DETERMINING AN APPROPRIATE TARGET BIOMASS REFERENCE POINT FOR THE NEW ZEALAND HOKI FISHERY

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1.0 INTRODUCTION

The New Zealand Harvest Strategy Standard (HSS) specifies that a key component of a Fisheries Plan is the determination of a **target level** for each QMS fish stock which is at least consistent with that specified in the HSS.

A target level is defined in the HSS as *"the desired biomass level or fishing mortality rate, or a catch, or proxies for each of these. Fish populations fluctuate in size even in the absence of fishing. With any harvest strategy the biomass will continually fluctuate. The average level around which biomass is expected to fluctuate constitutes the target biomass. Fishing mortality may also fluctuate around a target fishing mortality, and catch may fluctuate around an average target catch.*

There is no single target level applicable for all species and stocks. The targets chosen for individual stocks will vary depending on the biological characteristics of the stock, the harvest strategy adopted and the type, amount and quality of data available."

The target level is formulated to enable yields from stock that are consistent with the MSY while maintaining the biomass of the stock well above the level that would compromise the biological sustainability of the stock (**limit** reference points). The HSS defines **limits** *"as the point at which further reductions in stock size (or proxies) are likely to ultimately lead to an unacceptably high risk of stock collapse and/or a point at which current and future utility values are diminished or compromised. Limits (both "soft" and "hard") should be set well above extinction thresholds – rather, they should act as upper bounds on the zone where depensation may occur, and associated management actions should prevent stocks from falling into such zones."*

The HSS has adopted default values for the **soft limit** and **hard limit** based on international best practice. The default soft limit is ½ B_{MSY} or 20% B_0, whichever is higher. The default hard limit is 1/4 B_{MSY} or 10% B_0, whichever is higher (Figure 1).

Fish stocks rarely remain in an equilibrium state and the inherent variability in stock biomass should be incorporated in the formulation of the target level for a stock. A target level expressed as a specific reference level (for example, 40% of SB_0) will only ever be attainable in a transitory sense. To avoid frequent and potentially unnecessary management interventions, the biomass of a stock should be allowed to fluctuate about the target level within a specified **tolerance** (bracketed by a lower and an upper **threshold** level). A decline in the level of biomass below the lower threshold would invoke a management response that is intended to return the biomass to approximate the target level, whereas, a biomass level above the upper threshold may enable additional catch to be taken from the stock. The **lower threshold** of the target level should be established at a level that ensures there is sufficient time to implement a management measure (or set of measures) that maintains the stock at above the soft limit.

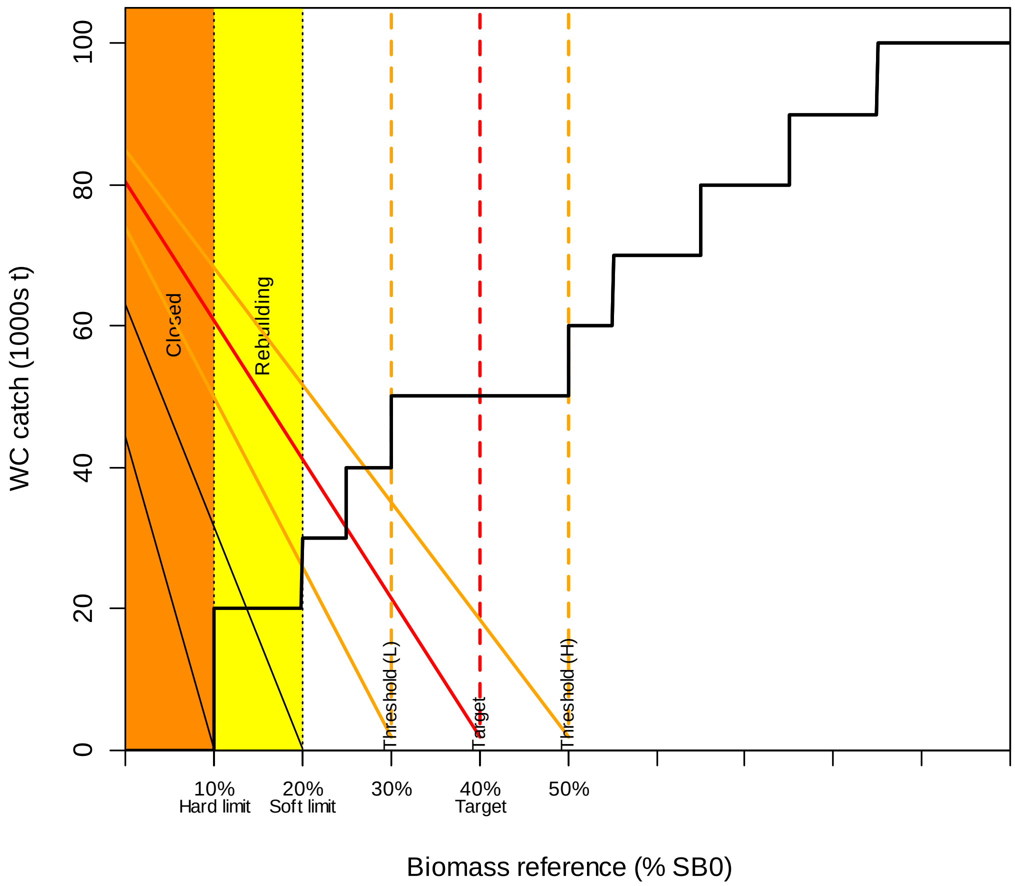

Figure 1. An example of a harvest strategy control rule that would conform with the Harvest Strategy Standard (modified from Ministry of Fisheries 2008). Catch is varied in accordance with the level of reference biomass. The dashed red vertical line represents the target biomass level and the dashed orange lines represent the lower and upper threshold biomass levels.

The current Interim Management Target (IMT) for the hoki fishery is 35–50% of the unfished spawning biomass (SB_0) which is considerably higher than the B_{MSY} level of about 25%. However, B_{MSY} is not an appropriate target for the fishery as managing the stock at this level would result in a high risk of the biomass falling to (very) low levels. A higher level of target biomass provides a buffer that affords managers sufficient time to detect and respond (through a reduction in TACC) to a sustained period of low recruitment. Further, a higher target biomass level enables fishery catch rates to be maintained at a desirable level.

The current IMT was essentially an "educated guess" by hoki fishery managers and was set at a level that was expected to maintain the spawning biomass above 20% of the unfished biomass level ("soft limit"). The performance of the IMT against this criterion had not been formally evaluated by the WG nor has the IMT been evaluated against other management objectives for the hoki fishery.

Managers and quota owners promote Management Strategy Evaluation (MSE) as a tool for evaluating appropriate target levels (and associated management strategies) for the management of New Zealand fish stocks. This is consistent with the HSS which specifies a number of performance criteria for evaluation of specific management strategies under an MSE framework, specifically.

i. the probability of achieving the MSY-compatible target or better is at least 50%;
ii. the probability of breaching the **soft limit** does not exceed 10%, and
iii. the probability of breaching the **hard limit** does not exceed 2%.

Haist et al (2005) conducted a MSE for hoki that examined alternative approaches to managing the fishery including constant annual TACCs and decision rules based on annual incremental adjustments to the TACCs using trawl surveys as the principal indicator of stock abundance.

The current study applies the results of the most recent (2009) hoki stock assessment to undertake a MSE to evaluate a range of alternative target levels for the hoki fishery (including the current Interim Management Target) that are consistent with the HSS. The evaluation is dependent on a limited range of management strategies for the fishery identified by key hoki quota owners. These include preferences in the distribution of catch between the main fishing grounds and a preference for relatively small, incremental changes in the TACC between years. The performance of the specific scenarios is assessed against the HSS criteria for evaluation of specific management strategies (above) and a range of performance indicators agreed by key hoki quota owners.

1.1 Fishery Performance Indicators

A meeting of key hoki quota owners (19 August 2009) agreed on a range of performance indicators for evaluating alternative management strategies for the hoki fishery. The specific performance indicators are as follow.

i. The maintenance of the hoki stock(s) above a level that would ensure the long-term sustainability of the fishery.
ii. Maximising the overall level of catch from the fishery within the current operating constraints of the fishery.
iii. Stability in the TACC and area catch limits; i.e., relatively infrequent changes in the TACC and relatively small changes in the TACC between years.
iv. The maintenance of catch rates from the main fisheries at or above current (2008/09) levels.
v. The maintenance of the average size of fish in the catch at or above current (2008/09) levels.

These fishery performance indicators were used as the principal criteria for evaluating the individual scenarios considered in the MSE analysis. For comparative purposes, a range of metrics were defined that quantified the elements of the individual performance indicators.

1.2 Hoki stock assessment model

Recent hoki stock assessments are fully detailed in Francis (2008 & 2009) and McKenzie (2009a & 2009b).

The current hoki stock assessment assumes the hoki fishery is comprised of two biologically distinct stocks (eastern and western). The stock structure is generalised in the assessment as follows.

- The eastern stock is resident on the Chatham Rise “home ground”. Juvenile hoki of the eastern stock reside on the Chatham Rise. Once mature, a fraction of the adult fish migrate to spawn in Cook Strait during July–September and return to the “home ground” following spawning.
- The western hoki stock spawns off the west coast of the South Island (WCSI). The progeny of the western stock move to the Chatham Rise and reside in this area as juvenile fish. Approaching sexual maturity, fish move from the Chatham Rise to the Sub Antarctic home ground. A fraction

of the fish resident in the Sub Antarctic home ground migrate to the WCSI to spawn during July–September, returning to their home ground after spawning.

The hoki assessment model integrates the assessment of the two stocks. The assessment is partitioned by stock (and sex) and is spatially and temporally disaggregated to reflect the assumed stock structure. The western stock is partitioned into the Chatham Rise nursery ground, Sub Antarctic home ground and the WCSI spawning ground, while the eastern stock is partitioned into the Chatham Rise nursery/home ground and Cook Strait spawning ground.

The annual cycle is divided into five time periods to represent the main seasonal fisheries and enable the transition (movement) of fish between fishing grounds. The non spawning fisheries in the Sub Antarctic and Chatham Rise occur during two time periods (December–March and April–June). Fish recruiting to the Sub Antarctic home ground are assumed to migrate from the Chatham Rise at the start of the April–June period. Migration to the two spawning grounds is assumed to occur during a short time period at the end of June. The two spawning fisheries occur during July–September and fish return to their respective home ground during October–November.

Two separate assessment models have been used in recent years. These models have different structural assumptions regarding the persistence of the older age classes in the population. The *Run 1.2* model assumes natural mortality is constant over all ages and allows the oldest age classes to become less vulnerable to the fishery due to an estimated decline in the selectivity of the older age classes in the spawning fisheries. Conversely, the *Run 1.1*model assumes that the older age classes are fully selected in the spawning fisheries and estimates an age-specific trend in natural mortality. The resulting estimates of natural mortality are high for the older age classes, thereby, removing these fish from the population.

The assessment models provide estimates of the following key parameters either directly or as derived parameters.

- Equilibrium recruitment R_0 for the eastern and western stocks.
- Annual recruitment estimates for 1972–2009 for the eastern and western stocks.
- Age and sex (*Run 1.1*model) specific movements from Chatham Rise to Sub Antarctic, Sub Antarctic to WCSI and Chatham Rise to Cook Strait.
- Selectivity of the commercial fisheries (Chatham Rise, Sub Antarctic, Cook Strait, and WCSI). The selectivity for the WCSI fishery includes annual variation relating to the mean day of the fishing season.
- Natural mortality at age for male and female hoki (*Run 1.1*model only).

Growth rates are stock and sex specific and assumed to be constant over time.

For the two models, the assessment generated point estimates from the mode of the posterior distribution (MPD). Uncertainty in the parameter estimates was quantified using an MCMC approach (posterior sample size of 1000).

2.0 METHODS

2.1 Overview

The principal objective of the study was to determine an appropriate target level of stock biomass for the hoki stock(s). For consistency with the current hoki assessment outputs and the Ministry of

Fisheries Harvest Strategy Standard (Ministry of Fisheries, 2008), the target biomass level was expressed as a percentage of the equilibrium, unexploited spawning biomass (%SB_0) with an equivalent target level applied to the two stocks (eastern and western). Multiple target levels were initially considered defined by a mean target level and an associated range (10%, 15%, and 20%). The bounds of the range represent the lower and upper thresholds of the target level (Table 1).

Table 1. The range of target biomass levels and associated lower and upper target thresholds considered in the analysis. Target levels are expressed as a percentage of SB_0.

Threshold (lower)	Target	Threshold (upper)
25%	30%	35%
30%	35%	40%
35%	40%	45%
25%	32.5%	40%
30%	37.5%	45%
35%	42.5%	50%
25%	35%	45%
30%	40%	50%
35%	45%	55%
25%	40%	55%

The individual target biomass levels were evaluated using an operating model that was configured to replicate the structure of from the 2009 hoki stock assessment. This model option was selected in preference to *Run 1.2* as it was considered to be the more conservative of the two options. For the *Run 1.1* model, the spawning component of the population was fully selected by the fishery, whereas, the spawning biomass of the alternative model (*Run 1.2*) is somewhat buffered by an invulnerable component of the population ("cryptic biomass"). Nonetheless, to examine the sensitivity of the MSE results to the different structural assumption of the two models, a number of specific scenarios were also tested using the alternative model.

The scenarios examined required a number of simplifying assumptions relating to the likely future catch distribution of hoki fishery. These catch scenarios were formulated through consultation with the main hoki quota owners and are described in Section 2.4. Key criteria for assessing the performance of specific management options were also defined through consultation with the quota owners.

The operating model included two components: 1) an initialisation period that used the model parameter estimates to reconstruct the estimated biomass trajectory for 1972–2009 and, thereby, determine the terminal (2009) population age structures, and 2) a projection period (2010–2040) that incorporated a sequence of simulated recruitments for both stocks and applied a range of decision rules (incorporating the target biomass level) to the resulting levels of stock biomass to determine annual catches for each fishery.

For each combination of target biomass and catch scenario, a set of (100+) simulations was conducted using the operating model. Each simulation used the parameter estimates from a randomly selected MCMC sample and a randomly generated sequence of recruitments for the projection period. Each simulation was defined by the following steps:

1. Initialise population (1972–2009).

2. Projection period (2010–2040). For each year of the projection:
   2.1. Determine population in year *x*.
   2.2. Remove catch by fishery in year *x*.
   2.3. Monitor population in year *x* ("monitoring phase")
   2.4. Assessment phase.
   2.5. Apply decision rules to determine catch by fishery in year *x*+1 ("management phase").
3. Compute statistics for simulation.

For each scenario, summary statistics were generated from the set of individual simulations.

2.2 Initialise population

The initialisation component of the operating model replicates the population dynamics of the current hoki stock assessment model(s), incorporating the input parameters (growth, length-wt relationship) and parameter estimates from the assessment to reconstruct the spatially disaggregated population age structures over the model period (1972–2009). The model was configured following the parameterisation of the CASAL model as described in Bull et al 2008. Model parameter estimates (MPD and MCMCs) from the 2009 hoki stock assessment model(s) were provided by A. McKenzie (NIWA Ltd).

The biomass trajectories derived from the operating models for the initialisation period (1972–2009) were very similar biomass trajectories from the stock assessment model for the MPD estimates (Figure 2) revealing that the population dynamics of the operating models closely approximates the hoki assessment models.

2.3 Projection period – simulated population

The second component of the operating model projected the stock forward from the terminal age structure (2009) for a 31 year period (2010–2040). For the projection period, the population dynamics and temporally invariant parameter estimates were equivalent to initialising period. For each simulation, annual recruitments for the western and eastern stocks were resampled from the estimates of recruitment from the recent period (1992–2007) from the selected MCMC sample. Average recruitment during 1992–2007 was lower (75%) than average for the western stock and slightly below (87%) average for the eastern stock.

Hoki recruitment exhibits a degree of autocorrelation over the short-term with periods of low, medium, or high recruitment persisting for 2–5 years. An element of autocorrelation was introduced to the sampled set of recruitments by randomly selecting whether or not to replicate an individual recruitment observation in the following year.

Fishery-specific catches were determined based on the individual catch scenario (Section 2.4) modified annually by a set of decision rules that assessed "current" levels of biomass relative to a specific target level of biomass and minimum biomass levels (soft and hard limits). Projected catches from the non spawning fisheries were apportioned between the two fishing seasons (December–March and April–June) in accordance with the catch distributions from recent years (Chatham Rise 55% and 45%; Sub Antarctic 70% and 30%).

2.4 Catch scenarios

Initial catches in the first year projection period (2010) were set at the increased TAC level of 110,000 t with catches apportioned to approximate the agreed split between the eastern and western fisheries.

A further increase in catch from 40,000 t to 60,000 t was assumed for the WCSI fishery in 2011 representing a TAC of 130,000 t.

For the remainder of the projection period, the annual catch for each fishery was determined based on the catch levels specified in the individual scenario. Catches for the non spawning fisheries (Chatham Rise and Sub Antarctic) were held constant at the prescribed level for the entire projection period. The rationale for maintaining a constant catch in the non spawning fisheries was to sustain a core fleet of vessels operating in the fishery throughout the year – the maintenance of a stable fleet was considered an important management objective by the key quota owners. Three levels of catch were considered for the Chatham Rise fishery (30 000 t, 40 000 t and 50 000 t) and all scenarios held the Sub Antarctic catch at 10,000 t per annum (Table 2).

For the spawning fisheries, catches were maintained at a specified level while the spawning biomass was within the target biomass range. For example, for a target biomass of 30–45% and a catch scenario with a target catch of 50,000 t for the WCSI fishery, annual catches were set at 50,000 t for the next year if the western spawning biomass was assessed to be between 30% and 45% of the equilibrium, unexploited level. The spawning biomass was monitored by proxy via trawl surveys of the adult component of the population on the "home grounds" (see below). The scenarios considered two levels of target catch for the WCSI fishery (50 000 t and 60 000 t) and a target level of 25,000 t for the Cook Strait fishery (Table 2).

Catches for the WCSI and Cook Strait fishery deviated from the target catch levels when the spawning biomass was assessed to be below or above the target biomass range, in accordance with a number of decision rules described in Section 2.6 (below). The catches for the fisheries were varied in accordance with the assessed biomass level; catches were increased incrementally when biomass was assessed to be larger than the upper level of the target range (above the upper threshold) and reduced when the biomass was assessed to be below the lower threshold of the target level.

Minimum and maximum levels of catch were set for the two spawning fisheries. The maximum level of catch for the Cook Strait fishery was set at 30,000 t following consultation with quota owners who indicated future catches from the fishery would be constrained by the current level of onshore processing capacity. A maximum catch of 100,000 t was specified for WCSI spawning fishery (Table 2).

Catches for the Cook Strait and WCSI fisheries were set to the minimum level if the spawning biomass was assessed to be at 10–20% of the SB_0 (i.e. below the "soft limit" of 20% SB_0 and above the "hard limit" of 10% SB_0). The catch was set to zero if the biomass was assessed to be at or below 10% SB_0 (see Section 2.6).

Table 2. Summary of the catch scenarios included in the analysis.

Scenario	Chatham Rise	Cook Strait	Sub Antarctic	WCSI
1	40,000 t	25,000 t (min 10,000; max 30,000)	10,000 t	50,000 t (min 20,000; max 100,000)
2	50,000 t	25,000 t (min 10,000; max 30,000)	10,000 t	50,000 t (min 20,000; max 100,000)
3	30,000 t	25,000 t (min 10,000; max 30,000)	10,000 t	60,000 t (min 20,000; max 100,000)
4	40,000 t	25,000 t (min 10,000; max 30,000)	10,000 t	60,000 t (min 20,000; max 100,000)

The four catch scenarios were combined with the 10 potential target biomass levels (Table 1) to generate 40 unique scenarios for evaluation. The individual scenarios are presented in Table 3.

Table 3. Specific scenarios of target biomass, threshold and target catch for WCSI and Cook Strait fisheries investigated in the study.

Scenario	Target	Tolerance	Threshold		Catch target (t)			
			lower	upper	WCSI	CS	C Rise	Sub A
1	0.35	0.1	0.25	0.45	50,000	25,000	40,000	10,000
2	0.35	0.1	0.25	0.45	50,000	25,000	50,000	10,000
3	0.35	0.1	0.25	0.45	60,000	25,000	30,000	10,000
4	0.35	0.1	0.25	0.45	60,000	25,000	40,000	10,000
5	0.4	0.15	0.25	0.55	50,000	25,000	40,000	10,000
6	0.4	0.15	0.25	0.55	50,000	25,000	50,000	10,000
7	0.4	0.15	0.25	0.55	60,000	25,000	30,000	10,000
8	0.4	0.15	0.25	0.55	60,000	25,000	40,000	10,000
9	0.4	0.1	0.3	0.5	50,000	25,000	40,000	10,000
10	0.4	0.1	0.3	0.5	50,000	25,000	50,000	10,000
11	0.4	0.1	0.3	0.5	60,000	25,000	30,000	10,000
12	0.4	0.1	0.3	0.5	60,000	25,000	40,000	10,000
13	0.45	0.1	0.35	0.55	50,000	25,000	40,000	10,000
14	0.45	0.1	0.35	0.55	50,000	25,000	50,000	10,000
15	0.45	0.1	0.35	0.55	60,000	25,000	30,000	10,000
16	0.45	0.1	0.35	0.55	60,000	25,000	40,000	10,000
17	0.425	0.075	0.35	0.5	50,000	25,000	40,000	10,000
18	0.425	0.075	0.35	0.5	50,000	25,000	50,000	10,000
19	0.425	0.075	0.35	0.5	60,000	25,000	30,000	10,000
20	0.425	0.075	0.35	0.5	60,000	25,000	40,000	10,000
21	0.325	0.075	0.25	0.4	50,000	25,000	40,000	10,000
22	0.325	0.075	0.25	0.4	50,000	25,000	50,000	10,000
23	0.325	0.075	0.25	0.4	60,000	25,000	30,000	10,000
24	0.325	0.075	0.25	0.4	60,000	25,000	40,000	10,000
25	0.375	0.075	0.3	0.45	50,000	25,000	40,000	10,000
26	0.375	0.075	0.3	0.45	50,000	25,000	50,000	10,000
27	0.375	0.075	0.3	0.45	60,000	25,000	30,000	10,000
28	0.375	0.075	0.3	0.45	60,000	25,000	40,000	10,000
29	0.3	0.05	0.25	0.35	50,000	25,000	40,000	10,000
30	0.3	0.05	0.25	0.35	50,000	25,000	50,000	10,000
31	0.3	0.05	0.25	0.35	60,000	25,000	30,000	10,000
32	0.3	0.05	0.25	0.35	60,000	25,000	40,000	10,000
33	0.35	0.05	0.3	0.4	50,000	25,000	40,000	10,000
34	0.35	0.05	0.3	0.4	50,000	25,000	50,000	10,000
35	0.35	0.05	0.3	0.4	60,000	25,000	30,000	10,000
36	0.35	0.05	0.3	0.4	60,000	25,000	40,000	10,000
37	0.4	0.05	0.35	0.45	50,000	25,000	40,000	10,000
38	0.4	0.05	0.35	0.45	50,000	25,000	50,000	10,000
39	0.4	0.05	0.35	0.45	60,000	25,000	30,000	10,000
40	0.4	0.05	0.35	0.45	60,000	25,000	40,000	10,000

2.5 Monitoring and assessment of the simulated population

Computation limitations preclude the MSE from replicating the annual hoki assessment process, whereby, an integrated stock assessment (incorporating trawl survey abundance indices and age frequency data) is conducted annually, including estimation of uncertainty (via MCMC) and future stock trends from a range of model projections.

Instead, the current study approach simply uses the simulated series of trawl surveys to assess the ("current") biomass level at each annual time-step. The annual trawl surveys indices were derived based on the assumption of fully selectivity of the recruited age classes, somewhat akin to incorporating the trawl surveys in a stock assessment model with the selectivity of the trawl surveys estimated with high precision. Trawl survey indices of recent recruitment (2+ age class) were used incorporated in the monitoring process to provide a crude indicator of short-term trends in spawning stock biomass (somewhat akin to undertaking stock projections).

During the projection period of the operating model, the population biomass was monitored by annual "trawl surveys" in the home grounds (Chatham Rise and Sub Antarctic). The surveys occurred in the middle of the December–March time interval and sampled the 5+ year old component of the stock. All 5+ age classes were assumed to be fully vulnerable (selectivity = 1.0) and, for each survey series, the survey catchability (*q*) was constant among surveys. The survey biomass estimates were assumed to have a normal error structure with a coefficient of variation of 30%.

For each year of the projection period, trawl survey biomass estimates were derived for each stock ($Etrawl_{year}$ and $Wtrawl_{year}$). Due to the variability in the trawl survey indices, a moving-average of three surveys was used to define the principal index for monitoring of the eastern ($Eindex_{year}$) and western ($Windex_{year}$) stocks, with twice the weight given to the last survey index. This was intended to somewhat replicate the incorporation of the trawl survey indices in a stock assessment model, thereby, removing the inter-annual variability in the trawl survey indices while still responding to the signal from the most recent year.

The annual, composite trawl survey indices were expressed relative to the corresponding equilibrium, unexploited reference biomass level ($Etrawl_{ref}$ and $Wtrawl_{ref}$) (Equation 1). The reference trawl survey biomass levels ($Etrawl_{ref}$ and $Wtrawl_{ref}$) were assumed to be known without error.

$$\boldsymbol{Eindex_{year}} = \frac{(\boldsymbol{Etrawl_{(year-2)}} + \boldsymbol{Etrawl_{(year-1)}} + \boldsymbol{2Etrawl_{year}})}{\boldsymbol{4Etrawl_{ref}}} \qquad \text{Equation 1}$$

In the projection period, a further annual trawl survey index ($JUVtrawl_{year}$) is derived for the abundance of 2+ fish on the Chatham Rise (eastern and western fish combined). The survey occurs in the middle of the December–March time interval which is consistent with the current Chatham Rise survey. The catchability of the 2+ cohort is assumed to be constant between surveys and the survey estimates are assumed to have a normal error structure with a c.v. of 30%. The average of the last three juvenile trawl survey indices is calculated to derive an index of recent recruitment ($JUVtrawl_{index}$) expressed as a proportion of the unexploited, equilibrium level of the 2+ fish abundance on the Chatham Rise (both stocks combined).

The annual sequence of fishery and survey events is summarised in the following Table.

Interval				
	Chatham Rise	Cook Strait	Sub Antarctic	WCSI
Oct–Nov		Return migration to CR.		Return migration to SA.
Dec–Mar	Recruitment of 1+ fish (both stocks). Non spawning fishery. Trawl surveys *Etrawl* and *JUVtrawl.*		Non spawning fishery. Trawl survey *Wtrawl.*	
Apr–Jun	Migration of W fish to SA. Non spawning fishery.		Non spawning fishery	
End Jun	Migration to CS		Migration to WCSI.	
Jul–Sep	-	Spawning fishery		Spawning fishery

During the projection period, an annual "assessment" occurs during April–June to determine the catches for the following year (commencing October). The principal trawl survey indices for the eastern ($Eindex_{year}$) and western ($Windex_{year}$) are compared to the lower and upper bounds of the target biomass level being evaluated under a specific scenario. A "management response" is codified via a number of decision rules (see next section).

2.6 Decision rules

The MSE process includes a "management phase" where management responses are implemented in response to the results of the "monitoring" and "assessment" phases. The current analysis applied a number of decision rules to determine the level of catch for the WCSI and Cook Strait fisheries in the next year based on the indices of stock abundance from the trawl surveys. Catches for the Chatham Rise and Sub Antarctic fisheries were held constant throughout the projection period.

The general formulation of the decision rule is illustrated by the example presented in Figure 1 and defined in Table 4. The decision rule has the following components.

1. When the reference biomass index ($Eindex_{year}$ or $Windex_{year}$) is between the lower and upper threshold of the target level of biomass (*Btarget*) the catch in the next year is set to the target catch ($Ctarget_{fishery}$) level for the scenario.
2. When the reference biomass is below the lower threshold of the target level of biomass (*Btarget*) and above the "soft limit" (20% SB_0) set the catch in the next year at a level below the target catch level. The catch is set relative to the difference between *Btarget* and the assessed biomass level ($Eindex_{year}$ or $Windex_{year}$). Catches are rounded to the nearest 5,000 t (Cook Strait) or 10,000 t (WCSI).
3. When the reference biomass is below the "soft limit" (20% SB_0) and above the "hard limit" (10% SB_0) set the catch in the next year to the minimum catch level $Cmin_{fishery}$ (20,000 t for WCSI or 10,000 t for Cook Strait).
4. When the reference biomass is below the "hard limit" (10% SB_0) set the catch in the next year to zero (for the relevant fishery).
5. When the reference biomass is above the upper threshold of the target level of biomass (*Btarget*) and recent (combined E and W) recruitment ($JUVtrawl_{index}$) is at least 75% of the long-term average level, set the catch in the next year at a level above the target catch level. The catch is set relative to the difference between the assessed biomass level ($Eindex_{year}$ or

$Windex_{year}$) and *Btarget*. Catches are rounded to the nearest 5,000 t (Cook Strait) or 10,000 t (WCSI).

6. When the reference biomass is above the upper threshold of the target level of biomass (*Btarget*) and recent (combined E and W) recruitment ($JUVtrawl_{index}$) is less than 75% of the average level, set the catch in the next year equal to the target catch level ($Ctarget_{fishery}$).
7. When the reference biomass is below the lower threshold of the target level of biomass (*Btarget*) and above the "soft limit" (20% SB_0) and recent (combined E and W) recruitment ($JUVtrawl_{index}$) is less than 75% of the average level, modify the catch level set by Rule 2. In this case, the catch in the next year is set to the maximum of either the minimum catch level $Cmin_{fishery}$ or the current year's catch minus a fixed quantity (5,000 t Cook Strait; 10,000 t WCSI).

An alternative set of decision rules were defined based on the exploitation rates in the spawning fisheries. In this case, the catch in the next year was set equal to a specified exploitation rate applied to the mid-season biomass in the current year (estimated with a c.v. of 30%). The catches for the non spawning fisheries were held constant (50,000 t Chatham Rise; 10,000 t Sub Antarctic). A range of exploitation rates were evaluated from 0.10 to 0.30.

2.7 Performance measures

A range of metrics were computed from the results of the set of 100+ simulations undertaken for each scenario. The metrics endeavoured to quantify the key performance indicators described in Section 1.1.

Metric	Description
Pr(SB < x% SB_0)	The percentage of the individual simulations that result in the mid-season spawning biomass declining below x% (10%, 20%, 25%, 30%) of the unexploited, equilibrium spawning biomass more than 10% of the years in the projection period.
Years below x% SB_0	The average number of years below 10% or 20% of SB_0 for simulations that are below 10% or 20% SB_0 of unexploited west coast South Island biomass in at least one year of the projection period.
Catch_avg	Average of the average catch from individual simulations by fishery (west coast South Island, Cook Strait, Sub Antarctic, and Chatham Rise).
Catch_sd	Average of the standard deviation of catch from individual simulations by fishery (west coast South Island, Cook Strait, Sub Antarctic, and Chatham Rise).
Catch_delta	Proportion of years when there is a change in the catch limit (increases and decreases) for each fishery.
VBio_median	Median (and 25% & 75% quantile) fishery specific vulnerable biomass (across years and simulations) relative to the level of vulnerable biomass in the 2009 reference year.
WT_median	Median (and 25% & 75% quantile) fishery-specific average weight of fish (in kg) in the catch (across years and simulations).
Fish_age_avg	Average fishery-specific average age of fish (in years) in the catch (across years and simulations).

Table 4. Details of the decision rules applied to determine the WCSI catch in the next year. A comparable set of decision rules were formulated for the Cook Strait fishery.

Rule	Component of rule		Outcome (catch in next year *year+1*)
	Biomass (current)	**Recent recruitment**	
1	$Windex_{year} \geq$ lower target threshold <u>and</u> $Windex_{year} \leq$ upper target threshold	-	$Ctarget_{fishery}$ (50,000 t or 60,000 t)
2	$Windex_{year} <$ lower target threshold $Windex_{year} \geq$ 20% (=soft limit)	-	$Ctarget_{fishery} - (Btarget - Windex_{year}/Wtrawl_{ref})$ * increment (increment = 10,000 t)
3	$Windex_{year} >$ 10% (=hard limit) <u>and</u> $Windex_{year} <$ 20% (=soft limit)	-	$Cmin_{fishery}$ (20,000 t)
4	$Windex_{year} <$ 10% (=hard limit)	-	0
5	$Windex_{year} >$ upper target threshold	$JUVtrawl_{index} > 0.75$	$Ctarget_{fishery} + (Windex_{year}/Wtrawl_{ref} - Btarget)$ * increment
6	$Windex_{year} >$ upper target threshold	$JUVtrawl_{index} < 0.75$	$Ctarget_{fishery}$
7	$Windex_{year} <$ lower target threshold $Windex_{year} \geq$ 20% (=soft limit)	$JUVtrawl_{index} < 0.75$	max($Cmin_{fishery}$, ($catch_{year}$ - increment))

3.0 RESULTS

For all the scenarios considered, there is a very low probability of the eastern stock spawning biomass (SB_{proj} *E*) declining below the soft limit (20% of SB_0 *E*) during the projection period (Table 5 and Figure 3).

For the western stock, there is considerably more variation in the probability of the spawning biomass (SB_{proj} *W*) declining below the soft limit (20% of SB_0 *W*) among the individual scenarios. Scenarios with a lower level for the lower threshold of the target range tended to have a considerably higher probability of declining below the soft limit (Figure 3). Conversely, scenarios with a higher target level (and a higher lower threshold) tended to have a lower probability of declining below the soft limit.

The probability of the western stock declining below the soft limit was correlated with the average level of catch from the WCSI fishery (Figure 4). Scenarios with a higher target catch for the WCSI fishery (i.e., the level of catch taken when the $Windex_{year}$ is within the target biomass range) tended to have a slightly higher probability of reducing the stock below the soft limit, although the difference in target catch between scenarios is relatively small (50,000 t versus 60,000 t).

The probability of the western stock declining below the soft limit was relatively insensitive to the level of catch assumed for the Chatham Rise fishery (30 000 t, 40 000 t or 50 000 t).

Overall, the set of decision rules incorporated in the analysis resulted in relatively frequent changes to the WCSI catch limit, with the catch limit changing between years about 30–50% of the time (i.e., about once every 2–3 years) (Figure 5). The frequency of changes in the WCSI catch limit was lower for scenarios with a higher tolerance associated with the target biomass level (Figure 5), while the frequency of larger (at least 20,000 t) changes in the WCSI catch limit was slightly higher for those scenarios with the higher tolerance (Figure 6).

The average weight of fish in the catch from the four main fisheries was insensitive to the individual scenario considered (include as an Appendix perhaps).

All scenarios yielded levels of fishery-specific vulnerable biomass (a proxy for fleet CPUE) that were, on average, higher than the corresponding level of vulnerable biomass in 2009. However, the vulnerable biomass from the Sub Antarctic and WCSI fisheries had the highest variability among the scenarios, with scenarios yielding the higher average catches from the WCSI fishery resulting in the lower levels of vulnerable biomass for both fisheries (and vice versa).

Of the 40 scenarios initially considered, a subset of the scenarios were selected that best satisfied the main performance indicators for the fishery (Table 5). The key criteria were a low probability of the western stock declining below the soft limit, a moderate average level of catch from the WCSI fishery, a moderate–high level of CPUE for the Sub Antarctic and WCSI fisheries, and relatively infrequent changes in the WCSI catch limit. Based on these criteria, 8 specific scenarios were identified which were characterised by a lower threshold of the target range of either 30% or 35% SB_0 and a target range of either 20% or 15% (30–50%, 35–55%, 35–50% and 30–45% SB_0). The scenarios with a lower threshold (30% SB_0) also had a lower target catch for the WCSI fishery (50,000 t compared to 60,000 t) indicating a strong interaction between these two variables of the decision rule.

Table 5. Summary of results for all scenarios based on the *Run 1.1* model. The preferred options are highlighted in grey.

Scenario	Target biomass		Target catch		Pr(*SB* < x% *SB*$_0$) W stock				Pr(*SB* < x% *SB*$_0$) E stock				WCSI catch			Cook Strait catch		
	Mean	Range (±)	WCSI	C Rise	10%	20%	25%	30%	10%	20%	25%	30%	Mean	s.dev	delta	Mean	s.dev	delta
1	0.35	0.1	50,000	40,000	0.020	0.110	0.310	0.490	0.000	0.000	0.010	0.030	48,583	16,338	0.360	27,903	2,981	0.188
2	0.35	0.1	50,000	50,000	0.000	0.110	0.250	0.490	0.000	0.010	0.010	0.060	49,066	16,395	0.389	28,248	2,667	0.188
3	0.35	0.1	60,000	30,000	0.000	0.120	0.320	0.520	0.000	0.000	0.000	0.020	54,476	19,611	0.381	27,952	2,849	0.191
4	0.35	0.1	60,000	40,000	0.000	0.110	0.270	0.440	0.000	0.000	0.000	0.100	54,776	18,836	0.361	28,002	2,959	0.196
5	0.4	0.15	50,000	40,000	0.000	0.076	0.192	0.384	0.000	0.000	0.004	0.024	47,401	15,256	0.292	26,848	3,128	0.224
6	0.4	0.15	50,000	50,000	0.000	0.064	0.172	0.360	0.000	0.004	0.012	0.028	46,870	15,243	0.289	26,948	3,057	0.213
7	0.4	0.15	60,000	30,000	0.000	0.110	0.260	0.500	0.000	0.000	0.010	0.060	53,179	18,231	0.278	26,790	3,117	0.228
8	0.4	0.15	60,000	40,000	0.000	0.130	0.230	0.520	0.000	0.010	0.010	0.020	51,417	18,738	0.279	26,860	2,992	0.221
9	0.4	0.1	50,000	40,000	0.000	0.056	0.184	0.376	0.000	0.000	0.016	0.040	46,799	16,226	0.411	27,415	3,304	0.223
10	0.4	0.1	50,000	50,000	0.000	0.064	0.176	0.348	0.000	0.000	0.012	0.024	46,564	15,849	0.409	27,286	3,433	0.245
11	0.4	0.1	60,000	30,000	0.000	0.096	0.248	0.504	0.000	0.000	0.012	0.032	50,145	18,980	0.386	27,390	3,359	0.238
12	0.4	0.1	60,000	40,000	0.000	0.088	0.184	0.380	0.000	0.000	0.008	0.044	52,775	18,447	0.399	27,222	3,490	0.238
13	0.45	0.1	50,000	40,000	0.000	0.080	0.170	0.310	0.000	0.000	0.000	0.020	43,490	16,128	0.416	26,797	3,603	0.260
14	0.45	0.1	50,000	50,000	0.000	0.080	0.150	0.320	0.000	0.000	0.010	0.020	42,534	14,801	0.390	26,610	3,829	0.271
15	0.45	0.1	60,000	30,000	0.000	0.070	0.220	0.370	0.000	0.000	0.000	0.000	50,631	17,315	0.398	26,622	3,954	0.270
16	0.45	0.1	60,000	40,000	0.000	0.070	0.230	0.430	0.000	0.000	0.000	0.030	49,500	17,811	0.387	26,143	4,044	0.281
17	0.425	0.075	50,000	40,000	0.000	0.052	0.164	0.400	0.000	0.004	0.012	0.040	44,415	15,853	0.444	26,888	4,003	0.256
18	0.425	0.075	50,000	50,000	0.000	0.032	0.124	0.284	0.000	0.000	0.000	0.028	44,450	15,361	0.446	26,986	4,068	0.251
19	0.425	0.075	60,000	30,000	0.000	0.076	0.220	0.440	0.000	0.000	0.000	0.016	49,379	18,842	0.426	27,001	3,953	0.248
20	0.425	0.075	60,000	40,000	0.004	0.080	0.204	0.436	0.000	0.000	0.008	0.024	50,166	18,375	0.433	27,172	3,875	0.241
21	0.325	0.075	50,000	40,000	0.000	0.080	0.260	0.440	0.000	0.000	0.020	0.030	51,034	17,226	0.439	28,576	2,605	0.139
22	0.325	0.075	50,000	50,000	0.000	0.130	0.300	0.470	0.000	0.010	0.010	0.080	49,303	16,686	0.427	28,462	2,830	0.155
23	0.325	0.075	60,000	30,000	0.000	0.150	0.260	0.560	0.000	0.000	0.000	0.030	54,272	19,756	0.405	28,662	2,474	0.147
24	0.325	0.075	60,000	40,000	0.000	0.120	0.300	0.500	0.000	0.010	0.030	0.080	54,562	19,185	0.395	28,714	2,493	0.147
25	0.375	0.075	50,000	40,000	0.000	0.060	0.220	0.410	0.000	0.010	0.010	0.040	46,645	15,472	0.430	27,907	3,176	0.195

Table 5 contd.

Scenario	Target biomass		Target catch		Pr(*SB* < x% SB_0) W stock				Pr(*SB* < x% SB_0) E stock				WCSI catch			Cook Strait catch		
	Mean	Range (±)	WCSI	C Rise	10%	20%	25%	30%	10%	20%	25%	30%	Mean	s.dev	delta	Mean	s.dev	delta
26	0.375	0.075	50,000	50,000	0.000	0.060	0.190	0.430	0.000	0.000	0.020	0.040	46,372	16,478	0.443	28,059	3,128	0.195
27	0.375	0.075	60,000	30,000	0.000	0.150	0.260	0.430	0.000	0.000	0.020	0.050	53,031	19,582	0.429	27,893	3,296	0.203
28	0.375	0.075	60,000	40,000	0.010	0.100	0.250	0.440	0.000	0.000	0.040	0.070	51,634	19,495	0.415	28,086	3,187	0.179
29	0.3	0.05	50,000	40,000	0.000	0.070	0.200	0.430	0.000	0.000	0.000	0.030	51,886	17,570	0.470	29,291	1,693	0.074
30	0.3	0.05	50,000	50,000	0.000	0.100	0.240	0.430	0.000	0.000	0.000	0.020	50,328	17,141	0.478	29,340	1,673	0.076
31	0.3	0.05	60,000	30,000	0.000	0.110	0.250	0.530	0.000	0.000	0.000	0.050	55,483	20,597	0.446	29,114	2,161	0.087
32	0.3	0.05	60,000	40,000	0.010	0.170	0.300	0.510	0.000	0.000	0.020	0.070	55,421	21,326	0.444	29,002	2,371	0.089
33	0.35	0.05	50,000	40,000	0.000	0.030	0.140	0.350	0.000	0.000	0.010	0.060	48,072	17,110	0.453	28,476	2,967	0.141
34	0.35	0.05	50,000	50,000	0.010	0.050	0.180	0.290	0.000	0.010	0.020	0.050	48,307	16,641	0.450	28,321	3,110	0.148
35	0.35	0.05	60,000	30,000	0.000	0.100	0.250	0.480	0.000	0.000	0.000	0.020	52,269	18,915	0.416	28,529	2,913	0.140
36	0.35	0.05	60,000	40,000	0.000	0.130	0.260	0.440	0.000	0.000	0.030	0.050	53,631	19,722	0.434	28,152	3,173	0.150
37	0.4	0.05	50,000	40,000	0.000	0.030	0.140	0.360	0.000	0.000	0.000	0.020	46,386	16,435	0.471	27,557	3,898	0.188
38	0.4	0.05	50,000	50,000	0.010	0.070	0.230	0.410	0.000	0.000	0.000	0.040	43,938	16,155	0.441	27,333	3,915	0.202
39	0.4	0.05	60,000	30,000	0.000	0.060	0.180	0.450	0.000	0.000	0.000	0.020	50,938	20,333	0.477	27,726	3,680	0.187
40	0.4	0.05	60,000	40,000	0.000	0.100	0.260	0.450	0.000	0.000	0.000	0.010	51,993	18,259	0.478	27,719	3,651	0.188

Higher levels of WCSI catch were taken from scenarios with a lower threshold of 35% SB_0 and a WCSI catch target of 60,000 t due to the higher target catch and, in particularly, the higher catches attained at biomass levels above the upper threshold (determined as a function of the target catch level). The overall level of catch (all fisheries combined) was also influenced by the assumed level of catch for the Chatham Rise.

Higher, short–term catches may be possible at higher stock levels than are prescribed under the various sets of decision rules. A trial was conducted based on a single scenario (scenario 9: target 40% SB_0, target range 30–50%, WCSI target catch 50,000 t), whereby, a higher catch increment (20,000 t) was applied to determine the level of WCSI catch above the upper threshold of the target biomass level. This resulted in a 5% increase in the average catch from the WCSI fishery with no increase in the probability of the stock declining below the soft limit.

For illustrative purposes, the performance of a single scenario (scenario 9) from the 8 preferred options was examined in detail. The scenario had a target biomass level of 40% SB_0 and an associated tolerance of 10% (target range 30–50%) and a target catch for the WCSI fishery of 50,000 t. For the selected scenario, the eastern spawning biomass generally remained well above both the lower threshold and the target biomass level (Figure 8).

For most of the simulations, the western stock spawning biomass (SB_{proj} *W*) was maintained at or above the target level during the projection period and the biomass was above the upper threshold for at least 25% of the time (Figure 9). There was a low incidence (less than 25%) of the biomass declining below the lower threshold of the target biomass range, a high probability of maintaining the biomass above the soft limit (20% SB_0) and a very low probability of the biomass declining to below the hard limit.

Nonetheless, the individual biomass trajectories varied considerably largely due to differences in the simulated recruitment series. Persistent periods of low recruitment resulted in sharp declines in the spawning biomass (Figure 9) although the operating model was generally able to detect the decline in recruitment and/or biomass and respond (via the catch based decision rules) quickly enough to avoid the spawning biomass declining below the soft limit. However, this resulted in considerable variation in the annual catch from the WCSI fishery both in the frequency of the change and, in the more extreme cases, the magnitude of the change in catch (Figure 10).

In those more extreme cases, the decision rules tended to maintain the catch at moderate levels (i.e., the target catch level) while the biomass declined rapidly due to recent low recruitment. This may be a function of using a moving average of the three last trawl surveys as the principal stock indicator coupled with the relatively high sampling error of the survey (c.v 30%). Consequently, under these conditions, the exploitation rate for the WCSI vulnerable biomass may increase rapidly to high levels before the decision rule is able to respond and reduce the level of catch (Figure 10).

For the specific scenario (9), simulated exploitation rates for the various fishery and stock components are presented in Figure 12. As previously described, exploitation rates were generally higher and more variable (among simulations) for the WCSI fishery, with a correspondingly high variation in the exploitation rates for the Sub Antarctic fishery. Exploitation rates for the Cook Strait and Chatham Rise (eastern and western stock components) fisheries were more stable than for the western fisheries and exploitation rates for the Cook Strait fishery were, on average, considerably lower than for the WCSI fishery (Figure 12).

An alternative set of decision rules were defined based on the exploitation rates in the spawning fisheries (see Section 2.6). The exploitation rate based decision rules resulted in a high degree of variation in the level of spawning biomass for the western stock (Figure 13). Exploitation rates of less than 20% resulted in a low probability of the stock declining below the soft limit (20% SB_0), while exploitation rates exceeding 25% resulted in at least a 10% probability of the stock declining below the soft limit.

Based on the results from evaluation of the simple exploitation rate based decision rule, a trial was conducted whereby the original set of decision rules (scenario 9) were augmented with an additional rule that limited the annual catch in the WCSI fishery so as to not exceed an exploitation rate of 25% (based on the mid season catch from the assessment year estimated with a c.v. of 30%). This resulted in a slight reduction in the probability of the biomass declining below the soft limit (4.0% compared to 5.6%).

The behaviour of a specific set of decision rules (scenario 9) was examined by comparing the level of catch prescribed to the WCSI fishery at various levels of spawning biomass. Overall, at lower levels of biomass, the decision rules for the western stock resulted in the level of catch being set at the prescribed level for a specific scenario. However, at higher biomass levels the higher levels of catch were frequently not attained. For this example, the catch was set at the target level (50,000 t) 55% of the time that the spawning biomass was within the target biomass range (30–50% SB_0), but was set at a level below the target catch 40% of the time (Table 6).

Table 6. An example of the level of catch set in the following year for the WCSI fishery for a specific scenario (9) relative to the level of mid–season spawning biomass. The specific scenario has a target biomass level of 40% with a 30% lower threshold and a 50% upper threshold, a minimum catch of 20,000 t and a target level of catch of 50,000 t. The number of observations represents the number of years in all simulations combined. The shaded cells indicate the expected level of catch at each biomass level.

Biomass level (*year*)	**N. obs**	**Catch level (*year* + 1)**		
		Catch = 0	**Catch = 20,000 t**	**Catch > 20,000 t**
$SB < 10\% \ SB_0$	1	1 (100%)	0 (0%)	0 (0%)
$SB \geq 10\% \ SB_0; SB \leq 20\% \ SB_0$	76	16 (21%)	48 (63%)	12 (16%)
		Catch < 50,000 t	**Catch = 50,000 t**	**Catch > 50,000 t**
$SB < 30\% \ SB_0$	325	267 (82%)	58 (18%)	0 (0%)
$SB \geq 30\% \ SB_0; SB \leq 50\% \ SB_0$	1,101	442 (40%)	602 (55%)	57 (5%)
$SB > 50\% \ SB_0$	1,275	126 (10%)	707 (55%)	444 (35%)

The deviation in the prescribed catch from the "expected" catch level is attributable to a number of factors. Firstly, the level of catch is determined based on the Sub Antarctic trawl survey indices which are incorporated in the decision rule as a proxy for spawning biomass. However, the age composition of the spawning biomass is mediated by the age-specific migration pattern and differs from the (assumed) selectivity applied to determine the trawl survey biomass. More crucially, the trawl survey is conducted in December–March, prior to the migration of fish from the Chatham Rise to the Sub Antarctic (April–June in the model). These fish are not sampled by the trawl survey although a significant proportion of these fish are assumed to contribute to the WCSI spawning biomass in July–September. Consequently, under non equilibrium conditions, the relationship between the trawl survey biomass and spawning biomass may weaken and, as applied in the operating model, the trawl survey indices may tend to under-estimate the relative level of spawning biomass.

Secondly, the relatively high sampling error and, more importantly, the effect of a 3–year moving average may reduce the responsiveness of the "management response". For example, if the biomass has recovered from a level below the lower threshold, the composite survey index is likely to still remain below the threshold and the catch would be set below the target catch level. Similarly, the decision rule will not immediately trigger an increase in catch (above the target level) when the biomass level exceeds the upper threshold of the target range.

Further, catch levels were frequently not set at a level higher than the target catch level when the spawning biomass was above the upper threshold of the target level (Table 6). This is due mainly to the additional constraints on the catch level relating to the recent level of recruitment (Rules 5–7).

The level of target catch is also an important component of the decision rule, particularly for the WCSI fishery. Ideally, the target level of catch should approximate the long-term average yield available from the specific fishery, thereby, allowing the spawning biomass to fluctuate about the target biomass level. However, if the target catch is miss-specified (lower or higher) the spawning biomass will tend towards the upper or lower threshold of the target biomass level and, on average, the resulting level of spawning biomass my deviate from the target biomass level.

The influence of the separate components of the decision rule was examined by rerunning the base scenario with elements of the decision rule excluded or modified. All the variations to the scenario resulted in levels of WCSI spawning biomass (indicated by the quartile range) that were generally higher than the target biomass level for the scenario target biomass range (30–50% SB_0) (Table 7).

Table 7. An evaluation of the influence of various components of the set of decision rules on the key performance measures for the WCSI fishery for a specific scenario (scenario 9). The 25% and 75% quartiles of the SB/SB_0 (WCSI fishery) from the projection period are reported as an indicator of the overall level of spawning biomass achieved under the specific set of decision rules.

Description	**Pr($SB < 20\% \, SB_0$) W stock**	**SB/SB_0 W stock**		**WCSI catch**	
		Q. 25%	Q. 75%	Mean	delta
Base (scenario 9)	0.06	37.5%	64.2%	46.799	0.411
Exclude recruitment indices (drop recruitment component of decision rules 5–7).	0.11	34.8%	59.3%	46,600	0.446
Single trawl survey index (rather than running average of three surveys)	0.00	38.3%	62.3%	45,382	0.541
Sub Antarctic trawl survey conducted in Apr–Jun (mid season), selectivity equivalent to WCSI migration parameters.	0.12	34.2%	57.8%	56,482	0.466
Limit exploitation rates for WCSI to 25% (in addition to decision rules 1–7).	0.04	38.9%	62.4%	46,693	0.463
Increase WCSI target catch to 60,000 t (scenario 12).	0.09	36.9%	62.3%	52,775	0.399
Double catch when biomass above upper threshold (modify decision rule 5).	0.06	37.1%	62.4%	49,068	0.400

Removing the recruitment components of decision rules 5–7 resulted in a slight reduction in the overall level of spawning biomass during the projection period with a corresponding increase in the probability of the biomass declining below the soft limit (from 6% to 11%) (Table 7). An alternative trawl survey index was computed that was more representative of the WCSI spawning biomass with the "survey" conducted in April–June (post immigration of the fish from the Chatham Rise) and a selectivity equivalent to the WCSI age-specific migration. Monitoring the stock based on this index also resulted in an increase in the average level of WCSI catch and a small reduction in the level of spawning biomass.

Overall, none of the additional scenarios considered resulted in the actual target level of spawning biomass being achieved and there are clearly a number of components of the operating model that result in a more conservative level of spawning biomass being realised. This was evident for other scenarios as well (Table 8) and, hence, the target biomass defined in the decision rule can not be directly translated to determine a target level of spawning biomass. Instead, the outcomes of the specific scenarios must be applied to infer an appropriate level of target spawning biomass. For example, the results of the decision rule evaluated under scenario 9 indicate that the lower threshold of the target biomass (30%) corresponds to a lower threshold of spawning biomass of about 35% SB_0. All the other selected scenarios also yielded a similar value for the lower threshold of spawning biomass (Table 8).

Table 8. A comparison of the target biomass level (as a percentage of SB_0) specified for a given scenario and the resulting level of spawning biomass achieved for the western stock. The 25% and 75% quartiles of the SB/SB_0 (WCSI fishery) from the projection period are reported as an indicator of the overall level of spawning biomass achieved under the specific set of decision rules.

Scenario	Target biomass				Realised SB/SB_0	
	Mean	Range (±)	Lower	Upper	Q. 25%	Q. 75%
9	40.0%	10%	30%	50%	37.5%	64.2%
10	40.0%	10%	30%	50%	38.3%	63.1%
15	45.0%	10%	35%	55%	37.8%	63.6%
16	45.0%	10%	35%	55%	36.9%	61.9%
19	42.5%	7.5%	35%	50%	35.5%	59.7%
20	42.5%	7.5%	35%	50%	36.1%	60.6%
25	37.5%	7.5%	30%	45%	36.7%	60.1%
26	37.5%	7.5%	30%	45%	36.1%	59.0%

For the selected subset of scenarios, the analysis was repeated using the operating model based on *Run 1.2*. These results were more optimistic than the results from the *Run 1.1* operating model, yielding 40% higher average catches for the WCSI fishery and a lower probability of the western spawning biomass declining below the soft limit (Table 9). However, the frequency and magnitude of changes in the WCSI catch limit was higher for the *Run 1.2* operating model. For *Run 1.2*, the catch from the Cook Strait fishery was maintained at the upper limit (30,000 t) for almost all simulations.

Table 9. Summary of results for a selected set of scenarios based on the ***Run 1.2*** model.

Scenario	Target biomass		Target catch		Pr(*SB* < x% SB_0) W stock				Pr(*SB* < x% SB_0) E stock				WCSI catch			Cook Strait catch		
	Mean	**Range (±)**	**WCSI**	**C Rise**	**10%**	**20%**	**25%**	**30%**	**10%**	**20%**	**25%**	**30%**	**Mean**	**s.dev**	**delta**	**Mean**	**s.dev**	delta
9	0.4	0.1	50,000	40,000	0.000	0.036	0.072	0.168	0.000	0.000	0.000	0.004	64,811	20,299	0.465	29,590	922	0.053
10	0.4	0.1	50,000	50,000	0.004	0.036	0.072	0.152	0.000	0.000	0.000	0.012	65,367	20,842	0.470	29,561	975	0.054
15	0.45	0.1	60,000	30,000	0.010	0.050	0.120	0.180	0.000	0.000	0.000	0.010	69,155	19,697	0.449	29,464	1,125	0.060
16	0.45	0.1	60,000	40,000	0.000	0.060	0.100	0.130	0.000	0.000	0.000	0.000	71,217	19,653	0.433	29,460	1,211	0.071
19	0.425	0.075	60,000	30,000	0.004	0.044	0.088	0.164	0.000	0.000	0.000	0.000	70,639	19,843	0.475	29,573	1,008	0.047
20	0.425	0.075	60,000	40,000	0.000	0.016	0.076	0.192	0.000	0.000	0.000	0.016	70,513	19,710	0.464	29,430	1,171	0.059
25	0.375	0.075	50,000	40,000	0.000	0.020	0.100	0.220	0.000	0.000	0.000	0.000	65,090	20,638	0.492	29,709	825	0.037
26	0.375	0.075	50,000	50,000	0.000	0.020	0.080	0.130	0.000	0.000	0.000	0.010	67,966	20,688	0.507	29,733	676	0.032

4.0 DISCUSSION

The model simulations indicate that a minimum target spawning biomass level (lower threshold) of 35% (of SB_0) is sufficient to meet the principal sustainability criteria of maintaining the spawning biomass above the "soft limit" while also performing well against the range of fishery related performance indicators. On that basis, a minimum target level of 35% SB_0 is considered appropriate for the management of the hoki fishery and, more specifically, the western stock which is more sensitive to the selection of the target level, for the limited range of catch scenarios evaluated.

The lower threshold of the target biomass (i.e., the minimum target level) is defined based on the minimum level of biomass required to prevent the spawning biomass declining below the soft limit following a period of low recruitment. The level of the lower threshold is dependent on the rapidity detection and response to a decline in the level of spawning biomass. The operating model used in this study represents a gross simplification of the annual monitoring and assessment process for hoki and, therefore, may under-estimate the ability of the assessment to detect a decline in stock biomass and initiate a management response. On that basis, a minimum target level of 35% SB_0 is considered to be a conservative lower threshold for the target biomass level.

Defining an appropriate upper level of the target range (upper threshold) is a compromise between stability of catch and maximising yield. The decision rules evaluated tended to result in upper levels of spawning biomass that were higher (typically 60–65% SB_0) than the specified upper threshold of the target biomass level. Alternative decision rules that generally maintained the spawning biomass below an upper threshold of 45–50% SB_0 would have resulted in higher levels of average catch from the WCSI fishery and more frequent changes in the catch limits. This could be achieved by modifying the existing decision rules to increase the levels of catch taken from the WCSI fishery at higher biomass levels.

Further trials that tested alternative decision rules with a more aggressive harvest strategy at higher stock sizes were only moderating successful at restricting the level of WCSI spawning biomass to below the upper threshold of the target biomass level (e.g. 50% SB_0). This is due to the delay in the operating model responding to a large increase in biomass driven by a succession of very high recruitments and the imposition of the upper catch limit for the WCSI fishery (100,000 t). The performance of the operating model could possibly be improved by refining the decision rules to respond to the likelihood of strong year classes in the entering the fishery, although this would be a risky strategy given that the relative proportion of eastern and western stocks that comprise the trawl survey recruitment index is unknown. An increase in the upper catch limit enabled higher yields to be taken at higher biomass levels, reducing the biomass to below the upper threshold of the target biomass level more rapidly.

Overall, it is likely that an upper threshold of either 45% or 50% (representing a target biomass range of 35–45% or 35–50% when the lower threshold is 35%) would represent a good compromise between the frequency of changes in annual catch and the average level of catch, at least for the WCSI fishery. Scenarios that consistently achieved levels of target biomass within this range were not comprehensively evaluated due to the difficulty in formulating a decision rule that responded to high biomass levels (see above). However, this is not necessary a failing of the operating model (including the specific decision rules) but indicative of the difficulties in optimising the yield from a stock that exhibits a high degree of short-term variability in recruitment. Therefore, it is likely that the catch based performance indicators (average catch and variation in catch) derived for the specific scenarios are indicative of the potential yields from the specific fisheries and overall stock (given the key assumptions discussed below).

The above conclusions are largely dependent on the framework (operating model) under which the various options were assessed. There are three key components of this framework that need to be considered to determine the applicability of the results of the operating model to the practical management of the fishery: 1) the structural assumptions of the operating model, 2) the parameterisation of the operating model, and 3) the appropriateness of the set of decision rules as a proxy for the management process.

The operating models adopted an identical model structure to that used in the current hoki assessments. Consequently, any miss-specification of the stock assessment model, in terms of the assumptions regarding stock structure (stock fidelity, movement dynamics, etc) or the parameterisation of key processes (e.g. selectivity, natural mortality, and movement), will be translated directly to the operating model. However, the performance of the operating model is likely to be less sensitive of a number of the key stock assumptions given that the principal indices for monitoring the stocks are based on trawl surveys of the areas of relatively high fish abundance. For example, the operating model will respond to a decline in the trawl survey indices regardless of where the fish were spawned or the proportion of the fish spawning during the next year and, thereby, reduce the likelihood that an important component of the spawning stock will be heavily depleted.

The two assessment models (*Run 1.1* and *Run 1.2*) contrast two alternative structural assumptions related to the interpretation of the low proportion of older fish observed in the catch. The current analysis focused on the more conservative of the two assessment models (*Run 1.1*); however, scenarios that achieved the performance criteria under *Run 1.1* also attained the criteria when evaluated using the alternative operating model (*Run 1.2*) indicating the conclusions of the current study are relatively insensitive to these two alternative sets of assumptions.

There are a number of important assumptions regarding the configuration (parameterisation) of the operating model during the projection period, principally relating to the sequence of recruitment indices and the accuracy of the trawl survey estimates. For each stock, recruitments were resampled from the estimates of absolute recruitment from 1992–2007; the period was selected on the basis that future recruitments (at least in the short-term) are more likely to be comparable with recent recruitments than historical recruitments. The simulations also incorporated a degree of autocorrelation within the projected recruitment series.

For the western stock, recruitments during 1992–2007 were highly variable and, on average, lower than for the longer-term period. Consequently, recruitment in the projection period was highly variable both inter-annually (although somewhat tempered by the prescribed autocorrelation) and among individual simulations. This resulted in a high degree of variation in the trends in spawning biomass and catch within and among simulations. The extent of the variation observed in the simulated data sets may approach the upper limit of the plausible magnitude of variation in stock biomass and, therefore, the proposed target levels of biomass (35–45% or 35–50% SB_0) are likely to be relatively robust to future fluctuations in recruitment.

Trawl surveys of recruited (5+ age class) biomass are the principal index of stock abundance during the projection period. The assumed accuracy (precision and bias) of the trawl survey indices is therefore crucial in determining the performance of individual scenarios evaluated by the operating model. The survey indices were assumed to have a c.v. of 30% — a moderate level of observation error and considerably higher than the empirical estimates of variance from the individual surveys (c.v. 10–15%) and the total error assumed in the assessment models (c.v. 20–25%) (Ministry of Fisheries 2009).

The observation error associated with the trawl survey estimates was assumed to be normally distributed. An alternative approach was considered using a lognormal error structure; however, this resulted in the infrequent simulation of a trawl survey biomass estimate that was substantially higher than the actual biomass. The operating model was unable to deal with these very high biomass estimates and, given that such exceptionally high biomass estimates have not been observed in either the time-series of Chatham Rise or Sub Antarctic surveys, the normal error structure was adopted.

The operating model also assumes that the catchability and selectivity of the trawl surveys is constant over time. These assumptions are likely to be biased to some extent, although there are few data available to formulate a prior for these parameters (sample from MCMCs perhaps?). To some extent, the interannual variation in catchability is incorporated in the assumed level of sampling error for the trawl surveys. However, a transitory (2–3 year) bias in the actual trawl survey biomass estimates would not be adequately evaluated under the current operating models. There is some suggestion the availability of hoki to the Sub Antarctic trawl survey may have been low in recent years (2004–2007). The current operating model would interpret such a negative bias in the trawl survey biomass estimates as low stock abundance resulting in a more conservative catch level for the WCSI fishery.

The operating model also assumes that the other key parameters (fishery selectivity, natural mortality, growth, movement, etc) are constant throughout the projection period. Hence, the operating model does not allow for the refinement of the estimates of these key parameters with the collection of additional data through the projection period. More crucially, unlike the actual stock assessment process, the operating model will also fail to identify sources of data conflict that may be attributable to a temporal trend in some of the key processes included in the model (especially, fishery selectivity).

The set of decision rules were formulated as an attempt to codify the assessment and decision making process. It is not intended that such a set of decision rules would be formally adopted and applied to the management of the hoki fishery. Nonetheless, the evaluation of each of these scenarios is dependent on the decision rules and, therefore, in adopting of a specific target biomass level (e.g. 35–45% or 35–50% SB_0) the fishery managers must be cognisant of the associated management strategies required to support the management of the fishery about the specific target level. For example, the decision rules invoke an immediate reduction in catch if the spawning biomass is “assessed” to be below the lower threshold of the target biomass. A similarly rapid response would be required by fisheries managers to ensure that there was no increase in the probability of the stock declining below the critical bench marks (soft and hard limits).

The decision rules also specify a range of “management” responses depending on survey estimates of recent recruitment. Specifically, catches are reduced from high levels if recent recruitment is estimated to be below average. Adherence to these decision rules resulted in a reduction in the probability that the spawning biomass would decline below the soft limit. This result indicates that these data should continue to be incorporated into annual assessments as is currently done through stock projections.

The decision rules specify a target level of catch for the two spawning fisheries. Under the decision rule, the catch is set at the target level if the biomass is assessed to be within the range of target biomass and varied as a proportion of the target level of catch when the biomass is assessed to be outside of that range. In the current analysis, the appropriate level of target catch assigned to a spawning fishery is mainly dependent on the level of (constant) catch taken from the non spawning fisheries, the average level of recruitment from the recent period (1992–2007), and, to a lesser extent, the target biomass level selected.

The current analysis indicated a target level of catch of 50,000–60,000 t was appropriate for the WCSI fishery for a target biomass level of 35–50% SB_0 (based on *Run 1.1*). The target level of catch should be routinely reviewed to incorporate the updated series of recent recruitment estimates from the stock assessment.

The level of catch is varied at biomass levels above and below the target biomass level, although the current decision rules limit the opportunity to maximise catch at higher biomass levels, due to the constraints related to the relatively small increase in catch between years. Further, the relatively low level of catch assigned to the Cook Strait fishery (limited to a maximum of 30,000 t) constrains the yield from the eastern stock in the model simulations. As a result, the eastern spawning biomass is maintained at a considerably higher level than the western stock.

The performance of the range of scenarios, specifically against the principal sustainability criteria, was relatively insensitive to the level of catch assumed for the Chatham Rise fishery (30 000 t, 40 000 t or 50 000 t). This is partly due to the relatively low level of catch assumed for the Cook Strait fishery. Higher levels of catch from the Chatham Rise fishery were not proposed by the hoki quota owners. For the range of scenarios investigated, an incremental increase in the assumed level of Chatham Rise catch would have a disproportionate impact on the western spawning stock, resulting in an increase in the probability of the stock declining below the soft limit.

The preferred scenarios indicate that the entire hoki fishery can sustain an average annual catch of about 130,000 t, although annual catches are likely to fluctuate by ±20,000 t every 2–3 years with most of the variation occurring in the catch from the WCSI fishery. It is important to emphasise that these conclusions are dependent on the assumed distribution of catch and, more crucially, future trends in recruitment.

It is envisaged that the implementation of an agreed target biomass level for the hoki fishery would require the formalisation of a number of agreed conditions under the Fishery Plan. These may include defining an appropriate level of catch for the non spawning fisheries, defining a target level of catch for each of the spawning fisheries, and defining the appropriate management response when the biomass is assessed to be below or above the target biomass range. The conditions might also include constraints on the annual exploitation rate for specific fisheries, although a cursory analysis (this study) suggested the inclusion of an additional decision rule specifying a maximum exploitation rate resulted in only a marginal improvement in the performance against the principal sustainability indicator.

A MSE approach provides the opportunity to evaluate alternative monitoring strategies, for example a consideration of the frequency of trawl surveys and assessments. This was beyond the scope of the current study, although some preliminary analyses were conducted to that compared scenarios with annual and biennial trawl surveys of the Sub Antarctic. The switch to biennial surveys (and assessments) resulted in a small increase (approx 2%) in the probability of the western stock declining below soft limit (20% SB_0). However, these results should be considered within the context of the operating model, particularly with regard to the assumptions relating to the trawl survey abundance indices (see above).

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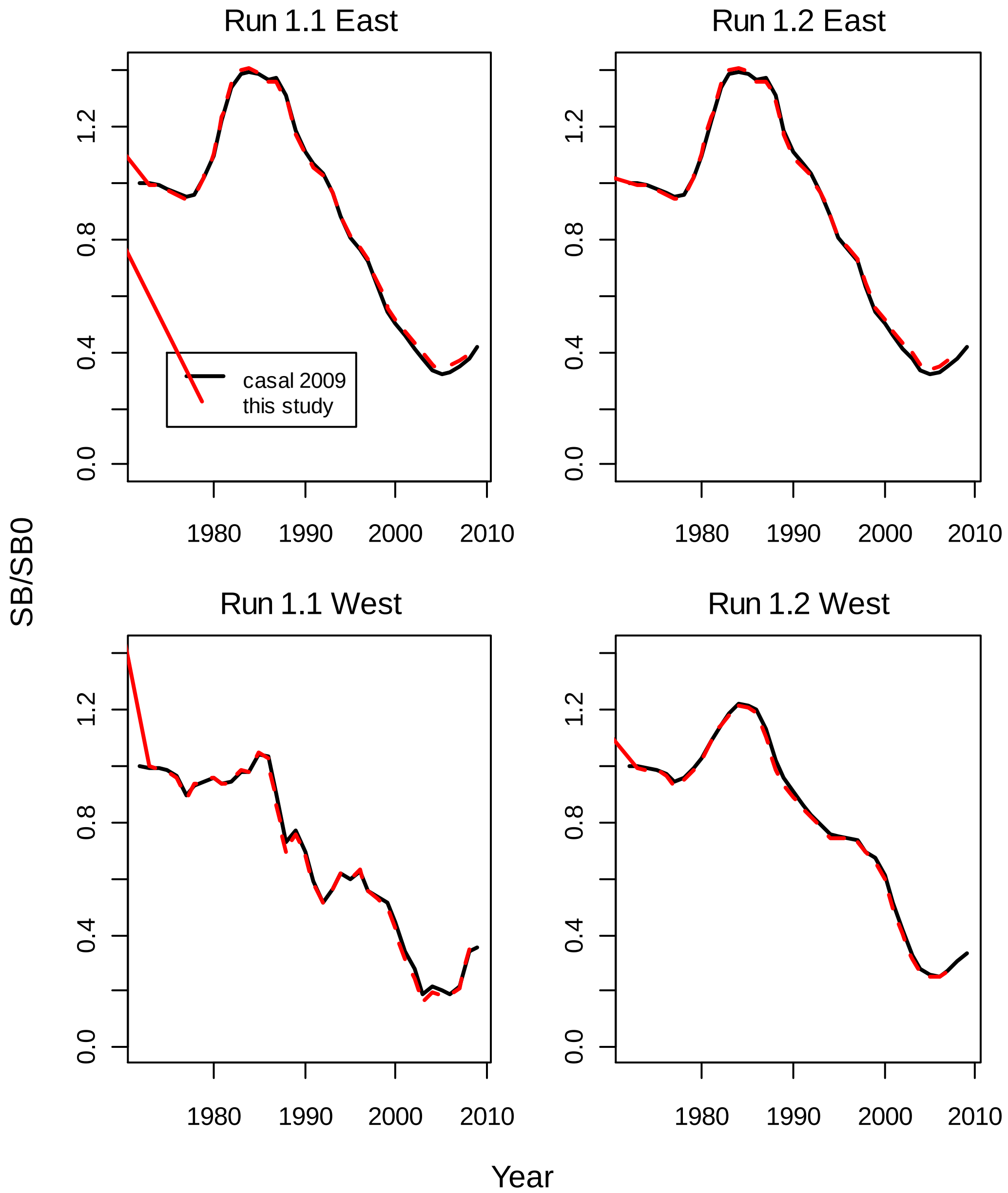

Figure 2. A comparison of the MPD spawning biomass trajectories for the western and eastern stocks for the two assessment models (run 1.1 and run 1.2) with the biomass trajectories derived from the current study.

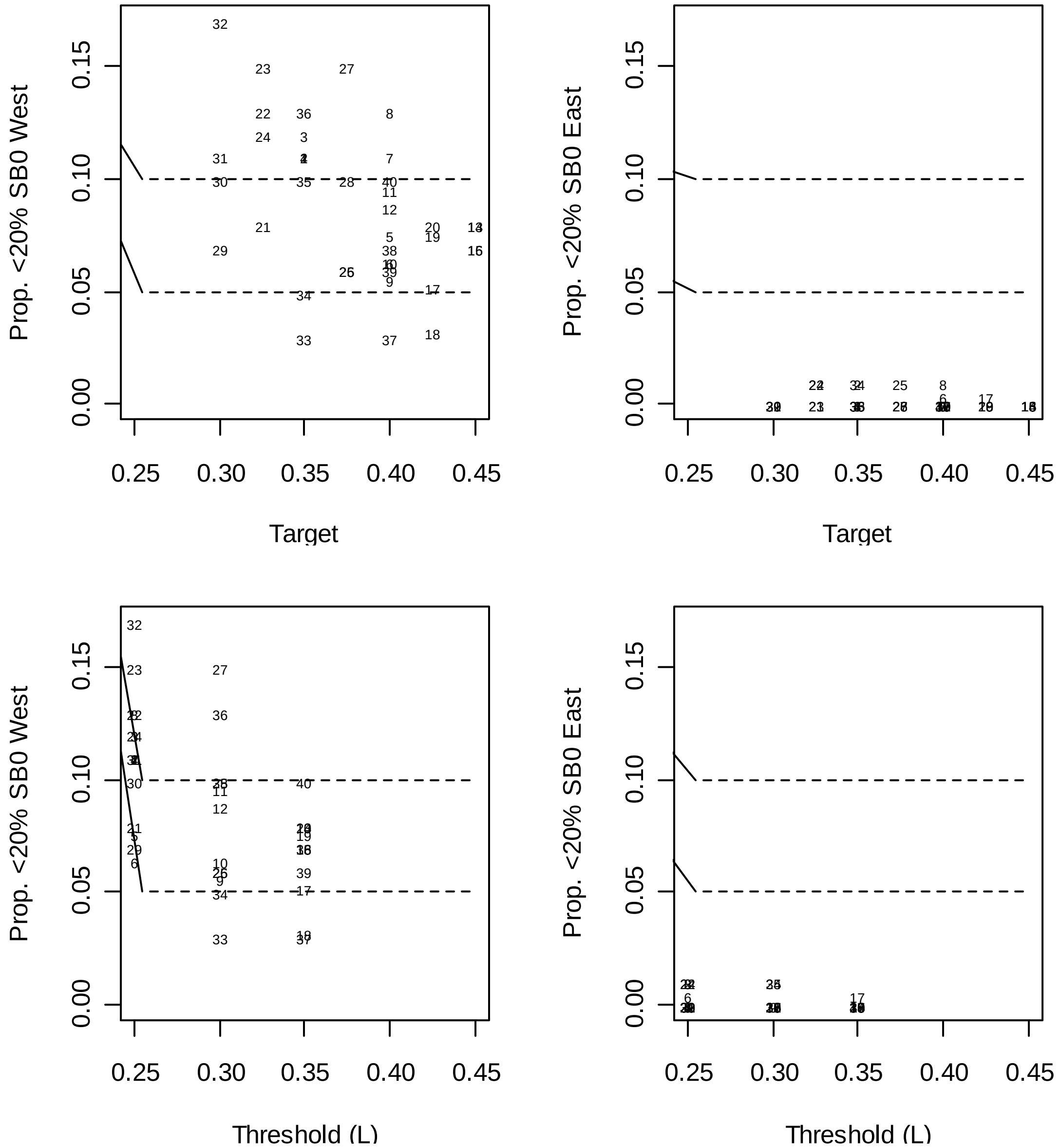

Figure 3. The probability of the western (left panels) and eastern (right panels) stock spawning biomass declining below 20% of the unexploited level (SB_0) for specific target (top) and lower thresholds of reference biomass. The individual scenarios are denoted by the number.

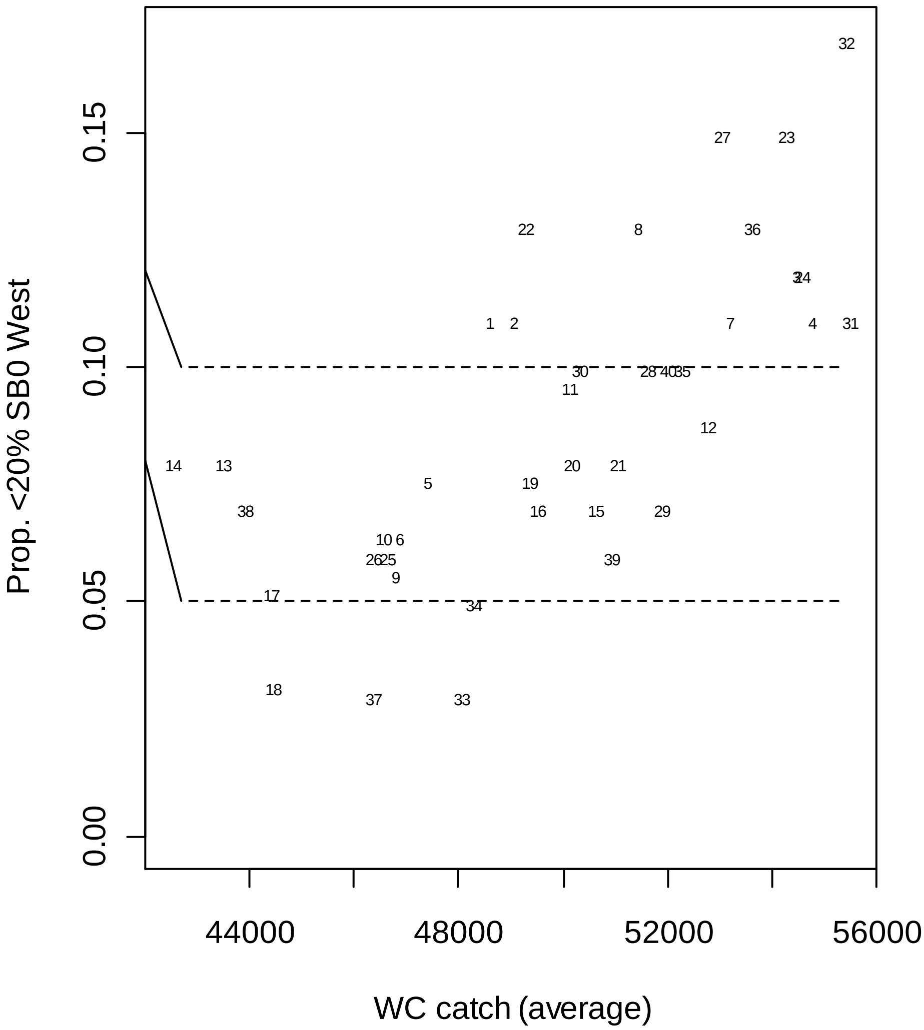

Figure 4. A comparison of the average annual WCSI catch (x–axis) and the probability of the western stock spawning biomass declining below 20% of the unexploited level (SB_0) (y–axis) for each scenario (denoted by the number).

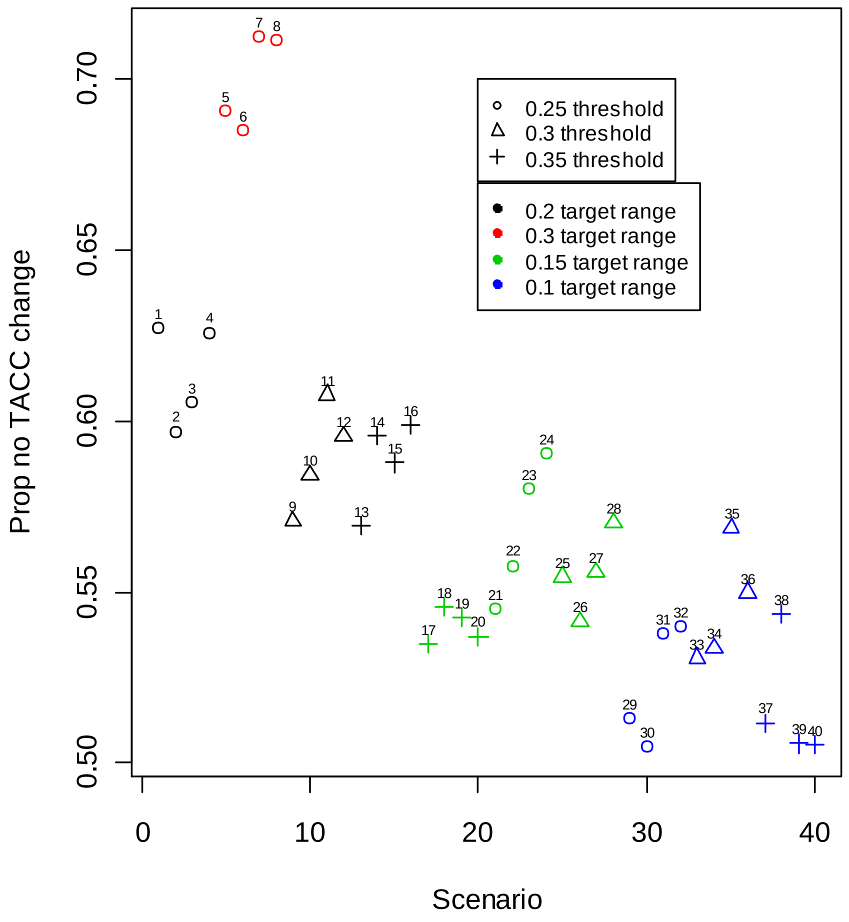

Figure 5. The proportion of years in the simulated projection period for which the WCSI catch limit remains unchanged between successive years, for each scenario (denoted by number). The legend specifies the lower threshold of the target biomass level (symbol) and the range about the target level (colour).

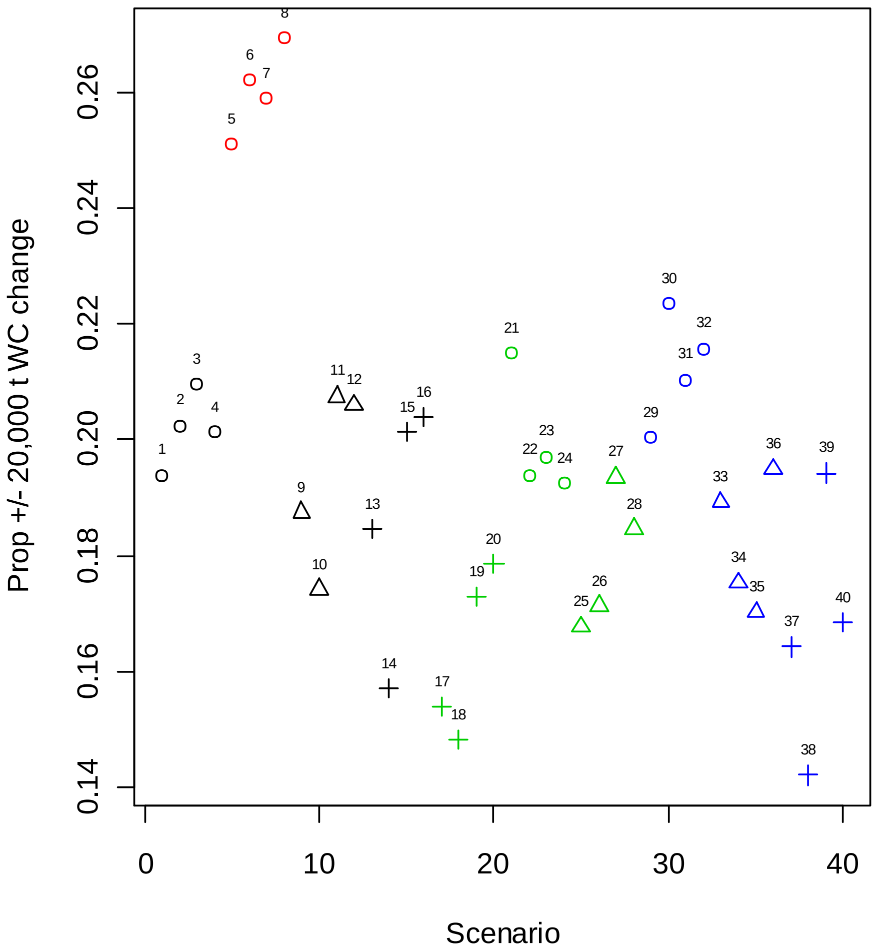

Figure 6. The proportion of years in the simulated projection period for which the WCSI catch limit changes by at least 20,000 t between successive years, for each scenario (denoted by number). The legend specifies the lower threshold of the target biomass level (symbol) and the range about the target level (colour).

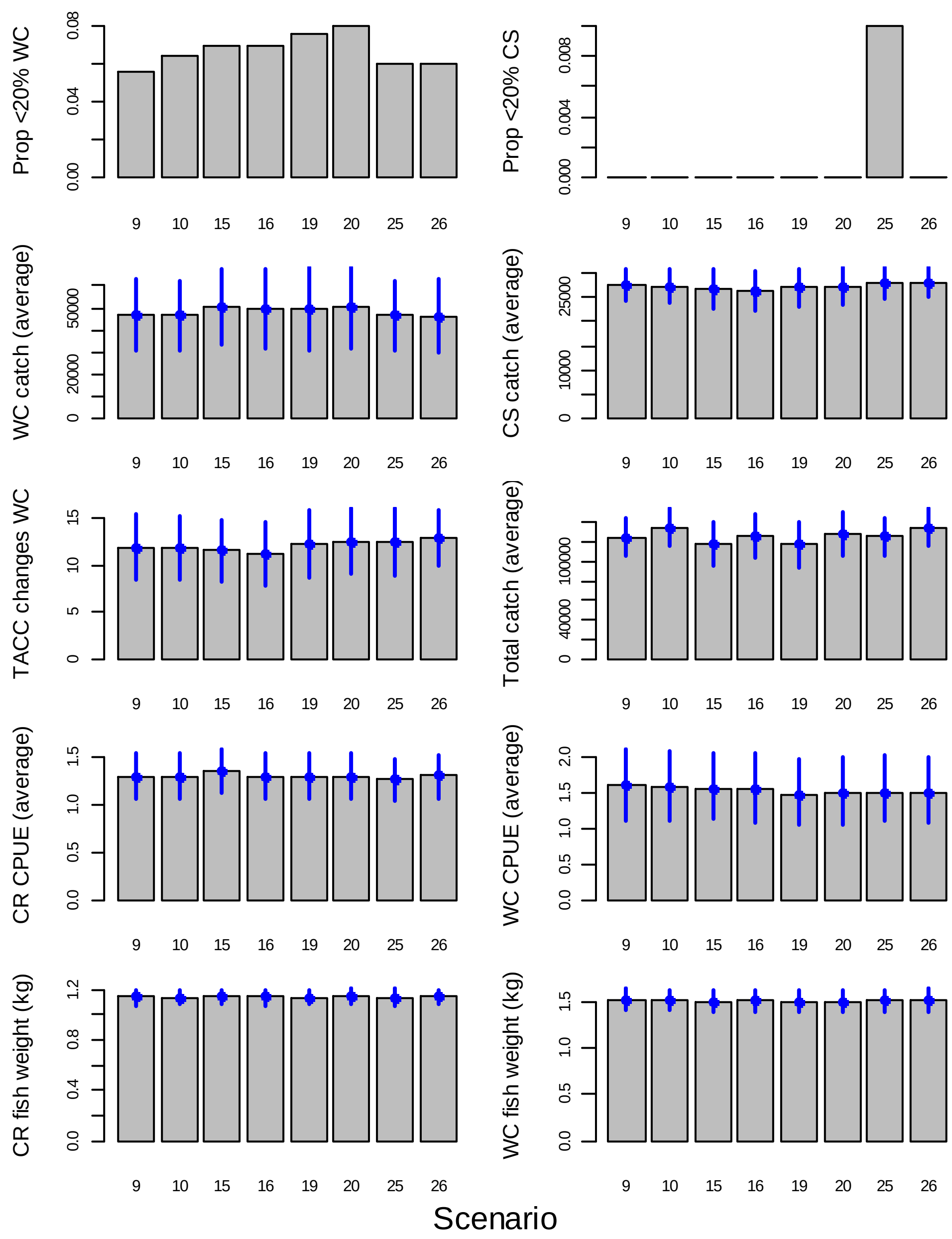

Figure 7. A comparison of the key performance indicators for the selected scenarios. The bars represent the mean value of the simulations and the lines represent the standard deviation.

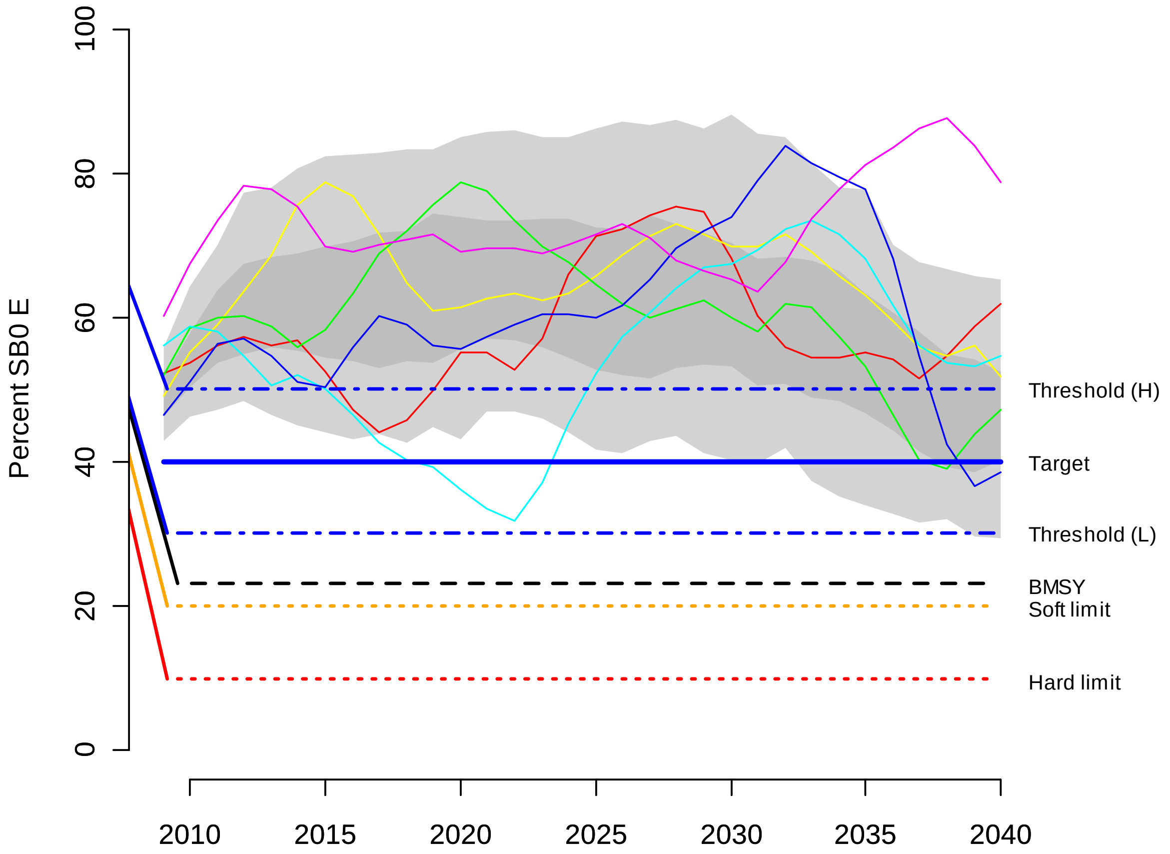

Figure 8. The simulated trend in Cook Strait spawning biomass relative to unexploited biomass (*SB/SB₀*) for scenario 9 (target level 0.40, lower threshold 0.30). The light grey area encompasses the 5–95% quantile range and the dark grey area encompasses the 25–75% quantile range of spawning biomass. The coloured lines are examples of individual biomass trajectories from the set of simulations.

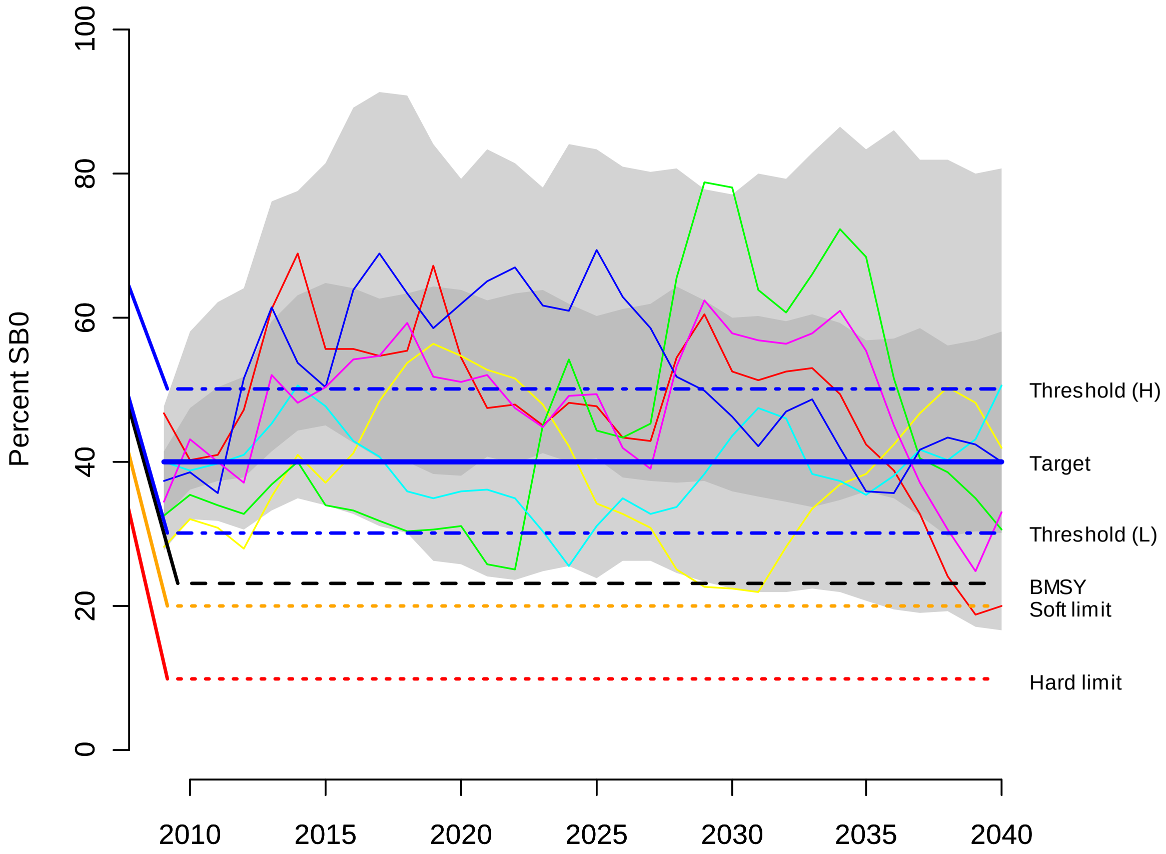

Figure 9. The simulated trend in WCSI spawning biomass relative to unexploited biomass (*SB/SB$_0$*) for scenario 9 (target level 0.40, lower threshold 0.30). The light grey area encompasses the 5–95% quantile range and the dark grey area encompasses the 25–75% quantile range of spawning biomass. The coloured lines are examples of individual biomass trajectories from the set of simulations.

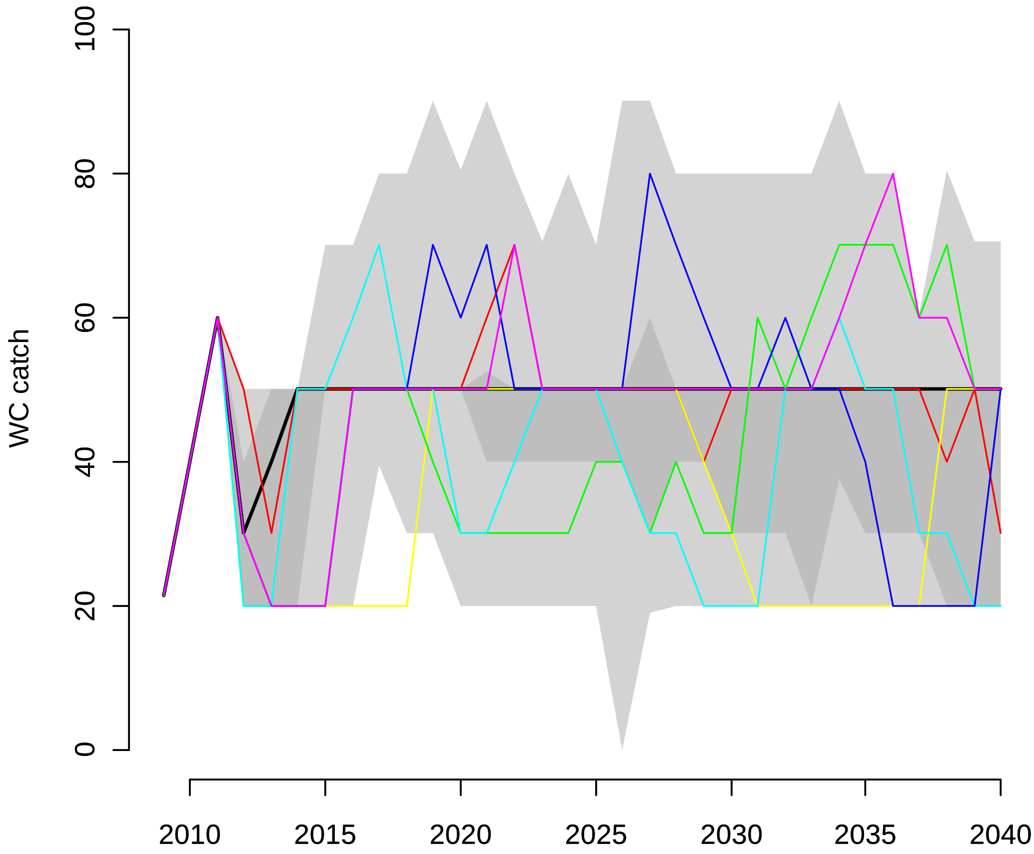

Figure 10. The simulated trend in WCSI annual catch for scenario 9 (target level 0.40, lower threshold 0.30). The light grey area encompasses the 5–95% quantile range and the dark grey area encompasses the 25–75% quantile range of the annual catch. The coloured lines are examples of individual biomass trajectories from the set of simulations.

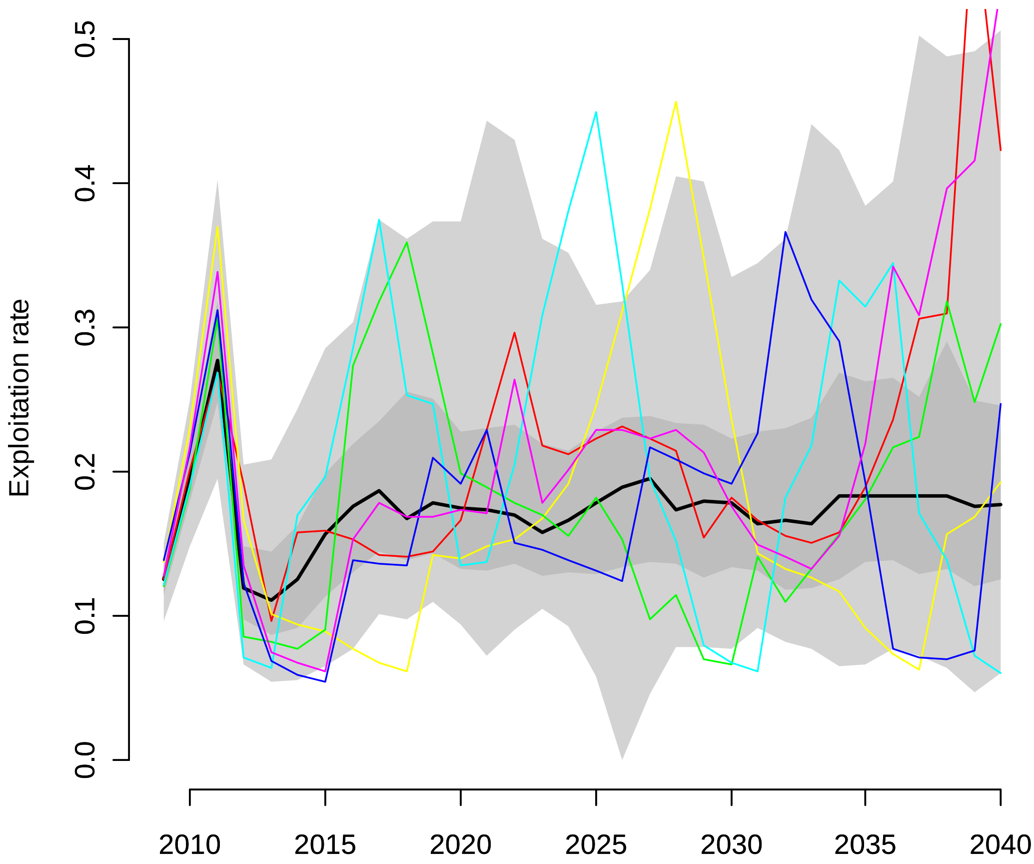

Figure 11. The simulated trend in the exploitation rate for the WCSI spawning fishery for scenario 9 (target level 0.40, lower threshold 0.30). The light grey area encompasses the 5–95% quantile range and the dark grey area encompasses the 25–75% quantile range of the exploitation rate. The coloured lines are examples of individual biomass trajectories from the set of simulations.

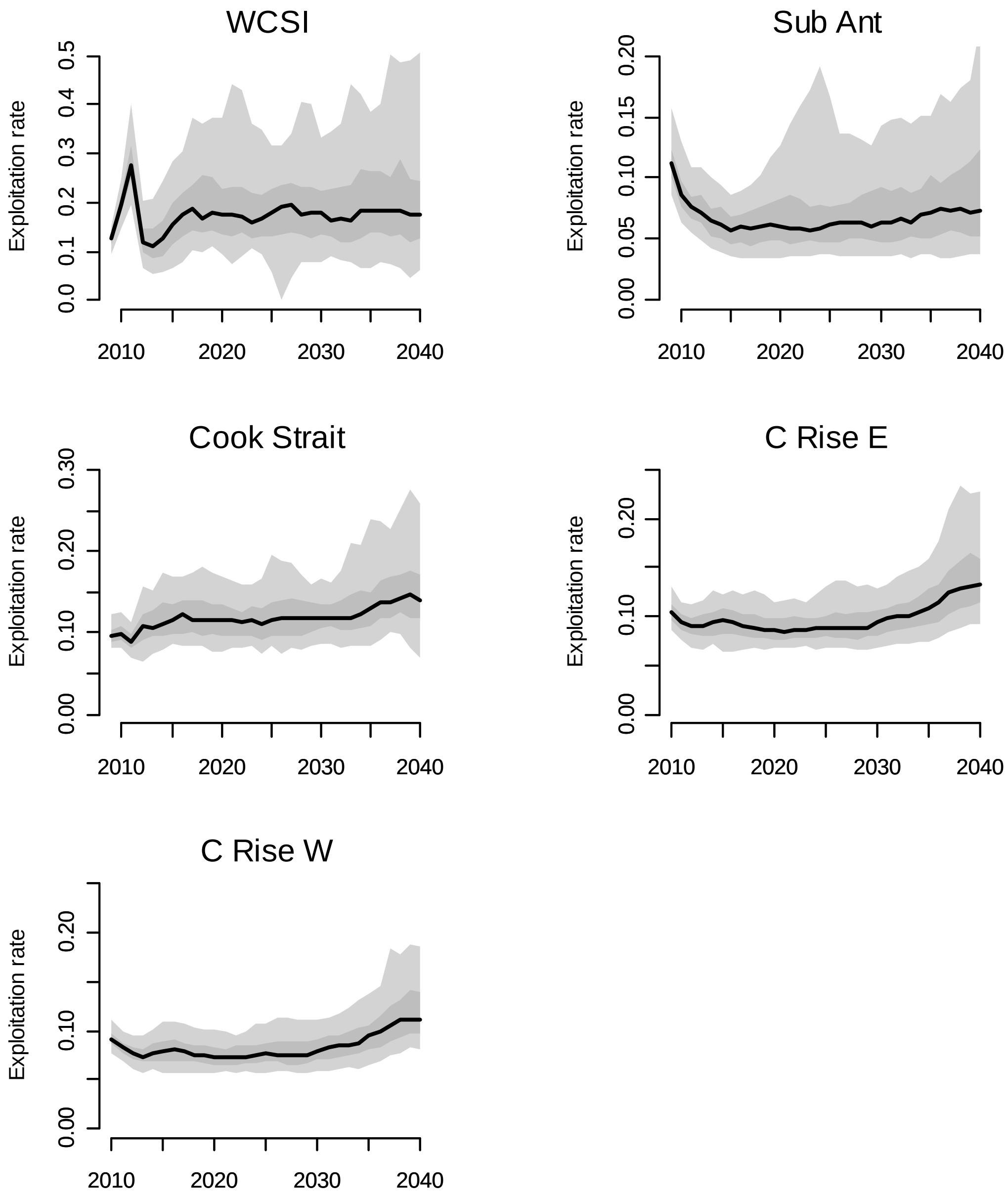

Figure 12. The simulated trend in exploitation rates by fishery/stock component for scenario 9 (target level 0.40, lower threshold 0.30). The light grey area encompasses the 5–95% quantile range and the dark grey area encompasses the 25–75% quantile range of spawning biomass.

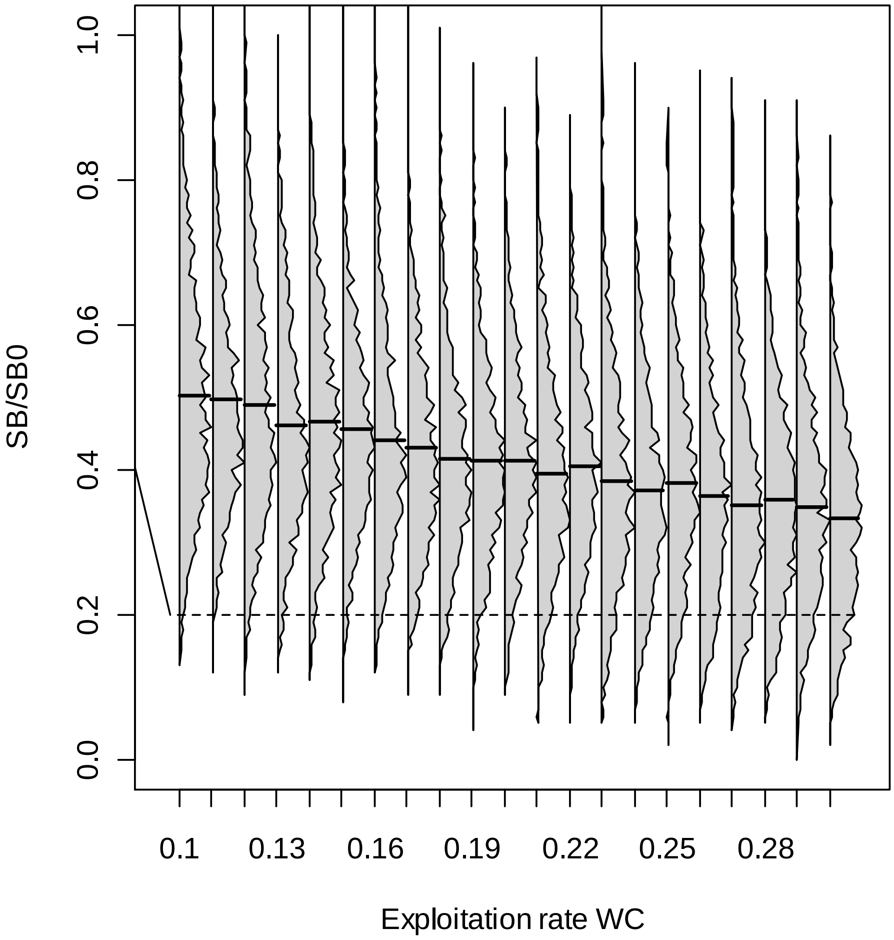

Figure 13. Distribution of WCSI spawning biomass relative to *SB0* during the projection period for an exploitation rate based decision rule. The x–axis represents the specific exploitation rate incorporated in the decision rule. An exploitation rate of about 0.25 results in approximately a 10% probability of the spawning biomass declining below 20% of the unexploited level.