ASSESSMENT OF CANDIDATE HARVEST DECISION RULES FOR COMPLIANCE TO THE PRECAUTIONARY APPROACH FRAMEWORK FOR THE SNOW CRAB FISHERY IN THE SOUTHERN GULF OF ST. LAWRENCE

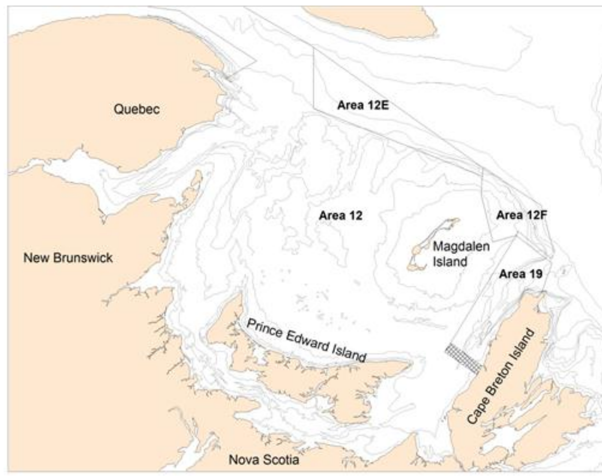


Figure 1: Map of the southern Gulf of St. Lawrence showing the Snow Crab Fishing Areas (CFAs).

Context:

Snow crab, Chionoecetes opilio, has been commercially exploited in the southern Gulf of St. Lawrence since the mid-1960s. The fishery is managed using an annual total allowable catch. Catches from a bottom trawl survey are used to estimate the biomass of commercial-size (>=95 mm carapace width) adult male snow crab and used to establish the annual total allowable catch. Reference points (limit reference point, upper stock reference point, maximum removal rate in the healthy zone) have been defined for this stock (DFO 2010, 2012). Harvest decision rules are required to complete the elements of the fishery decision-making framework incorporating the precautionary approach (PA) (DFO 2009). A joint DFO/Industry working group was convened to develop harvest decision rules that conform to the PA framework. It was agreed that the working group would submit their work for peer review to assess whether the candidate harvest decision rules conformed to the PA policy.

This document provides an assessment of the compliance to the PA of candidate harvest decision rules for the snow crab fishery of the southern Gulf of St. Lawrence. The science peer review was conducted January 29-31, 2014 in Moncton, NB. Participants at the science review were from DFO Science, DFO Fisheries Management, fishing industry, Aboriginal organizations, provincial governments, and invited external experts.

SUMMARY

- Candidate decision rules for the snow crab fishery of the southern Gulf of St. Lawrence were assessed for compliance with the Precautionary Approach framework.
- Precautionary Approach compliance was assessed based on the condition that there must be a very low probability (<= 5%) of the stock falling into or remaining in the critical zone due to fishing exploitation.
- The compliance of candidate rules was assessed using simulated recruitments which included values much lower and higher than recruitment values observed over the assessment time period; it was concluded that this was an appropriate method for assessing compliance.
- PA compliant decision rules tested included candidates with removal rates in the healthy zone above the defined maximum removal rate value of 0.346.
- The choice among PA compliant decision rules for use in fisheries management decisions is not a science role.

BACKGROUND

In 2009, Fisheries and Oceans Canada published the Sustainable Fisheries Framework that provides the basis for ensuring Canadian fisheries are conducted in a manner which support conservation and sustainable use. The framework is comprised of a number of policies for the conservation and sustainable use of fisheries resources including "A Fishery Decision-Making Framework Incorporating the Precautionary Approach" (DFO 2009). The Fishery Decision-making framework (the PA) applies where decisions on harvest strategies or harvest rates for a stock must be taken on an annual basis or other time frame to determine Total Allowable Catch (TAC) or other measures to control harvests. This is the case for snow crab from the southern Gulf of St. Lawrence (sGSL).

There are three components to the general decision framework for the PA:

1. Reference points and stock status zones (Healthy, Cautious and Critical) (Fig. 2),
2. Harvest strategy and harvest decision rules, and
3. The need to take into account uncertainty and risk when developing reference points and developing and implementing decision rules.

Element (1) of the framework has been completed for snow crab from the sGSL. Reference points and stock status zones in units of commercial-size (>= 95 mm carapace width CW) adult male snow crab biomass have been defined for the sGSL biological unit (DFO 2010, 2012). Element (2) of the framework is the subject of this advisory report. Element (3) has been considered in the definition of reference points and is taken into account in the analysis of the harvest strategy and the decision rules for the snow crab fishery of the sGSL.

A joint DFO-Industry working group was tasked with developing candidate harvest strategies and decision rules for the snow crab fishery of the sGSL, assessing if the rules were compliant with the PA framework, and presenting the list of candidate decision rules for consideration by the Southern Gulf Snow Crab Advisory Committee. The assessment of the compliance of candidate decision rules was submitted for peer review. This report provides advice on the definition of PA compliance and advises on the method and criteria for assessing candidate decision rules for PA compliance for the snow crab fishery of the sGSL.

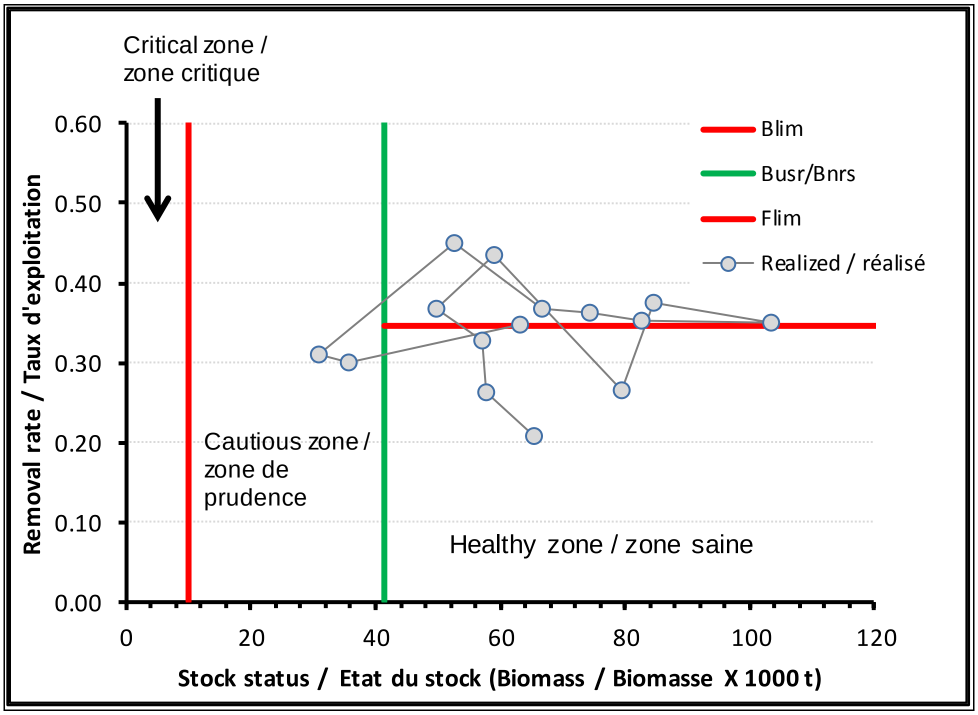


Figure 2. Precautionary Approach diagram showing the reference points, the status zones, and the history of the southern Gulf of St. Lawrence snow crab commercial biomass and exploitation rates corresponding to the 1998 to 2012 fisheries.

Snow crab biology and fishery

Snow crab (*Chionoecetes opilio*) growth to maturity is characterized by a terminal molt; once a crab is fully mature, it stops molting and hence growing in size (Conan and Comeau 1986). Males reach the terminal molt at sizes ranging from 40 to 150 mm CW, whereas females reach terminal molt at smaller sizes, ranging from 30 to 95 mm CW. After molting, crabs have a soft shell and are engorged with water. It takes about 8-10 months for the carapace of a commercial-size (>= 95 mm carapace width) crab to harden. It takes 12 to 14 years for male snow crab to grow to the commercial size.

In the sGSL, molting of snow crab occurs from December-April, prior to the fishery. Adult soft-shelled male crabs are only able to participate in reproductive activities in the year following the terminal molt (Conan et al. 1988; Moriyasu et al. 1988). After terminal molt, time to peak body condition (shell hardness and muscle content) is 2 to 3 years and male life expectancy is about 7 years. However, the appearance and integrity of the body may decline continuously after terminal molt through exoskeleton fouling and limb loss.

Management of the southern Gulf of St. Lawrence snow crab fishery is based on quotas and effort controls (trap allocations, trap dimensions, and seasons). The minimum legal carapace width for males is 95 mm, females are not harvested and soft-shell and white crab is not targeted by the fishery. Baited traps, constructed of wire or tubular steel, are used to catch crab, mainly on mud or sand-mud bottoms at temperatures ranging from -1 to 4.5°C, and depths ranging from 50 to 280 m.

The assessment of snow crab for the provision of catch advice is based on a fishery independent bottom trawl survey that covers the area of the southern Gulf potentially occupied by snow crab (DFO 2014). The estimated biomass of commercial size adult male snow crab from the survey has ranged from a low of 30,920 t (95% confidence interval range of 27,237 to 34,959 t) in 2009 to a high of 103,429 t (95% confidence interval range of 91,029 to 117,036 t) in 2004. The survey estimates of total biomass are quite precise, the annual coefficients of variation ranging from 5.2% to 11.6%, with a mean of 7.6% for the time series (1997 to 2012).

ASSESSMENT

Reference points consistent with the Precautionary Approach (DFO 2009) were first defined for the snow crab (*Chionoecetes opilio*) biological unit of the southern Gulf of St. Lawrence in 2010 and revised in 2012 to account for the change in the surface area used to estimate the biomass (DFO 2010, 2012). The estimate of B_{MSY} (51,700 t) was taken as 50% of the maximum commercial biomass over a productive period, i.e. 50% of 103,400 t (DFO 2012). The upper stock reference point (B_{USR} = 41,400 t) was estimated as 80% of $B_{MSY.}$ The limit reference point (B_{lim}) was chosen as the lowest biomass of hard shell commercial-sized adult male crab (post-fishery as estimated from the trawl survey) which produced good recruitment rates of juvenile crab at Instar VIII (DFO 2010). The B_{lim} value was estimated at 10,000 t. The estimate of F_{MSY} was taken as the average exploitation rate over the productive period used to estimate B_{MSY} and represented a value of 0.346, the average exploitation rate (harvest in year t divided by biomass in year t-1 estimated from the trawl survey) over the 1998 to 2009 fishery period (DFO 2012).

Candidate decision rules examined

Harvest decision rules share features in each of the three PA zones (DFO 2009). When the stock is in the critical zone, the harvest rate (taking into account all sources of removals) must be kept to the lowest level possible. The exploitation rate in the cautious zone decreases as the stock declines from the healthy zone towards the critical zone. The removal rate in the healthy zone is at a maximum value at a stock status level which is >= B_{USR}. The removal rate within zones may vary depending on whether the recruitment is increasing or decreasing.

All the decision rules examined by the working group are linear in form and are defined by inflection points with currencies along the stock status axis and the removal rate axis of the PA reference diagram. Candidate decision rules share a number of general features and by varying a few parameters, a wide range of rules can be defined. The working group examined a number of candidate rule structures which differed in the number and values of inflection points within the cautious zone and within the healthy zone (Fig. 3).

The default rule uses the reference points defined for the snow crab stock (Fig. 3A, 3D). The removal rate increases linearly in the cautious zone from a value of ER_{crit} (removal rate in the critical zone) when the commercial biomass (CB) <= B_{lim} (10,000 t) to a maximum removal rate of 0.346 (F_{lim}) when CB >= B_{USR} (41,400 t). The default value for ER_{crit} was set to 0. Alternatives to the default rule in the cautious zone included:

- A “threshold” rule (Fig. 3B) with a removal rate slope which is similar to the default rule when the CB is < B_{USR} and >= a threshold value (B_{crit}). When the CB is < B_{crit}, the removal rate falls abruptly to ER_{crit}.
- An “intermediate” rule (Fig. 3C) defines two removal rate slopes in the cautious zone articulated at a fixed commercial biomass and removal rate pivot point. The pivot point proposed by the working group corresponded to the removal rate value agreed by industry for the 2011 fishery (ER_{low} = 0.30) based on the 2010 survey CB value (B_{low} = 36,000 t) (DFO 2013).

Removal rate alternatives to the default rule in the healthy zone included (Fig. 3):

- A “step” rule (Fig. 3E) consisting of four removal rate levels in the healthy zone was proposed. When CB >= B_{USR} but < B_{MSY} (51,700 t), then the removal was set at F_{lim} (0.346). When the CB >= B_{MSY} but < B_{max} (defined as 61,700 = B_{MSY} + 10,000 t) then the removal rate was set at ER_{mid} = 0.362 or 0.382 depending on whether recruitment was decreasing over year or increasing over year, respectively. When CB >= B_{max}, the removal rate was set at ER_{max} = 0.3979. The inflection points correspond to values within the 1998 to 2009 fisheries period which were used to define the reference points for this stock (DFO 2013).
- A “proportional” rule (Fig. 3F) has one inflection point set at the maximum estimated CB value (B_{max} = 103,400 t) and a maximum removal rate value corresponding to the maximum exploitation rate (ER_{max} = 0.45) realized for the stock (DFO 2013). The removal rate between B_{USR} and B_{max} increases linearly from F_{lim} to ER_{max}. When the CB >= B_{max}, the removal rate is fixed at ER_{max}.

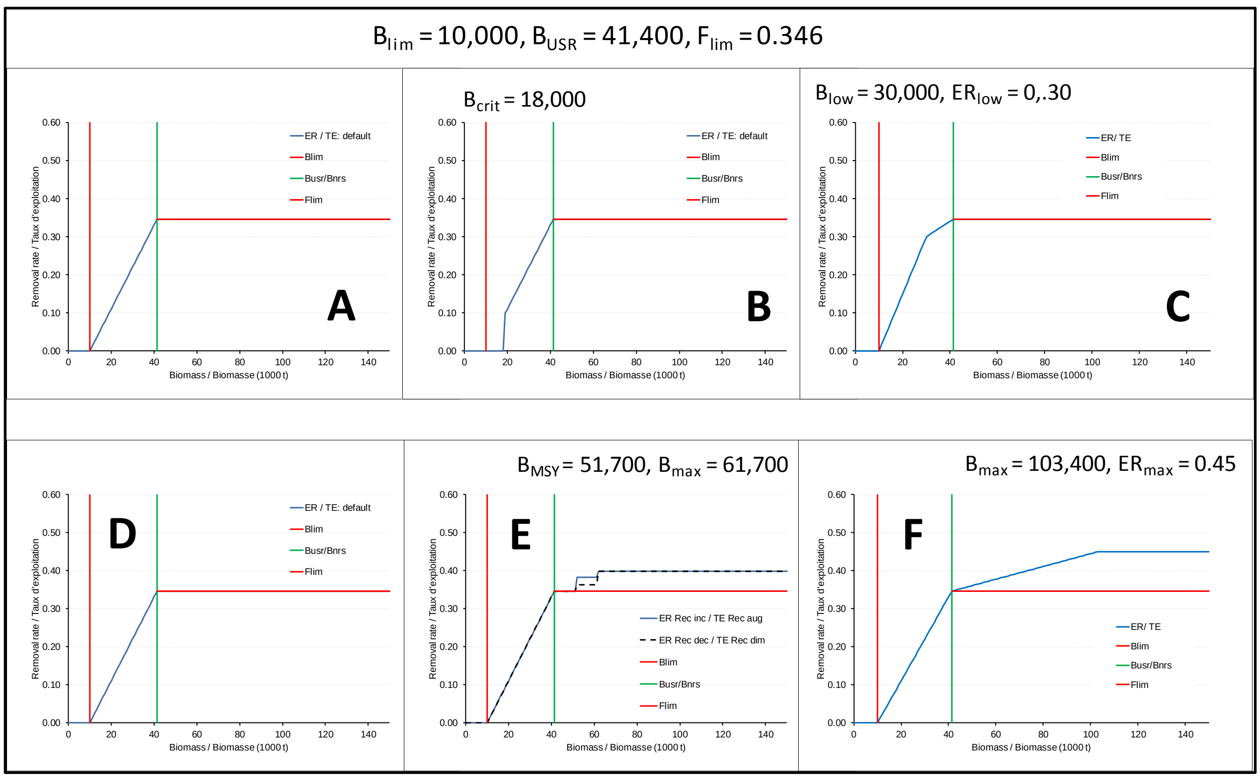
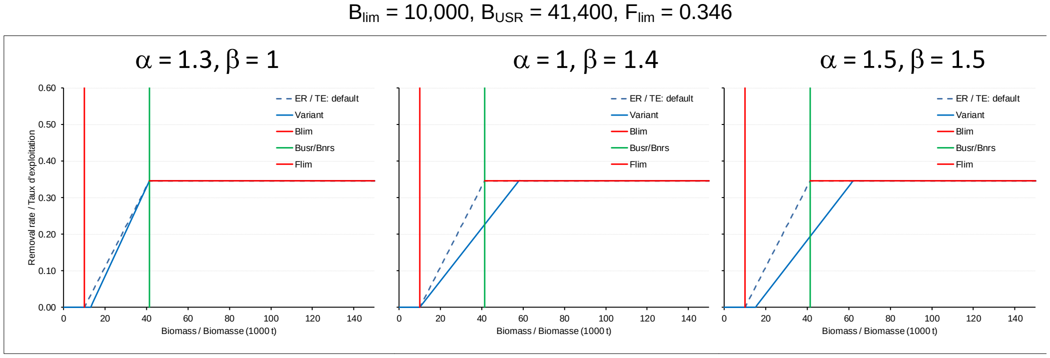


Figure 3. Default decision rule (A, D) and alternatives for removal rate rules in the cautious zone (B, C) and for the healthy zone (E, F).

Variants of the candidate rule structures included removal rate rules that varied with the stock trajectory (Fig. 4). For example, the removal rate on a stock in the cautious zone could differ if in one instance the stock status is improving (e.g. recruitment increasing) versus an alternate situation when the stock status is declining (e.g. recruitment decreasing). The “step” rule for the healthy zone described above is a stock trajectory dependent rule. The inflection point values of all the candidate rule structures were varied to find those which would produce PA compliant rules. The displacement of the inflection points is not the same as changing the reference points.



$$ER = ER_{crit} + (F_{lim} - ER_{crit}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{lim} * \alpha}\right)\right)$$

$$\alpha \geq 1;\ \beta \geq 1$$

Figure 4. Examples of inflection point variants of the cautious zone default linear rule and the equation used to derive the removal rate line. The default removal rate in the cautious zone is shown as a dashed line.

Defining PA compliance

The PA policy (DFO 2009) is not explicit in defining the necessary conditions for harvest strategies and harvest decision rules to be compliant with the policy. In general terms, if the stock status indicator is in the critical zone, removals from all sources must be kept to the lowest level possible. If the stock is in the cautious zone, the removal rate must be progressively adjusted to avoid the stock falling to the critical zone. When the stock is in the healthy zone, the removal rate should not exceed the defined removal rate corresponding to F_{MSY} and management actions should react to a declining trend towards the cautious zone (DFO 2009). The stock in this case refers to the commercial sized (>= 95 mm CW) adult male snow crab from the southern Gulf of St. Lawrence biological unit.

Based on these general principles, a candidate decision rule was judged to be PA compliant if there was a very low probability (<= 5%) of the stock falling into or remaining in the critical zone due to fishing exploitation.

Removal rate considerations in the healthy zone

The F_{MSY} (F_{lim}) value defined for the southern Gulf of St. Lawrence stock is based on the average exploitation rate realized in the fishery during a period considered to have been productive and which was used to define B_{MSY} (DFO 2010). The exploitation rates of those years (1998 to 2009) were established annually through a consultation process with industry taking into account the scientific assessment. Using an average value over the same period used to define B_{MSY} was convenient. As stated in DFO (2010, 2012), it is unknown if the average biomass over the period 1997 to 2008 is a good proxy for B_{MSY} because recruitment of terminal molted large males from these biomass levels has only been measured to date for a few year classes.

There are a number of biological and fisheries considerations for considering a removal rate value in the healthy zone that exceeds the proxy F_{MSY} value presently defined. When snow crab reach maturity, they undergo a terminal molt. At terminal molt, there is no further growth in size, or weight over time. As well, as male crabs age their reproductive potential declines. This contrasts with many other species, crustaceans such as lobster and most fish species, for which animals generally get larger as they age, even after attaining maturity. For these species, there can be accrued benefits from reduced exploitation as older animals may have more important contributions to spawning biomass as they get older and larger. For snow crab, total adult male reproductive biomass can only increase year on year with new recruitment as there is no annual increase in the biomass of terminally molted animals. In addition, life expectancy of terminal molted crab is limited to about 7 years maximum.

The fishery targets only large adult male snow crab of carapace width >= 95 mm and the economic value is highest for the clean hard shell snow crab which are two to three years post terminal molt.

With these considerations, candidate decision rules with variable removal rates in the healthy zone that exceeded the presently defined removal rate were examined for compliance with the PA.

Criteria to compare decision rules and assess compliance with the PA

Based on the PA policy, there should be a very low probability (<5%) of the stock falling into the critical zone (DFO 2009). The performance of decision rules was quantified for the following criteria:

- The number of years when the residual biomass (mating biomass after the fishery) would be less than B_{lim} with a probability > 0.05.
- The number of years when the fishery was open and the probability that the residual biomass (mating biomass after the fishery) would be less than B_{lim} is > 0.05 in the fishery year.
- Combinations of annual changes in the stock status indicator within the PA zones.

Simulation method for assessing relative performance of decision rules

The performance of decision rules was assessed by simulating a sequence of commercial biomass values and TAC decisions over a large number of years based on a candidate decision rule. The simulation and analysis of the decision rules is conducted as follows (for clarity, all references to commercial biomass, recruitment biomass, residual biomass and landings are in terms of commercial size (>= 95 mm carapace width) adult (terminal molted) male snow crab). From an initial year with an estimate of commercial biomass, the TAC is selected according to the decision rule under consideration. The residual biomass is then calculated based on the estimate of the commercial biomass available for the fishery, discounted for non-fishing loss of crab, and assuming the TAC is captured. The estimated or simulated recruitment is then added to the residual biomass and this represents the commercial biomass available for the next year's fishery.

The necessary inputs for these analyses include:

- commercial biomass estimate for the first year,
- an estimate of the loss rate prior to the fishery, and
- a sequence of recruitment biomass values in subsequent years.

The estimated recruitment values for the 1997 to 2012 time period have been at levels which resulted in the commercial biomass prior to the fishery being in the healthy zone in 14 of the 16 assessed years and in the cautious zone (biomass < 41,400 t) in 2 of the 16 years assessed (DFO 2013). For simulated years 2013 to 2047, a recruitment series was simulated to mimic the approximately ten year periodicity in peak to peak abundance of crab. The average values were deliberately lowered in the first half of the simulated series and then deliberately increased in the second half of the simulated series to explore the performance of the decisions rules over a wide range of recruitment levels (Fig. 5).

In the absence of fisheries, the simulated commercial biomass of snow crab fluctuates according to the recruitment variations (Fig. 5). Despite the low mean recruitments simulated for 2017 to 2020 (mean values varying between 4,300 and 6,800 t) and again in 2026 to 2030 (mean values varying between 4,200 and 9,400 t), the simulated residual biomass remains above B_{lim} in all years (P>0.95) and the commercial biomass remains in the healthy zone in 45 of the 50 years (remains in the cautious zone in one year; moves from healthy to cautious in two years, from cautious to healthy in two years) (Fig. 5).

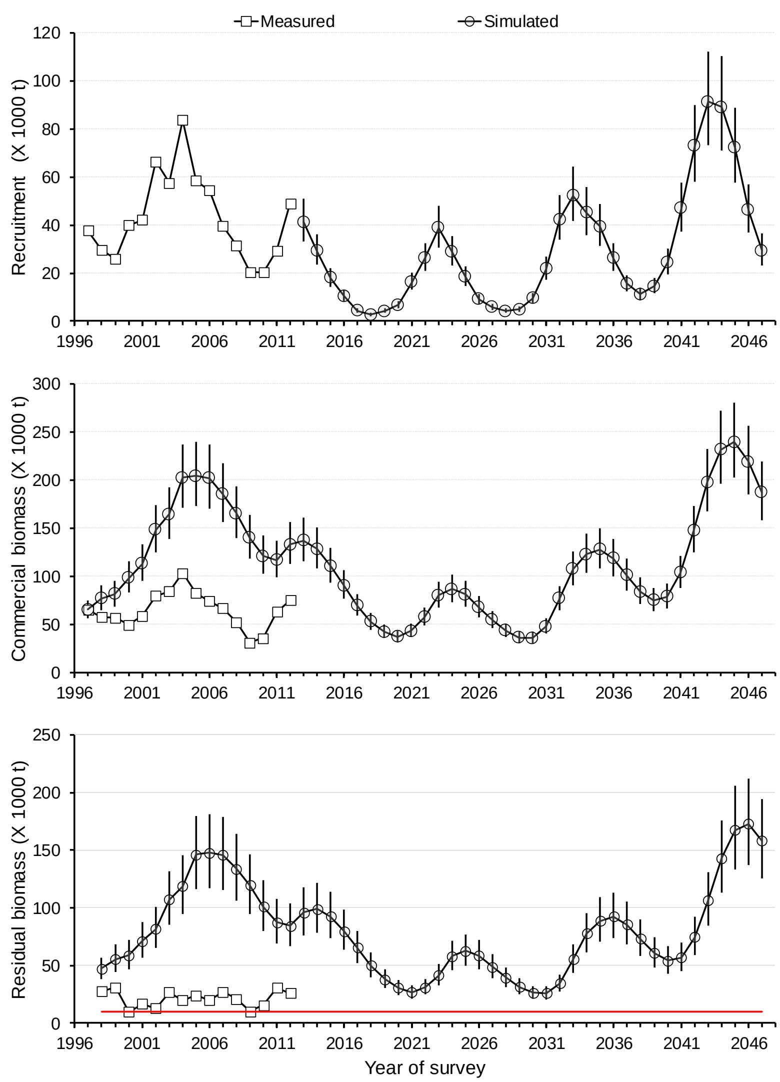


Figure 5. Trends in the simulated recruitment (upper panel), the simulated commercial biomass (middle panel), and the simulated residual biomass (lower panel) in the absence of any fishing exploitation, used to assess performance of candidate decision rules.

A total of 5,000 Monte Carlo simulations were used to incorporate observation errors associated with the assessment of the commercial biomass. As the interest was to compare the relative performance of the rules, the same 5,000 Monte Carlo draws of the relevant variables were used (5,000 values of the commercial biomass estimate for the first year of the simulation, 5,000 values of the proportion of the commercial biomass which is lost prior to the fishery for all years, and 5,000 annual recruitment biomass values, which vary by year).

Results of performance of the decision rules and PA compliance

There are a large number of potential decision rule combinations which can be generated from the few alternatives for the cautious zone, the healthy zone, stock trajectory dependent, and the variants described above (Figs. 3 and 4). Examination of these combinations and their performance relative to the PA compliance criteria indicated that the rule in the cautious zone was the primary determining factor for PA compliance.

In the simulated recruitment series with periods of very low recruitment without fishing (Fig. 5), the simulated residual biomass remains above B_{lim} in all years (P>0.95) and the commercial biomass remains in the healthy zone in 45 of the 50 years. A large number of compliant rule variations for which the residual biomass was never <= B_{lim} with probability > 5% could be defined (Appendices 1 to 3). A total of 12 variants of the linear rule, the step rule, and the proportional rule in the healthy zone with two variants in the cautious zone (threshold, intermediate) were examined and concluded to be PA compliant. The only differences in performance of these rules are in the number of years when the stock is in the healthy zone and in the cautious zone. These rules most often resulted in periods when the fishery would be closed or with a very low TAC.

Details of the twelve PA compliant candidate decision rules consisting of variations of removal rate rules in the cautious zone (default linear, B_{crit}, B_{low}&ER_{low}, B_{crit}&B_{low}&ER_{low}) and for variants in the healthy zone were developed by the working group and are summarized in Appendices 1 to 3.

Sources of Uncertainty

The simulated recruitment series is an attempt to mimic the periodicity of the recruitment oscillations measured for the snow crab stock of the southern Gulf of St. Lawrence. The results of the analyses should be robust to the recruitment series simulated and the conformity of the rules in regards to the precautionary approach can be appropriately compared.

There is no stock and recruitment dynamic modelled in the simulated time series of recruitment. The simulated series of recruitment therefore does not represent the expected trajectory of the snow crab stock nor does the analysis of the decision rules, and in particular a conclusion on rules which are PA compliant, be interpreted as an indication of how the stock will perform in the future. The simulated recruitment series is used to contrast the relative performance of candidate decision rules with identical recruitment time series and in particular, the performance of the rules over a range of recruitment abundances which could occur in the future, particularly low recruitment states.

The conformity of the rules in respect to the PA is specific to the uncertainties assumed in this model. The uncertainties incorporated in the model include the estimates of non-fishing losses between survey years, and the observation uncertainty associated with the assessment. A fixed observation uncertainty value associated with the assessment of the commercial biomass was used (on the log scale, standard deviation of 0.10). For the assessed years 1997 to 2012, the range in the standard deviation was 0.051 to 0.115. If the uncertainty in the assessed commercial biomass is higher than the value used, PA compliant variants of the candidate rules would be different with more cautious values for the inflection points at which removal rate rules are defined.

It was assumed that there was no error in the reporting of landings, and that in any year, the TAC was harvested. The fishery is managed under very tight reporting controls, associated primarily with dockside monitoring, so the values are considered to be of high quality.

CONCLUSIONS AND ADVICE

The condition under which harvest decision rules are assessed for compliance to the PA policy is that there must be a very low probability (<= 5%) of the stock falling into or remaining in the critical zone due to fishing exploitation.

The performances of candidate rules relative to PA compliance were assessed using simulated recruitments which included values which were much lower than any recruitment values observed over the 1998 to 2012 time series. Oscillations of recruitment were modelled to mimic the periodicity of the abundances noted for snow crab. This is an appropriate method to assess these decision rules.

The choice of a fixed observation error value for the estimation of the commercial biomass for the simulations which was within the range of annual values but higher than the mean value is sufficient for evaluating performance of the candidate rules.

Removal rates above 0.346 in the healthy zone can be PA compliant based on the criteria used in this analysis.

In all the years in the simulation, it was possible to develop decision rules for which the residual biomass never fell below B_{lim}. Twelve rules presented by the working group were assessed to be PA compliant. Other rules could be developed and tested.

The candidate decision rules assessed would benefit from a review in another five years, as additional stock dynamic data are obtained. Until then, the prognosis from the assessment suggests that although the recruitment will remain variable, there is no indication of a recruitment failure of the type modelled in the simulated recruitment series.

PA compliance of candidate decision rules is assessed exclusively on the basis of the criteria associated with stock status. Examples of socio-economic criteria to choose among PA compliant rules were described by the working group, including maximum TAC and the minimum number of years when TACs are less than a critical value for the industry. The choice among these PA compliant decision rules is not a science decision.

SOURCES OF INFORMATION

This Science Advisory Report is from the Fisheries and Oceans Canada, Canadian Science Advisory Secretariat, regional advisory meeting of January 29-31, 2014 on the assessment of the status of the southern Gulf of St. Lawrence snow crab stock. Additional publications from this process will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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DFO. 2014. Assessment of snow crab in the southern Gulf of St. Lawrence (Areas 12, 19, 12E and 12F) and advice for the 2014 fishery. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2014/008.

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APPENDIX

Appendix 1. Harvest decision rules based on a default linear rule in the healthy zone which were evaluated to be PA compliant.

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<tr><th>PA representation of rule</th><th>Parameters and equations</th></tr>
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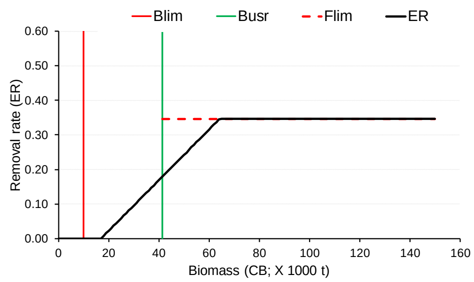

</td><td>
B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ;
F_{lim} = 0.346 ; α= 1.7 ; β = 1.55
<u>Cautious zone</u>

$$If\ CB \le B_{lim} * \alpha\ then\ ER = ER_{crit}$$

$$If\ B_{lim} * \alpha < CB \le B_{USR} * \beta\ then\ ER = ER_{crit} + (F_{lim} - ER_{crit}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{lim} * \alpha}\right)\right)$$

<u>Healthy zone</u>

$$If\ CB > B_{USR} * \beta\ then\ ER = F_{lim} = 0.346$$
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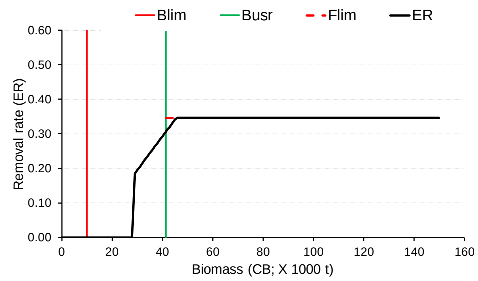

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B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ;
F_{lim} = 0.346 ; B_{crit} = 28,000 ; α= 1 ; β = 1.1
<u>Cautious zone</u>

$$If\ CB \le B_{crit}\ then\ ER = ER_{crit}$$

$$If\ B_{crit} < CB \le B_{USR} * \beta\ then\ ER = ER_{crit} + (F_{lim} - ER_{crit}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{lim} * \alpha}\right)\right)$$

<u>Healthy zone</u> : same as above
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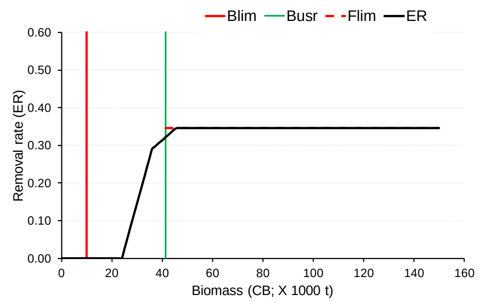

</td><td>
B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ;
F_{lim} = 0.346 ; B_{low} = 36,000 ; ER_{low} = 0.29 ;
α= 2.4; β = 1.1
<u>Cautious zone</u>

$$If\ CB \le B_{lim} * \alpha\ then\ ER = ER_{crit}$$

$$If\ B_{lim} * \alpha < CB \le B_{low}\ then\ ER = ER_{crit} + (ER_{low} - ER_{crit}) * \left(1 - \left(\frac{B_{low} - CB}{B_{low} - B_{lim} * \alpha}\right)\right)$$

$$If\ B_{low} < CB \le B_{USR} * \beta\ then\ ER = ER_{low} + (F_{lim} - ER_{low}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{low}}\right)\right)$$

<u>Healthy zone :</u> same as above
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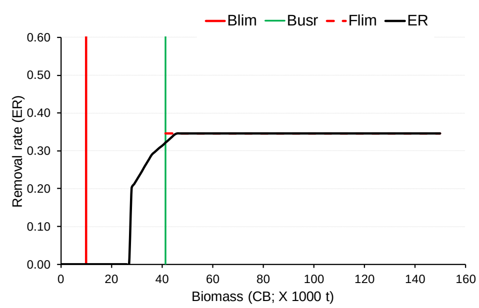

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B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ;
F_{lim} = 0.346 ; B_{crit} = 27,000 t ; B_{low} = 36,000 ;
ER_{low} = 0.29 ; α= 1; β = 1.1
<u>Cautious zone</u>

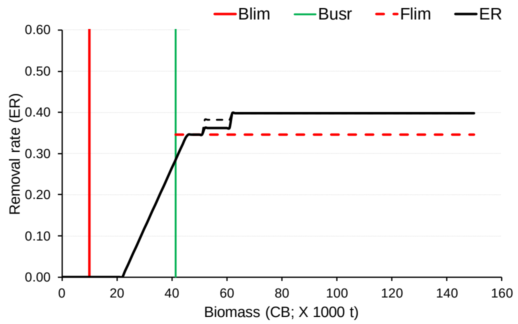
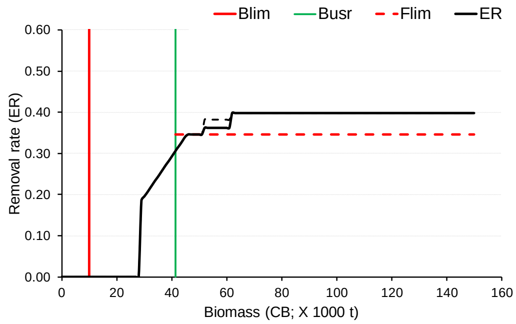
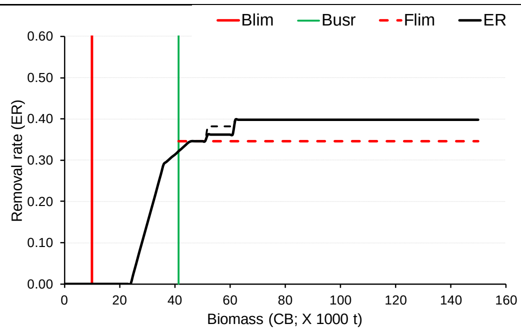
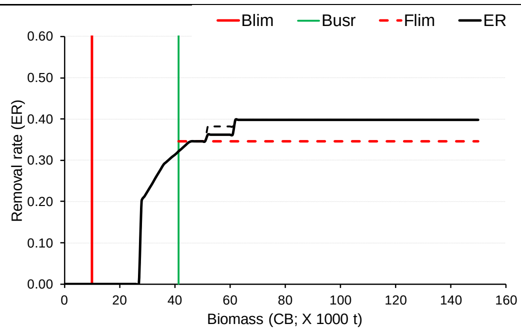
$$If\ CB \le B_{crit}\ then\ ER = ER_{crit}$$

$$If\ B_{crit} < CB \le B_{low}\ then\ ER = ER_{crit} + (ER_{low} - ER_{crit}) * \left(1 - \left(\frac{B_{low} - CB}{B_{low} - B_{lim} * \alpha}\right)\right)$$

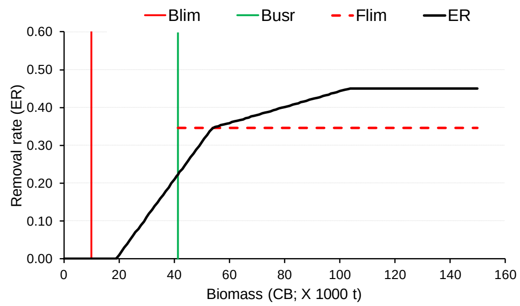
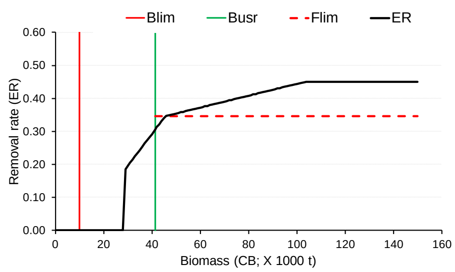
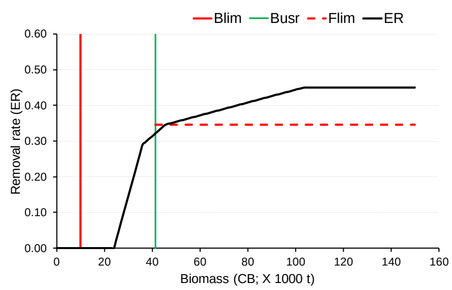
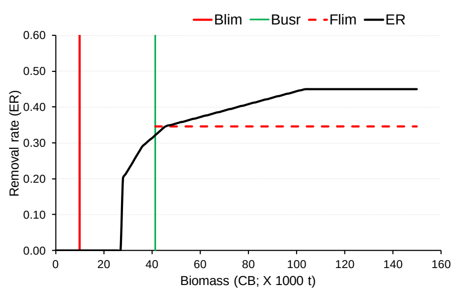
$$If\ B_{low} < CB \le B_{USR} * \beta\ then\ ER = ER_{low} + (F_{lim} - ER_{low}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{low}}\right)\right)$$

<u>Healthy zone :</u> same as above
</td></tr>
</table>

Appendix 2. Harvest decision rules based on a step rule in the healthy zone which were evaluated to be PA compliant.

PA representstation of rule	Parameters and equations
	B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; B_{msy} = 51,700 ; B_{max} = 61,700 t ; ER_{crit} = 0 ; F_{lim} = 0.346 : α= 2.2 ; β = 1.1 <u>Cautious zone</u> $If\ CB \le B_{lim} * \alpha\ then\ ER = ER_{crit}$ $If\ B_{lim} * \alpha < CB \le B_{USR} * \beta\ then\ ER = ER_{crit} + (F_{lim} - ER_{crit}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{lim} * \alpha}\right)\right)$ <u>Healthy zone</u> $If\ B_{USR} * \beta < CB \le B_{msy}\ then\ ER = F_{lim} = 0.346$ $If\ B_{msy} < CB \le B_{max}$ and $if\ recruit\ y+1 < recruit\ y\ then\ ER = ER_{mid} = 0.362$ $if\ recruit\ y+1 \ge recruit\ y\ then\ ER = ER_{mid} = 0.382$ $If\ CB > B_{max}\ then\ ER = ER_{max} = 0.3979$
	B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ; F_{lim} = 0.346 ; B_{crit} = 28,000 ; α= 1 ; β = 1.1 <u>Cautious zone</u> $If\ CB \le B_{crit}\ then\ ER = ER_{crit}$ $If\ B_{crit} < CB \le B_{USR} * \beta\ then\ ER = ER_{crit} + (F_{lim} - ER_{crit}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{lim} * \alpha}\right)\right)$ <u>Healthy zone</u>: same as above
	B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ; F_{lim} = 0.346 ; B_{low} = 36,000 t ; ER_{low} = 0.29 ; α= 2.4 ; β = 1.1 <u>Cautious zone</u> $If\ CB \le B_{lim} * \alpha\ then\ ER = ER_{crit}$ $If\ B_{lim} * \alpha < CB \le B_{low}\ then\ ER = ER_{crit} + (ER_{low} - ER_{crit}) * \left(1 - \left(\frac{B_{low} - CB}{B_{low} - B_{lim} * \alpha}\right)\right)$ $If\ B_{low} < CB \le B_{USR} * \beta\ then\ ER = ER_{low} + (F_{lim} - ER_{low}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{low}}\right)\right)$ <u>Healthy zone</u>: same as above
	B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ; F_{lim} = 0.346 ; B_{low} = 36,000 t ; ER_{low} = 0.29 ; B_{crit} = 27,000 t ; α= 1; β = 1.1 <u>Cautious zone</u> $If\ CB \le B_{crit}\ then\ ER = ER_{crit}$ $If\ B_{crit} < CB \le B_{low}\ then\ ER = ER_{crit} + (ER_{low} - ER_{crit}) * \left(1 - \left(\frac{B_{low} - CB}{B_{low} - B_{lim} * \alpha}\right)\right)$ $If\ B_{low} < CB \le B_{USR} * \beta\ then\ ER = ER_{low} + (F_{lim} - ER_{low}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{low}}\right)\right)$ <u>Healthy zone</u>: same as above

Appendix 3. Harvest decision rules based on a proportional rule in the healthy zone which were evaluated to be PA compliant.

<table>
<tr><th>PA represenstation of rule</th><th>Parameters and equations</th></tr>
<tr><td>
</td><td>B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; B_{max} = 103,400 t ;
ER_{crit} = 0 ; F_{lim} = 0.346 ; α= 1.9 ; β = 1.3
<u>Cautious zone</u>
$If\ CB \le B_{lim} * \alpha\ then\ ER = ER_{crit}$
$If\ B_{lim} * \alpha < CB \le B_{USR} * \beta\ then\ ER = ER_{crit} + (F_{lim} - ER_{crit}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{lim} * \alpha}\right)\right)$
<u>Healthy zone</u>
$If\ B_{USR} * \beta < CB \le B_{max}\ then\ ER = F_{lim} + (ER_{max} - F_{lim}) * \left(1 - \left(\frac{B_{max} - CB}{B_{max} - B_{USR} * \beta}\right)\right)$
$If\ CB > B_{max}\ then\ ER = ER_{max} = 0.45$</td></tr>
<tr><td>
</td><td>B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ; F_{lim} = 0.346 ;
B_{crit} = 28,000 ; α= 1 ; β = 1.1
<u>Cautious zone</u>
$If\ CB \le B_{crit}\ then\ ER = ER_{crit}$
$If\ B_{crit} < CB \le B_{USR} * \beta\ then\ ER = ER_{crit} + (F_{lim} - ER_{crit}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{lim} * \alpha}\right)\right)$
<u>Healthy zone</u>: same as above</td></tr>
<tr><td>
</td><td>B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ; F_{lim} = 0.346 ;
B_{low} = 36,000 ; ER_{low} = 0.29 ; α= 2.4; β = 1.1
<u>Cautious zone</u>
$If\ CB \le B_{lim} * \alpha\ then\ ER = ER_{crit}$
$If\ B_{lim} * \alpha < CB \le B_{low}\ then\ ER = ER_{crit} + (ER_{low} - ER_{crit}) * \left(1 - \left(\frac{B_{low} - CB}{B_{low} - B_{lim} * \alpha}\right)\right)$
$If\ B_{low} < CB \le B_{USR} * \beta\ then\ ER = ER_{low} + (F_{lim} - ER_{low}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{low}}\right)\right)$
<u>Healthy zone</u>: same as above</td></tr>
<tr><td>
</td><td>B_{lim} = 10,000 t ; B_{USR} = 41,400 t ; ER_{crit} = 0 ; F_{lim} = 0.346 ;
B_{low} = 36,000 ; ER_{low} = 0.29 ; B_{crit} = 27,000 t ;
α= 1; β = 1.1
<u>Cautious zone</u>
$If\ CB \le B_{crit}\ then\ ER = ER_{crit}$
$If\ B_{crit} < CB \le B_{low}\ then\ ER = ER_{crit} + (ER_{low} - ER_{crit}) * \left(1 - \left(\frac{B_{low} - CB}{B_{low} - B_{lim} * \alpha}\right)\right)$
$If\ B_{low} < CB \le B_{USR} * \beta\ then\ ER = ER_{low} + (F_{lim} - ER_{low}) * \left(1 - \left(\frac{B_{USR} * \beta - CB}{B_{USR} * \beta - B_{low}}\right)\right)$
<u>Healthy zone</u>: same as above</td></tr>
</table>

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