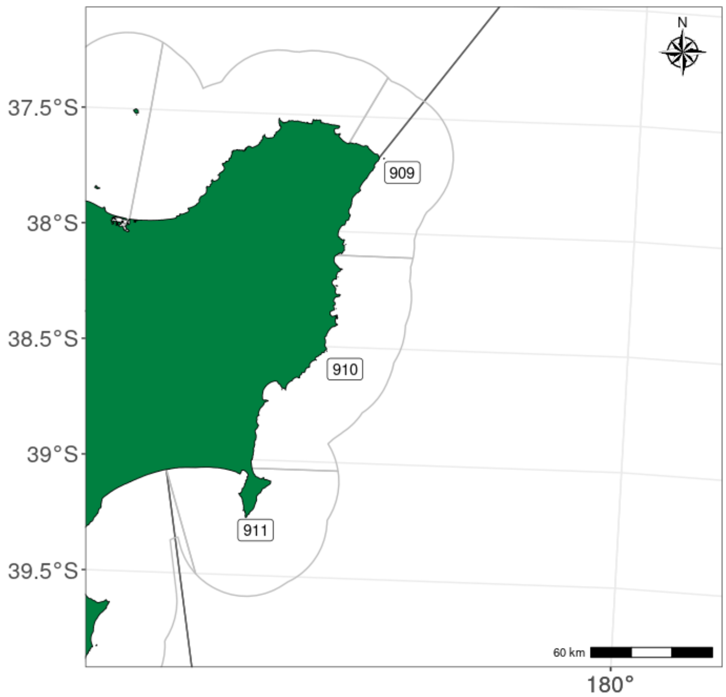

Figure 14: CRA 3 QMA and its statistical areas.

The CRA 3 stock assessment assumed two regions. Region 1 included statistical areas 909+910 and region 2 included statistical area 911 (Figure 14). Two base case models tested two alternative growth assumptions. The base model *r1_qdrift* excluded tags at liberty less than one year whereas *r2_qdrift* included all tag-recapture data. In general, adjusted vulnerable biomass estimated by *r2_qdrift* was slightly higher than the adjusted vulnerable estimated by *r1_qdrift* (Figure 15). The RLWG moved forward with two base models, therefore reference levels were calculated for each base model independently.

The last year of the 2019 CRA 3 stock assessment was the 2018–19 fishing year, where recruitment deviates were estimated for 1945–2016. In CRA 3, both length and CPUE data were available from 1986 onwards. To calculate the reference levels, 30-year projections and SSB_0^{data} used for the risk constraint were based on estimated recruitment deviates for 31 years, from 1986 to 2016 (Figure 16, Figure 17).

Due to minimum legal size restrictions in CRA 3 relative to maturation, the stock assessment estimated a very large biomass of mature, spawning females (i.e., minimum legal size 60 mm tail width (TW), and estimated size at 50% maturity of 40.2 mm TW; Webber et al. 2020). Therefore, the *SSB* in CRA 3 remained well above the soft limit of 20% SSB_0^{data} under all investigated rules. Despite high fishing mortality rates, none of the fixed catch or fixed *F* rules in either base model had greater than 0.05 probability of falling below the soft limit (i.e., none were risk-constrained). Thus, reference levels for both region 1 (statistical areas 909 and 910) and region 2 (statistical area 911) in both base models were determined based on maximising the catch and fixed catch rules that were not catch-constrained.

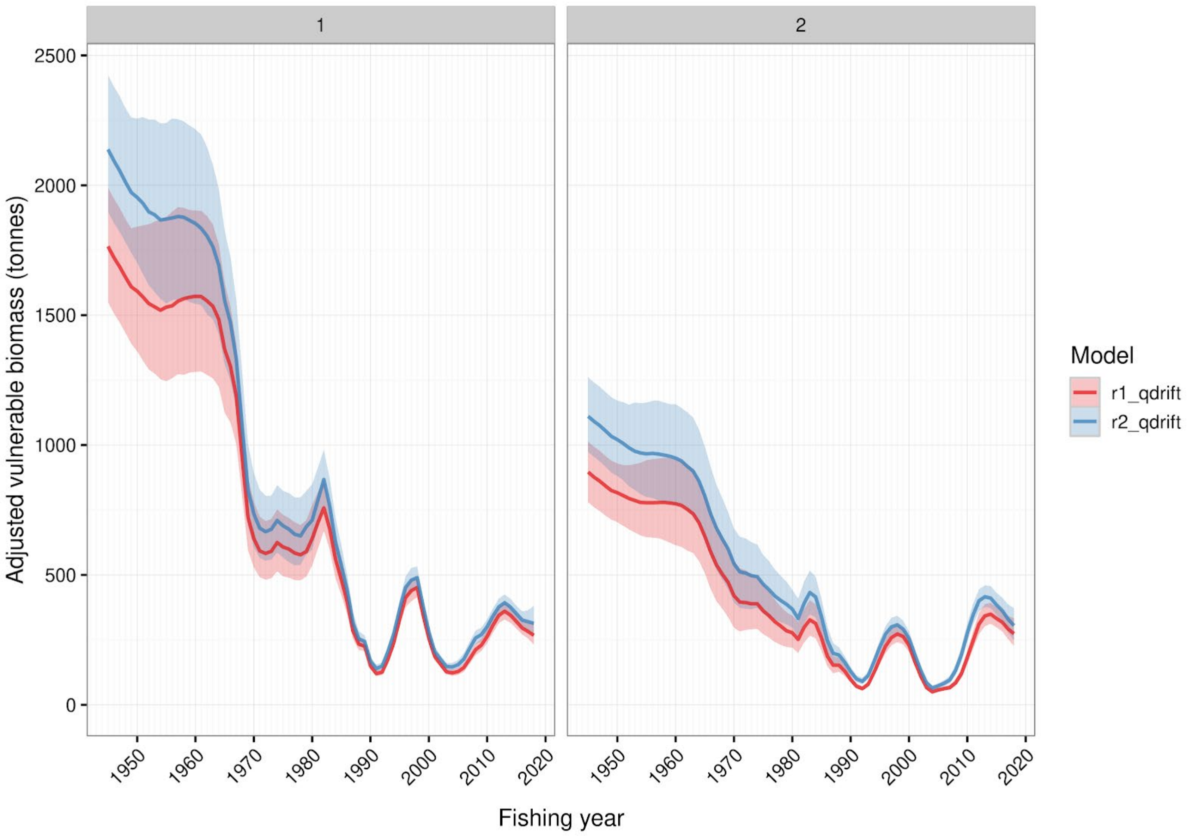

Figure 15: CRA 3 base model comparison: Comparison of adjusted vulnerable biomass in CRA 3 (region 1 = statistical areas 909+910, region 2 = statistical area 911) between the two CRA 3 base models in the 2019 assessment. *r1_qdrift* removed all tags at liberty less than one year and *r2_qdrift* included all tag-recapture data.

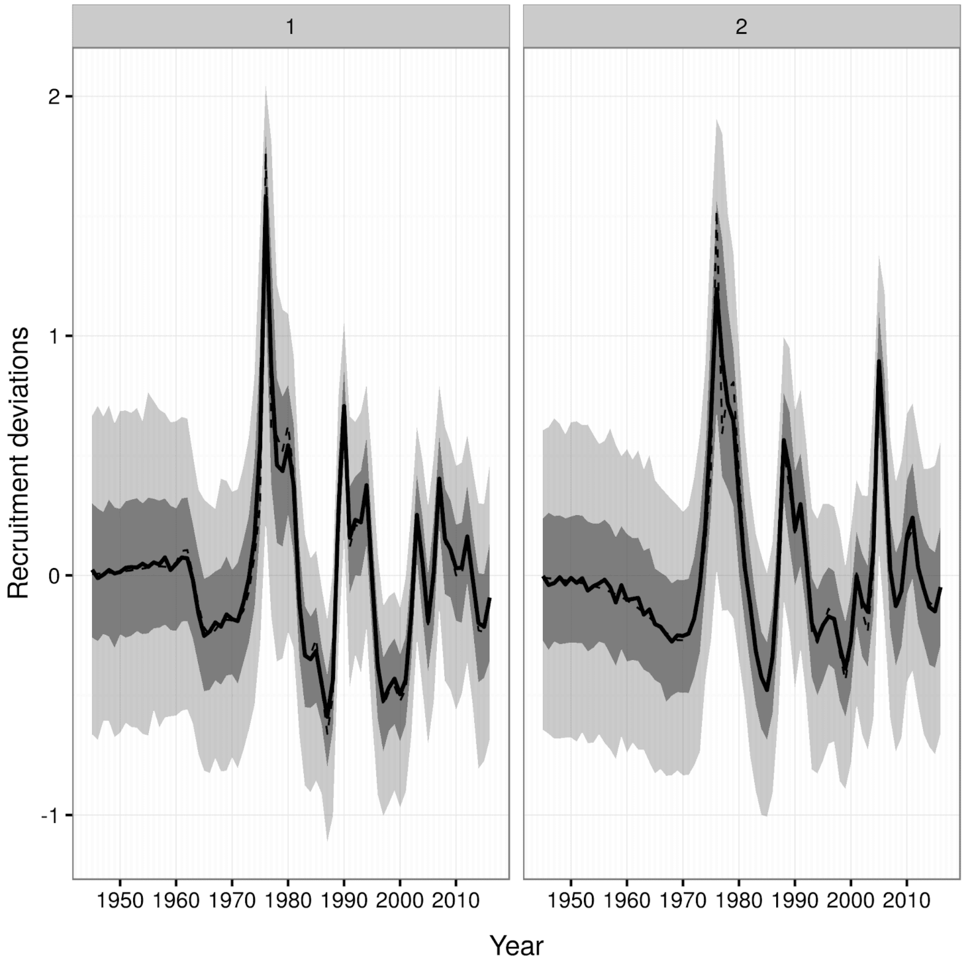

Figure 16: CRA 3 *r1_qdrift* recruitment deviates: Estimated recruitment deviates from the 2019 CRA 3 stock assessment for region 1 (statistical areas 909+910) and region 2 (statistical area 911). Recruitment deviates from 1986 to 2016 were used for the 30-year projections and to calculate SSB_0^{data} for use in the risk constraint. The dashed line shows the MAP estimates, the solid line shows the median of the posterior distribution, and shading shows the 50% and 90% credible intervals.

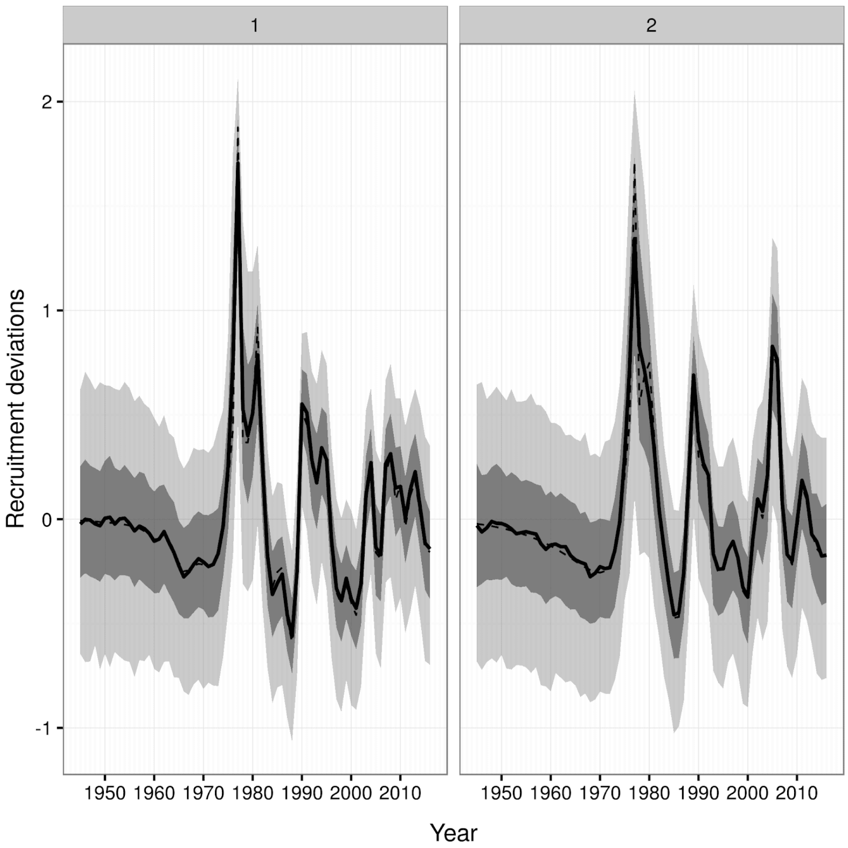

Figure 17: CRA 3 *r2_qdrift* recruitment deviates: Estimated recruitment deviates from the 2019 CRA 3 stock assessment for region 1 (statistical areas 909+910) and region 2 (statistical area 911). Recruitment deviates from 1986 to 2016 were used for the 30-year projections and to calculate SSB_0^{data} for use in the risk constraint. The dashed line shows the MAP estimates, the solid line shows the median of the posterior distribution, and shading shows the 50% and 90% credible intervals.

3.3.1 Base model *r1_qdrift*

Base model *r1_qdrift* (here referred to as '*r1*') removed tags at liberty less than one year. For *r1* in region 1, a fixed *F* of 3.0 maximised the average annual catch while meeting the risk constraints; this fixed *F* rule was associated with an average of 149 tonnes of vulnerable biomass, 198 tonnes of annual total catch (153 tonnes of annual SL catch), and a catch CV of 0.178 over time and simulation replicates (Table 3, Figure 18, Figure 19, Figure 20).

For *r1* in region 1, a total fixed catch of 175 tonnes (130 tonnes of SL catch with the remainder fixed NSL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 322 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.034. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 4.4% of years and simulation replicates. A fixed SL catch of 135 tonnes or greater failed the catch constraint (Table 3, Figure 18, Figure 19, Figure 20).

For *r1* in region 2, a fixed *F* of 3.3 maximised the average annual catch while meeting the risk constraints; this fixed *F* rule was associated with an average of 57 tonnes of vulnerable biomass, 143 tonnes of annual total catch (108 tonnes of annual SL catch), and a catch CV of 0.219 over time and simulation replicates (Table 3, Figure 18, Figure 19, Figure 20).

For *r1* in region 2, a total fixed catch of 125 tonnes (90 tonnes of SL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 166 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.033. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 2.8% of years and simulation replicates. A fixed SL catch of 95 tonnes or greater failed the catch constraint (Table 3, Figure 18, Figure 19, Figure 20).

For *r1* in region 1, the average vulnerable biomass between the distributions associated with each maximum constrained rule was 236 tonnes. For *r1* in region 2, the average vulnerable biomass between the distributions associated with each maximum constrained rule was 111 tonnes (Table 3, Figure 21). Since this was based on the 2019 stock assessment, CRA 3 would have had a probability of 0.732 of being above the region 1 reference level, a negligible probability of being below the region 2 reference level, and a probability of 0.999 of being above the reference level for CRA 3 overall in the 2018–19 fishing year (Table 3, Table 4). CRA 3 would have a negligible probability of being below the vulnerable biomass associated with the maximum constrained fixed F rule in both regions in 2018. There was a probability of 0.053, 0.994, and 0.589 of the vulnerable biomass being below the reference levels associated with the maximum constrained fixed catch rule in region 1, region 2, and overall for CRA 3 in 2018 (Figure 21).

Table 3: CRA 3 *r1_qdrift* fixed catch, fixed *F*, and averages by region: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints for CRA 3 *r1_qdrift* regions 1 (statistical areas 909+910) and region 2 (statistical area 911), as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2019 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

Value	Region 1 (areas 909 and 910) Status from 2018–19 fishing year	Region 2 (911)
Total catch	197 tonnes (145 commercial, 6 recreational, 46 NSL)	151 tonnes (111 commercial, 5 recreational, 35 NSL)
Vulnerable biomass	257 tonnes (5th percentile = 208 tonnes, 95th percentile = 323 tonnes)	240 tonnes (5th percentile = 186 tonnes, 95th percentile = 310 tonnes)

Value	Fixed catch	Fixed F	Average	Fixed catch	Fixed F	Average
Average annual catch	175 (175–176)	197 (146–261)	186 (152–244)	125 (125–125)	143 (97–199)	133 (103–184)
Vulnerable biomass (B_R)	322 (108–604)	149 (102–207)	236 (104–529)	166 (55–306)	57 (37–83)	111 (39–270)
Relative vulnerable biomass (B/B_0)	0.184 (0.062–0.346)	0.085 (0.057–0.121)	0.134 (0.058–0.303)	0.186 (0.061–0.345)	0.064 (0.040–0.095)	0.125 (0.043–0.304)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.581 (0.422–0.769)	0.519 (0.395–0.671)	0.550 (0.404–0.733)	0.649 (0.470–0.853)	0.568 (0.426–0.737)	0.608 (0.441–0.814)
Relative spawning biomass (SSB/SSB_0^{data})	0.908 (0.696–1.130)	0.839 (0.665–1.043)	0.874 (0.405–1.097)	0.820 (0.617–1.041)	0.718 (0.426–0.903)	0.769 (0.441–0.996)
Catch CV	0.034	0.178	–	0.033	0.219	–
Probability below soft limit	0.000	0.000	–	0.000	0.000	–
Probability 2018 vulnerable biomass is above reference level	0.094	1.000	0.732	0.994	1.000	1.000

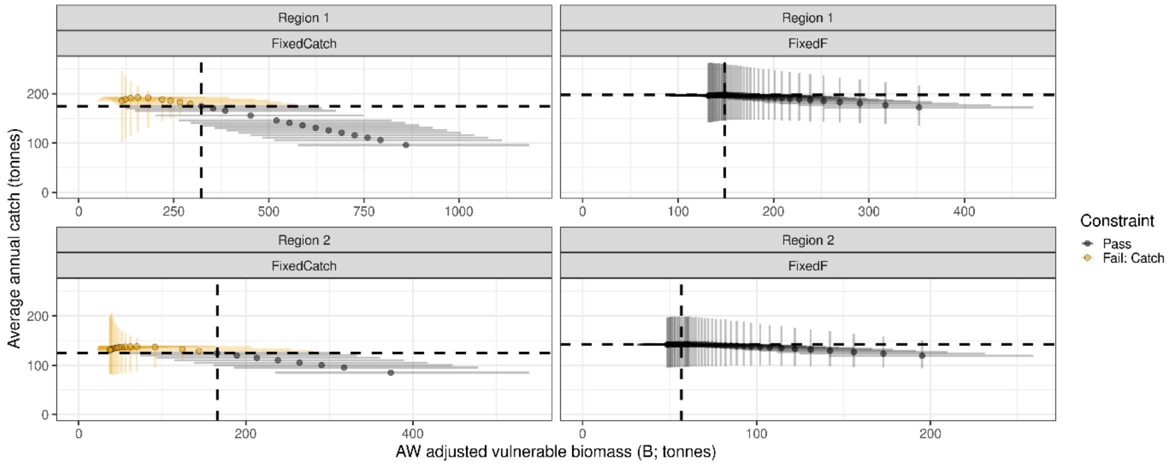

Figure 18: CRA 3 *r1_qdrift* vulnerable biomass vs. catch: adjusted vulnerable biomass (*B*) compared with average annual catch for fixed catch and fixed *F* rules by region. Points show the average autumn-winter (AW) adjusted vulnerable biomass and annual catch by harvest control rule, segments show the 90th percentiles of *B* (horizontal) and catch (vertical) by rule. The dashed line shows the rule that maximises catch and meets the risk constraints in each region.

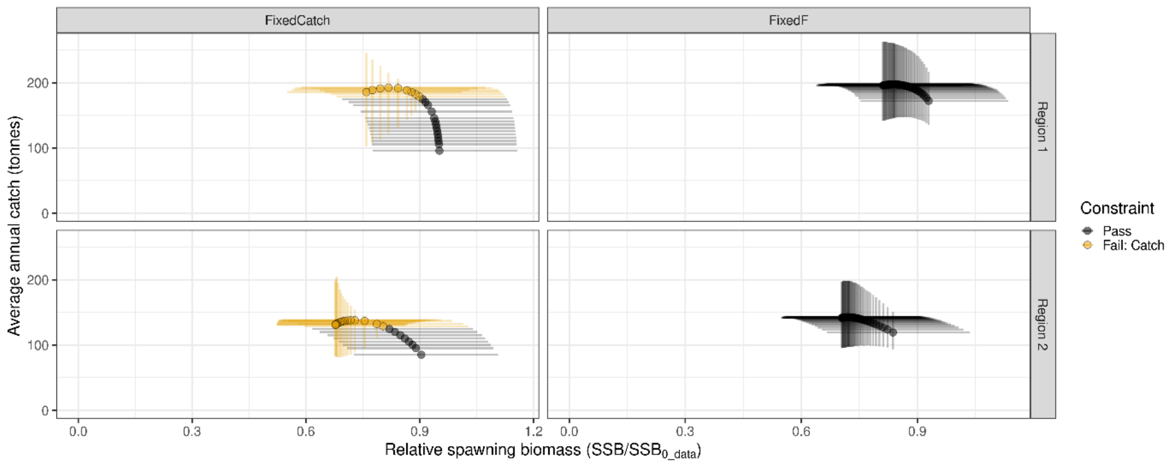

Figure 19: CRA 3 *r1_qdrift* relative spawning biomass vs. catch: relative spawning biomass (SSB/SSB_0^{data}) compared with average annual catch for fixed catch and fixed *F* rules by region. Points show the average SSB/SSB_0^{data} and annual catch by harvest control rule and segments show the 90th percentiles of *B* (horizontal) and catch (vertical) by rule.

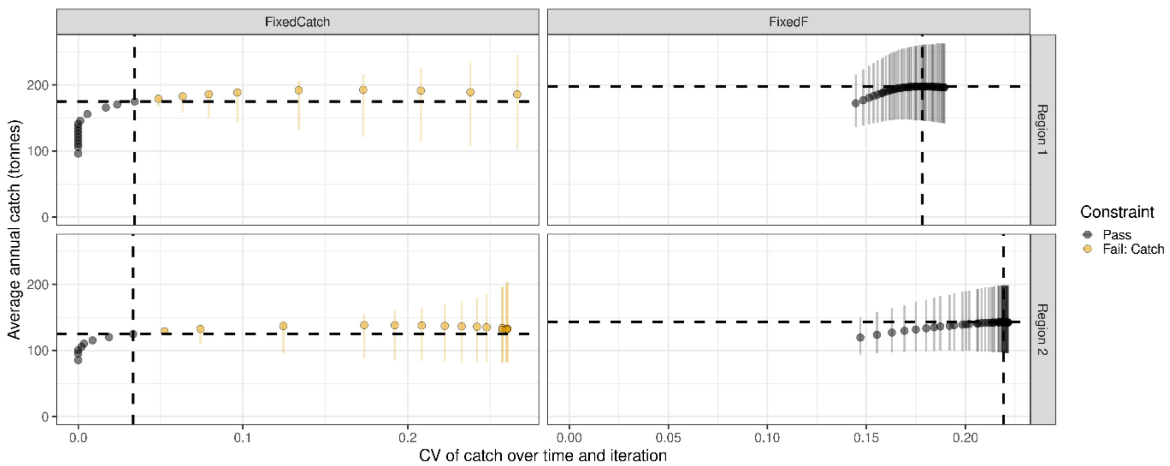

Figure 20: CRA 3 *r1_qdrift* CV vs. catch: CV of catch over time and iteration compared with the average annual catch for fixed catch and fixed *F* rules by region. Points show the average CV and annual catch by harvest control rule, segments show the 90th percentiles of catch by rule, and the dashed line shows the rule that maximises catch and meets risk constraints for each region.

Table 4: CRA 3 overall *r1_qdrift* fixed catch, fixed *F*, and averages: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints for CRA 3 overall, as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2019 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

Value	Status from 2018–19 fishing year
Total catch	348 tonnes (256 commercial, 11 recreational, 81 NSL)
Vulnerable biomass	501 tonnes (5th percentile = 420 tonnes, 95th percentile = 602 tonnes)

Value	Fixed catch	Fixed F	Average
Average annual catch	300 (291, 301)	340 (269, 424)	320 (276, 403)
Vulnerable biomass	488 (239, 804)	205 (154, 268)	347 (162, 717)
Relative vulnerable biomass (B/B_0)	0.184 (0.090, 0.304)	0.078 (0.056, 0.104)	0.131 (0.060, 0.273)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.605 (0.479, 0.745)	0.536 (0.439, 0.649)	0.571 (0.450, 0.716)
Relative spawning biomass (SSB/SSB_0^{data})	0.874 (0.723, 1.034)	0.792 (0.667, 0.931)	0.833 (0.684, 1.003)
Probability 2018 vulnerable biomass was above reference level	0.589	1.000	0.999

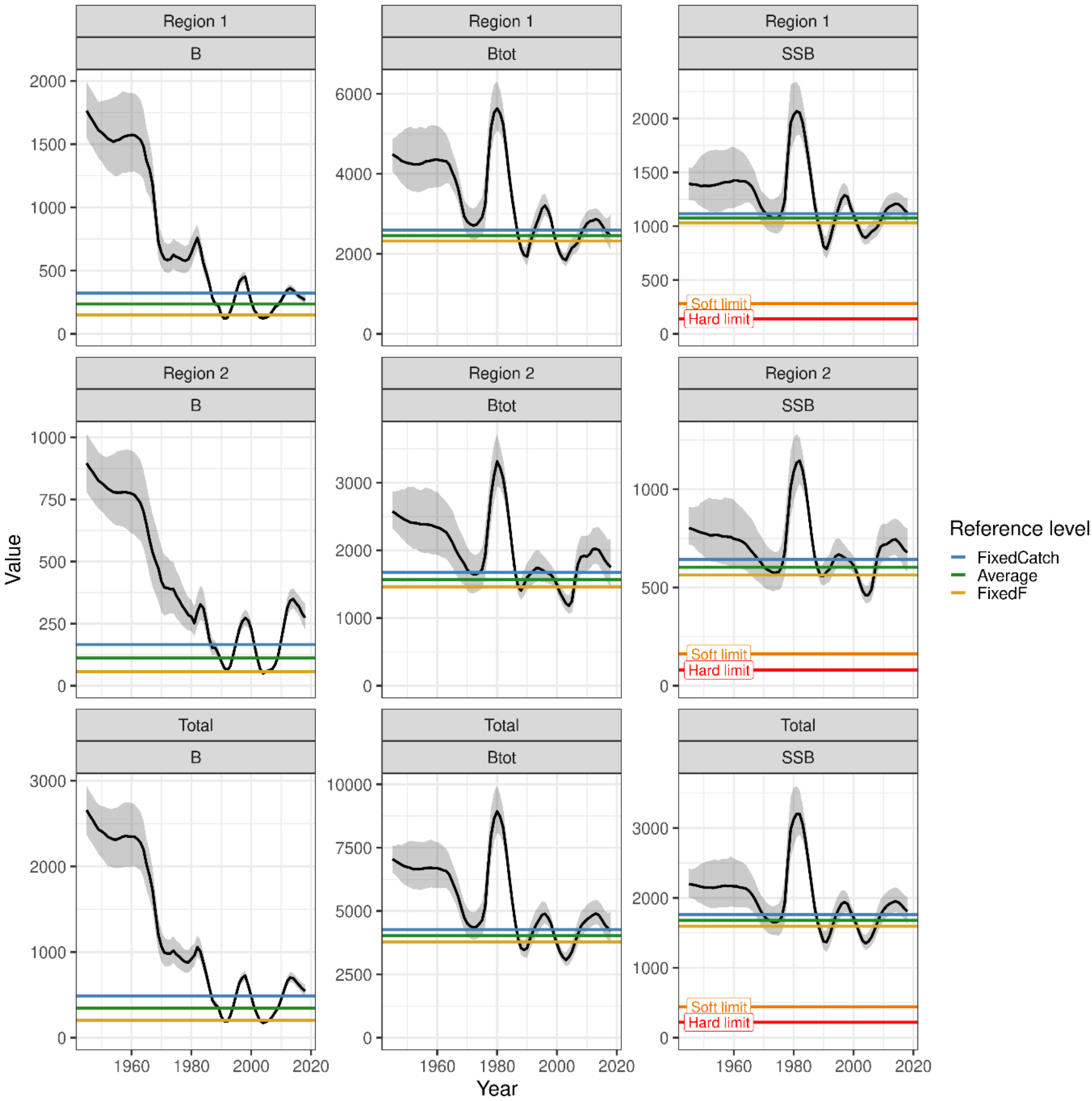

Figure 21: CRA 3 *r1_qdrift* reference level: CRA 3 autumn-winter (AW) adjusted vulnerable biomass (*B*), total biomass (B^{tot}), and spawning stock biomass (*SSB*) median and 90th credible intervals for region 1 (statistical areas 909+910), region 2 (area 911) and total for CRA 3 from the 2019 stock assessment compared with the average of the distributions of vulnerable biomass associated with the maximum constrained fixed catch and fixed *F* rules and the average of the latter two distributions, also compared with the soft and hard limits for *SSB*. The 'average' adjusted vulnerable biomass *B* is the reference level B_R.

3.3.2 Base model *r2_qdrift*

Base model *r2_qdrift* (here referred to as '*r2*') included all tag-recapture data regardless of time at liberty. For *r2* in region 1, a fixed *F* of 2.15 maximised the average annual catch while meeting the risk constraints; this fixed *F* rule was associated with an average of 168 tonnes of vulnerable biomass, 197 tonnes of annual total catch (152 tonnes of annual SL catch), and a catch CV of 0.170 over time and simulation replicates (Table 5, Figure 22, Figure 23, Figure 24).

For *r2* in region 1, a total fixed catch of 180 tonnes (135 tonnes of SL catch with the remainder fixed NSL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 360 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.040. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 4.4% of years and simulation replicates. A fixed SL catch of 140 tonnes or greater failed the catch constraint (Table 5, Figure 22, Figure 23, Figure 24).

For *r2* in region 2, a fixed F of 2.10 maximised the average annual catch while meeting the risk constraints; this fixed F rule was associated with an average of 72 tonnes of vulnerable biomass, 134 tonnes of annual total catch (99 tonnes of annual SL catch), and a catch CV of 0.205 over time and simulation replicates (Table 5, Figure 22, Figure 23, Figure 24).

For *r2* in region 2, a total fixed catch of 120 tonnes (85 tonnes of SL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 200 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.035. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 2.6% of years and simulation replicates. A fixed SL catch of 90 tonnes or greater failed the catch constraint (5, Figure 22, Figure 23, Figure 24).

For *r2* in region 1, the average vulnerable biomass between the distributions associated with each maximum constrained rule was 264 tonnes. For *r2* in region 2, the average vulnerable biomass between the distributions associated with each maximum constrained rule was 138 tonnes (Table 5, Figure 25). Since this was based on the 2019 stock assessment, CRA 3 would have had a probability of 0.827 of being above the region 1 reference level, a negligible probability of being below the region 2 reference level, and a probability of 0.998 of being above the reference level for CRA 3 overall in the 2018–19 fishing year (Table 5, Table 6). CRA 3 would have a negligible probability of being below the vulnerable biomass associated with the maximum constrained fixed F rule in both regions in 2018. There was a probability of 0.157, 0.953, and 0.575 of the vulnerable biomass being below the reference levels associated with the maximum constrained fixed catch rule in region 1, region 2, and overall for CRA 3 in 2018 (Figure 25).

Table 5: CRA 3 *r2_qdrift* fixed catch, fixed F, and averages: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints for CRA 3 *r2_qdrift* regions 1 (statistical areas 909+910) and region 2 (statistical area 911), as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2019 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

	Region 1 (areas 909 and 910)			Region 2 (911)		
Value	Status from 2018–19 fishing year					
Total catch	197 tonnes (145 commercial, 6 recreational, 46 NSL)			151 tonnes (111 commercial, 5 recreational, 35 NSL)		
Vulnerable biomass	299 tonnes (5th percentile = 237 tonnes, 95th percentile = 377 tonnes)			278 tonnes (5th percentile = 212 tonnes, 95th percentile = 354 tonnes)		
Value	Fixed catch	Fixed F	Average	Fixed catch	Fixed F	Average
Average annual catch	181 (181, 181)	197 (147, 256)	188 (153, 241)	120 (120 120)	134 (94, 183)	127 (100, 171)
Vulnerable biomass (B_R)	360 (116, 683)	168 (115, 234)	264 (115, 599)	200 (61, 369)	72 (48, 104)	136 (49, 323)
Relative vulnerable biomass (B/B_0)	0.168 (0.053, 0.320)	0.078 (0.052, 0.111)	0.123 (0.052, 0.281)	0.180 (0.055, 0.331)	0.065 (0.042, 0.096)	0.123 (0.044, 0.294)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.509 (0.360, 0.679)	0.440 (0.340, 0.556)	0.474 (0.346, 0.643)	0.542 (0.378, 0.728)	0.450 (0.337, 0.584)	0.496 (0.349, 0.684)
Relative spawning biomass (SSB/SSB_0^{data})	0.894 (0.685, 1.098)	0.820 (0.668, 0.993)	0.857 (0.674, 1.063)	0.754 (0.553, 0.967)	0.644 (0.506, 0.807)	0.699 (0.518, 0.922)
Catch CV	0.040	0.170	–	0.035	0.205	–
Probability below soft limit	0.000	0.000	–	0.000	0.000	–
Probability 2018 vulnerable biomass is above reference level	0.157	1.00	0.827	0.953	1.00	1.00

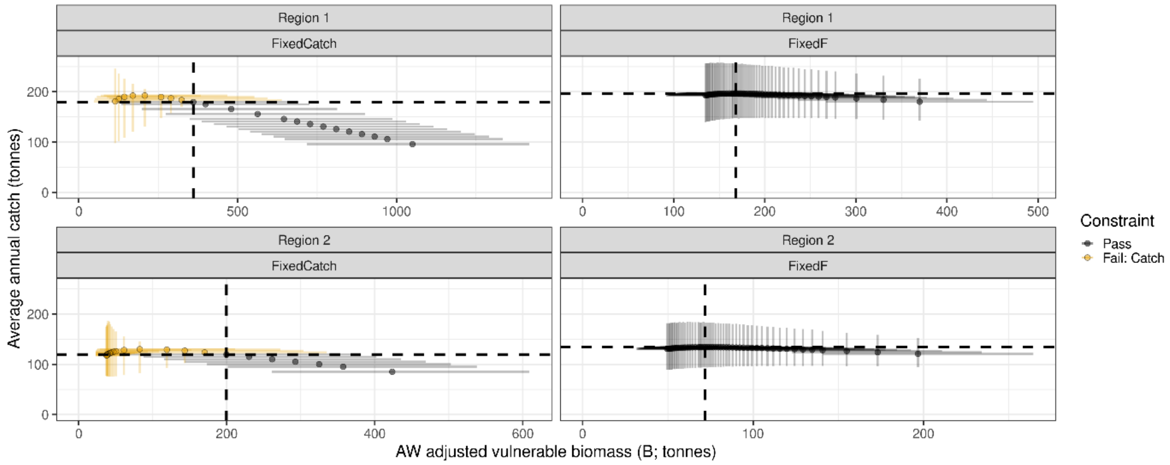

Figure 22: CRA 3 *r2_qdrift* vulnerable biomass vs. catch: adjusted vulnerable biomass (*B*) compared with average annual catch for fixed catch and fixed *F* rules by region. Points show the average autumn-winter (AW) adjusted vulnerable biomass and annual catch by harvest control rule, segments show the 90th percentiles of *B* (horizontal) and catch (vertical) by rule. The dashed line shows the rule that maximises catch and meets the risk constraints in each region.

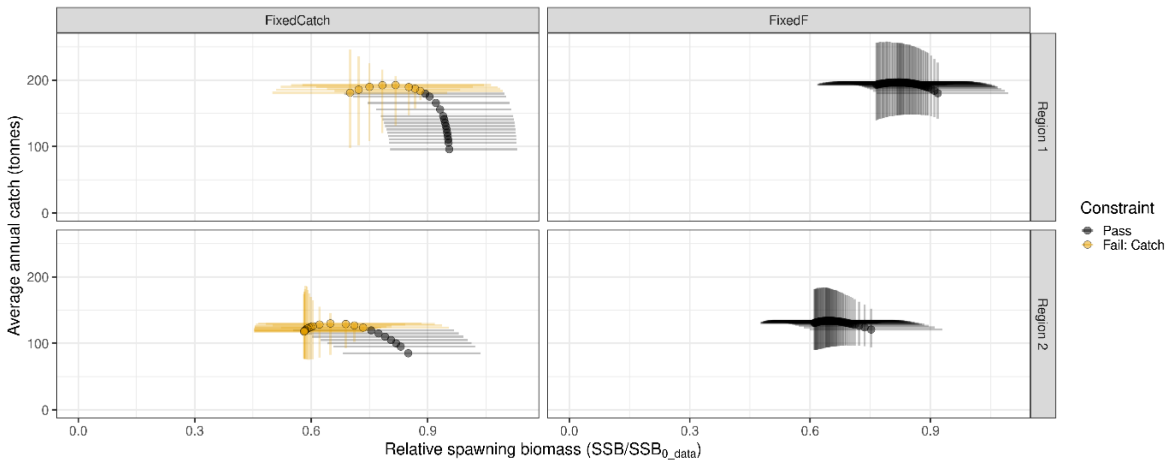

Figure 23: CRA 3 *r2_qdrift* relative spawning biomass vs. catch: relative spawning biomass (SSB/SSB_0^{data}) compared with average annual catch for fixed catch and fixed *F* rules by region. Points show the average SSB/SSB_0^{data} and annual catch by harvest control rule and segments show the 90th percentiles of *B* (horizontal) and catch (vertical) by rule.

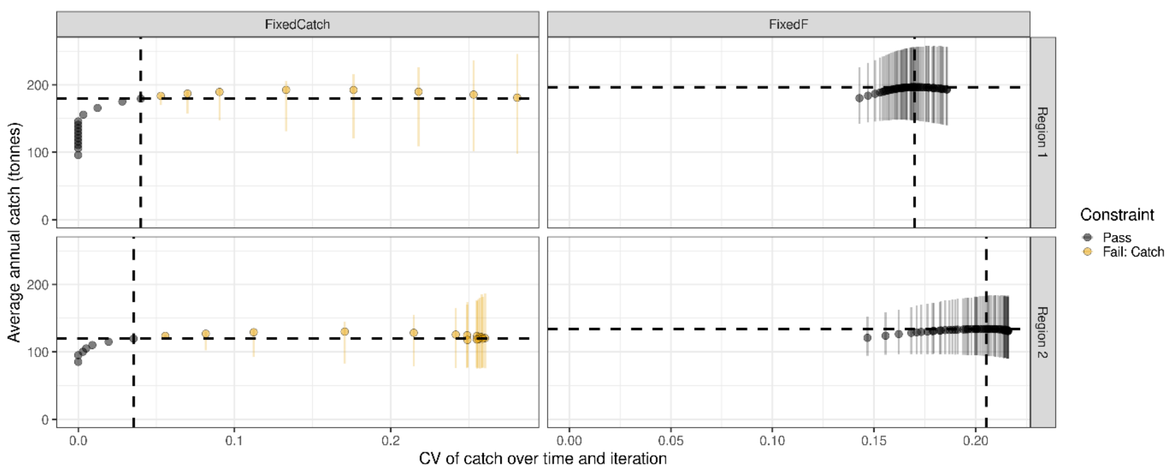

Figure 24: CRA 3 *r2_qdrift* CV vs. catch: CV of catch over time and iteration compared with the average annual catch for fixed catch and fixed *F* rules by region. Points show the average CV and annual catch by harvest control rule, segments show the 90th percentiles of catch by rule, and the dashed line shows the rule that maximises catch and meets risk constraints for each region.

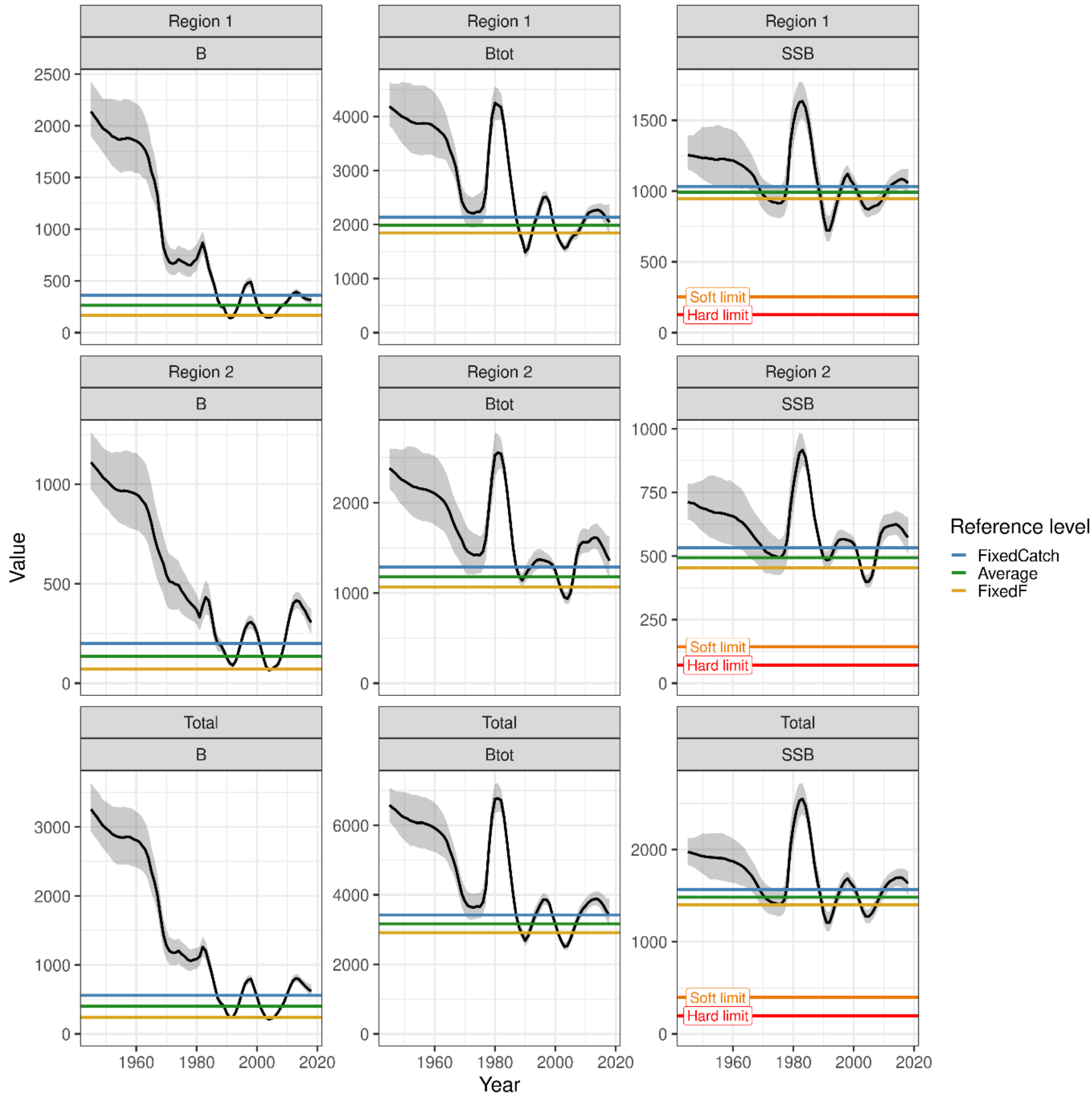

Figure 25: CRA 3 *r2_qdrift* reference level: CRA 3 autumn-winter (AW) adjusted vulnerable biomass (*B*), total biomass (B^{tot}), and spawning stock biomass (*SSB*) median and 90th credible intervals for region 1 (statistical areas 909+910), region 2 (area 911) and total for CRA 3 from the 2019 stock assessment compared with the average of the distributions of vulnerable biomass associated with the maximum constrained fixed catch and fixed *F* rules and the average of the latter two distributions, also compared with the soft and hard limits for *SSB*. The 'average' adjusted vulnerable biomass *B* is the reference level B_R.

Table 6: CRA 3 overall *r2_qdrift* fixed catch, fixed *F*, and averages: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints for CRA 3 overall, as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2019 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

Value	Status from 2018–19 fishing year		
Total catch	348 tonnes (256 commercial, 11 recreational, 81 NSL)		
Vulnerable biomass	501 tonnes (5th percentile = 420 tonnes, 95th percentile = 602 tonnes)		
Value	**Fixed catch**	**Fixed F**	**Average**
Average annual catch	299 (289, 301)	331 (265, 407)	315 (272, 388)
Vulnerable biomass (B_R)	560 (270, 911)	240 (180, 313)	400 (188, 828)
Relative vulnerable biomass (B/B_0)	0.172 (0.082, 0.282)	0.074 (0.054, 0.099)	0.123 (0.057, 0.256)
Relative total biomass ($B^{\mathrm{tot}}/B_0^{\mathrm{tot}}$)	0.520 (0.405, 0.647)	0.443 (0.365, 0.534)	0.481 (0.375, 0.619)
Relative spawning biomass ($SSB/SSB_0^{\mathrm{data}}$)	0.841 (0.692, 0.992)	0.753 (0.644, 0.877)	0.797 (0.656, 0.961)
Probability 2018 vulnerable biomass was above reference level	0.575	1.000	0.998

3.4 CRA 4

The CRA 4 fishery extends from the Wairoa River in northern Hawke's Bay, southwards through Hawke Bay, the Wairarapa and the Wellington coasts, then north to the Manawatu River on the Kapiti coast (Figure 1, Figure 26).

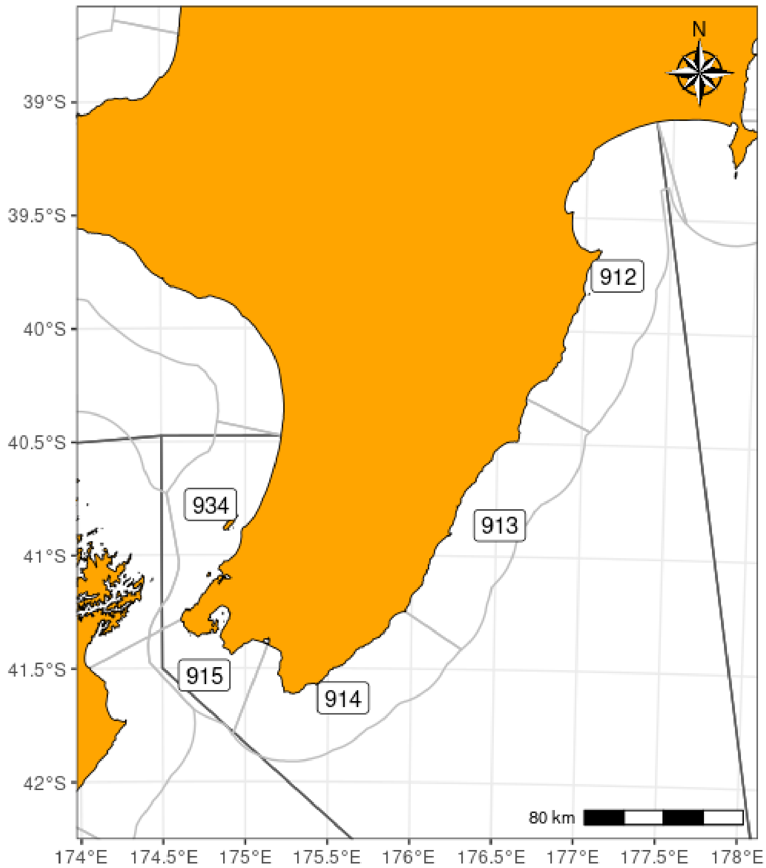

Figure 26: CRA 4 QMA and its statistical areas.

Due to minimum legal size restrictions in CRA 4 relative to maturation, the stock assessment estimated a very large biomass of mature, spawning females (i.e., minimum legal size 60 mm TW, and estimated size at 50% maturity of 41.7 mm TW; Rudd et al. 2021). Therefore, the *SSB* in CRA 4 remained well above the soft limit of 20% SSB_0^{data} under all investigated rules. Despite high fishing mortality rates, none of the fixed catch or fixed *F* rules had greater than 0.05 probability of falling below the soft limit (i.e., none were risk-constrained). Thus, the reference level was determined based on maximising the catch from fixed *F* and fixed catch rules that were not catch-constrained.

The last year of the 2020 CRA 4 stock assessment was the 2019–20 fishing year, where recruitment deviates were estimated for 194–-2017. In CRA 4, both length and CPUE data were available from 1986 onwards. To calculate the reference levels, 30-year projections and SSB_0^{data} used for the risk constraint were based on estimated recruitment deviates for 32 years, from 1986 to 2017 (Figure 27).

CRA 4 projections identified that a fixed *F* of 3.0 maximised the average annual catch while meeting the risk constraints; this fixed *F* rule was associated with an average of 231 tonnes of vulnerable biomass, 566 tonnes of annual total catch (530 tonnes of annual SL catch), and a catch CV of 0.176 over time and simulation replicates. The average annual catch is greater than the average vulnerable biomass because the vulnerable biomass is only the start-of-year vulnerable biomass that excludes mature females, whereas the average annual catch occurs throughout the year. None of the rules were risk-constrained (Table 7, Figure 28, Figure 29, Figure 30).

A total fixed catch of 486 tonnes (450 tonnes of SL catch with the remainder fixed NSL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 547 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.034. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 4.3% of years and simulation replicates. A fixed SL catch of 460 tonnes or greater failed the catch constraint (Table 7, Figure 28, Figure 29, Figure 30).

The average vulnerable biomass between the distributions associated with each maximum constrained rule was 389 tonnes (Table 7, Figure 31). Since this was based on the 2020 stock assessment, CRA 4 would have had a probability of 0.695 of being above this reference level in 2019. CRA 4 would have had a probability of 0.102 of being above the vulnerable biomass associated with the maximum constrained fixed catch rule and a probability of 0.990 of being above the vulnerable biomass associated with the maximum constrained fixed *F* harvest rule start of the 2019–20 fishing season (Figure 31).

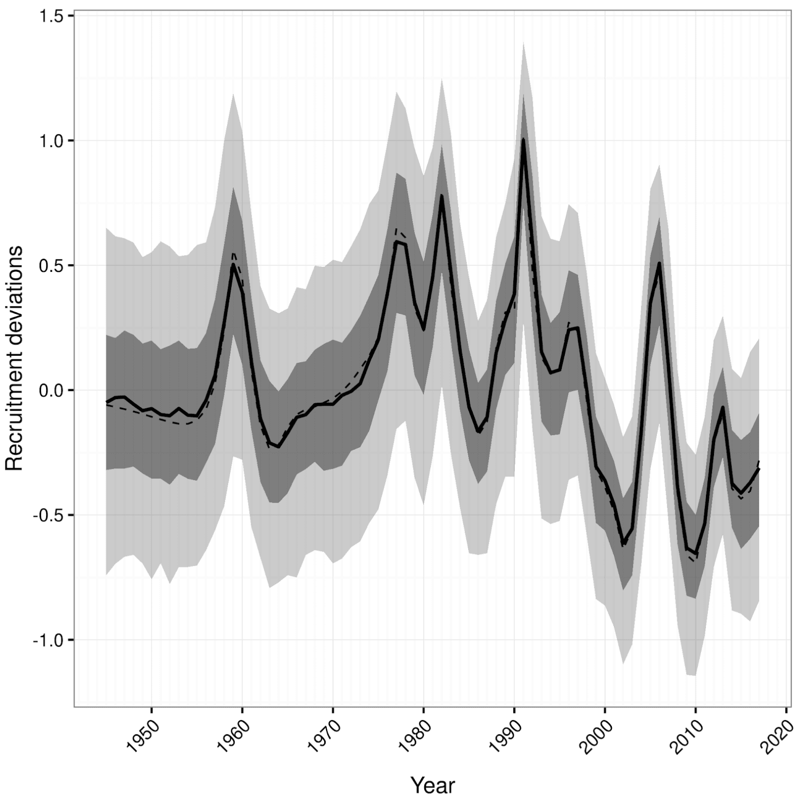

Figure 27: CRA 4 recruitment deviates: Estimated recruitment deviates from the 2020 CRA 4 stock assessment. Recruitment deviates from 1986 to 2017 were used for the 30-year projections and to calculate SSB_0^{data} for use in the risk constraint. The dashed line shows the MAP estimates, the solid line shows the median of the posterior distribution, and shading shows the 50% and 90% credible intervals.

Table 7: CRA 4 fixed catch, fixed F, and averages: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints, as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2020 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

Value	Status from 2019–20 fishing year		
Total catch	359 tonnes (280 commercial, 40 recreational, 39 NSL)		
Vulnerable biomass	433 tonnes (5th percentile = 283 tonnes, 95th percentile = 576 tonnes)		
Value	**Fixed catch**	**Fixed F**	**Average**
Average annual catch	488 (488, 488)	566 (423, 749)	526 (437, 696)
Vulnerable biomass (B_R)	547 (144, 1038)	231 (159, 324)	389 (155, 906)
Relative vulnerable biomass (B/B_0)	0.162 (0.043, 0.299)	0.070 (0.045, 0.105)	0.116 (0.040, 0.263)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.524 (0.353, 0.717)	0.451 (0.328, 0.603)	0.488 (0.337, 0.680)
Relative spawning biomass (SSB/SSB_0^{data})	0.708 (0.478, 0.961)	0.592 (0.450, 0.764)	0.650 (0.459, 0.905)
Catch CV	0.034	0.176	–
Probability below soft limit	0.000	0.000	–
Probability 2019 vulnerable biomass was above reference level	0.102	0.990	0.695

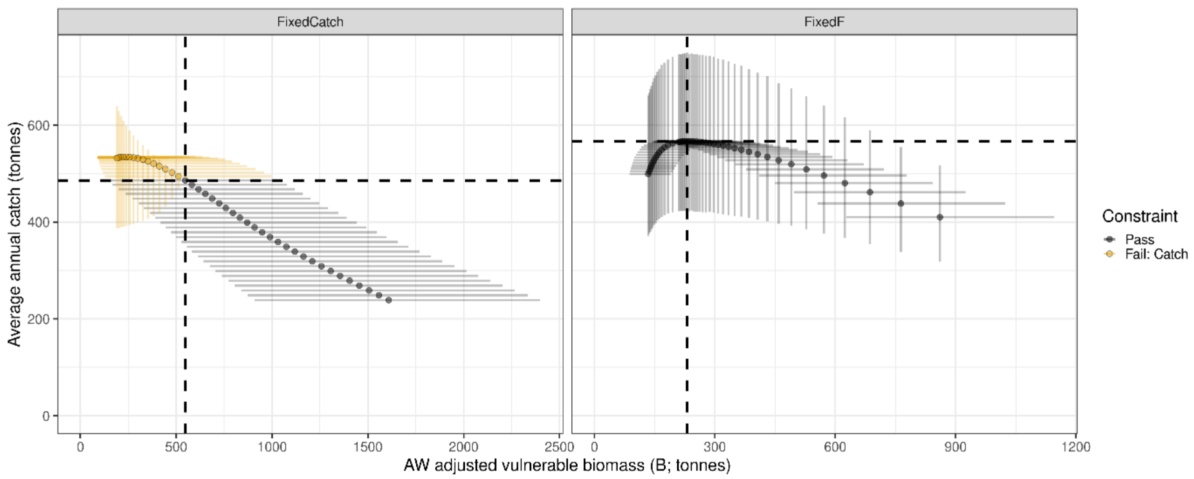

Figure 28: CRA 4 vulnerable biomass vs. catch: adjusted vulnerable biomass (B) compared with average annual catch for fixed catch and fixed F rules. Points show the average autumn-winter (AW) adjusted vulnerable biomass and annual catch by harvest control rule, segments show the 90th percentiles of B (horizontal) and catch (vertical) by rule. The dashed line shows the rule that maximises catch and meets the risk constraints.

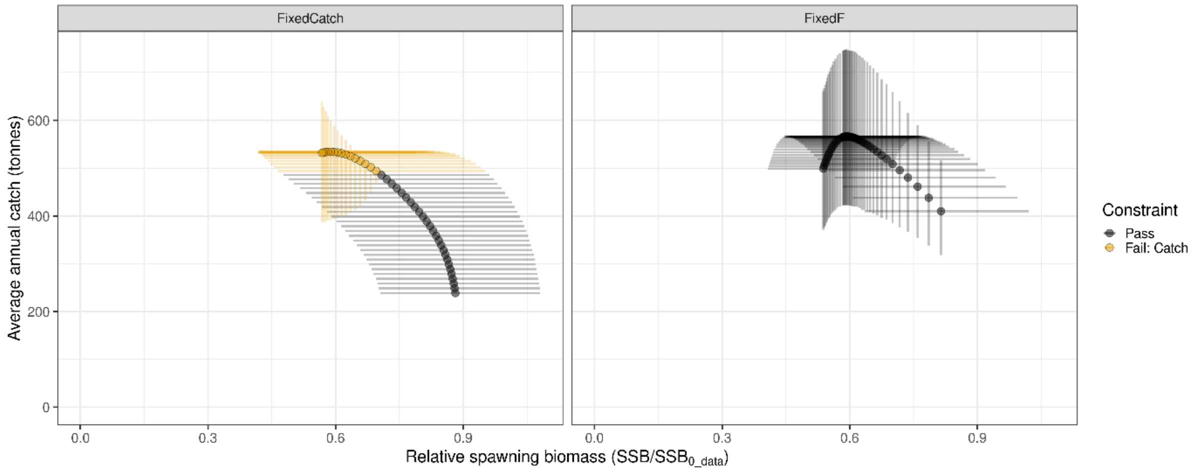

Figure 29: CRA 4 relative spawning biomass vs. catch: relative spawning biomass (SSB/SSB_0^{data}) compared with average annual catch for fixed catch and fixed F rules. Points show the average SSB/SSB_0^{data} and annual catch by harvest control rule and segments show the 90th percentiles of B (horizontal) and catch (vertical) by rule.

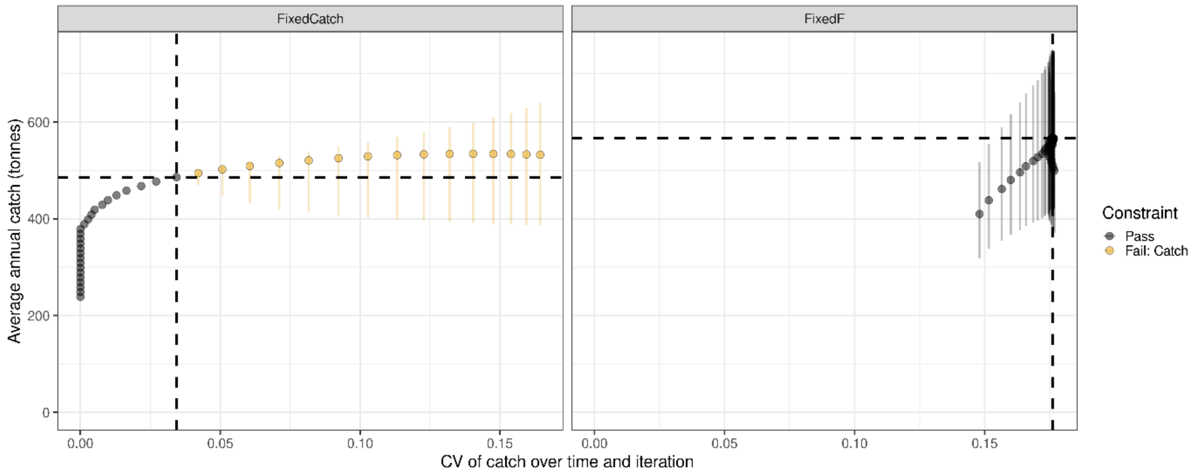

Figure 30: CRA 4 CV vs. catch: CV of catch over time and iteration compared with the average annual catch for fixed catch and fixed F rules. Points show the average CV and annual catch by harvest control rule, segments show the 90th percentiles of catch by rule, and the dashed line shows the rule that maximises catch and meets risk constraints.

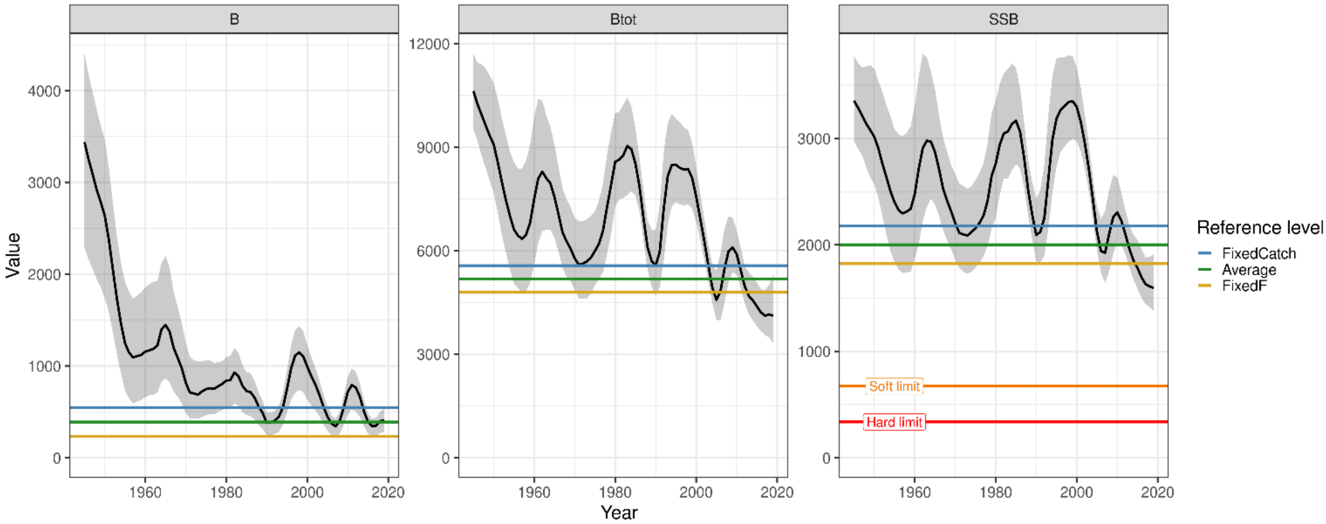

Figure 31: CRA 4 reference level: CRA 4 autumn-winter (AW) adjusted vulnerable biomass (*B*), total biomass (B^{tot}), and spawning stock biomass (*SSB*) median and 90% credible intervals from the 2020 stock assessment compared with the average of the distributions of vulnerable biomass associated with the maximum constrained fixed catch and fixed *F* rules and the average of the latter two distributions, also compared with the soft and hard limits for *SSB*. The 'average' adjusted vulnerable biomass *B* is the reference level B_R.

3.5 CRA 5

The CRA 5 QMA includes Tasman Bay and Golden Bay as well as the Marlborough Sounds (Figure 1, Figure 32). It extends down the northern part of the east coast of the South Island, past Kaikōura and Banks Peninsula as far down as the Waitaki River.

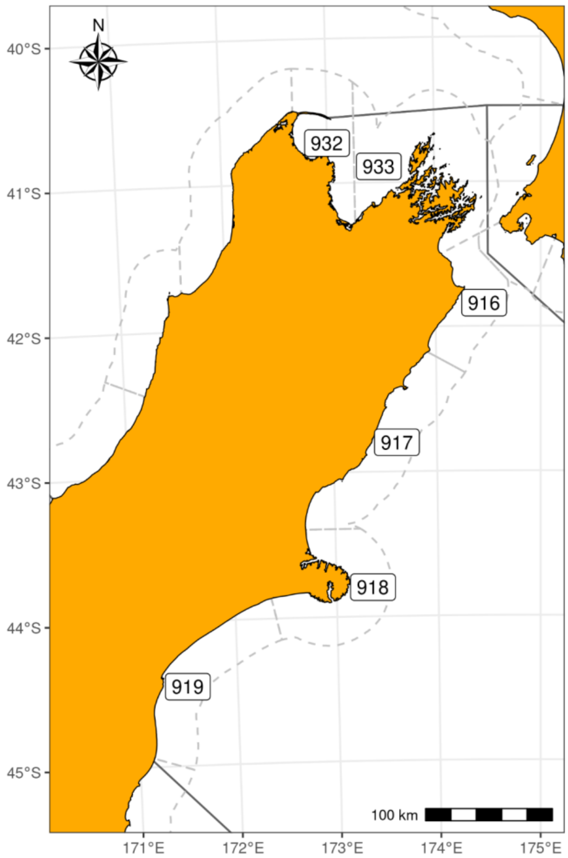

Figure 32: CRA 5 QMA and its statistical areas.

The last year of the 2020 CRA 5 stock–assessment was the 2019–20 fishing year, and recruitment deviates were estimated for 1945-2017. CRA 5 was a two-region assessment, where region 1 included statistical areas 917+918+919 and region 2 included statistical areas 916+932+933 (Figure 32). In CRA 5, both length and CPUE data were available from 1989 onwards, with CPUE data available for autumn-winter (AW) 2019. To calculate the reference levels, 30-year projections and SSB_0^{data} used for the risk constraint were based on estimated recruitment deviates for 29 years, from 1989 to 2017 (Figure 33).

In region 1 (statistical areas 917+918+919), a fixed F of 2.0 maximised the average annual catch while meeting the risk constraints; this fixed F rule was associated with an average of 283 tonnes of vulnerable biomass, 497 tonnes of annual total catch (473 tonnes of annual SL catch), and a catch CV of 0.240 over time and simulation replicates. Fixed F rates greater than 2.0 resulted in lower average annual catch and were risk-constrained with fixed F greater than 3.30 (Table 8, Figure 34, Figure 35, Figure 36).

In region 1, a total fixed catch of 384 tonnes (360 tonnes of SL catch with the remainder fixed NSL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 668 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.039. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 4.7% of years and simulation replicates. A fixed SL catch of 365 tonnes or greater failed the catch constraint; none of the fixed catch rules failed the risk constraint in region 1 (Table 8, Figure 34, Figure 35, Figure 36).

In region 2 (statistical areas 916+932+933), a fixed F of 2.9 maximised the average annual catch while meeting the risk constraints; this fixed F rule was associated with an average of 106 tonnes of vulnerable biomass, 238 tonnes of annual total catch (131 tonnes of annual SL catch) and a catch CV of 0.247 over time and simulation replicates (Table 8, Figure 34, Figure 35, Figure 36).

In region 2, a total fixed catch of 191 tonnes (185 tonnes of SL catch with the remainder fixed NSL catch) maximised average annual catch while meeting the risk and catch constraints, with an associated 284 tonnes of vulnerable biomass on average. The maximum fixed catch rule that passed risk and catch constraints had a CV of catch over time of 0.032. This was greater than zero because 99% of the specified fixed catch value could not be fully removed from the fishery for 3.8% of years and simulation replicates. A fixed SL catch of 190 tonnes or greater failed the catch constraint and a fixed SL catch of 260 tonnes or greater failed the catch and risk constraints (8, Figure 34, Figure 35, Figure 36).

In region 1, the average vulnerable biomass between the distributions associated with each maximum constrained rule was 476 tonnes (Table 8, Figure 37). In region 2, the average vulnerable biomass between the distributions associated with each maximum constrained rule was 195 tonnes (Table 8, Figure 37). Since this was based on the 2020 stock assessment, CRA 5 would have had a negligible probability of being below the reference level in any region and overall for fishing season 2019–20 (Table 8, Table 9). CRA 5 would also have a negligible probability of being below the vulnerable biomass associated with the maximum constrained fixed F rule in both regions in 2019. There were negligible probabilities of being below the vulnerable biomass associated with the maximum constrained fixed catch rules in region 1 and overall, and a probability of 0.987 of being above the vulnerable biomass associated with the maximum constrained fixed catch rule in region 2 in 2019 (Figure 37).

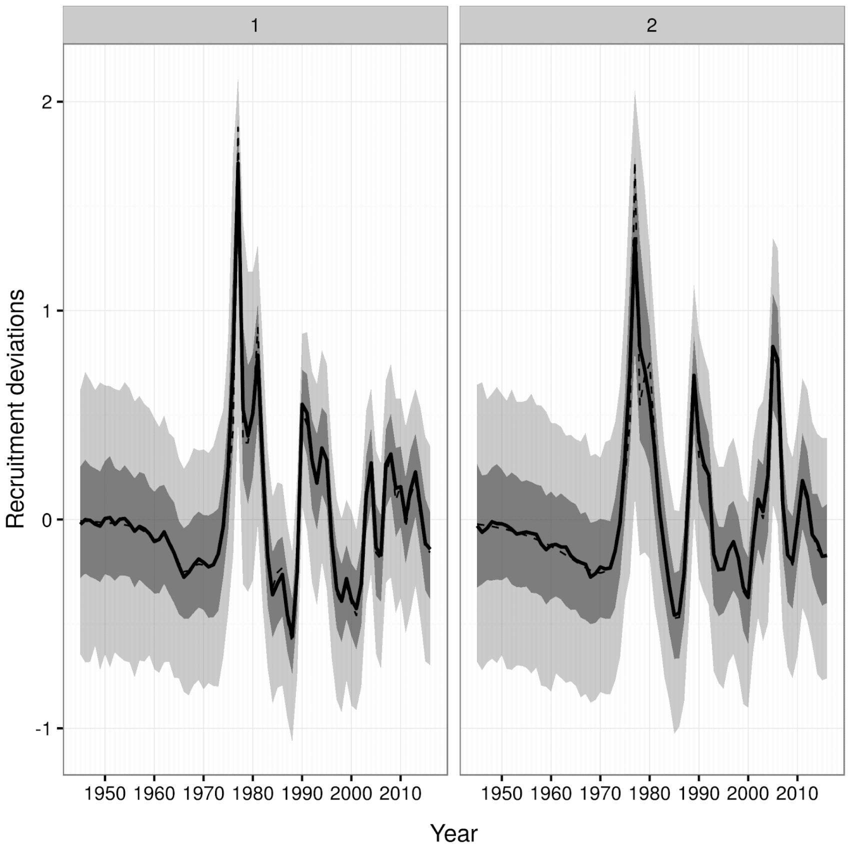

Figure 33: CRA 5 recruitment deviates: Estimated recruitment deviates from the 2020 CRA 5 stock assessment for region 1 (statistical areas 917+918+919) and region 2 (statistical area 916+932+933). Recruitment deviates from 1989 to 2017 were used for the 30-year projections and to calculate SSB_0^{data} for use in the risk constraint. The dashed line shows the maximum *a posteriori* (MAP) estimates, the solid line shows the median of the posterior distribution, and shading shows the 50% and 90% credible intervals.

Table 8: CRA 5 fixed catch, fixed F, and averages by region: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints, as well as the average between the maximum constrained rules for region 1 (statistical areas 917+918+919) and region 2 (statistical areas 916+932+933). Total catch and estimated vulnerable biomass from the 2020 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

	Region 1 (areas 917+918+919)	Region 2 (916+932+933)
Value	Status from 2019–20 fishing year	
Total catch	358 tonnes (271 commercial, 60 recreational, 27 NSL)	86 tonnes (65 commercial, 14 recreational, 6 NSL)
Vulnerable biomass	1650 tonnes (5th percentile = 1260 tonnes, 95th percentile = 2222 tonnes)	382 tonnes (5th percentile = 305 tonnes, 95th percentile = 477 tonnes)

Value	Fixed catch	Fixed F	Average	Fixed catch	Fixed F	Average
Average annual catch	387 (385, 387)	497 (330, 716)	441 (346, 657)	191 (191, 191)	238 (152, 342)	314 (164, 314)
Vulnerable biomass (B_R)	668 (205, 1 316)	283 (187, 411)	476 (191, 1 129)	284 (105, 525)	106 (72, 152)	195 (77, 457)
Relative vulnerable biomass (B/B_0)	0.207 (0.066, 0.398)	0.089 (0.058, 0.128)	0.148 (0.060, 0.345)	0.170 (0.062, 0.312)	0.064 (0.040, 0.092)	0.117 (0.045, 0.272)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.590 (0.352, 0.853)	0.397 (0.280, 0.542)	0.494 (0.295, 0.790)	0.543 (0.362, 0.751)	0.371 (0.267, 0.504)	0.457 (0.284, 0.697)
Relative spawning biomass (SSB/SSB_0^{data})	0.633 (0.334, 0.897)	0.324 (0.232, 0.437)	0.479 (0.244, 0.842)	0.662 (0.421, 0.911)	0.360 (0.263, 0.479)	0.511 (0.279, 0.852)
Catch CV	0.039	0.240	–	0.032	0.247	–
Probability below soft limit	0.0062	0.0091	–	0.0007	0.0006	–
Probability 2019 vulnerable biomass is above reference level	1.00	1.00	1.00	0.987	1.00	1.00

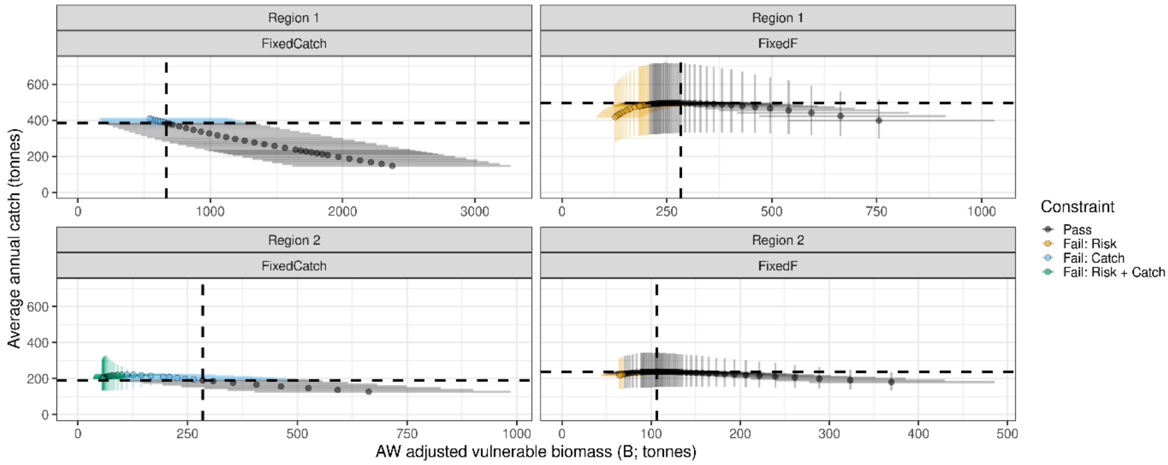

Figure 34: CRA 5 vulnerable biomass vs. catch: adjusted vulnerable biomass (*B*) compared with average annual catch for fixed catch and fixed *F* rules by region. Points show the average autumn-winter (AW) adjusted vulnerable biomass and annual catch by harvest control rule, segments show the 90th percentiles of *B* (horizontal) and catch (vertical) by rule. The dashed line shows the rule that maximises catch and meets the risk constraints in each region.

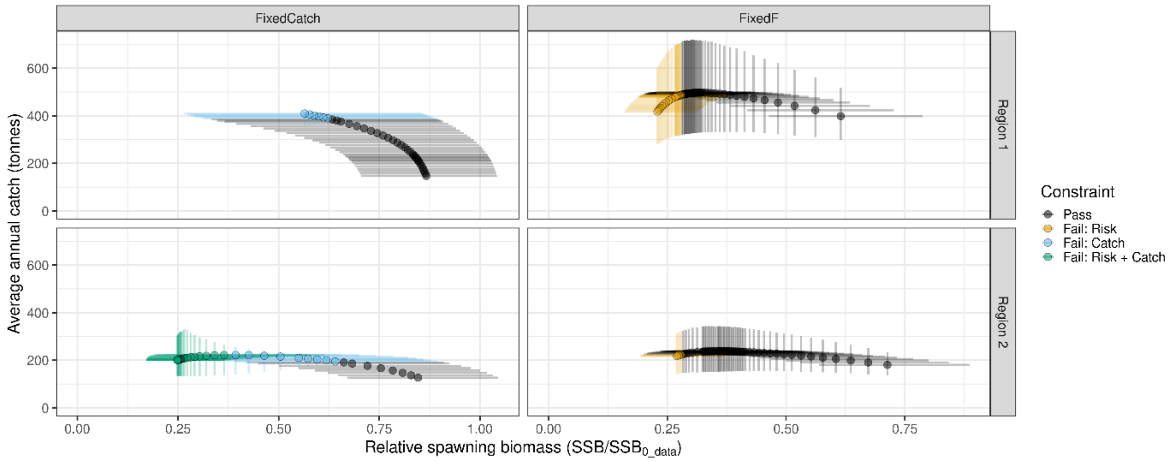

Figure 35: CRA 5 relative spawning biomass vs. catch: relative spawning biomass ($SSB/SSB_0^{\mathrm{data}}$) compared with average annual catch for fixed catch and fixed *F* rules by region. Points show the average $SSB/SSB_0^{\mathrm{data}}$ and annual catch by harvest control rule and segments show the 90th percentiles of *B* (horizontal) and catch (vertical) by rule.

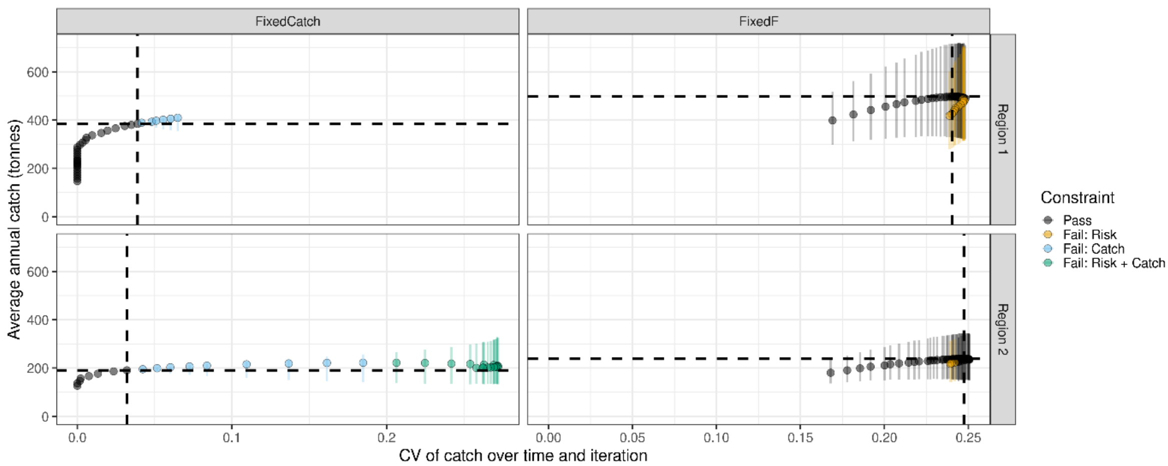

Figure 36: CRA 5 CV vs. catch: CV of catch over time and iteration compared with the average annual catch for fixed catch and fixed *F* rules by region. Points show the average CV and annual catch by harvest control rule, segments show the 90th percentiles of catch by rule, and the dashed line shows the rule that maximises catch and meets risk constraints for each region.

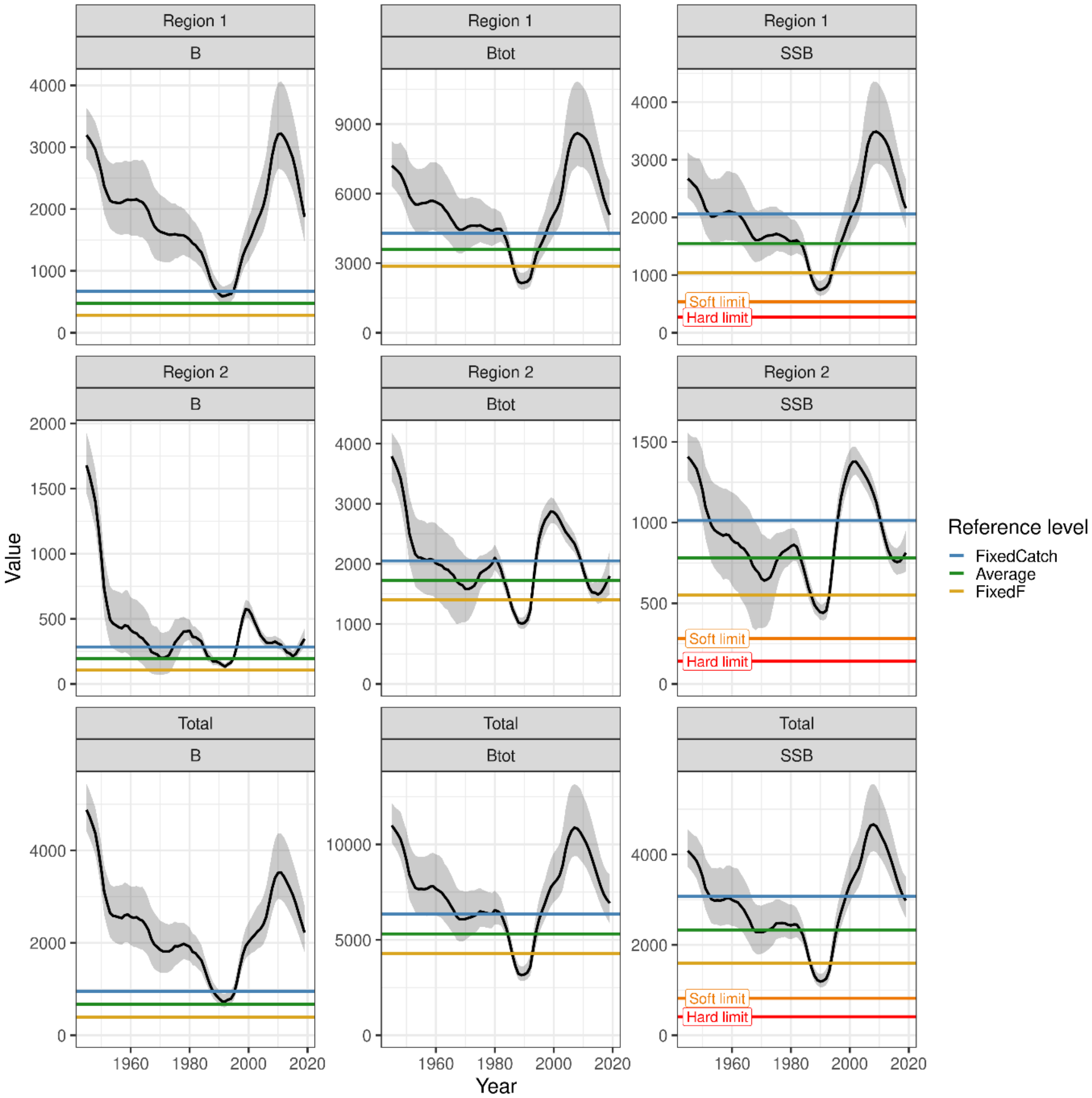

Figure 37: CRA 5 reference levels: CRA 5 autumn-winter (AW) adjusted vulnerable biomass (*B*), total biomass (B^{tot}), and spawning stock biomass (*SSB*) median and 90% credible intervals from the 2020 stock assessment for region 1 (statistical areas 917+918+919), region 2 (statistical areas 916+932+933), and total for CRA 5 compared with the average of the distributions of vulnerable biomass associated with the maximum constrained fixed catch and fixed *F* rules and the average of the latter two distributions, also compared with the soft and hard limits for *SSB*. The 'average' adjusted vulnerable biomass *B* is the reference level B_R.

Table 9: CRA 5 overall fixed catch, fixed F, and averages: mean values of derived quantities (with 5th and 95th percentiles in parentheses) associated with harvest control rules that maximise catch while meeting constraints for CRA 5 overall, as well as the average between the maximum constrained rules. Total catch and estimated vulnerable biomass from the 2020 stock assessment are provided for context. NSL is non-size-limited catch (i.e., customary and illegal removals).

Value	Status from 2019–20 fishing year		
Total catch	444 tonnes (336 commercial, 74 recreational, 33 NSL)		
Vulnerable biomass	2031 tonnes (5th percentile = 1632 tonnes, 95th percentile = 2604 tonnes)		
Value	**Fixed catch**	**Fixed F**	**Average**
Average annual catch	575 (555, 578)	735 (540, 981)	655 (549, 914)
Vulnerable biomass (B_R)	953 (441, 1 639)	390 (284, 527)	671 (300, 1 459)
Relative vulnerable biomass (B/B_0)	0.195 (0.090, 0.332)	0.080 (0.057, 0.109)	0.137 (0.061, 0.297)
Relative total biomass ($B^{\text{tot}}/B_0^{\text{tot}}$)	0.575 (0.403, 0.767)	0.388 (0.297, 0.499)	0.481 (0.312, 0.725)
Relative spawning biomass (SSB/SSB_0^{data})	0.644 (0.431, 0.845)	0.335 (0.262, 0.425)	0.490 (0.276, 0.804)
Probability 2019 vulnerable biomass was above reference level	1.000	1.000	1.000

4. DISCUSSION

The reference levels developed in this paper for New Zealand red rock lobster stocks are capable of functioning as B_{MSY} proxies and hence lower bounds on biomass management targets by maximising catch (meeting fishery goals) while meeting risk constraints (meeting ecological goals) because they are based on the biomass vulnerable to fishing. The fixed catch rule predictably served as the lower bound on average annual catch and the maximum constrained fixed F rule served as an upper bound. Fixed F rules are theoretical and cannot be used for management in practice because it is not possible to accurately know the size of the vulnerable biomass and hence to adjust catch limits appropriately nor does the fisheries management system always respond in a timely and appropriate way. However, fixed catch rules would be unreasonable to consider as an acceptable target over the medium- to long-term (e.g., 20 years or more) because catch limits are routinely addressed and potentially adjusted at least every five years, if not more frequently.

Averaging the vulnerable biomass resulting from the maximum constrained fixed catch and constrained fixed F rules incorporates distinct advantages compared with MSY-based reference points sometimes used around the world. 'Deterministic' MSY is based on life history theory and simple model assumptions and usually fails to incorporate stock assessment uncertainty or shifts in stock dynamics (e.g., a decade of low recruitment). Although MSY estimates can be updated with each stock assessment and include parameter uncertainty, the accuracy cannot be experimentally confirmed unless the average catch is allowed to exceed the MSY. Deterministic MSY is generally considered a lower bound rather than a target because of its intent to maximise catch given a set of poorly defined or assumed biological parameters. Targets based on deterministic MSY principles are often set at a proportion of SSB_{MSY} using general rules-of-thumb based on life history, meta-analysis of what has been successful for similar species, or stock-specific simulation studies. This study represents a specific characterisation of rock lobster reference levels by a) basing the reference level on vulnerable biomass, because this is more relevant than *SSB* for managing rock lobster, b) including a *SSB* threshold as a risk constraint, and c) maximising catch considering upper and lower bounds on harvest strategies.

MPs using CPUE as the input were explored in early iterations of this work but did not move forward for defining reference levels for at least two reasons. Choosing a reference level based on MP rules would have 1) required many subjective decisions to apply to all eight rock lobster stocks with enough transparency and consistency, and 2) MPs based on CPUE are currently suspended due to the lack of continuity in the CPUE index after switching to an electronic data collection programme in 2019. Using the average vulnerable biomass between the two extremes of fixed catch and fixed *F* is a simple approach based on model-based projections that can be updated with each stock assessment, easily communicated to stakeholders, and integrated into future rock lobster MPs.

We have demonstrated this reference level approach for five recent rock lobster stock assessments: CRA 1, 2, and 4 were single-region assessments and CRA 3 and 5 were two-region assessments. The reference levels estimated by this procedure, across QMAs, regions, and models fall in the range of 11–15% of the unfished, adjusted vulnerable biomass (Table 10). Both fixed catch and fixed *F* that maximise yield while meeting risk constraints vary by QMA. Although it makes intuitive sense that the fixed catch level would vary based on different population sizes, fixed *F* also varies by QMA due to variability in growth rates, estimated natural mortality, and selectivity across sexes and regions (if present).

These simulation-based reference levels can lead to more defensible and potentially more acceptable (to stakeholders) management decisions compared with *ad-hoc* management based on targets that have not been fully evaluated. For instance, the 2019 CRA 1 stock assessment estimated the vulnerable biomass would decrease when the current catch was projected five years into the future. This led to a management recommendation to decrease the catch to maintain the stock at the level of the 2019 vulnerable biomass, which was selected as an interim management goal until a more refined approach to setting catch limits could be adopted. However, the recent CRA 1 and CRA 4 stock assessments estimated that the adjusted vulnerable biomass was close to or above the reference levels generated by the procedure followed in this report. The reference levels specified by this paper represent an improvement in making informed and defensible management decisions, either through an evaluated MP or another management approach.

One notable aspect of the CRA 2 estimated reference level is the large difference between the vulnerable biomass associated with maximum constrained fixed catch and constrained fixed *F* rules, and the uncertainty around those distributions. The large difference between the two maximum constrained levels and the associated uncertainty further demonstrates the importance to use an intermediate (average) level for the reference biomass rather than either of the extreme targets. The disparity in reference level biomass stemming from the two harvest control rules could be due to the shorter time series in the CRA 2 stock assessment (which began with a non-equilibrium biomass in 1979) or the steep recent decline in the biomass trajectory. The CRA 2 population was estimated in 2017 to be below the soft limit (20% SSB_0, where SSB_0 was the estimated equilibrium unfished *SSB*), prompting a rebuilding plan to take effect. When CRA 2 is re-assessed in 2022, the reference level estimated using this procedure will be an important component for determining the effectiveness of the rebuilding plan and future predictions for the stock.

For both two-region stocks (CRA 3 and CRA 5), each region was estimated to have a different status relative to the reference level vulnerable biomass. For example, in the case of fixed *F* rules in CRA 3 region 1 (statistical areas 909 and 910), average vulnerable biomass (at the beginning of the year, not including females for both base runs) was often below the average annual catch, with an average relative vulnerable biomass below 10% of the unfished vulnerable biomass. Although the projections estimated that these rules would not violate the risk constraints due to the very high level of sub-MLS mature female lobsters, maintaining such a low vulnerable biomass as a reference level is generally not desired by the RLWG and stakeholders because the low availability of legal lobsters would require the release of many sub-legal lobsters. Instead of using the maximum constrained fixed catch as the reference level, the alternative of averaging the reference levels associated with the maximum constrained fixed catch and fixed *F* rules served as a more acceptable goal to stakeholders. Furthermore, the approach of taking the average vulnerable biomass between the maximum constrained fixed catch and maximum constrained fixed F rules was more heavily weighted to the fixed catch reference level in CRA 3 region 1 and the fixed F reference level in CRA 3 region 2. This demonstrates that taking the average reference level from the upper and lower bounds of the projected control rules does not necessarily favour one fishing tactic over the other but represents an intermediate solution.

As was seen for CRA 1, both 2019 CRA 3 stock assessment base models estimated that the vulnerable biomass would decline under current catch levels over the next five years, with a steeper decline in region 2 than in region 1. By updating the reference level from the 2019 vulnerable biomass to the estimated reference levels in this study, CRA 3 could allow a decline in vulnerable biomass overall, effected by an increase in vulnerable biomass in region 1 but allowing for a decrease in vulnerable biomass in region 2.

Neither CRA 3 nor CRA 4 were risk-constrained due to the large proportion of mature females that are below the MLS in each QMA. Because of the existence of this large population of mature females that are not vulnerable to the fishery, the spawning biomass is never estimated to decline to levels close to the soft limit, despite high fixed catch and fixed F rules. Instead, the reference levels for these stocks were defined by the fixed F rules that maximised catch plus the constraint on the fixed catch rules that prevented vulnerable biomass from dropping below the fixed catch value.

Meeting the proposed reference levels could be achieved using a range of approaches. Ideally, MPs could be implemented based on observed or predicted CPUE, predicted vulnerable biomass, or another observable biomass indicator. One option would be to select an MP rule with at least a 0.50 probability of meeting the reference level on average over a specified time period. In the absence of acceptable MP rules, a suite of fixed catch rules could be evaluated over a pre-specified time frame (e.g., 5 years, 10 years) and by selecting the fixed catch rule with a 0.50 or higher probability of remaining above the reference level in that time frame.

The reference levels are calculated as the average of the vulnerable biomass distributions associated with the maximum constrained fixed catch and maximum constrained fixed F rules. Uncertainty in the reference level is presented as credible intervals of the averaged distribution. In practice, this distribution could be sampled from within future stock assessments to propagate more uncertainty when doing calculation of B_{current}/B_R for example. However, draws from the reference level distribution would not be guaranteed to align with corresponding draws from the posterior distribution of the stock assessment. For the example of calculating B_{current}/B_R, reference level draws that are based on low vulnerable biomass could end up paired with draws of the vulnerable biomass from the stock assessment at high biomass levels. Instead, uncertainty in the reference level could be dealt with using MPs based on estimated vulnerable biomass from rapid assessment updates.

This study described routine projection functions that can be applied to all New Zealand rock lobster stock assessments to empirically calculate and update reference levels that are specific to each stock assessment. The process of calculating constrained MSYs by control rule type and taking their average vulnerable biomass explicitly considers fishery and ecological objectives through reproducible code. The process also has the potential to add additional constraints if managers and stakeholders so specify. These model-derived reference levels are stock-specific because they are based on the current best understanding of the stock, both in terms of its biology and its fishery. This approach is more relevant than classic simple *MSY*-based reference points which rarely include stock and fishery-specific considerations.

Table 10: Summary of reference levels across QMAs.

QMA, including region and model if applicable	Assessment year	Reference level (B_R, tonnes)	B_R / B_0
CRA 1	2019	454.4	0.142
CRA 2	2017	437.9	0.115
CRA 3, region 1, *r1_qdrift*	2019	235.6	0.134
CRA 3, region 2, *r1_qdrift*		111.3	0.125
CRA 3, total, *r1_qdrift*		346.8	0.131
CRA 3, region 1, *r2_qdrift*		264.2	0.123
CRA 3, region 2, *r2_qdrift*		135.8	0.123
CRA 3, total, *r2_qdrift*		399.9	0.123
CRA 4	2020	389.1	0.116
CRA 5, region 1	2020	475.8	0.148
CRA 5, region 2		195.4	0.117
CRA 5, total		671.2	0.137

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Caddy, J.F.; McGarvey, R. (1996). Targets or Limits for Management of Fisheries? *North American Journal of Fisheries Management 16*: 479–487.

Francis, R.I.C.C.; Mace, P.M. (2005). An evaluation of some alternative harvest strategies. *New Zealand Fisheries Assessment Report 2005/60*. 30 p.

Hilborn, R. (2002). The dark side of reference points. *Bulletin of Marine Science 70*: 403–408.

Hilborn, R.; Walters, C.J. (1992). Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman & Hall, London.

Holt, S.J.; Talbot, L.M. (1978). New principles for the conservation of wild living resources. *Wildlife Monographs 59*: 3–33.

Larkin, P.A. (1977). An Epitaph for the Concept of Maximum Sustained Yield. *Transactions of the American Fisheries Society 106*: 1–11.

Mace, P.M. (1994). Relationships between Common Biological Reference Points Used as Thresholds and Targets of Fisheries Management Strategies. *Canadian Journal of Fisheries and Aquatic Sciences 51 (1)*: 110–122. https://doi.org/10.1139/f94-013

Ministry of Fisheries (2008). Harvest strategy standard for New Zealand fisheries. Ministry of Fisheries, New Zealand Government. 30 p. Available online at https://fs.fish.govt.nz/Doc/16543/harveststrategyfinal.pdf.ashx

Punt, A.E.; Smith, A.D.M. (2001). The gospel of maximum sustainable yield in fisheries management: birth, crucifixion and reincarnation. *In*: Reynolds, J.D.; Mace, G.M.; Redford, K.H.: Robinson, J.G. (Eds.), pp. 41–66. Conservation of Exploited Species. University Press, Cambridge.

Rudd, M.B.; Pons, M.; Roberts, J.; Webber, D.N.; Starr, P.J. (2021). The 2020 stock assessment of rock lobsters (*Jasus edwardsii*) in CRA 4. *New Zealand Fisheries Assessment Report 2021/80.* 112 p.

Rudd, M.B.; Roberts, J.; Large, K.; Webber, D.N.; Starr, P.J. (2020). The 2019 stock assessment of rock lobsters (*Jasus edwardsii*) in CRA 1. *New Zealand Fisheries Assessment Report 2020/44.* 78 p.

Stan Development Team (2016). Stan modeling language: users guide and reference manual. Version 2.12.0. 581 p.

Thorson, J.T.; Cope, J.M.; Branch, T.A.; Jensen, O.P. (2012). Spawning biomass reference points for exploited marine fishes, incorporating taxonomic and body size information. *Canadian Journal of Fisheries and Aquatic Sciences 69 (9)*: 1556–1568. https://doi.org/10.1139/f2012-077

Webber, D.N.; Haist, V.; Starr, P.J.; Edwards, C.T.T. (2018b). A new model for the assessment of New Zealand rock lobster (*Jasus edwardsii*) stocks and an exploratory multi-area CRA 4 assessment. *New Zealand Fisheries Assessment Report 2018/53*. 111 p.

Webber, D.N.; Starr, P.J.; Haist, V.; Rudd, M.; Edwards, C.T.T. (2018a). The 2017 stock assessment and management procedure evaluation for rock lobsters (*Jasus edwardsii*) in CRA 2. *New Zealand Fisheries Assessment Report 2018/17*. 87 p.

Webber, D.N.; Starr, P.J. (2020a). Operational management procedures for New Zealand rock lobster stocks (Jasus *edwardsii*) in 2019–20. *New Zealand Fisheries Assessment Report 2020/31.* 33 p.

Webber, D.N.; Starr, P.J. (2020b). Operational management procedures of New Zealand rock lobster (*Jasus edwardsii*) stocks for 2020–21. *New Zealand Fisheries Assessment Report 2020/46.* 29 p.

Webber, D.N.; Roberts, J.; Rudd, M.B.; Starr, P.J.; Large, K. (2020). The 2019 stock assessment of rock lobsters (*Jasus edwardsii*) in CRA 3. *New Zealand Fisheries Assessment Report 2020/42.* 93 p.

Webber, D.N.; Starr, P.J.; Roberts, J.; Rudd, M.B.; Pons, M. (2021). The 2020 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 5. *New Zealand Fisheries Assessment Report 2021/62*. 91 p.