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Evaluation of Compliance to the Precautionary Approach of Harvest Decision Rules for the Snow Crab (*Chionoecetes opilio*) Stock of the Southern Gulf of St. Lawrence

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on Decision Rules for Snow Crab from the Southern Gulf of St. Lawrence

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

This research document presents the work of a joint DFO-Industry working group tasked with developing candidate harvest strategies and decision rules for the snow crab (*Chionoecetes opilio*) fishery of the southern Gulf of St. Lawrence. Variants of harvest decision rules in which exploitation rate vary with stock size in the cautious zone and in the healthy zone of the Precautionary Approach (PA) framework are described. Performance of the candidate rules are assessed using a simulated time series of recruitments over 50 years that incorporates observation errors equivalent to those from the current stock assessment model. Criteria for assessing compliance of candidate harvest decision rules to the PA are presented. The primary criterion for assessing if a rule is PA compliant is for less than 5% chance of the stock falling below B_{lim} due to fishing activities over all years in the simulation rather than a single fishing year. Examination of performance of candidate rules indicated that the harvest decision rule profile in the cautious zone was the primary determining factor for PA compliance. A total of twelve variants of harvest decision rules examined by the working group were considered to be PA compliant. The assessment of the compliance of candidate decision rules was submitted for peer review at the DFO Science peer review meeting of January 29-31, 2014. The conclusions of the science peer review of compliance of harvest decision rules to the PA are presented in the science advisory report (DFO 2014).

RÉSUMÉ

Ce document de recherche présente les travaux d'un groupe de travail conjoint du MPO et de l'industrie chargé d'élaborer des propositions de stratégies de récolte et de règles de décision pour la pêche au crabe des neiges (*Chionoecetes opilio*) dans le Sud du golfe du Saint-Laurent. Les auteurs décrivent des variantes des règles de décision dans lesquelles les taux d'exploitation varient selon la taille du stock dans la zone de prudence et dans la zone saine du cadre de l'approche de précaution (AP). Le rendement des règles proposées est évalué à l'aide d'une série chronologique simulée du recrutement sur 50 ans, laquelle incorpore des erreurs d'observation équivalentes à celles des modèles d'évaluation des stocks actuels. Les auteurs présentent des critères pour l'évaluation de la conformité avec l'AP des propositions de règles de décision relatives aux captures. Le critère principal pour évaluer si une règle est conforme à l'AP est de vérifier s'il y a un risque inférieur à 5 % que le stock tombe sous la B_{lim} en raison des activités de pêche au fil des années dans la simulation plutôt que dans une année particulière. L'examen du rendement des règles candidates a permis de constater que le profil de la règle de décision en matière de captures dans la zone de prudence était le principal facteur déterminant pour ce qui est de la conformité avec l'AP. Au total, douze variantes des règles de décision en matière de captures évaluées par le groupe de travail ont été considérées comme conformes à l'AP. L'évaluation de la conformité des règles de décision proposées a été soumise à un examen par les pairs durant la réunion d'examen scientifique par des pairs du MPO du 29 au 31 janvier 2014. Les conclusions de l'examen scientifique par des pairs au sujet de la conformité à l'AP des règles de décision en matière de captures sont présentées dans l'avis scientifique (MPO 2014).

INTRODUCTION

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 provides the foundation of an ecosystem-based and precautionary approach to fisheries management in Canada. 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" (hereafter referred to as the PA) (DFO 2009). This decision making framework, or the PA, is the one considered in this document in the context of the snow crab (*Chionoecetes opilio*) resource and fishery of the southern Gulf of St. Lawrence (sGSL).

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 sGSL as the fishery is managed on the basis of a TAC which is established annually (DFO 2012b).

The chronology of the development of the PA framework is provided in DFO (2009). In general, the PA is "about being cautious when scientific information is uncertain, unreliable or inadequate and not using the absence of adequate scientific information as a reason to postpone or fail to take action to avoid serious harm to the resource" (DFO 2009).

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

1. reference points and stock status zones (Healthy, Cautious and Critical) (Fig. 1),
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 sGSL. Reference points and stock status zones in units of commercial-size (>= 95 mm carapace width) adult male snow crab biomass have been defined for the sGSL biological unit (DFO 2010, 2012b). The reference points, for biomass and for the removal rate in the healthy zone, were defined according to guidance provided in DFO (2009). For the production area of snow crab of the sGSL (57,840 km^2), the biomass limit reference point equals 10,000 t of commercial size adult male snow crab mating biomass evaluated after the fishery, and the upper stock reference point (delimiting the cautious and the healthy zones) is defined as 41,400 t of commercial size adult male snow crab mating biomass before the fishery. The removal rate reference in the healthy zone was defined as 0.346 of the commercial size adult male snow crab mating biomass (Fig. 1; DFO 2012b).

Element (2) of the framework is the subject of this document.

Element (3) has been considered in the definition of reference points and is discussed in this document in the analysis of the harvest strategy and the decision rules for the snow crab fishery of the sGSL.

The contents of this document were developed by a joint DFO-Industry working group (Appendix 1) 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 DFO Fisheries Resource Management and the sGSL snow crab fishing industry at the Snow Crab Advisory Committee meeting in February 2014. It was agreed that the assessment of the compliance of candidate decision rules be submitted for peer review at the DFO Science peer review meeting at the end of January 2014. The working group first met in March 2013 to discuss and agree on the guiding principles and the objectives of the fishery. In a second meeting on September 18, 2013, elements of decision rules were described, candidate rules were developed, and evaluation criteria for assessing the performance of the rules were refined. In the final face-to-face meeting on November 6, 2013, candidate decision rules were reviewed and assessed against the criteria for compliance to the PA, and a final list of candidate rules was agreed upon for evaluation at the science peer review. This document describes the approach used to assess decision rule performance and compliance and to provide a review of candidate decision rules which could be considered at the Snow Crab Advisory Committee meeting for application to the setting of annual TACs for the southern Gulf of St. Lawrence snow crab fishery.

The document is organized as follows:

1. A review of snow crab biology, terminology, and dynamics relevant to the discussion of decision rules.
2. Background on snow crab fishery and assessment of the southern Gulf of St. Lawrence.
3. Description of reference points defined for snow crab of southern Gulf of St. Lawrence.
4. Our interpretation of what PA compliance means.
    a. Removal rate considerations in the healthy zone.
5. Criteria to compare decision rules and assess compliance with the PA.
6. Description of the simulation method for assessing relative performance of decision rules.
7. Description of decision rules examined by the working group.
8. Results of performance of the decision rules and compliance with the PA.
9. Conclusions and uncertainties.

BACKGROUND

REVIEW OF SNOW CRAB BIOLOGY, TERMINOLOGY, AND DYNAMICS RELEVANT TO THE DEVELOPMENT OF DECISION RULES

Snow crab (*Chionoecetes opilio*) growth and full 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). It takes 12 to 14 years for male snow crab to grow to the commercial size >= 95 mm carapace width.

In the sGSL, molting of snow crab occurs from December-April, prior to the fishery (Watson 1972; Conan et al. 1988; Sainte-Marie et al. 1995; Benhalima et al. 1998; Hébert et al. 2002). Crab normally molt every year, although some animals do not molt annually and are referred to as skip molters, until they reach the adult phase via a final or “terminal” molt (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 (Conan and Comeau 1986).

After molting, crabs have a soft shell and are engorged with water. It takes about 8-10 months for the carapace of an adult soft-shelled male to harden (Hébert et al. 2002) and one year to attain maximal meat yield (Dufour et al. 1997).

After terminal molt, male life expectancy is 7+ years and time to peak body condition (shell hardness and muscle content) is 2 to 3 years (Fonseca et al. 2008). However, the appearance and integrity of the body may decline continuously after terminal molt through exoskeleton fouling and limb loss (Conan and Comeau 1986; Sainte-Marie et al. 1995; Comeau et al. 1998; Fonseca et al. 2008). Female life expectancy after terminal molt is about 4 to 6 years (Sainte-Marie et al. 2008).

Females that mature and mate for the first time, primiparous females, undergo the terminal molt between December and April and mate immediately after their terminal molt, while their carapace is still soft (Watson 1969; Moriyasu and Conan 1988). Multiparous females refer to females which are repeat spawners (second brood or more) and their mating season occurs from late-May to early-June, after egg hatching (Conan and Comeau 1986; Moriyasu and Conan 1988; Sainte-Marie and Hazel 1992; Moriyasu and Comeau 1996; Sainte-Marie et al. 1999). The mature females in the sGSL normally carry their eggs for two years under the abdomen (Mallet et al. 1993; Moriyasu and Lanteigne 1998).

Snow crab reproduction dynamics are complex and involve paired matings with intense competition between males for mating partners and potentially as well between females (in some circumstances). Males guard females after mating and large males guard females longer than small males.

Adult soft-shelled male crab are only able to participate in reproductive activities in the year following the terminal molt (Conan et al. 1988; Moriyasu et al. 1988).

Terminology and chronology of snow crab molting, fishery, and assessment

Adult soft-shelled (carapace conditions 1 and 2) males of legal size when observed in the fishery are referred to as soft-shell crab or white crab (Hébert et al. 2013). When sampled in the survey of the assessment year, these stages of crab are referred to as recruitment (Fig. 2). The carapace will harden over the fall and winter and they will be able to compete for and mate with females the following winter and spring; they therefore become part of the mating biomass as of Jan. 1 of assessment year + 1 (Fig. 2). Because the carapace will have hardened (carapace condition 3), they will become commercially marketable and part of the commercial biomass for the fishery of assessment year + 1 Adult male commercial size snow crab with a hard shell (carapace conditions 3 to 5) as measured in the survey are referred to as residual biomass, or the remaining mating biomass after the fishery of the year (Fig. 2). The sum of the recruitment biomass and the residual biomass as measured in the survey in year y equals the commercial biomass for the fishery in year y + 1 (Fig. 2).

Background on snow crab fishery and assessment of the southern Gulf of St. Lawrence

Snow crab has been commercially exploited in the southern Gulf of St. Lawrence (sGSL) since the mid-1960s. Baited traps, constructed of tubular steel, are used to catch crab, mainly on mud or sand-mud bottoms at temperatures ranging from -0.5 to 4.5°C, and depths ranging from 50 to 280 m. Management of the fisheries is based on quotas (by management area and distributed among licenses holders) and effort controls (number of licenses, trap allocations, trap dimensions, and seasons) (Hébert et al. 2013). The landing of females is prohibited and only hard-shelled males ≥ 95 mm carapace width (CW) are commercially exploited. Soft-shelled males have low commercial value due to their lower meat content and can be discarded at sea. Details of the fishery are provided in Hébert et al. (2014).

The snow crab fishery in the sGSL occurs as soon as the sGSL is clear of ice, in late April to early May, in snow crab fishing areas 12, 12E, and 12F, and closes in mid-July or earlier if the quota is caught. The fishery takes place during the reproductive period of snow crab. In Area 19, the fishing season starts in July and ends in mid-September or earlier if the quota is reached.

The fisheries landings during 1998 to 2012 ranged from 9,549 t in 2010 to a high of 36,118 t in 2005 (Table 1). The exploitation rates, expressed as the ratio of landings to the estimated commercial biomass of the previous year, varied between 20.8% in 1998 and 45.0% in 2008 (Table 1).

Assessment of abundance

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 sGSL potentially occupied by snow crab (Hébert et al. 2014). Although the bottom trawl survey began in 1988, there have been important changes in survey coverage and sampling intensity over time. Following on a framework meeting of the assessment methods for snow crab from the southern Gulf, a standardized time series beginning in 1997 was accepted for the purpose of stock assessment, development of reference points, and provision for catch advice (Table 1) (DFO 2012a; Hébert et al. 2014). The short time series of estimated abundances and the years (12 to 14) required for snow crab to reach the commercial size means that the estimated recruitments of snow crab of 1997 to 2011 are the majority related to the fisheries and the spawning stocks of unassessed years (1983 to at most 2000).

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 27,237 to 34,959 t) in 2009 to a high of 103,429 t (95% confidence interval range 91,029 to 117,036 t) in 2004 (Table 1). 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 (Table 1). The annual estimates of recruitment biomass are less precise, ranging between 8.2% and 25.7%, with a mean of 13.5% over the time series (Table 1).

DESCRIPTION OF REFERENCE POINTS DEFINED FOR SNOW CRAB OF SOUTHERN GULF OF ST. LAWRENCE

Reference points consistent with the Precautionary Approach (DFO 2009) were first defined for the snow crab biological unit of the southern Gulf of St. Lawrence in 2010 based on an assessment of the biomass of commercially exploitable snow crab in a surface area of 44,302 km² (DFO 2010). Following a science framework review of assessment methods for snow crab in the fall of 2011 (DFO 2012a), it was recommended that the snow crab abundance for the southern Gulf of St. Lawrence biological unit be assessed based on a surface area polygon of 57,840 km². Revised reference points to account for the change in biomass values associated with the change in polygon area were defined (DFO 2012b) using the same approach from DFO (2010).

The estimate of B_{MSY} was taken as 50% of the maximum biomass over a productive period, identified as the 1997 to 2008 assessment period (DFO 2010; Tables 1, 2). The maximum biomass value during this time period was estimated at 103,400 t, in 2004 and the B_{MSY} value is therefore 51,700 t (Figure 1; Table 2; DFO 2012b).

As per DFO (2010), the upper stock reference point (B_{USR}) was estimated as 80% of B_{MSY} and equals 41,400 t of commercial-sized adult male crab of all carapace conditions as estimated from the trawl survey (DFO 2012b). These crab are hard shell commercial-sized adult male crab as of 1 January of the year following the trawl survey.

The limit reference point 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 and was measured in 2000 (DFO 2012b; Table 1).

The estimate of F_{MSY} was taken as the average exploitation rate over the productive period used to estimate B_{MSY}. The F_{lim} value was calculated at 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 (Table 2; DFO 2012b).

Other reference values of interest identified by the working group in the development of candidate decision rules are presented in Table 2.

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 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 harvest decision rule must provide for an adjustment of the removal rate depending on the stock's location within the cautious zone and the following conditions would apply:

- the removal rate must be progressively adjusted to avoid the stock falling to the critical zone,
- the risk tolerance for a preventable decline of the stock will vary from very low to medium depending upon the location of stock within the cautious zone (DFO 2009), and
- management actions must arrest declines and promote growth of the stock to the healthy 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).

Based on these general principles, the following criteria were proposed for assessing whether decision rules are PA compliant.

- There must be a very low probability (<= 5%) of the stock falling into or remaining in the critical zone due to fishing exploitation.
- When the stock is in the cautious zone, the exploitation rate must be adjusted such that the stock does not decline further (i.e. stays in the cautious zone) or returns to the healthy zone.
- Where possible, keep the stock in the healthy zone. This is interpreted as the exploitation rate adjusted to the stock status. The exploitation rate at a given state of the stock could be different for conditions where recruitment over year is declining or increasing.

Removal rate considerations in the healthy zone

Some of the candidate decision rules presented in this document include removal rate options in the healthy zone that exceed the maximum removal rate reference (0.346) presently defined for the snow crab stock of the southern Gulf of St. Lawrence. This could be considered a violation of the principles of the PA and justification for considering these options for the snow crab stock is required.

The F_{MSY} (F_{lim}) value defined for the southern Gulf of St. Lawrence stock is a proxy value 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 were not defined on the basis of stock recruitment considerations but rather the result of annual consultations with industry. Using an average value over the same period used to define B_{MSY} was convenient and defensible. As stated in DFO (2010, 2012b), 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 for a few year classes to date.

When snow crab reach maturity, they undergo a terminal molt. At terminal molt, there is no further growth in size, or weight over time. 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, 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.

Large adult male snow crab are of biological and fishery value. Although it is recognized that all adult male crab have a value for reproduction, the particular intrinsic value of the large (>= 95 mm carapace width) adult male crab to future recruitment and especially of the large male phenotype cannot be discounted (DFO 2010). 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. 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, variable removal rates in the healthy zone which exceeded the presently defined removal rate from DFO (2010, 2012b) could be consistent with the PA and were explored in candidate decision rules.

CRITERIA TO COMPARE DECISION RULES AND ASSESS COMPLIANCE WITH THE PA

The assessment of the performance of decision rules relative to the conditions identified in the PA policy considered aspects related to resource conservation and to resource utilization.

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 (Table 3):

- Number of years when the residual biomass (mating biomass after the fishery) would be less than B_{lim} with $P > 0.05$.

- 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 such as:
    - Number of years when the point estimate of the commercial biomass for the fishery year begins in the healthy zone, in the cautious zone, or in the critical zone and remains in that zone.
    - Number of years the commercial biomass for the fishery year begins in healthy zone or the cautious zone and declines for the next fishery year to a lower zone (cautious or critical, respectively).
    - Number of years when the point estimate of the commercial biomass for the fishery year begins in the critical or the cautious zone and increases for the following year into a higher zone (cautious or healthy, respectively).

For socio-economic considerations, the following outcomes were tabulated for each decision rule (Table 3):

- Sum of TACs and average annual TACs when the fishery was open, specific to the decision rule.
- Number of years when the fishery is closed or less than a defined threshold based on socio-economic considerations.
- Average percentage of commercial biomass for the fishery which is comprised of recruitment biomass (clean hard shell, carapace condition 3).

DESCRIPTION OF THE 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 of TAC decisions over a large number of years. In summary, the simulation and analysis of the decision rules was 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 was selected according to the decision rule under consideration. The residual biomass was 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 was captured. The estimated or simulated recruitment was then added to the residual biomass and this represented the commercial biomass available for the next year's fishery. The necessary inputs for these analyses included: 1) commercial biomass estimate for the first year, 2) an estimate of the loss rate prior to the fishery, and 3) a sequence of recruitment biomass values in subsequent years.

The commercial biomass (residual biomass plus recruitment biomass) estimates for the southern Gulf have ranged from a low of 30,920 t to a high of 103,429 t during 1997 to 2012 (Table 1). The observation error associated with the commercial biomass estimate, expressed as the coefficient of variation, was 8.8% in 1997 and has ranged from 5.2% to 11.6% over the 1997 to 2012 time series (Table 1).

Recruitment biomass (commercial size adult male crab of carapace conditions 1 and 2) as estimated from the survey has ranged from a low of less than 21,000 t in 2009 and 2010 to a high of just under 84,000 t in 2004 (Table 1). Snow crab recruitment has been characterized by oscillations and for the southern Gulf stock, the low values of recruitment were separated by a 10 to 12 year period (Table 1). As it takes between 10 to 12 years for snow crab to recruit to the commercial sized adult male stage in the southern Gulf, the measured recruitments in the time series have been the result of mating biomasses (males and females) whose values have not been estimated with an accepted model (DFO 2012a). The survey estimates of recruitment biomass have observation errors (expressed as CV) that range from 8.2% to 25.7% over the time series (Table 1).

There are differences (called loss) of commercial biomass between the survey in year 1 and the survey in year 2 which are not attributable to reported fishery landings. This difference (termed non-fishing directed mortality) could be attributed to a number of factors including misattribution of recruitment and residual crab categories in the survey, variability in survey estimates, natural mortality, non-directed fishery induced mortalities, as well as crab movement in and out of the sampling area (Hébert et al. 2014). The proportional difference over year is calculated as:

$$ResB_{y+1} = CB_y * \left(1 - Loss_{y+1}\right) - Landings_{y+1}$$

with

$$CB_y = estimated\ commercial\ biomass\ in\ the\ survey\ in\ year\ y$$

$$ResB_{y+1} = estimated\ residual\ biomass\ in\ the\ survey\ in\ year\ y+1$$

The estimates of the proportions of the biomass available to the fishery (1 – Loss) have ranged annually from 0.58 to 0.82.

SIMULATION PROCESS

Monte Carlo simulation was used to incorporate observation errors associated with the assessment. A total of 5,000 simulations were used to assess the performance of the decision rules. As we were interested in the relative performance of the rules, we used the same 5,000 Monte Carlo draws of the relevant variables. The variables for which the values were fixed across all the rules were:

- the 5,000 values of the commercial biomass estimate for the first year of the simulation,
- the 5,000 values of the proportion of the commercial biomass which is lost prior to the fishery, for all years, and
- the 5,000 annual recruitment biomass values, which vary by year.

A lognormal distribution was assumed for the commercial biomass (*CB*) and the recruitment biomass (*RecB*) assessment estimates (Table 1).

$$CB_y \sim LN\left(\tilde{\mu}_{CB,y},\ \tilde{\sigma}^2_{CB,y}\right)$$

$$RecB_y \sim LN\left(\tilde{\mu}_{RecB,y},\ \tilde{\sigma}^2_{RecB,y}\right)$$

with

$$\tilde{\mu}_{.,y} = \ln\mu_{.,y} - \frac{\tilde{\sigma}^2_{.,y}}{2}$$

$$\tilde{\sigma}^2_{.,y} = \ln\left(\frac{\sigma^2_{.,y}}{\mu^2_{.,y}} + 1\right)$$

and $\mu_{.,y}$ and $\sigma_{.,y} = \mu_{.,y} * CV_{.,y}$ from Table 1 for the years 1997 to 2012.

All the simulations began with the commercial biomass estimate from the trawl survey in 1997 (65,310 t with a CV of 8.8%; Table 1). A vector of 5,000 commercial biomass values with observation error was generated assuming a lognormal distribution.

A vector of 5,000 values for the loss rate parameter (Loss) was generated from the life stage recruitment predictive model developed by Surette and Wade (2006) and updated by Wade et al. (2014) which takes into account the observation errors of the commercial biomass and the residual estimates from the assessment. The distribution of the 5,000 values of *Loss*, based on the mean value of the most recent five years, is normally distributed with a mean of 0.28 and a 90% confidence interval range of 0.18 to 0.38.

The recruitment biomasses have been estimated for the 1998 to 2012 assessment years (Table 1). For these years, 5,000 values were generated based on the mean and CV from the survey estimates (Table 1; Fig. 3).

The estimated residual biomass post-fishery for 1998 to 2012 and the estimated commercial biomass from the survey for the years 1998 to 2012 were calculated based on the proportion of the biomass available prior to the fishery and the Total Allowable Catch (TAC) as defined by the decision rule under consideration. Specifically, the dynamic process was modelled as follows:

For year = 1998 to 2012

$$TAC_y = \overline{CB}_{y-1} * ER_y$$

$$\overline{ResB}_y = \overline{CB}_{y-1} * (1 - \overline{Loss}) - TAC_y$$

$$\overline{CB}_y = \overline{ResB}_y + \overline{RecB}_y$$

with

$$TAC_y = total\ allowable\ catch\ in\ year\ y$$

$$\overline{CB}_y = mean\ commercial\ biomass\ in\ year\ y$$

$$ER_y = exploitation\ rate\ from\ the\ decision\ rule\ and\ \overline{CB}_{y-1}$$

$$\overline{ResB}_y = mean\ residual\ biomass\ in\ year\ y$$

$$\overline{Loss} = mean\ loss\ rate\ of\ commercial\ biomass\ before\ the\ fishery$$

$$\overline{RecB}_y = mean\ recruitment\ biomass\ in\ year\ y$$

The 5,000 Monte Carlo simulations are used to model the observation errors associated with the assessment and to assess the PA compliance of the decision rules to the PA.

For s = 1 to 5,000

$$CB_{y-1,s} \sim LN\left(\widetilde{CB}_{y-1}, \tilde{\sigma}^2_{CB,y-1}\right)$$

$$ResB_{y,s} = CB_{y-1,s} * (1 - Loss_s) - TAC_y$$

$$RecB_{y,s} \sim LN\left(\widetilde{RecB}_y, \tilde{\sigma}^2_{RecB,y}\right)$$

$$CB_{y,s} = ResB_{y,s} + RecB_{y,s}$$

$$P.Crit_{y,s} = 1\ if\ \left(ResB_{y,s} \le B_{lim}\right)$$

$$Crit_{y,s} = 1\ if\ \left(CB_{y,s} \le B_{lim}\right)$$

$$Caut_{y,s} = 1\ if\ \left(B_{lim} < CB_{y,s} < B_{USR}\right)$$

$$Healthy_{y,s} = 1 \; if \; (CB_{y,s} \geq B_{USR})$$

For the year 1997, the Monte Carlo values of the commercial biomass were drawn using the mean and standard deviation (σ) values from the assessment (Table 1).

$$CB_{1997,s} \sim LN(11.083, \; 0.0876^2)$$

For 1998 to 2012, a standard deviation (on the log scale) of 0.10 was used for the commercial biomass estimates, i.e.

$$CB_{y,s} \sim LN(\widetilde{CB}_y, \; 0.10^2)$$

The average standard deviation (log scale) from the assessments of 1998 to 2012 is 0.076 with a minimum to maximum range of 0.051 to 0.115.

For the 1998 to 2012 recruitment time series, the mean and standard deviation values from the assessment were used (Table 1).

Simulated recruitments

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 (Table 1; Fig. 1). We were interested in assessing the performance of the decision rules particularly at low but also at high recruitment phases of the stock. For the 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. 3). Specifically, an artificial recruitment time series with observation uncertainties (Fig. 3) was generated as follows:

- The mean expected recruitment for 2013 is provided by the life stage forecast model of Wade et al. (2014).
- As indicated previously, the recruitment dynamic of snow crab in the southern Gulf has been observed to follow oscillations with a period of about 10 to 12 years (Table 1; Fig. 3). Subsequent recruitments for the years 2014 to 2047 (34 years) were modelled assuming a ten-year period (peak to peak; trough to trough). This was done by setting the mean recruitment in year y as the average recruitment of years y-11 to y-9.
- Between 2014 and 2022, the mean recruitment was deliberately reduced to levels which were less than the average values of the previous period (i.e. y-11 to y-9).
- Between 2023 and 2047, the mean recruitment was deliberately increased to levels greater than the mean values of the previous period.
- To model the uncertainty in the measured recruitment in the assessment for 2013 to 2047 recruitments, the mean observation error (log scale) from the estimated recruitment time series (1998 to 2012) was used, i.e.

$$RecB_{y,s} \sim LN(\widetilde{RecB}_y, \; 0.132^2)$$

- As was the case with the commercial biomass value for the initial year and the values of the loss rate, once a series of 5,000 Monte Carlo draws for annual recruitments were generated, they were fixed for all candidate decision rule evaluations.

The analyses were performed using analytical and summary functions programmed in Excel spreadsheets. Excel was chosen over other platforms because it is broadly available, used extensively, and once the analytical features were programmed, the spreadsheets could be used by the working group members to explore candidate decision rules.

What the simulated recruitment series is and is not

The premise described in DFO (2010) is that there must be an intrinsic value of the large adult male phenotype to the recruitment of that phenotype in subsequent generations. There was no stock and recruitment dynamic modelled in the simulated time series of recruitment. The stock and recruitment link between the estimated abundance of commercial size adult male mating biomass and recruitment of commercial size adult male crab has not been shown in any stocks of snow crab. 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 judgement on rules which are PA compliant based on our criteria indicate how the stock will perform in the future. In the absence of a demonstrated stock and recruitment dynamic, we wanted 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.

In the absence of fisheries, the commercial biomass of snow crab fluctuates according to the recruitment variations in the simulations (Fig. 4). 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, moves from cautious to healthy in two years) (Fig. 4).

DESCRIPTION OF DECISION RULES EXAMINED BY THE WORKING GROUP

The three PA zones are defined by the reference points specific to the southern Gulf of St. Lawrence snow crab stock: the biomass limit reference point (B_{lim}) of 10,000 t, and the biomass upper stock reference point (B_{USR}) of 41,400 t (Fig. 1). A maximum removal rate reference (F_{lim}) of 0.346 has also been defined (Table 2).

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 an absolute minimum. 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 were linear in form, i.e. the removal rates varied linearly between inflection points. All candidate decision rules were defined by inflection points with units along the stock status axis and the removal rate axis of the PA reference diagram (Table 2). Candidate decision rules shared a number of general features and by varying a few parameters, a wide range of rules could be defined and assessed.

The working group examined a number of candidate rule structures which differed in the number and values of inflection points, as proposed by participants. The proposals included inflection points within the cautious zone and inflection points within the healthy zone.

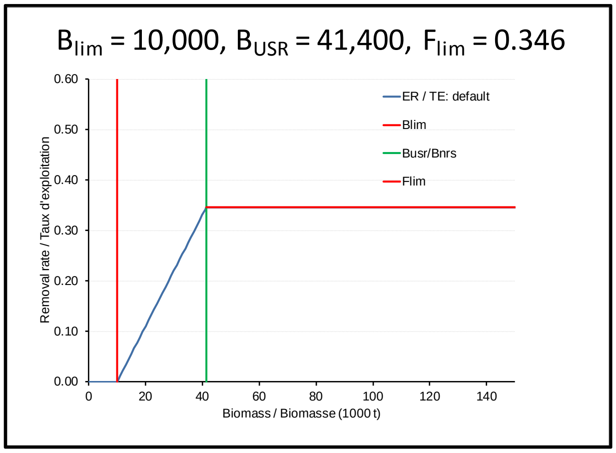
DEFAULT RULE

The default rule used the reference points defined for the snow crab stock. 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 at 0.

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

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

$$If\ CB > B_{USR}\ then\ ER = 0.346$$

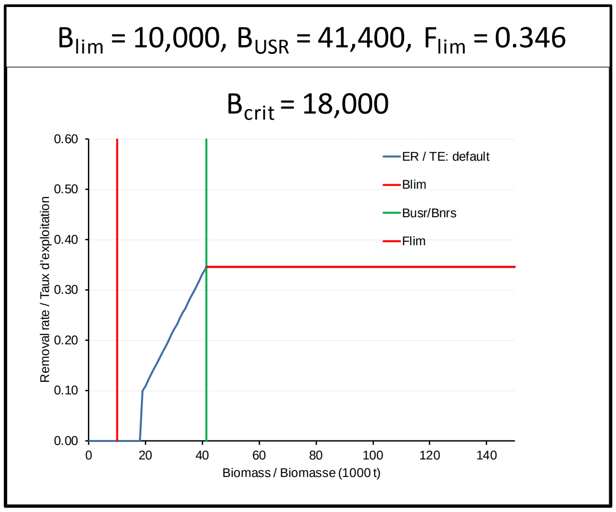


Alternatives to the default rule in the cautious zone

The “threshold” rule has a removal rate slope which is similar to the default rule when the CB is < B_{USR} and >= an intermediate value (B_{crit}). When the CB is < B_{crit}, the removal rate falls abruptly to ER_{crit}.

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

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



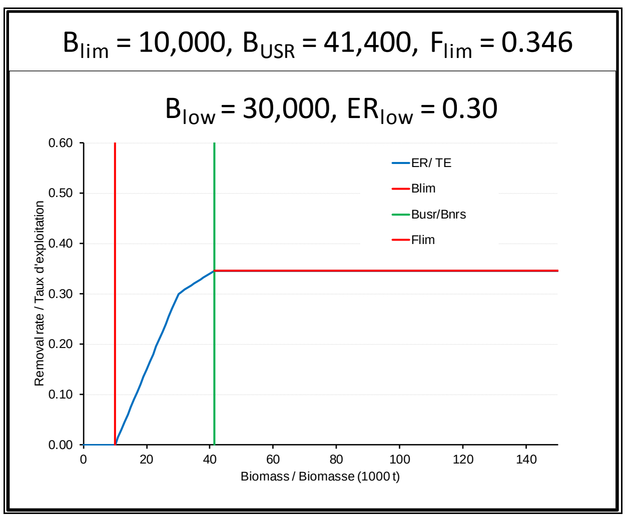
The “intermediate” rule defines two removal rate slopes in the cautious zone articulated at a fixed commercial biomass and removal rate pivot point. The pivot point proposed by the working group corresponded to the removal rate value agreed by industry for the 2011 fishery (0.30) based on the 2010 survey CB value (36,000 t) (Tables 1 and 2).

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

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

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

For illustrative purposes in the example figure below, B_{low} = 30,000 t and ER_{low} = 0.30.



Alternatives to the default rule in the healthy zone

A “step” rule 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 0.346 (F_{lim}). When CB >= B_{MSY} but < B_{max} (defined as 61,700 = B_{MSY} + 10,000 t) then the removal rate was set at 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 0.3979. The inflection points correspond to values within the 1998 to 2009 fisheries period used to define the reference points for this stock (Tables 1 and 2).

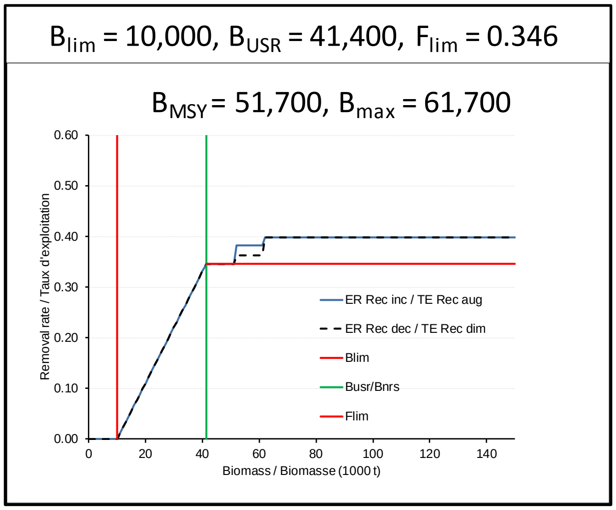
$$If\ B_{USR} < CB \leq B_{MSY}\ then\ ER = 0.346$$

$$If\ B_{MSY} < CB \leq B_{max},\ and$$

$$Rec_{y+1} \leq Rec_y\ then\ ER = 0.362$$

$$Rec_{y+1} > Rec_y\ then\ ER = 0.382$$

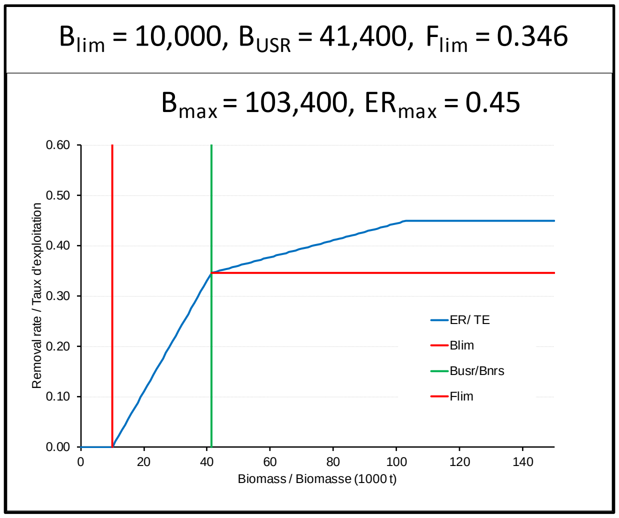
$$If\ B_{max} < CB\ then\ ER = 0.3979$$



A “proportional” rule has one inflection point set at the maximum estimated CB value (B_{max} = 103,400) and a maximum removal rate value corresponding to the maximum exploitation rate (ER_{max} = 0.45) realized for the stock (Tables 1 and 2). 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} (Table 2).

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

$$If\ B_{max} < CB\ then\ ER = ER_{max}$$



Variants of the candidate rule structures

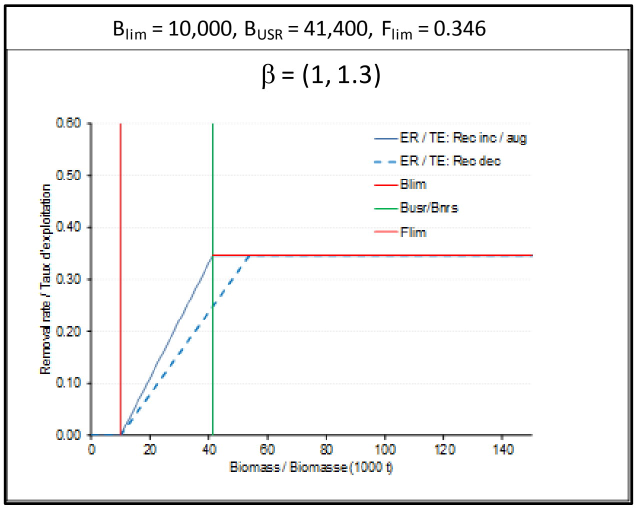
Removal rate dependent on stock trajectory

As an optional element of the PA policy, management actions could also be determined on the basis of the stock trajectory (DFO 2009). 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). Variants of decision rules that differ in the removal rate relative to the stock trajectory were explored. The approach considered was to reduce the removal rate from the base value when the recruitment was declining. For snow crab from the southern Gulf of St. Lawrence, there is a very good forecast model of incoming recruitment two years prior to the fishery (Surette and Wade 2006; Wade et al. 2014). Removal rates that account for a declining recruitment were calculated by increasing the biomass inflection point values. This effectively reduced the slope of the removal rate line. For example, a removal rate rule in the cautious zone that varied with stock trajectory would be written as follows:

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

$$\beta = 1 \; if \; stock \; trajectory \; increasing$$

$$\beta > 1 \; if \; stock \; trajectory \; decreasing$$



The “step” rule for the healthy zone described in the previous section is a stock trajectory dependent rule.

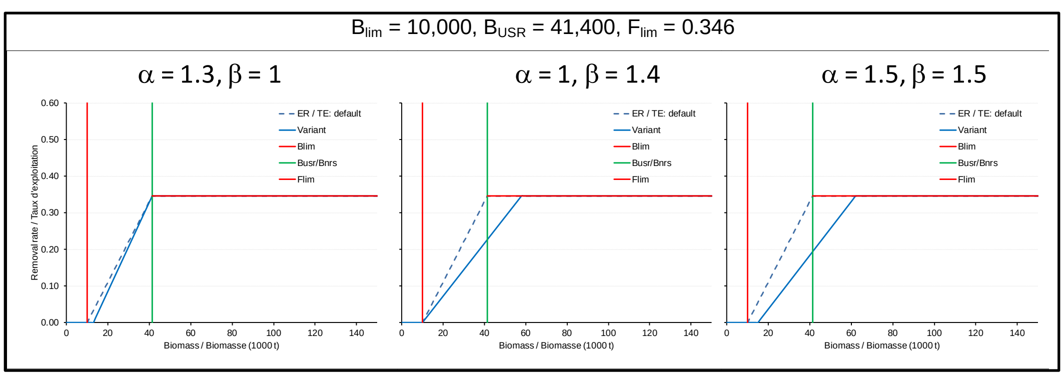
Variants of rules for PA compliance

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. Using a similar format to the rules that varied the removal rate with the stock trajectory, the inflection point values were changed, effectively changing the biomass values at which the corresponding values of the removal rates (ER_{crit}, F_{lim}, ER_{max}, etc.) are applied and thus changing the slope of the removal rate lines.

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

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

Examples of inflection point variants of the cautious zone default linear rule are shown below; for illustrative purposes, the default removal rate in the cautious zone is shown as a dashed line.



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. 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 based on the resource conservation criteria. As such, we examined in detail the default linear rule to illustrate how the choice of the variants could be made based on one criterion of resource conservation and one criterion from the socio-economic group. We then examined specific decision rules proposed by the working group and variants which would potentially make the rules PA compliant.

The results for each rule are presented for the criteria described in Table 3. Supporting figures for each rule examined include PA framework diagrams which show the location of the removal rate relative to the biomass value of the stock (by coloured symbol with red indicating that the probability is greater than 5% of the residual biomass after the fishery being less than or equal to B_{lim}) and on annual basis the exploitation rate for the rule and the corresponding probability of the residual biomass being <= B_{lim}.

ANALYSIS OF DECISION RULES

Default linear rule showing combinations and options for stock trajectory rules

Variants of the linear rule, without a stock trajectory feature, were examined to determine which combination(s) of inflection point variations of the rule in the cautious zone would satisfy a resource conservation criterion and a socio-economic criterion (Table 4). As a reminder, the linear rule has the removal rate increasing linearly from ER_{crit} (by default = 0) at $\alpha * B_{lim}$ ($\alpha >= 1$) to a maximum removal rate of 0.346 at $\beta * B_{USR}$ ($\beta >= 1$). Over the 50 year simulation, the probability was greater than 5% that the residual biomass would be <= B_{lim} in 12 years when $\alpha = \beta = 1$ but the fishery would not have closed in any of those years (Table 4). The probability of falling below B_{lim} was less than 5% for a default linear rule with $\alpha = 2$ and $\beta = 1.2$, or $\alpha = 1$ and $\beta = 2.4$, and a number of other combinations of α and β (Table 4). Fishery closures occurred when $\alpha = 1.6$ and $\beta = 1$ to $\alpha = 2$ and $\beta = 2.1$ and other combinations. Increases in α or β result in reduced exploitation rates on the stock and therefore less harvest in the fishery. An optimal choice that respects the resource conservation objective (not falling below B_{lim}) and has the least consequence on catches (number of years fishery is closed) occurs at $\alpha = 1.7$ and $\beta = 1.55$ (Table 4).

Without stock dependent trajectory variant

The default linear rule (α and $\beta = 1$) did not result in any advised fishery closures but the residual biomass fell below B_{lim} in 12 out of 50 years in the simulation and in 1 of the 15 years for which recruitment has been assessed (1998 to 2012) (Table 5; Fig. 5). With inflection points for the removal rate line set at $\alpha = 1.7$ (biomass = 17,000 t) and $\beta = 1.1$ (biomass = 45,540 t), the fishery would have closed in 2 of 50 years but the residual biomass in those years would still have a greater than 5% chance of being below B_{lim} (Table 5; Fig. 5). The residual biomass had a high probability of being <= B_{lim} because the exploitation rates in previous years were too high relative to the reduced incoming recruitment values. Only by increasing β to 1.55 (and keeping α at 1.7) was it possible to avoid with very high probability (P>0.95) the residual biomass falling below B_{lim} in all years (Table 5; Fig. 5). Under this rule ($\alpha = 1.7$, $\beta = 1.55$), the commercial biomass remained most often in the healthy zone (32 of 50 years) and least often in the cautious zone (12 of 50 years) (Table 5) and therefore this rule met the resource conservation criteria for PA compliance. The fishery was never closed but the annual TAC in a given year could be quite small (< 100 t) and the sum of TACs over all years, during 1998 to 2012, and the average TACs were all less than the values for the other variants of the default rule.

Stock trajectory dependent variant

Three stock trajectory dependent variants which would be PA compliant are shown in Table 5 and Figure 6. The two rules which include a stock trajectory dependent value for β resulted in the stock being most frequently in the healthy zone (32 of 50 years). The fisheries could have remained open in all years, and the sum of the TACs and the average annual TAC over years were similar between these two rules and for the most part similar to those corresponding to the PA compliant rule that excluded a stock trajectory consideration (Table 5). There was no obvious benefit with the simulated time series of recruitment of including a stock trajectory dependent rule.

Step rule in the healthy zone

The industry participants proposed a step rule in the healthy zone and two variants for a rule in the cautious zone (threshold rule (Fig. 7), and the intermediate rule (Fig. 8)). The step rule in the healthy zone is a stock trajectory dependent rule.

Threshold rule

With a B_{crit} (commercial biomass value where the removal rate falls to ER_{crit}) value of 21,000 t and β = 1.1, there are two years out of 50 when the residual biomass was <= B_{lim} (with P > 0.05) (Table 6; Fig. 7). The fishery would have closed in seven years including the two years when the residual biomass was less than B_{lim}. The commercial biomass would have been in the healthy zone in 26 of 50 years and in 12 of 15 years during 1998 to 2012 assessed period (Table 6).

To be fully PA compliant, the B_{crit} value needed to increase to 28,000 t with β = 1.1 (Table 6; Fig. 7). Under this rule, the fishery would have been closed in 11 of 50 years and 0 of 15 years during 1998 to 2012 assessed period but the sum of the TACs was essentially similar to the other variant of B_{crit} (Table 6).

Intermediate rule

The inflection point of the intermediate rule proposed by the industry (B_{low} = 36,000, ER_{low} = 0.30) and the α = 1.7 and β = 1.1 variants derived for the linear rule did not produce a PA compliant rule (Table 6; Fig. 8). The residual biomass was <= B_{lim} (P > 0.05) in 7 of 50 years and in 1 of 15 years during 1998 to 2012 assessed period. With B_{low} = 36,000, ER_{low} reduced to 0.29, α increased to 1.8, and β = 1.1, the residual biomass was <= B_{lim} (P > 0.05) in 2 of 50 years even with the fishery closed in those years (Table 6; Fig. 8).

A PA compliant variant rule included a stock trajectory dependent variant in the cautious zone and reducing ER_{low} to 0.26 (Table 6; Fig. 8). Under this variant, the fishery would be closed in 5 of 50 years and the sum of TACs was slightly lower than the values for the other variants of this rule.

Proportional rule in the healthy zone

A linear rule in the cautious zone was used to examine the proportional rule in the healthy zone. A stock trajectory dependent variant in the cautious zone was also examined.

Without stock trajectory dependence

With α = 1.7 and β = 1.1, the proportional rule option in the healthy zone resulted in similar performance for the resource conservation criteria as the linear default rule with similar settings (Table 7; Fig. 9). The residual biomass was <= B_{lim} (P > 0.05) in 2 of 50 years and the stock was in the healthy zone in 27 of 50 years, in 12 of 15 years during the 1998 to 2012 assessed period

(Table 7; Fig. 9). The fishery was closed in two of those years. A fully PA compliant rule was realized with $\alpha = 1.9$ and $\beta = 1.3$ (Table 7; Fig. 9). The fishery was closed in two of those years and the sum of the TACs was predictably lower than the previous variant of this rule.

Stock trajectory dependent variant

A PA compliant stock trajectory dependent variant of the proportional rule that has a value for β (1.1, 1.3) that varies with the trajectory of the recruitment has similar performance for the resource conservation criteria as the variant that did not include this condition. The sum of the TACs was slightly higher with this variant (Table 7; Fig. 9).

COMPARISON OF DECISION RULES

Two options for PA compliance were considered. In the first case, termed potentially compliant, the residual biomass fell below B_{lim} due to low incoming recruitment rather than due to fishing in the current assessment year, since the fishery was closed. In the second case, termed fully compliant rules, the residual biomass does not fall below B_{lim} regardless of the strength of the incoming recruitment and fisheries exploitation in all years was adjusted to ensure this condition. For discussion purposes and pending advice from the peer review meeting, rules for these two options were examined.

Potentially compliant rules

Potentially compliant rules are those for which the probability of the residual biomass in that year being $<= B_{lim}$ ($P > 0.05$) even though the fishery that year was closed, i.e. the residual biomass fell to $<= B_{lim}$ for reasons of poor recruitment rather than exploitation by the fishery that year. The four rules examined included a linear rule (without stock dependent trajectory), the step rule in the healthy zone with two variants in the cautious zone (threshold, intermediate), and a proportional rule (without stock dependent trajectory) (Table 8). The only differences in performance of these rules for the resource conservation criteria was in the number of years when the stock was in the healthy zone and in the cautious zone. The linear rule had the stock most often in the healthy zone (28 of 50 years, 12 of 15 during the 1998 to 2012 assessed period) followed by the proportional rule (27 of 50 years, 12 of 15 for the recent assessed period), and the step rule variants (26 of 50 years, 12 of 15 years for the recent assessed period) (Table 8). Relative to the socio-economic criteria, the linear rule and the proportional rule had the smallest number of years with the fishery closed whereas the step rule with the threshold variant had the most number of years with fishery closures. Although the threshold step rule had the most number of years when the fishery would be closed, the sum of the TACs over all years was higher than for the linear rule and only slightly lower than for the step rule with the intermediate variant and the proportional rule. The average TAC with the fishery open was highest for the threshold variant, because for the other rules, the annual TAC could be very small (less than 100 t) whereas the minimum TAC for the threshold rule was just under 3,000 t (Table 8).

Fully compliant rules

A comparison of performance of six fully compliant rules is provided in Table 8. Two of the rules did not consider the stock trajectory whereas four of the rules had a stock-trajectory dependent variant. Over all these rules, the default linear rules had the best performance on the resource conservation criteria with the stock being in the healthy zone in 30 or 32 of 50 years (15 of 15 years in the 1998 to 2012 period) and in the cautious zone in 12 or 14 years (0 of 15 years in the recent period). This better performance on the resource conservation criteria resulted in reduced performance on the socio-economic criteria for total TACs and average TACs

(Table 9). Of the remaining rules, the proportional rule with a variant for stock trajectory had the best performance with fewer years with fishery closures, and the highest overall sum of TACs (over 50 years and the recent 15 years). If however, there was a minimum TAC value for economic viability of the fishery, the step rule with the threshold rule was roughly equivalent.

Details of a range of fully 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}) for the linear rule in the healthy zone (Appendix 2 tables and figures), the step rule in the healthy zone (Appendix 3 tables and figures) and the proportional rule in the healthy zone (Appendix 4 tables and figures) are summarized in the appendices. The conclusions of the peer review of PA compliance of decision rules are provided in DFO (2014).

DEPENDENCE OF RESULTS ON MODEL ASSUMPTIONS

The performances of the rules are subject to the simulated recruitment series, the observation uncertainties used, and the other model assumptions. The simulated recruitment series mimiced the periodicity and the range of the recruitment oscillations measured for the snow crab stock of the southern Gulf of St. Lawrence (Fig. 3). The results of the analyses should be robust to the recruitment series simulated, however, absolute values were not and only the relative performance of the rules can be appropriately compared.

The performances of the rules were specific to the uncertainties assumed in this model. The uncertainties incorporated in the model included the estimates of non-fishing losses between survey years, and the observation uncertainty associated with the assessment. We used a standard deviation (sigma, on the log scale) of 0.10 for the assessment error of the commercial biomass in the simulations. For the assessed years 1997 to 2012, the range in sigma was 0.051 to 0.115. If the assumed uncertainty was higher, the performance results would be different, and alternate variations of the rules would need to be considered. For example, if the uncertainty in the assessed commercial biomass was 0.15 rather than 0.10 as modelled here, the parameters of the proportional rule without the stock trajectory dependent variant that would be fully PA compliant would be $\alpha = 2$, $\beta = 1.7$, and additionally $\gamma = 1.4$ (the inflection point for biomass in the healthy zone where $ER_{max} = 0.45$ would be 145,600 t rather than the B_{max} value of 103,400 t) rather than the values shown in Table 8.

We assumed there was no error in the reporting of landings, and that in any year, the TAC was captured. 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

The performance of rules was assessed using simulated recruitments which included values 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. Despite having collapsed the recruitment of snow crab to very low values, means of less than 10,000 t during a five year period, the reproductive biomass (as measured in the survey as residual biomass) in the absence of fishing remained well above B_{lim} (5th percentile never fell below 10,000 t).

When fishing was simulated, there were years when the probability of the biomass being $\leq B_{lim}$ was greater than 5% even though the fishery that year was closed. Initially, this was considered to be a consequence of the modelled recruitment dynamic and the low stock abundance was considered to be incidental to fishing and therefore not a concern in the assessment of PA compliance. If this interpretation was correct, then PA compliant decision rules would require the mean of the assessed biomass estimate where exploitation is zero (or the lowest level possible) to be about 1.7 to 1.8 times B_{lim}, i.e. 17,000 to 18,000 t and the mean of the assessed biomass value in the healthy zone at which the exploitation rate could be set at 0.346 or higher to be raised by about 1.1 times B_{USR} (45,540 t).

Removal rates above 0.346 in the healthy zone may be PA compliant based on the criteria assessed in this analysis. The step decision rule proposed by the group with the threshold rule in the cautious zone would be PA compliant at a B_{crit} value of 21,000 t and an inflection point in the healthy zone corresponding to 110% of B_{USR} as discussed above. The proportional decision rule analyses indicated that a maximum exploitation rate of 0.45 could be allowed for stock biomass levels above 103,400 t but higher values (>= 0.49) would not be PA compliant based on the assessment criteria used; in fact, setting the exploitation rate at 0.49 at biomass levels above 103,400 t produced instances when a fishery TAC selected resulted in a greater than 5% chance of the residual biomass falling below B_{lim}.

In all the years in the simulation, it was possible to develop decision rules for which the residual biomass never fell below B_{lim}. These rules most often resulted in periods when the fishery would be closed or with a very low TAC. At the peer review meeting, it was concluded that rules would be PA compliant if there was less than 5% chance of the stock falling below B_{lim} due to fishing activities in any year, not just the year in question.

Several candidate rules could be PA compliant. The threshold rule in the cautious zone is a simple rule and it resulted in the most frequent number of fishery closures, but had higher minimum annual TAC values and maintained overall TAC values as high as other rules for which fishery closures were less frequent. In the rules with less frequent closures, the annual TAC prescribed by the rules was often of a very small value, less than 1,000 t, and this may not be an economically viable TAC for the industry. The social and economic consequences of low annual TACs or of fishery closures were not considered in this assessment.

The decision rule should be as simple as possible. A simple rule that provides the same results should be chosen preferentially over a more complex rule. There was no indication in this analysis with the simulated recruitment series of better performance in terms of resource conservation criteria of a stock trajectory dependent rule in the cautious zone. The proportional rule with a stock trajectory dependent rule in the cautious zone did result in slightly higher TAC values than the rule without this feature.

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.

Once the conservation criteria are met, the choice of decision rules by managers could be based on the socio-economic criteria outlined, such as those that provide the maximum TAC and the minimum of years when TACs are less than a critical value for the industry but that value was not stipulated by the working group and was not assessed.

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TABLES

Table 1. Estimated commercial biomass (t; total, as recruitment, as residual) from the survey (1997 to 2012) and fishery landings (t) and associated exploitation rates (1998 to 2012) for the snow crab biological unit of the southern Gulf of St. Lawrence.

	Commercial biomass								
	Total		Recruitment		Residual				
Year of survey	estimate (t)	CV (%)	estimate (t)	CV (%)	estimate(t)	CV (%)	Year of the fishery	Landings (t)	Exploitation rate (%)
1997	65,310	8.8	37,619	17.5	27,690	11.5	1998	13,575	20.8
1998	57,595	11.6	29,818	25.7	27,775	13.8	1999	15,110	26.2
1999	57,051	8.7	25,874	23.7	31,177	10.9	2000	18,712	32.8
2000	49,823	10.4	39,845	13.2	9,977	19.9	2001	18,262	36.7
2001	59,150	10.7	42,243	15.0	16,905	14.3	2002	25,691	43.4
2002	79,559	8.8	66,481	10.9	13,075	11.1	2003	21,163	26.6
2003	84,423	8.0	57,503	12.4	26,919	11.8	2004	31,675	37.5
2004	103,429	6.4	83,702	8.3	19,726	10.9	2005	36,118	34.9
2005	82,537	5.8	58,398	9.4	24,140	12.6	2006	29,121	35.3
2006	74,285	5.8	54,371	8.2	19,914	10.4	2007	26,867	36.2
2007	66,660	5.2	39,635	9.0	27,025	7.3	2008	24,458	36.7
2008	52,564	6.0	31,555	11.2	21,010	7.9	2009	23,642	45.0
2009	30,920	6.4	20,520	9.8	10,399	9.7	2010	9,549	30.9
2010	35,795	6.1	20,351	13.9	15,444	9.2	2011	10,708	29.9
2011	63,162	6.1	29,394	16.8	33,768	8.8	2012	21,956	34.8
2012	74,997	6.6	48,969	11.7	26,028	8.5	2013	na	na

Table 2. Precautionary approach reference points defined for the biological unit of the southern Gulf of St. Lawrence snow crab stock and inflection points and reference values proposed by the working group for the development of candidate decision rules.

Reference value acronym	Definition	Reference value (units)
B_{lim}	Biomass limit reference point, delimiting the critical zone and the cautious zone	10,000 t (hard shell commercial adult male crab post-fishery expressed as residual biomass from the survey)
B_{USR}	Biomass upper stock reference point, delimiting the cautious zone and the healthy zone	41,400 t (commercial adult male crab all carapace conditions from the trawl survey)
F_{MSY} (F_{lim})	Removal rate at BMSY, also expressed as the maximum removal rate in the healthy zone	0.346 (landings in year t divided by commercial biomass from the survey in year t-1)
B_{MSY}	Biomass at maximum sustainable yield	51,700 t (calculated as 50% of maximum commercial adult male snow crab during a productive period 1997 to 2008, survey years)
B_{crit}	Biomass value in the cautious zone where exploitation rate falls to ERcrit when the stock biomass is below Bcrit	User defined, greater than B_{lim} and less than B_{USR}
B_{low}	Biomass value in the cautious zone corresponding to an exploitation value of ERlow, acts as an inflection point for the exploitation rate rule in the cautious zone	User defined (Industry proposed value of estimated biomass in 2010 of 36,000 t and for which an exploitation rate of 30% was agreed for the 2011 fishery)
B_{max}	Maximum biomass in the healthy zone for maximum exploitation rate (see ERmax)	103,400 t (maximum estimated commercial adult male crab all carapace conditions from the trawl survey in 2004)
		61,700 t (industry proposed value corresponding to B_{MSY} + 10,000 t)
ER_{crit}	Maximum exploitation rate when the stock is in the critical zone	User defined (by default set to 0, but can be varied to explore candidate decision rules)
ER_{low}	Exploitation rate value in the cautious zone corresponding to a biomass value of B_{low}, acts as an inflection point for the exploitation rate rule in the cautious zone	User defined (Industry proposed value of 0.30 which was the agreed exploitation rate for the 2011 fishery, based on an estimated biomass in 2010 of 36,000 t; see B_{low})
ER_{targ}	Target exploitation rate in the healthy zone when biomass > B_{USR} and < B_{max}	User defined (Industry proposed step rule with exploitation rate depending on trend in recruitment) 0.382, if recruitment is increasing 0.362, if recruitment is decreasing
ER_{max}	Maximum exploitation rate in the healthy zone when biomass > B_{max}	User defined 0.450 (landings of 23,642 t in fishery year 2009 from an estimated commercial biomass of 52,564 t from the survey in 2008)
		0.3979 (Industry proposed value when estimated biomass >= 61,700 t)

Table 3. Criteria for assessing performance of decision rules for compliance with the PA and associated categorization of risk levels as per DFO (2009).

Resource conservation criteria
• Number of years residual biomass <= B_{lim} (P > 0.05)
• Number of years fishery is open and residual biomass <= B_{lim} (P > 0.05)
• Number of years fishery is closed and residual biomass <= B_{lim} (P > 0.05)
• Location of biomass within stock status zones (over one year)
o Healthy to healthy
o Healthy to cautious
o Healthy to critical
o Cautious to cautious
o Cautious to critical
o Critical to critical
o Critical to cautious
o Critical to healthy
o Cautious to healthy
Socio-economic criteria
• Number of years fishery is closed (or < threshold TAC value)
• Sum of TAC values over years
• Average TAC over all years
• Average TAC when fishery open
• Minimum and maximum TAC over years
• Average (%) recruitment (carapace condition 3) of commercial biomass

Risk of decline[1]	Risk category
< 5%	Very low
5% - 25%	Low
25% - 50%	Moderate
~50%	Neutral
50%-75%	Moderately High
75%-95%	High
>95%	Very High

[1] Accounts for quantifiable risk only

Table 4. Criteria for selecting inflection points for the linear rule in the cautious zone based on the number of years the residual biomass <= Blim (P>0.05) (upper table) and the number of years the fishery would be closed (lower table). The diagnostics of the parameters corresponding to the shaded cell with the border (α = 1.7; β = 1.55) are shown in Table 5.

α \ β	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45	1.5	1.55	1.6	1.65	1.7	1.8	1.85	1.9	2	2.1	2.2	2.3	2.4
Number of years when Residual biomass < B_{lim} (P > 0.05)																							
1	12	9	8	8	7	5	5	5	5	5	5	5	4	4	4	4	4	3	2	2	1	1	0
1.1	11	8	8	7	5	5	5	5	5	5	4	4	4	4	4	4	4	2	1	1	1	0	0
1.2	11	8	6	6	5	5	5	5	5	4	4	4	4	4	4	1	1	1	1	1	0	0	0
1.3	11	6	6	5	5	5	5	5	4	4	4	4	4	3	1	1	1	1	1	0	0	0	0
1.4	9	6	5	5	5	5	4	4	4	4	4	2	1	1	1	1	1	1	0	0	0	0	0
1.5	9	5	5	5	4	4	4	3	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0
1.6	8	5	4	3	3	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
1.7	6	2	2	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
1.8	5	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.9	5	3	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	4	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of years when fishery closed																							
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.6	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.7	2	2	2	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
1.8	2	2	2	2	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
1.9	4	4	4	3	2	2	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0
2	5	5	5	4	4	4	4	4	4	3	2	2	1	1	1	1	1	1	1	1	0	0	0

Table 5. Performance of the default linear rule in the cautious zone and the default linear rule in the healthy zone for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series. The first number represents the value for the entire time series (1998 to 2047) while the values in parentheses are for the 1998 to 2012 period. For the stock trajectory dependent rules, the values in parentheses are for increasing recruitment and decreasing recruitment, respectively. Summary figures are in Figures 5 and 6. Symbols for PA compliance are: not PA compliant = ☒, fully PA compliant = ✓, potentially PA compliant = ?.

Rule parameters	Not stock trajectory dependent			Stock trajectory dependent		
	A: α= 1, β = 1	B: α= 1.7, β = 1.1	C: α= 1.7, β = 1.55	D: α= (1.7; 2.0), β = 1.4	E: α= 1.7, β = (1.4, 1.55)	F: α= (1.7, 1.8), β = (1.4, 1.5)
Resource conservation criteria						
Number of years residual biomass <= B_{lim} (P > 0.05)	12 (1) ☒	2 (0) ?	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is open and residual biomass <= B_{lim} (P > 0.05)	12 (1) ☒	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= B_{lim} (P > 0.05)	0 (0)	2 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Movement of biomass within stock status zones (begins, ends over one year)						
Healthy to healthy	26 (13)	28 (13)	32 (15)	30 (15)	32 (15)	32 (15)
Healthy to cautious	4 (1)	4 (1)	3 (0)	3 (0)	3 (0)	3 (0)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	16 (0)	14 (0)	12 (0)	14 (0)	12 (0)	12 (0)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	4 (1)	4 (1)	3 (0)	3 (0)	3 (0)	3 (0)
PA compliant	☒	?	✓	✓	✓	✓
Socio-economic criteria						
Number of years fishery is closed	0 (0)	2 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Sum of TAC over years	894,777 (358,217)	880,522 (356,506)	848,027 (342,238)	857,118 (347,267)	852,859 (346,007)	854,321 (346,435)
Average TAC when fishery open	17,896 (23,881)	18,344 (23,767)	16,961 (22,816)	17,142 (23,151)	17,057 (23,067)	17,086 (23,096)
Minimum and maximum TAC over years	604 to 47,353 (10,634 to 40,871)	228 to 47,391 (9,573 to 40,875)	88 to 47,491 (8,489 to 40,920)	109 to 47,464 (8,830 to 40,904)	95 to 47,466 (8,971 to 40,906)	97 to 47,463 (8,916 to 40,904)
Average (%) recruitment of commercial biomass	54.7% (61.2%)	53.2% (60.9%)	50.6% (58.4%)	51.3% (59.2%)	50.9% (58.9%)	51% (59%)

Table 6. Performance of the industry proposed "step" decision rule with two rule alternatives in the cautious zone (threshold, intermediate) for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series. Summary figures for these are in Figures 7 and 8. Symbols for PA compliance are: not PA compliant = ☒, fully PA compliant = ✓, potentially PA compliant = ?.

Rule parameters	Threshold rule in the cautious zone		Intermediate rule in the cautious zone		
	A: α= 1, β = 1.1, B_{crit} = 21,000 t	B: α= 1, β = 1.1, B_{crit} = 28,000 t	D: α= 1.7, β = 1.1, B_{low} = 36,000, ER_{low} = 0.30	E: α= 1.8, β = 1.1, B_{low} = 36,000, ER_{low} = 0.29	F: α= (2.0, 2.3), β = 1.1 B_{low} = 36,000, ER_{low} = 0.26
Resource conservation criteria					
Number of years residual biomass <= B_{lim} (P > 0.05)	2 (0) ?	0 (0) ✓	7 (1) ☒	2 (0) ?	0 (0) ✓
Number of years fishery is open and residual biomass <= B_{lim} (P > 0.05)	0 (0) ✓	0 (0) ✓	5 (1) ☒	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= B_{lim} (P > 0.05)	2 (0)	0 (0)	2 (0)	2 (0)	0 (0)
Movement of biomass within stock status zones (begins, ends over one year)					
Healthy to healthy	26 (12)	26 (12)	26 (12)	26 (12)	26 (12)
Healthy to cautious	4 (1)	4 (1)	4 (1)	4 (1)	4 (1)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	16 (1)	16 (1)	16 (1)	16 (1)	16 (1)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	4 (1)	4 (1)	4 (1)	4 (1)	4 (1)
PA compliant	?	✓	☒	?	✓
Socio-economic criteria					
Number of years fishery is closed	7 (0)	11 (0)	2 (0)	2 (0)	5 (0)
Sum of TAC over years	926,416 (372,773)	916,682 (372,753)	931,347 (374,128)	928,935 (373,820)	921,595 (372,982)
Average TAC when fishery open	21,545 (24,852)	23,505 (24,850)	19,403 (24,942)	19,353 (24,921)	20,480 (24,865)
Minimum and maximum TAC over years	2,938 to 51,065 (10,022 to 44,358)	6,310 to 51,064 (10,020 to 44,356)	157 to 51,047 (10,872 to 44,356)	12 to 51,053 (10,658 to 44,356)	13 to 51,061 (10,121 to 44,358)
Average (%) recruitment of commercial biomass	55.6% (64.1%)	54.7% (64.1%)	56.1% (64.4%)	55.9% (64.3%)	55.1% (64.1%)

Table 7. Performance of the proportional decision rule in the healthy zone with a linear rule in the cautious zone for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series. Summary figures are in Figure 9. Symbols for PA compliance are: not PA compliant = ☒, fully PA compliant = ✓, potentially PA compliant = ?.

Rule parameters	Not stock trajectory dependent			Stock trajectory dependent
	A: α= 1, β = 1	B: α= 1.7, β = 1.1	C: α= 1.9, β = 1.3	D: α= 1.9, β = (1.1, 1.3)
Resource conservation criteria				
Number of years residual biomass <= B_{lim} (P > 0.05)	15 (4) ☒	2 (0) ?	0 (0) ✓	0 (0) ✓
Number of years fishery is open and residual biomass <= B_{lim} (P > 0.05)	15 (4) ☒	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= B_{lim} (P > 0.05)	0 (0)	2 (0)	0 (0)	0 (0)
Movement of biomass within stock status zones (begins, ends over one year)				
Healthy to healthy	25 (12)	27 (12)	27 (12)	27 (12)
Healthy to cautious	4 (1)	4 (1)	4 (1)	4 (1)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	17 (1)	15 (1)	15 (1)	15 (1)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	4 (1)	4 (1)	4 (1)	4 (1)
PA compliant	☒	?	✓	✓
Socio-economic criteria				
Number of years fishery is closed	0 (0)	2 (0)	2 (0)	2 (0)
Sum of TAC over years	963,971 (383,575)	946,775 (380,019)	923,548 (371,089)	933,229 (377,989)
Average TAC when fishery open	19,279 (25,572)	19,724 (25,335)	19,241 (24,739)	19,442 (25,199)
Minimum and maximum TAC over years	603 to 56,138 (10,346 to 51,506)	227 to 56,159 (9,743 to 51,652)	62 to 56,194 (8,773 to 51,998)	60 to 56,162 (9,578 to 51,652)
Average (%) recruitment of commercial biomass	58.2% (66.2%)	56.4% (65.4%)	54.5% (63.6%)	55.2% (64.8%)

Table 8. Contrasting decision rules which could be considered PA compliant based on the probability of mating biomass in the TAC decision year being below B_{lim} is less than 5% due to fishing. Symbols for PA compliance are: not PA compliant = ☒, fully PA compliant = ✓, potentially PA compliant = ?.

Rule parameters	Linear rule B: α= 1.7, β = 1.1 Figure 5	Step rule A: α= 1, β = 1.1, B_{crit} = 21,000 t Figure 7	Step rule E: α= 1.8, β = 1.1, B_{low} = 36,000, ER_{low} = 0.29 Figure 8	Proportional rule B: α= 1.7, β = 1.1 Figure 9
Resource conservation criteria				
Number of years residual biomass <= B_{lim} (P > 0.05)	2 (0) ?	2 (0) ?	2 (0) ?	2 (0) ?
Number of years fishery is open and residual biomass <= B_{lim} (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= B_{lim} (P > 0.05)	2 (0)	2 (0)	2 (0)	2 (0)
Movement of biomass within stock status zones (begins, ends over one year)				
Healthy to healthy	28 (13)	26 (12)	26 (12)	27 (12)
Healthy to cautious	4 (1)	4 (1)	4 (1)	4 (1)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	14 (0)	16 (1)	16 (1)	15 (1)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	4 (1)	4 (1)	4 (1)	4 (1)
PA compliant	?	?	?	?
Socio-economic criteria				
Number of years fishery is closed	2 (0)	7 (0)	2 (0)	2 (0)
Sum of TAC over years	880,522 (356,506)	926,416 (372,773)	928,935 (373,820)	946,775 (380,019)
Average TAC when fishery open	18,344 (23,767)	21,545 (24,852)	19,353 (24,921)	19,724 (25,335)
Minimum and maximum TAC over years	228 to 47,391 (9,573 to 40,875)	2,938 to 51,065 (10,022 to 44,358)	12 to 51,053 (10,658 to 44,356)	227 to 56,159 (9,743 to 51,652)
Average (%) recruitment of commercial biomass	53.2% (60.9%)	55.6% (64.1%)	55.9% (64.3%)	56.4% (65.4%)

Table 9. Contrasting decision rules which would be PA compliant based on the probability of residual biomass being below B_{lim} is less than 5% in any year due to fishing. Symbols for PA compliance are: not PA compliant = ☒, fully PA compliant = ✓, potentially PA compliant = ?.

	Not stock trajectory dependent		Stock trajectory dependent			
	Linear rule	Proportional rule	Linear rule	Step rule	Step rule	Proportional rule
Rule parameters	C: α= 1.7, β = 1.55 Figure 5	C: α= 1.9, β = 1.3 Figure 9	D: α= (1.7; 2.0), β = 1.4 Figure 6	B: α= 1, β = 1.1, B_{crit} = 28,000 t Figure 7	F: α= (2.0, 2.3), β = 1.1, B_{low} = 36,000, ER_{low} = 0.26 Figure 8	D: α= 1.9, β = (1.1, 1.3) Figure 9
Resource conservation criteria						
Number of years residual biomass <= B_{lim} (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is open and residual biomass <= B_{lim} (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= B_{lim} (P > 0.05)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Movement of biomass within stock status zones (begins, ends over one year)						
Healthy to healthy	32 (15)	27 (12)	30 (15)	26 (12)	26 (12)	27 (12)
Healthy to cautious	3 (0)	4 (1)	3 (0)	4 (1)	4 (1)	4 (1)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	12 (0)	15 (1)	14 (0)	16 (1)	16 (1)	15 (1)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	3 (0)	4 (1)	3 (0)	4 (1)	4 (1)	4 (1)
PA compliant	✓	✓	✓	✓	✓	✓
Socio-economic criteria						
Number of years fishery is closed	0 (0)	2 (0)	0 (0)	11 (0)	5 (0)	2 (0)
Sum of TAC over years	848,027 (342,238)	923,548 (371,089)	857,118 (347,267)	916,682 (372,753)	921,595 (372,982)	933,229 (377,989)
Average TAC when fishery open	16,961 (22,816)	19,241 (24,739)	17,142 (23,151)	23,505 (24,850)	20,480 (24,865)	19,442 (25,199)
Minimum and maximum TAC over years	88 to 47,491 (8,489 to 40,920)	62 to 56,194 (8,773 to 51,998)	109 to 47,464 (8,830 to 40,904)	6,310 to 51,064 (10,020 to 44,356)	13 to 51,061 (10,121 to 44,358)	60 to 56,162 (9,578 to 51,652)
Average (%) recruitment of commercial biomass	50.6% (58.4%)	54.5% (63.6%)	51.3% (59.2%)	54.7% (64.1%)	55.1% (64.1%)	55.2% (64.8%)

FIGURES

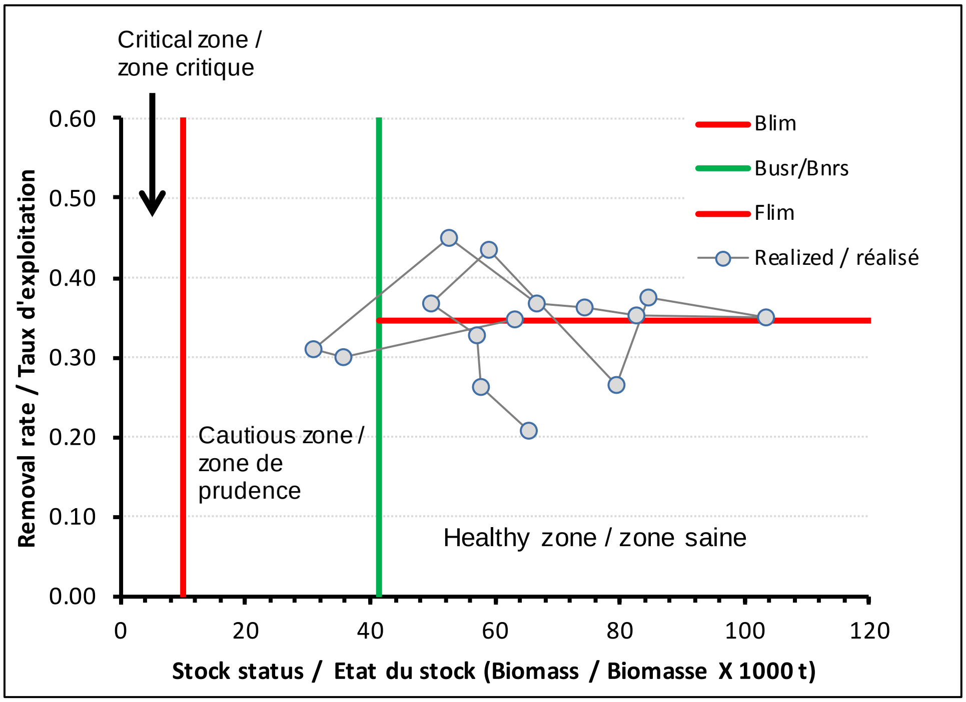


Figure 1. Precautionary Approach diagram (as per DFO 2009) showing the reference points, the status zones, and the history of the southern Gulf of St. Lawrence commercial biomass and exploitation rate values corresponding to the 1998 to 2012 fisheries.

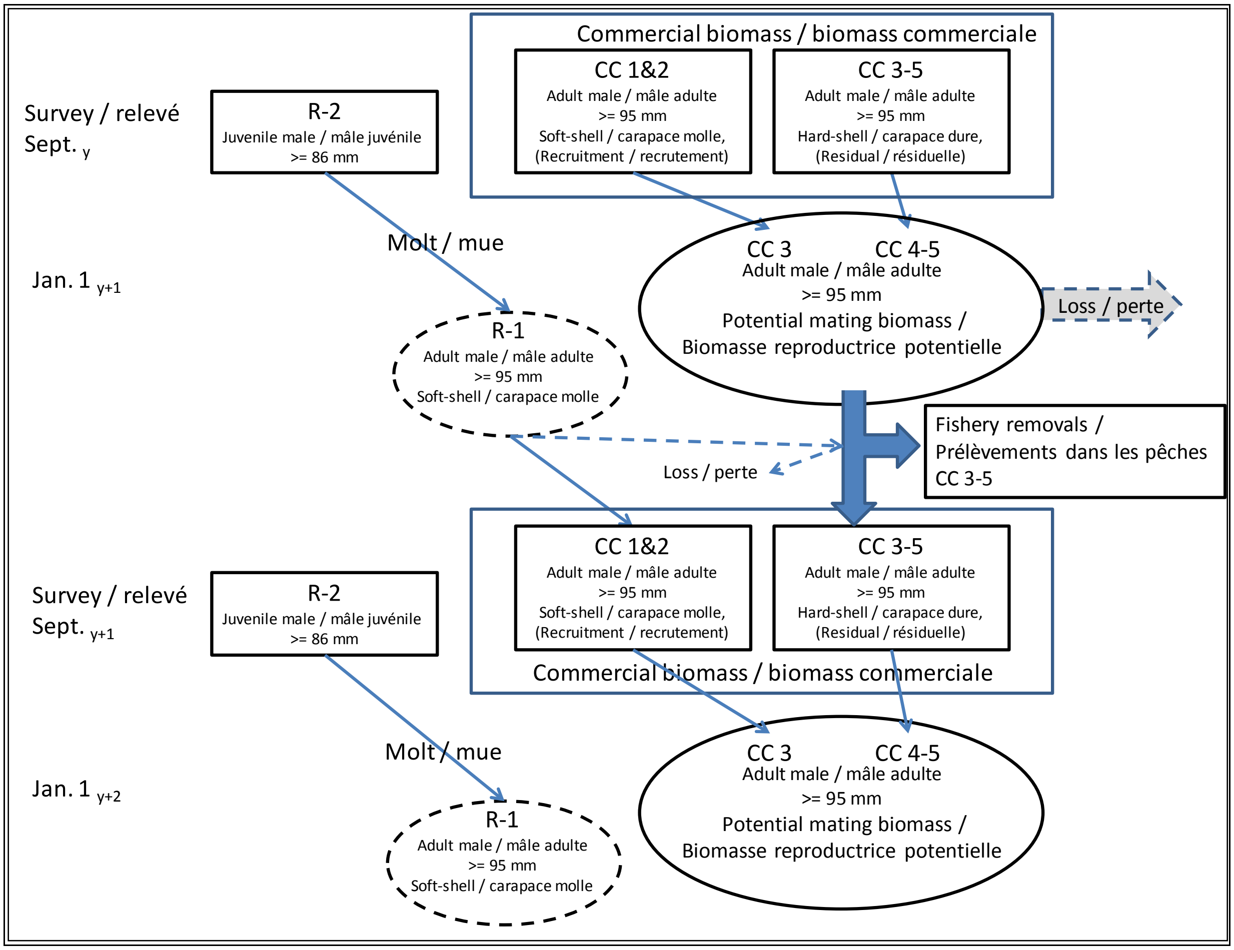


Figure 2. Schematic of the chronology and the snow crab specific terminology used to describe the juvenile stage (R-2) prior to the terminal molt to the commercial size adult male stage (>=95 mm carapace width), the recruitment (R-1; carapace condition 1 and 2, soft shell), and the residual (carapace condition 3 to 5; hard shell) biomass. As of January 1, the soft-shell crab (recruitment) estimated in the summer and fall survey become hard shell crab, are able to mate, and summed to the residual biomass from the survey become the potential mating biomass and the commercial size adult male biomass available to the fishery.

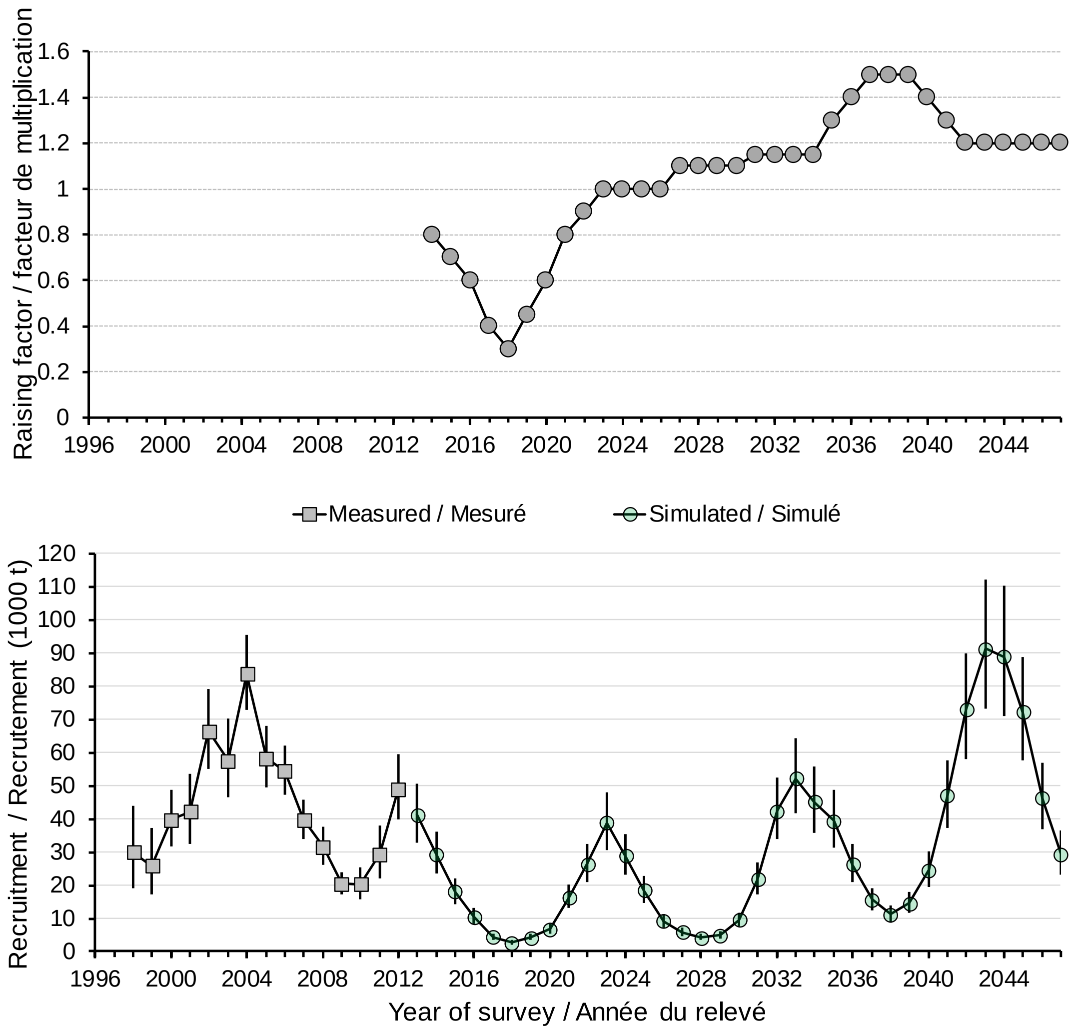


Figure 3. Raising factors (upper panel) and estimated and simulated recruitment biomass time series (lower panel) for the southern Gulf of St. Lawrence. The simulated series is arbitrary in the absolute levels and based on assumptions of the period of oscillations of recruitment observed in snow crab stocks. The simulated mean recruitments are calculated as the products of the means of the recruitment values from years y-11 to y-9 and the corresponding (by year) raising factors.

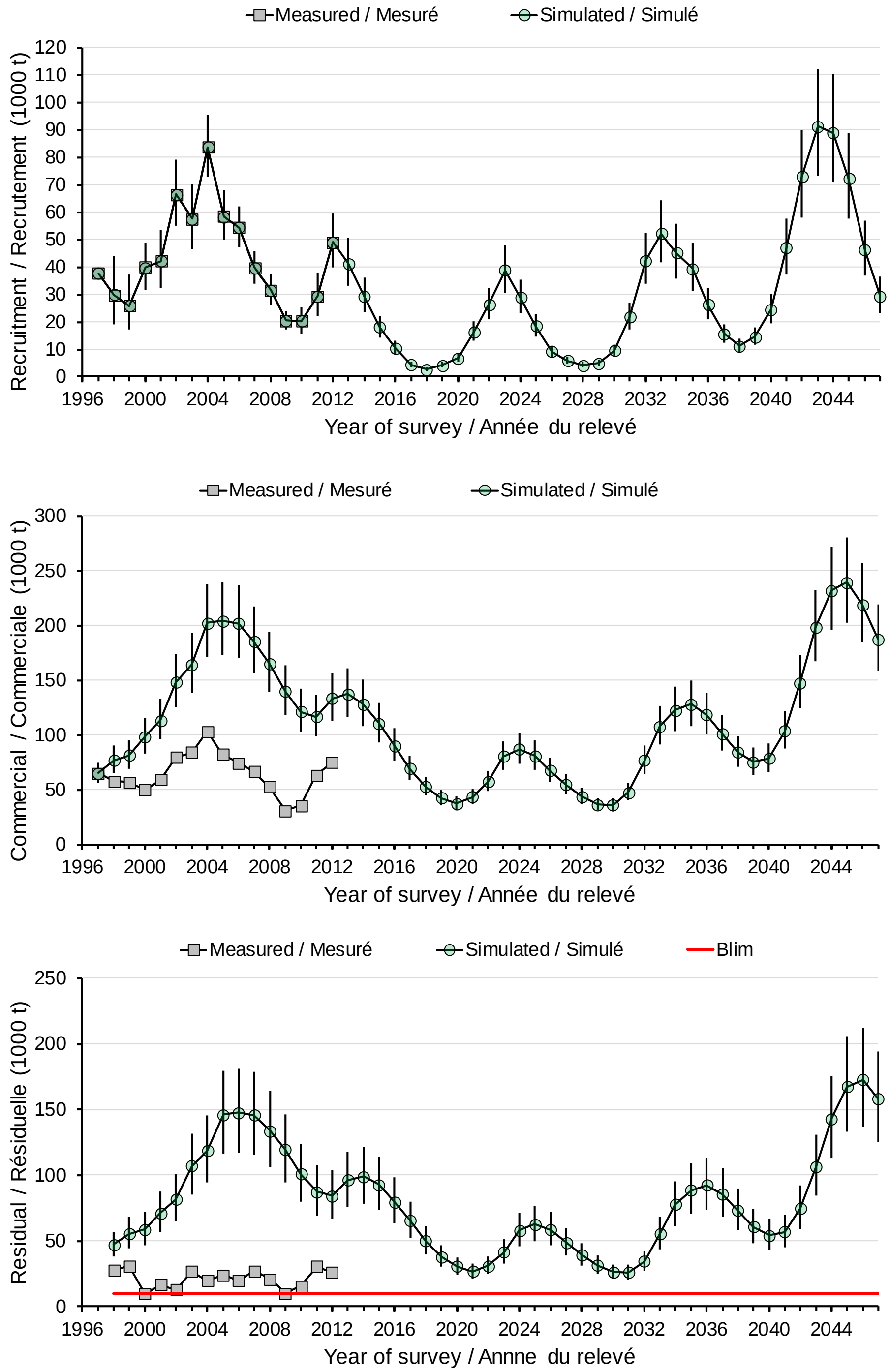


Figure 4. Trends in the simulated recruitment (upper panel), the simulated commercial biomass (middle panel), and the simulated residual biomass (lower panel) in the absence of any fishing exploitation.

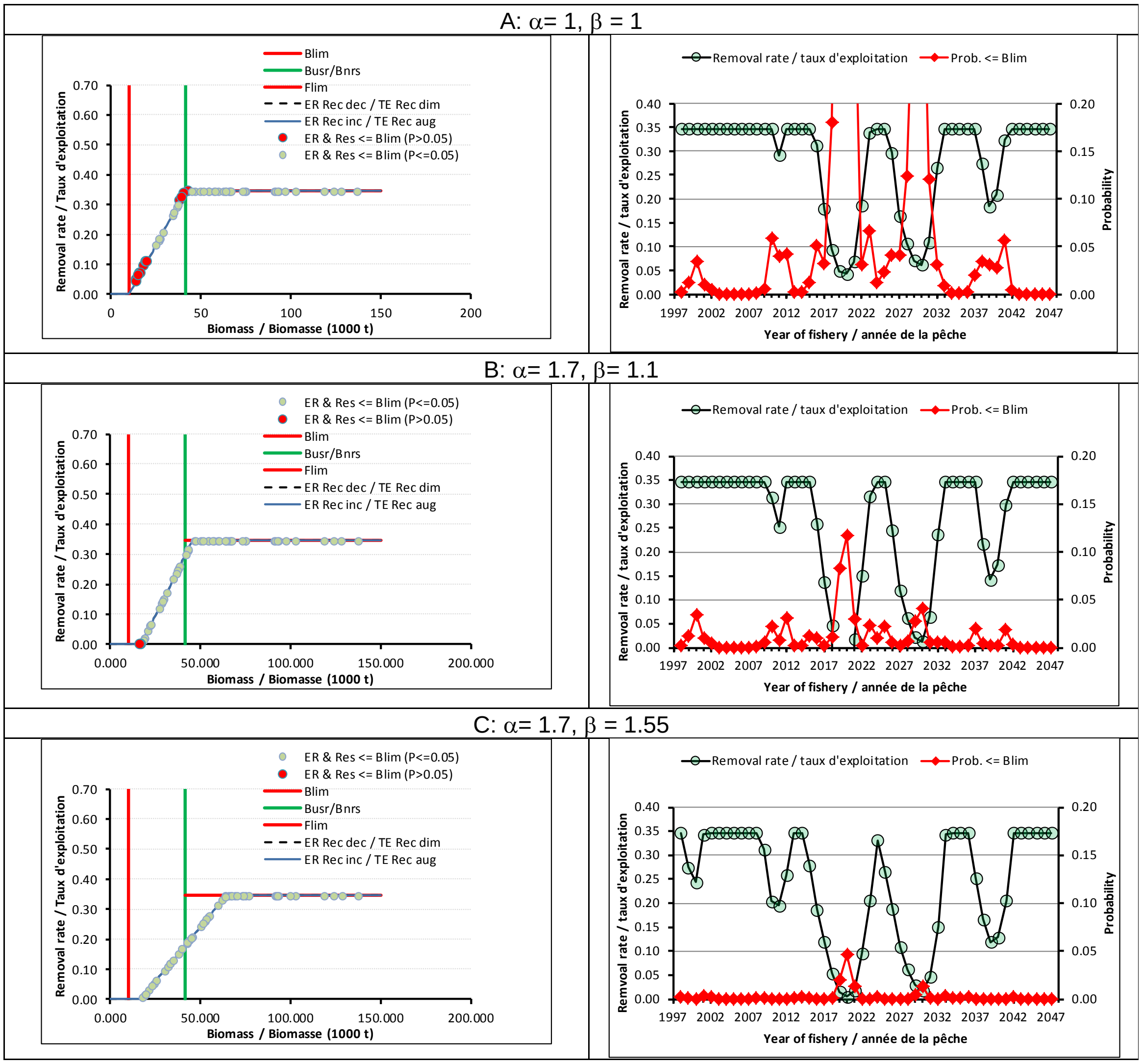


Figure 5. Summary figures of performance of three variants of the default linear rule in the cautious zone for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series ignoring stock trajectory. Performance values for these rules are given in Table 5.

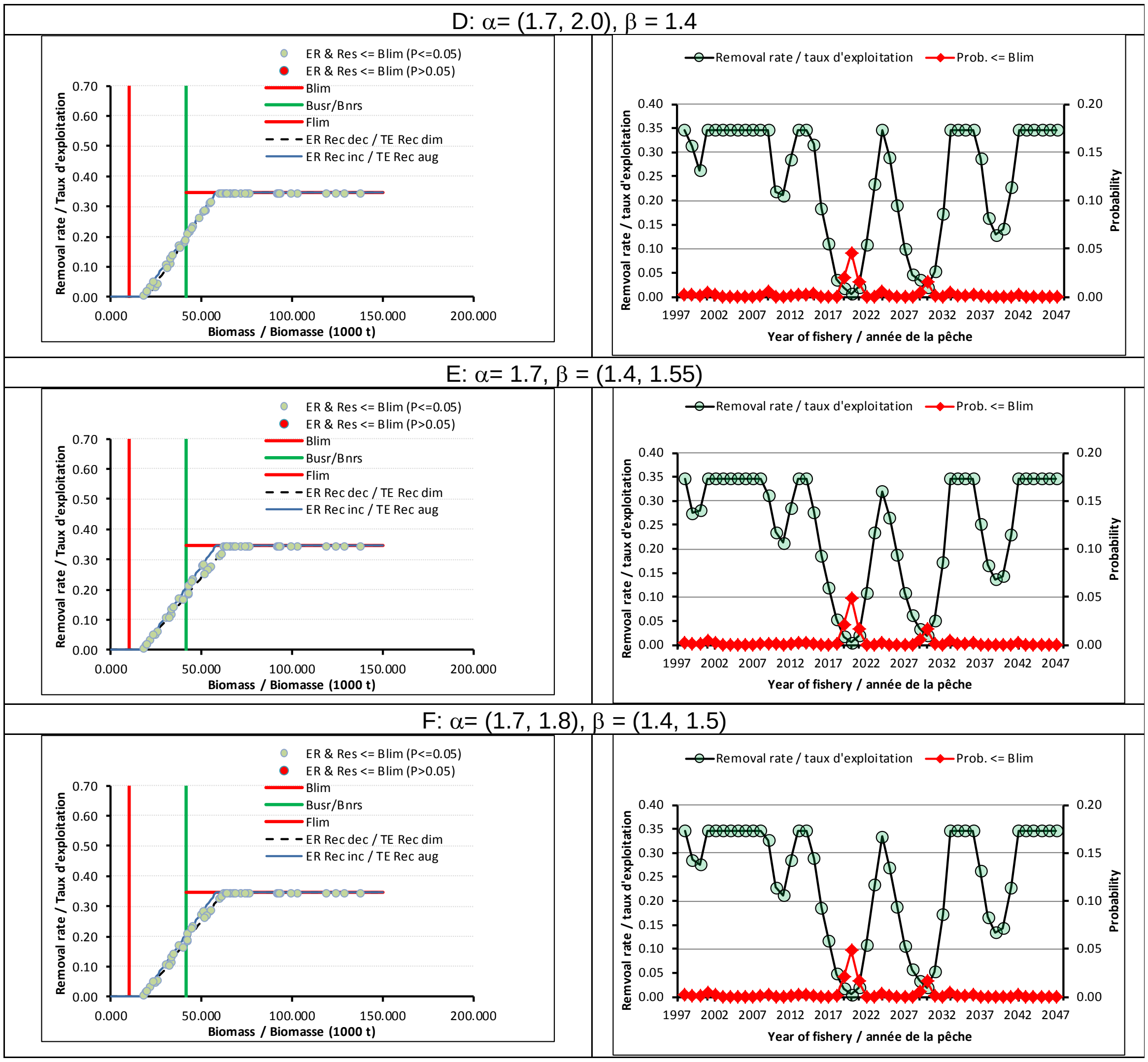
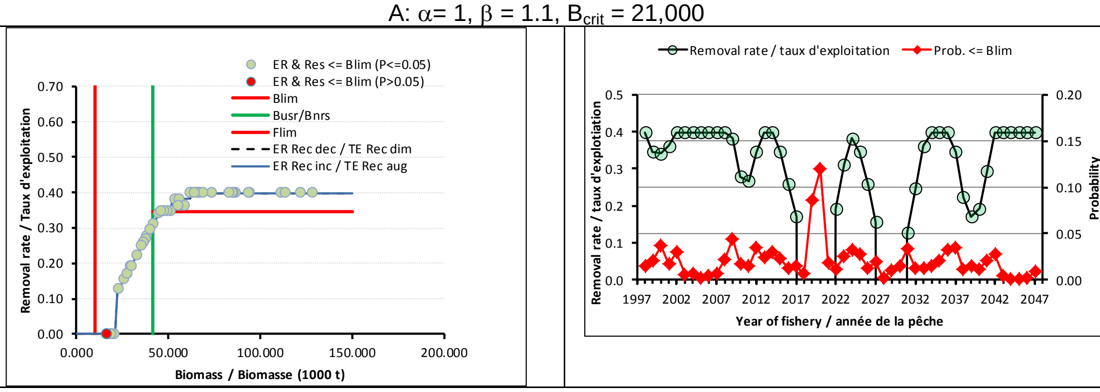


Figure 6. Summary figures of performance of three variants of the default linear rule in the cautious zone that incorporate the stock trajectory for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series. Performance values for these rules are given in Table 5.

A: α= 1, β = 1.1, B_{crit} = 21,000



B: α= 1, β = 1.1, B_{crit} = 28,000

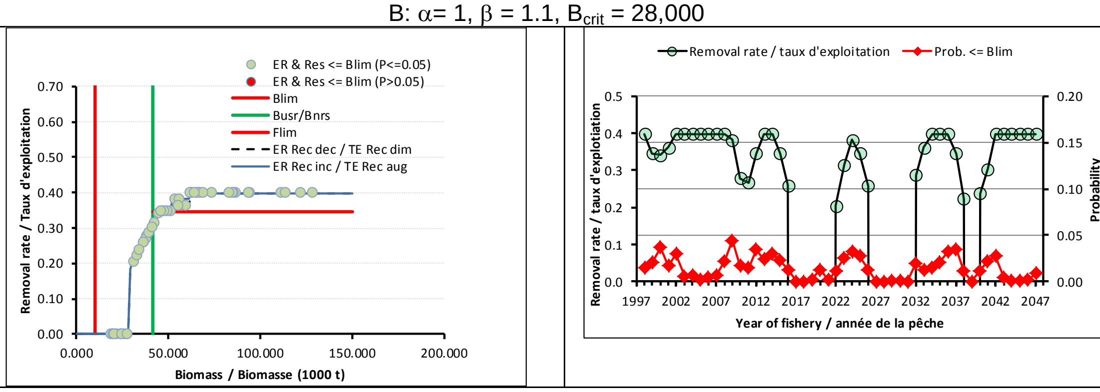


Figure 7. Summary figures of performance of two variants of the "step" rule in the healthy zone combined with the "threshold" rule in the cautious zone for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series. Performance values for these rules are given in Table 6.

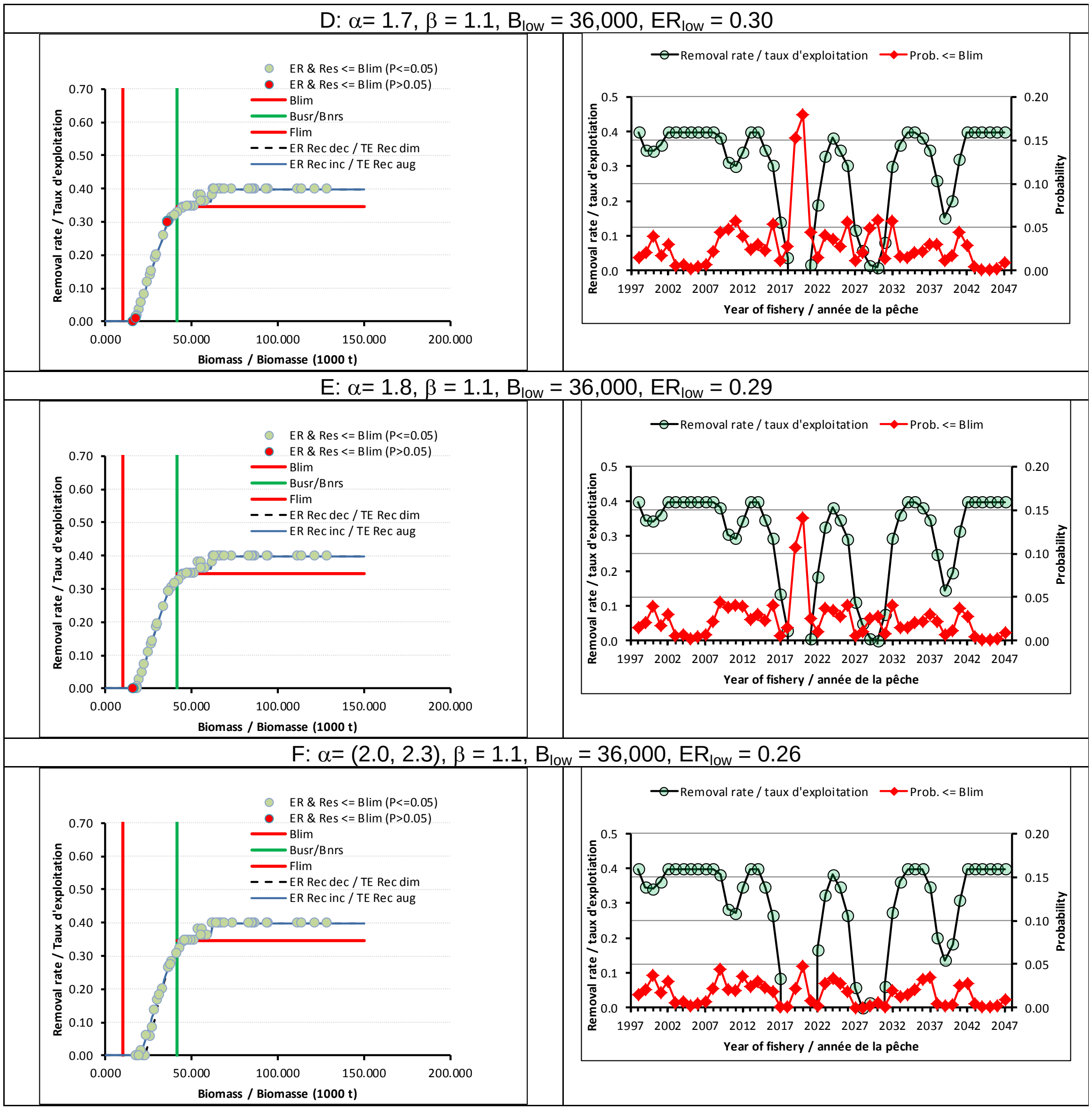


Figure 8. Summary figures of performance of three variants of the "step" rule in the healthy zone combined with the "intermediate" rule in the cautious zone for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series. Performance values for these rules are given in Table 6.

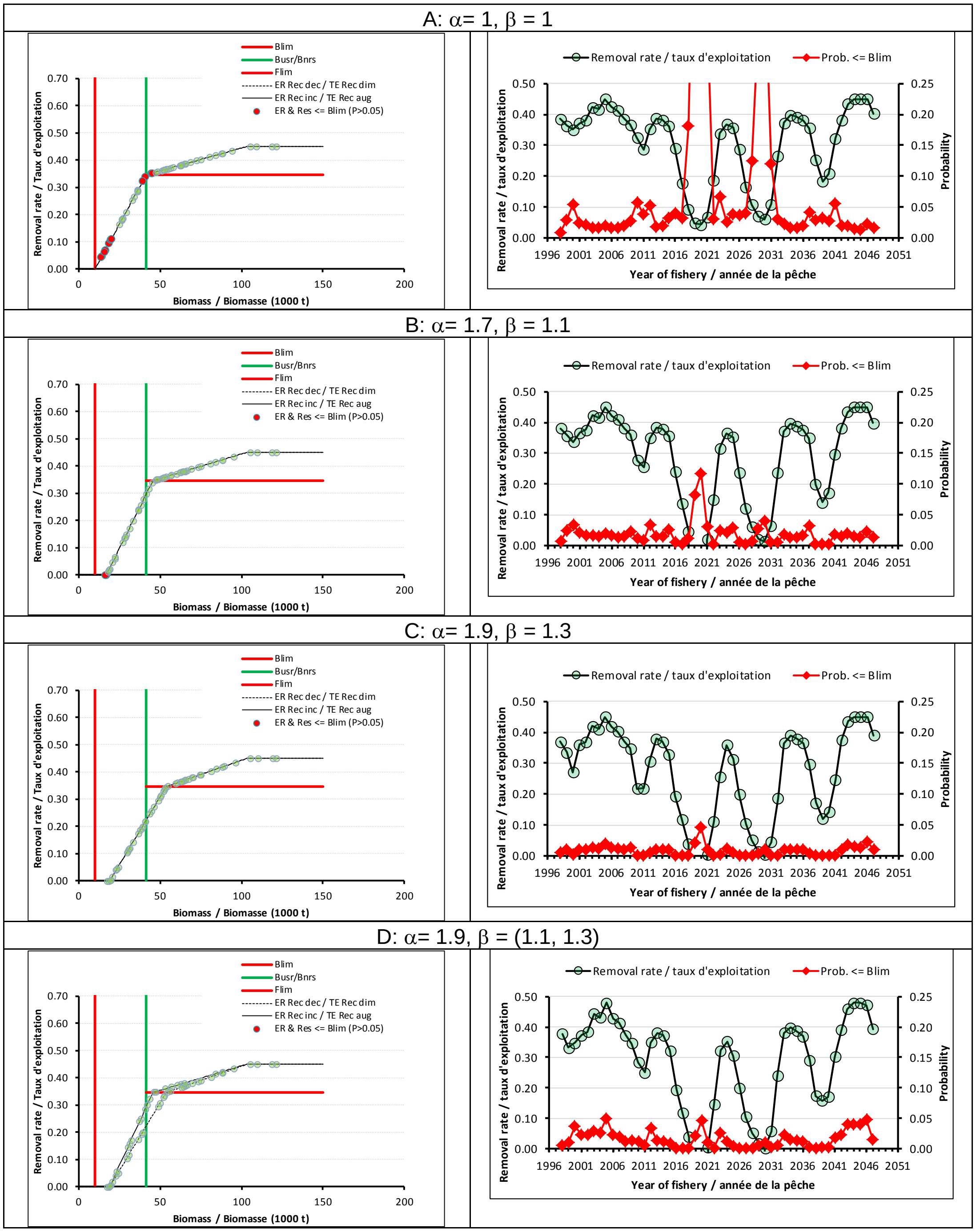


Figure 9. Summary figures of performance of four variants of the proportional rule in the healthy zone combined with the linear rule in the cautious zone for the estimated (1998 to 2012) and simulated (2013 to 2047) recruitment series. Performance values for these rules are given in Table 7.

APPENDICES

Appendix 1. List of members of the joint DFO/Industry working group on Decision Rules for Snow Crab from the Southern Gulf of St. Lawrence.

Name	Affiliation
Adams, Brian	North of Smokey – Inverness South Fishermen's Association
Beaton, Gordon	Maritimes Fishermen's Union (Local 4)
Bonnell, Chris	Esgenoopetij First Nation
Bonnell, Dean	Esgenoopetij First Nation
Boudreau, Paul	Regroupement des pêcheurs professionnels des îles de la Madeleine
Bourque, Bruno Pierre	Groupe de pêcheurs de la zone F
Campbell, Tommy	Area 19 Snow Crab Fishermen’s Association
Chaput, Gérald	DFO Science Branch
Courtenay, Robert	North of Smokey – Inverness South Fishermen's Association
Couture, John	Unama'ki Institute
Desbois, Daniel	Association des Crabiers Gaspésiens
Francis, Cory	Mi’kmaw Conservation Group
Gionet, Joël	Association des crabiers acadiens
Haché, Robert	Association des crabiers acadiens
Hardy, Matthew	DFO Fisheries and Aquaculture Management
Hébert, Marcel	DFO Science Branch
Hébert, Réjean	DFO Fisheries and Aquaculture Management
Hennessey, Frank	Area 12E Representative
Lambert-Koizumi, Catherine	Association de gestion halieutique autochtone Mi’kmaq et Malécite
Landry, Jérome	Groupe de pêcheurs de la zone F
Lanteigne, Marc	DFO Science Branch
Leblanc, Léonard	Gulf of NS Fishermen's Coalition
MacEachern, Leroy	DFO Fisheries and Aquaculture Management
MacLean, Basil	Area 19 Snow Crab Fishermen’s Association
Mallet, Manon	DFO Policy and Economics
Metallic, Christopher	Listuguj Mi'gMaq
Morin, Bernard	DFO Fisheries and Aquaculture Management
Moriyasu, Mikio	DFO Science Branch
Nikoloyuk, Jordan	Atlantic Policy Congress of First Nation Chiefs
Noël, Hubert	Crabiers du Nord-Est
Noël, Martin	Association des pêcheurs professionnels crabiers acadiens Inc.
Norsworthy, Peter	Affiliation of Seafood Producers of Nova Scotia
Richard, Josée	DFO Fisheries and Aquaculture Management
Thiboutot, Chantale	DFO Fisheries and Aquaculture Management

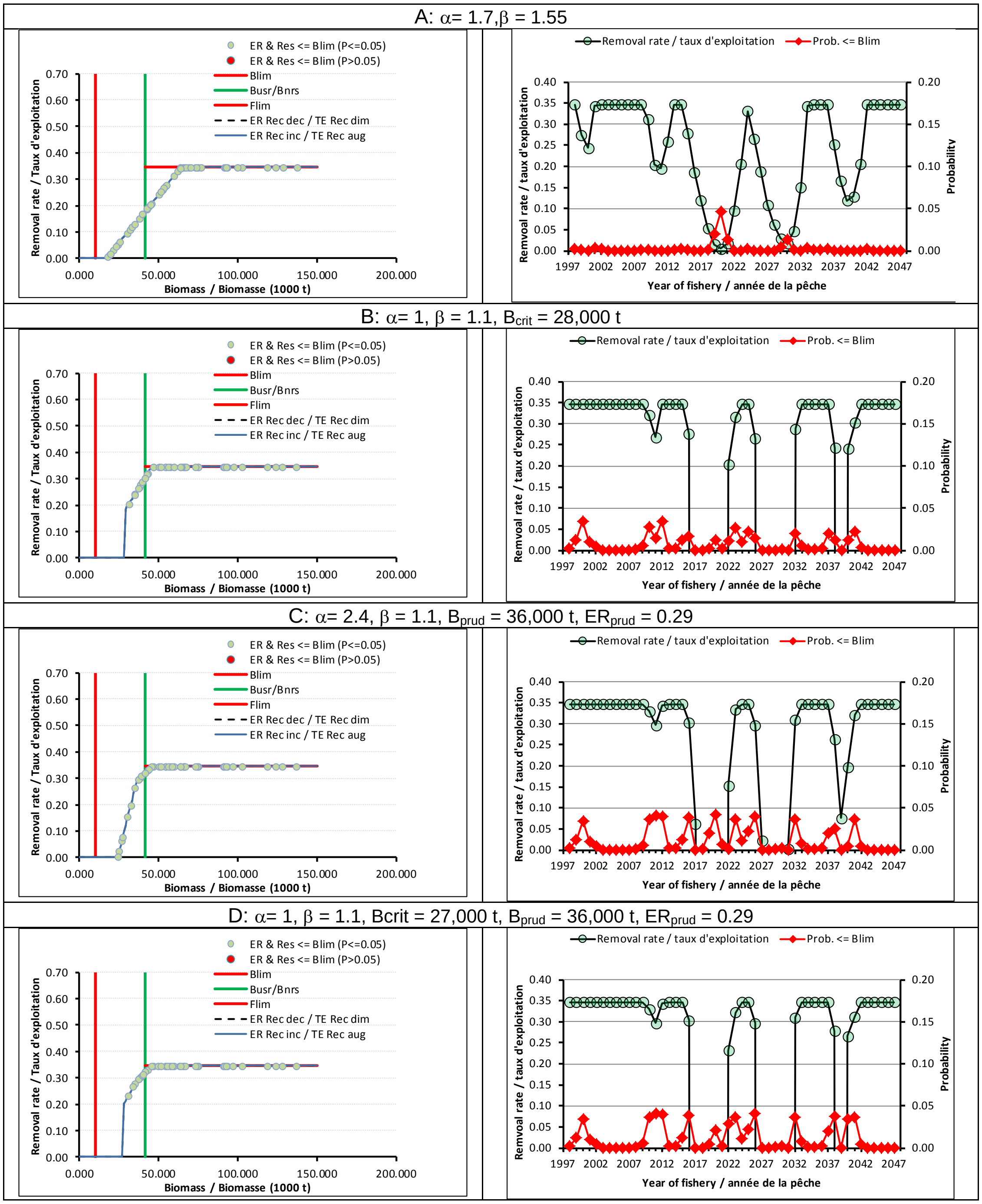
Appendix 2. Table 1. Performance of four variants of harvest decisions rules in the cautious zone combined with the linear rule in the healthy zone which would be fully PA compliant based on the probability of residual biomass being <= B_{lim} is less than 5% in any year. The rules are not stock trajectory dependent. Symbols for PA compliance are: not PA compliant = ☒, fully PA compliant = ✓, potentially PA compliant = ?.

Rule parameters	A α= 1.7,β = 1.55	B α= 1, β = 1.1 B_{crit} = 28,000 t	C α= 2.4, β = 1.1 B_{prud} = 36,000 t, ER_{prud} = 0.29	D α= 1, β = 1.1 Bcrit = 27,000 t B_{prud} = 36,000 t, ER_{prud} = 0.29
Resource conservation criteria				
Number of years residual biomass <= Blim (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is open and residual biomass <= Blim (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= Blim (P > 0.05)	0 (0)	0 (0)	0 (0)	0 (0)
Movement of biomass within stock status zones (begins, ends over one year)				
Healthy to healthy	32 (15)	27 (13)	27 (13)	27 (13)
Healthy to cautious	3 (0)	4 (1)	4 (1)	4 (1)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	12 (0)	15 (0)	15 (0)	15 (0)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	3 (0)	4 (1)	4 (1)	4 (1)
PA compliant	✓	✓	✓	✓
Socio-economic criteria				
Number of years fishery is closed	0 (0)	11 (0)	7 (0)	11 (0)
Sum of TAC over years	848,027 (342,238)	873,910 (357,022)	879,663 (357,824)	878,817 (357,839)
Average TAC over all years	16,961 (22,817)	17,478 (23,801)	17,593 (23,855)	17,576 (23,856)
Average TAC when fishery open	16,961 (22,816)	22,408 (23,801)	20,457 (23,855)	22,534 (23,856)
Minimum and maximum TAC over years	88 to 47,491 (8,489 to 40,920)	6,324 to 47,379 (10,091 to 40,872)	49 to 47,366 (11,017 to 40,870)	7,125 to 47,365 (11,018 to 40,871)
Average (%) recruitment of commercial biomass	50.6% (58.4%)	52.6% (61%)	53.1% (61.2%)	53% (61.2%)

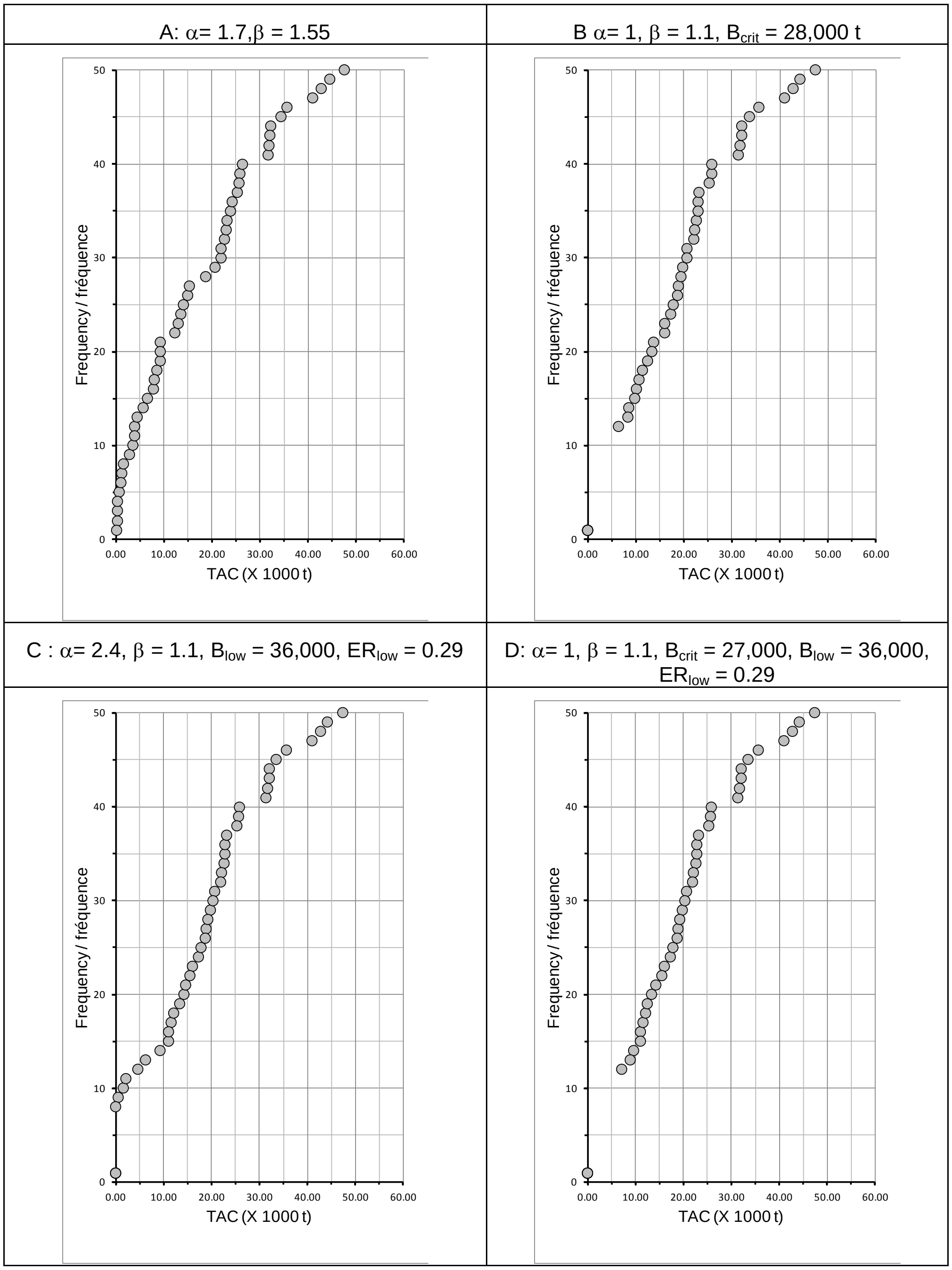
Appendix 2 Table 2. Removal rates and TAC per 1000 t increment of commercial biomass of snow crab for four variants of harvest decisions rules in the cautious zone and the linear rule in the healthy zone that are fully PA compliant. The rules are not stock trajectory dependent.

	A α= 1.7, β = 1.55		B α= 1, β = 1.1, B_{crit} = 28,000 t		C α= 2.4, β = 1.1, B_{low} = 36,000 t, ER_{low} = 0.29		D α= 1, β = 1.1, B_{crit} = 27,000 t, B_{low} = 36,000 t, ER_{low} = 0.29	
Biomass (X 1000 t)	ER	TAC (X 1000 t)	ER	TAC (X 1000 t)	ER	TAC (X 1000 t)	ER	TAC (X 1000 t)
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0.007	0.1	0	0	0	0	0	0
19	0.015	0.3	0	0	0	0	0	0
20	0.022	0.4	0	0	0	0	0	0
21	0.029	0.6	0	0	0	0	0	0
22	0.037	0.8	0	0	0	0	0	0
23	0.044	1.0	0	0	0	0	0	0
24	0.051	1.2	0	0	0	0	0	0
25	0.059	1.5	0	0	0.024	0.6	0	0
26	0.066	1.7	0	0	0.048	1.3	0	0
27	0.073	2.0	0	0	0.073	2.0	0	0
28	0.081	2.3	0	0	0.097	2.7	0.201	5.6
29	0.088	2.6	0.185	5.4	0.121	3.5	0.212	6.1
30	0.095	2.9	0.195	5.8	0.145	4.4	0.223	6.7
31	0.103	3.2	0.204	6.3	0.169	5.2	0.234	7.3
32	0.110	3.5	0.214	6.9	0.193	6.2	0.245	7.9
33	0.117	3.9	0.224	7.4	0.218	7.2	0.257	8.5
34	0.125	4.2	0.234	7.9	0.242	8.2	0.268	9.1
35	0.132	4.6	0.243	8.5	0.266	9.3	0.279	9.8
36	0.139	5.0	0.253	9.1	0.290	10.4	0.290	10.4
37	0.147	5.4	0.263	9.7	0.296	10.9	0.296	10.9
38	0.154	5.9	0.273	10.4	0.302	11.5	0.302	11.5
39	0.161	6.3	0.282	11.0	0.308	12.0	0.308	12.0
40	0.169	6.7	0.292	11.7	0.313	12.5	0.313	12.5
41	0.176	7.2	0.302	12.4	0.319	13.1	0.319	13.1
41.4	0.179	7.4	0.306	12.7	0.322	13.3	0.322	13.3
42	0.183	7.7	0.312	13.1	0.325	13.7	0.325	13.7
43	0.191	8.2	0.321	13.8	0.331	14.2	0.331	14.2
44	0.198	8.7	0.331	14.6	0.337	14.8	0.337	14.8
45	0.205	9.2	0.341	15.3	0.343	15.4	0.343	15.4
46	0.213	9.8	0.346	15.9	0.346	15.9	0.346	15.9
47	0.220	10.3	0.346	16.3	0.346	16.3	0.346	16.3
48	0.227	10.9	0.346	16.6	0.346	16.6	0.346	16.6
49	0.235	11.5	0.346	17.0	0.346	17.0	0.346	17.0
50	0.242	12.1	0.346	17.3	0.346	17.3	0.346	17.3
51	0.249	12.7	0.346	17.6	0.346	17.6	0.346	17.6
52	0.257	13.4	0.346	18.0	0.346	18.0	0.346	18.0
53	0.264	14.0	0.346	18.3	0.346	18.3	0.346	18.3
54	0.271	14.7	0.346	18.7	0.346	18.7	0.346	18.7
55	0.279	15.3	0.346	19.0	0.346	19.0	0.346	19.0
56	0.286	16.0	0.346	19.4	0.346	19.4	0.346	19.4
57	0.293	16.7	0.346	19.7	0.346	19.7	0.346	19.7
58	0.301	17.4	0.346	20.1	0.346	20.1	0.346	20.1
59	0.308	18.2	0.346	20.4	0.346	20.4	0.346	20.4

Biomass (X 1000 t)	A α= 1.7,β = 1.55 ER	TAC (X 1000 t)	B α= 1, β = 1.1, B_{crit} = 28,000 t ER	TAC (X 1000 t)	C α= 2.4, β = 1.1, B_{low} = 36,000 t, ER_{low} = 0.29 ER	TAC (X 1000 t)	D α= 1, β = 1.1, B_{crit} = 27,000 t, B_{low} = 36,000 t, ER_{low} = 0.29 ER	TAC (X 1000 t)
60	0.315	18.9	0.346	20.8	0.346	20.8	0.346	20.8
61	0.323	19.7	0.346	21.1	0.346	21.1	0.346	21.1
62	0.330	20.5	0.346	21.5	0.346	21.5	0.346	21.5
63	0.337	21.3	0.346	21.8	0.346	21.8	0.346	21.8
64	0.345	22.1	0.346	22.1	0.346	22.1	0.346	22.1
65	0.346	22.5	0.346	22.5	0.346	22.5	0.346	22.5
66	0.346	22.8	0.346	22.8	0.346	22.8	0.346	22.8
67	0.346	23.2	0.346	23.2	0.346	23.2	0.346	23.2
68	0.346	23.5	0.346	23.5	0.346	23.5	0.346	23.5
69	0.346	23.9	0.346	23.9	0.346	23.9	0.346	23.9
70	0.346	24.2	0.346	24.2	0.346	24.2	0.346	24.2



Appendix 2 Figure 1. Summary performance plots of four variants of harvest decisions rules in the cautious zone combined with the linear rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= Blim is less than 5% in any year. The rules are not stock trajectory dependent.



Appendix 2 Figure 2. Summary plots of the cumulative Total Allowable Catch (TAC) over 50 years for four variants of harvest decisions rules in the cautious zone combined with the linear rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= Blim is less than 5% in any year. The rules are not stock trajectory dependent.

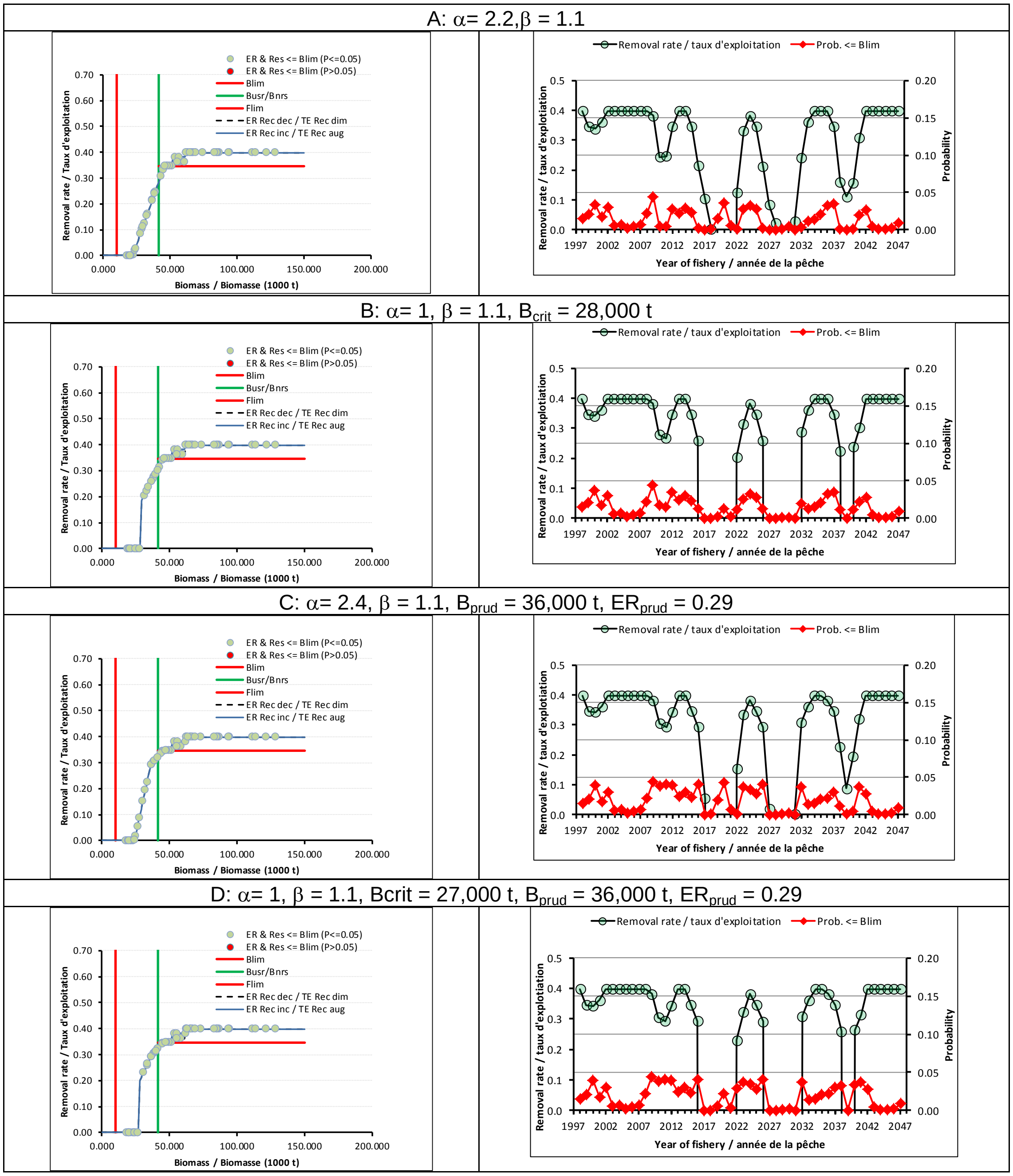
Appendix 3 Table 1. Performance of four variants of the harvest decision rules in the cautious zone combined with the step decision rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= Blim being less than 5% in any year. The step decision rule in the healthy zone is stock trajectory dependent. Symbols for PA compliance are: not PA compliant = ☒, fully PA compliant = ✓, potentially PA compliant = ?.

Rule parameters	B: α= 2.2, β = 1.1	B: α= 1, β = 1.1, B_{crit} = 28,000 t	F: α= 2.4, β = 1.1, B_{low} = 36,000, ER_{low} = 0.29	F: α= 1, β = 1.1, B_{crit} = 27,000 t, B_{low} = 36,000, ER_{low} = 0.29
Resource conservation criteria				
Number of years residual biomass <= Blim (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is open and residual biomass <= Blim (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= Blim (P > 0.05)	0 (0)	0 (0)	0 (0)	0 (0)
Movement of biomass within stock status zones (begins, ends over one year)				
Healthy to healthy	27 (12)	26 (12)	26 (12)	26 (12)
Healthy to cautious	4 (1)	4 (1)	4 (1)	4 (1)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	15 (1)	16 (1)	16 (1)	16 (1)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	4 (1)	4 (1)	4 (1)	4 (1)
PA compliant	✓	✓	✓	✓
Socio-economic criteria				
Number of years fishery is closed	5 (0)	11 (0)	7 (0)	11 (0)
Sum of TAC over years	915,761 (371,403)	916,747 (372,775)	921,977 (373,835)	921,545 (373,829)
Average TAC over all years	18,315 (24,760)	18,335 (24,852)	18,440 (24,922)	18,431 (24,922)
Average TAC when fishery open	20,350 (24,760)	23,506 (24,852)	21,441 (24,922)	23,629 (24,922)
Minimum and maximum TAC over years	79 to 51,069 (9,405 to 44,356)	6,312 to 51,066 (10,021 to 44,359)	47 to 51,053 (10,658 to 44,357)	7,086 to 51,049 (10,658 to 44,355)
Average (%) recruitment of commercial biomass	54.6% (63.8%)	54.7% (64.1%)	55.2% (64.3%)	55.2% (64.3%)

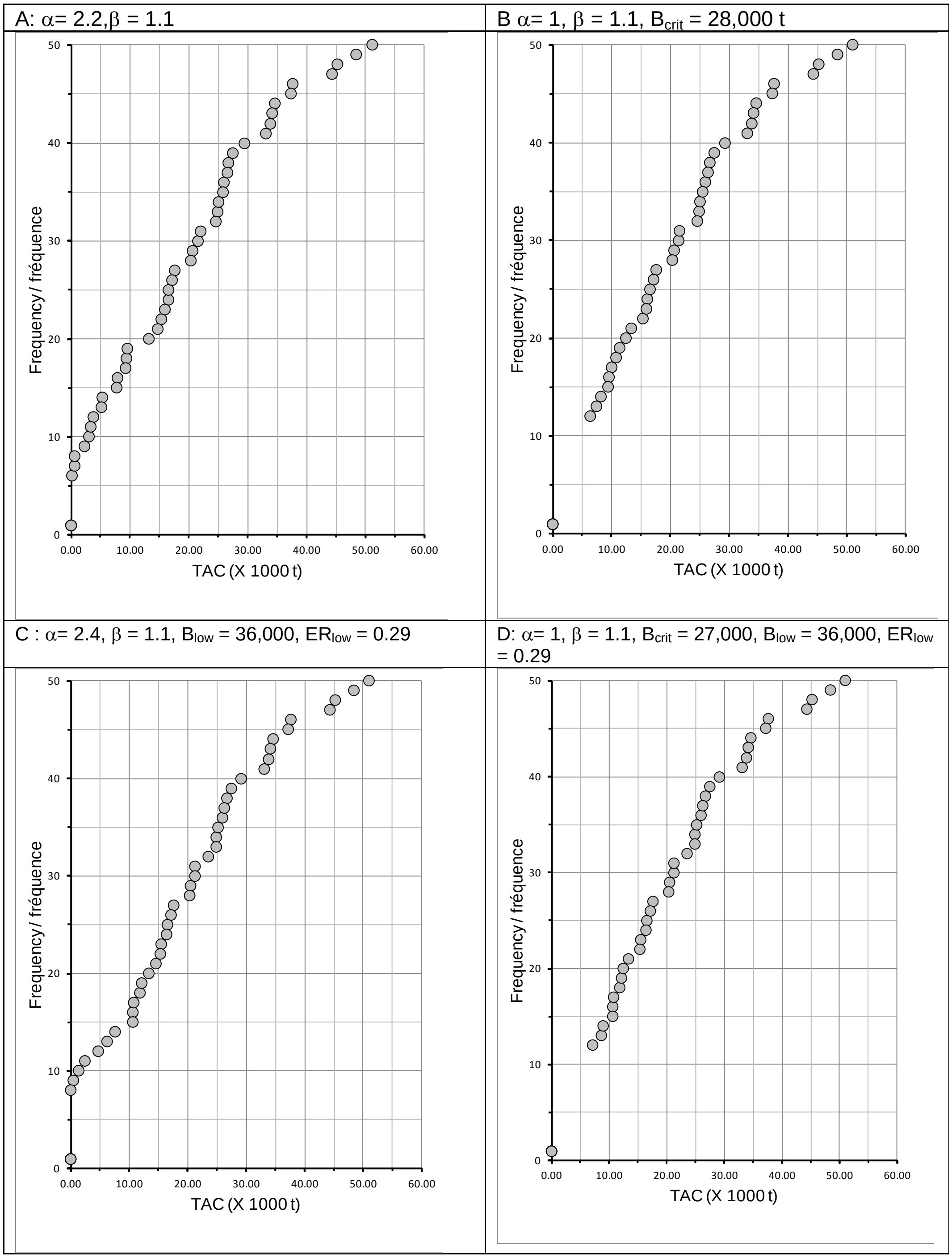
Appendix 3 Table 2. Removal rates and TAC per 1000 t increment of commercial biomass of snow crab for variants of the harvest decision rules in the cautious zone combined with a step decision rule in the healthy zone which are fully PA compliant. The values for ER and TAC in parentheses correspond to the values of the step rule in the healthy zone for which the stock trajectory is increasing.

	B: α= 2.2, β = 1.1		B: α= 1, β = 1.1, B_{crit} = 28,000 t		C: α= 2.4, β = 1.1, B_{low} = 36,000 t, ER_{low} = 0.29		D: α= 1, β = 1.1, B_{crit} = 27,000 t, B_{low} = 36,000 t, ER_{low} = 0.29	
Biomass (X 1000 t)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
23	0.015	0.3	0	0	0	0	0	0
24	0.029	0.7	0	0	0	0	0	0
25	0.044	1.1	0	0	0.024	0.6	0	0
26	0.059	1.5	0	0	0.048	1.3	0	0
27	0.073	2.0	0	0	0.073	2.0	0	0
28	0.088	2.5	0	0	0.097	2.7	0.201	5.6
29	0.103	3.0	0.185	5.4	0.121	3.5	0.212	6.1
30	0.118	3.5	0.195	5.8	0.145	4.3	0.223	6.7
31	0.132	4.1	0.204	6.3	0.169	5.2	0.234	7.3
32	0.147	4.7	0.214	6.9	0.193	6.2	0.245	7.9
33	0.162	5.3	0.224	7.4	0.217	7.2	0.257	8.5
34	0.176	6.0	0.234	7.9	0.242	8.2	0.268	9.1
35	0.191	6.7	0.243	8.5	0.266	9.3	0.279	9.8
36	0.206	7.4	0.253	9.1	0.290	10.4	0.290	10.4
37	0.22	8.2	0.263	9.7	0.296	10.9	0.296	10.9
38	0.235	8.9	0.273	10.4	0.302	11.5	0.302	11.5
39	0.25	9.7	0.282	11.0	0.308	12.0	0.308	12.0
40	0.265	10.6	0.292	11.7	0.313	12.5	0.313	12.5
41	0.279	11.5	0.302	12.4	0.319	13.1	0.319	13.1
41.4	0.285	11.8	0.306	12.7	0.322	13.3	0.322	13.3
42	0.294	12.3	0.312	13.1	0.325	13.7	0.325	13.7
43	0.309	13.3	0.321	13.8	0.331	14.2	0.331	14.2
44	0.323	14.2	0.331	14.6	0.337	14.8	0.337	14.8
45	0.338	15.2	0.341	15.3	0.343	15.4	0.343	15.4
46	0.346	15.9	0.346	15.9	0.346	15.9	0.346	15.9
47	0.346	16.3	0.346	16.3	0.346	16.3	0.346	16.3
48	0.346	16.6	0.346	16.6	0.346	16.6	0.346	16.6
49	0.346	17.0	0.346	17.0	0.346	17.0	0.346	17.0
50	0.346	17.3	0.346	17.3	0.346	17.3	0.346	17.3
51	0.346	17.6	0.346	17.6	0.346	17.6	0.346	17.6
52	0.362 (0.382)	18.8 (19.9)	0.362 (0.382)	18.8 (19.9)	0.362 (0.382)	18.8 (19.9)	0.362 (0.382)	18.8 (19.9)
53	0.362 (0.382)	19.2 (20.2)	0.362 (0.382)	19.2 (20.2)	0.362 (0.382)	19.2 (20.2)	0.362 (0.382)	19.2 (20.2)
54	0.362 (0.382)	19.5 (20.6)	0.362 (0.382)	19.5 (20.6)	0.362 (0.382)	19.5 (20.6)	0.362 (0.382)	19.5 (20.6)
55	0.362 (0.382)	19.9 (21.0)	0.362 (0.382)	19.9 (21.0)	0.362 (0.382)	19.9 (21.0)	0.362 (0.382)	19.9 (21.0)
56	0.362 (0.382)	20.3 (21.4)	0.362 (0.382)	20.3 (21.4)	0.362 (0.382)	20.3 (21.4)	0.362 (0.382)	20.3 (21.4)
57	0.362 (0.382)	20.6 (21.8)	0.362 (0.382)	20.6 (21.8)	0.362 (0.382)	20.6 (21.8)	0.362 (0.382)	20.6 (21.8)
58	0.362 (0.382)	21.0 (22.2)	0.362 (0.382)	21.0 (22.2)	0.362 (0.382)	21.0 (22.2)	0.362 (0.382)	21.0 (22.2)
59	0.362 (0.382)	21.4 (22.5)	0.362 (0.382)	21.4 (22.5)	0.362 (0.382)	21.4 (22.5)	0.362 (0.382)	21.4 (22.5)
60	0.362 (0.382)	21.7 (22.9)	0.362 (0.382)	21.7 (22.9)	0.362 (0.382)	21.7 (22.9)	0.362 (0.382)	21.7 (22.9)
61	0.362 (0.382)	22.1 (23.3)	0.362 (0.382)	22.1 (23.3)	0.362 (0.382)	22.1 (23.3)	0.362 (0.382)	22.1 (23.3)
62	0.398	24.7	0.398	24.7	0.398	24.7	0.398	24.7
63	0.398	25.1	0.398	25.1	0.398	25.1	0.398	25.1
64	0.398	25.5	0.398	25.5	0.398	25.5	0.398	25.5

	B: α= 2.2, β = 1.1		B: α= 1, β = 1.1 B_{crit} = 28,000 t		C: α= 2.4, β = 1.1 B_{low} = 36,000 t, ER_{low} = 0.29		D: α= 1, β = 1.1 B_{crit} = 27,000 t B_{low} = 36,000 t, ER_{low} = 0.29	
Biomass (X 1000 t)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)	ER (Rec↑)	TAC (X 1000 t) (Rec↑)
65	0.398	25.9	0.398	25.9	0.398	25.9	0.398	25.9
66	0.398	26.3	0.398	26.3	0.398	26.3	0.398	26.3
67	0.398	26.7	0.398	26.7	0.398	26.7	0.398	26.7
68	0.398	27.1	0.398	27.1	0.398	27.1	0.398	27.1
69	0.398	27.5	0.398	27.5	0.398	27.5	0.398	27.5
70	0.398	27.9	0.398	27.9	0.398	27.9	0.398	27.9



Appendix 3 Figure 1. Summary performance plots of four variants of the harvest decision rules in the cautious zone combined with a step decision rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= B_{lim} is less than 5% in any year.



Appendix 3 Figure 2. Summary plots of the cumulative TAC over 50 years for four variants of the harvest decision rules in the cautious zone with a step decision rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= B_{lim} is less than 5% in any year.

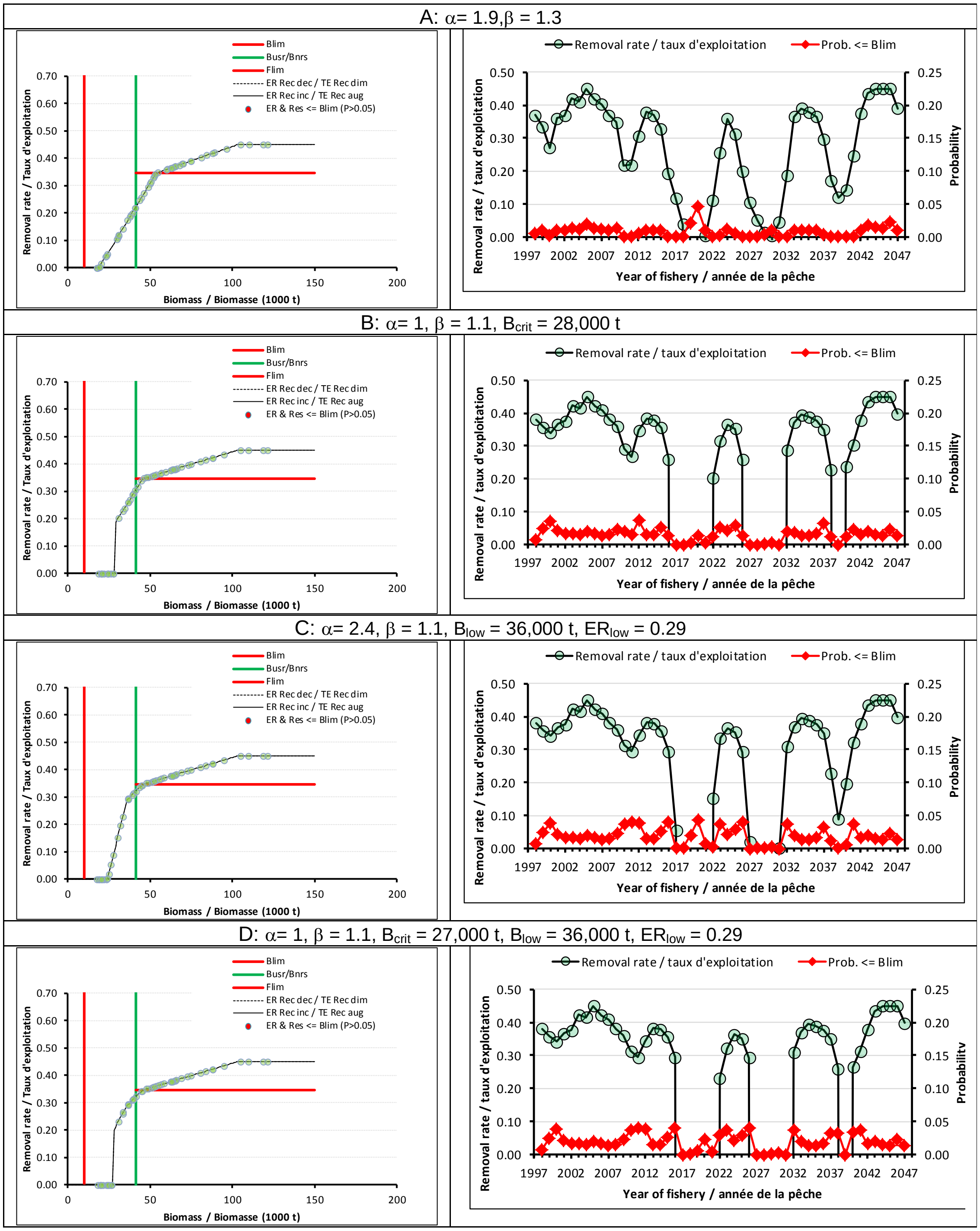
Appendix 4 Table1. Performance of four variants of the harvest decision rules in the cautious zone combined with the proportional decision rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= Blim is less than 5% in any year. The rules are not stock-trajectory dependent. Symbols for PA compliance are: not PA compliant = ⌧, fully PA compliant = ✓, potentially PA compliant = ?.

Rule parameters	A α= 1.9, β = 1.3	B α= 1, β = 1.1, B_{crit} = 28,000 t	C α= 2.4, β = 1.1, B_{low} = 36,000, ER_{low} = 0.29	D α= 1, β = 1.1, B_{crit} = 27,000, B_{low} = 36,000, ER_{low} = 0.29
Resource conservation criteria				
Number of years residual biomass <= Blim (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is open and residual biomass <= Blim (P > 0.05)	0 (0) ✓	0 (0) ✓	0 (0) ✓	0 (0) ✓
Number of years fishery is closed and residual biomass <= Blim (P > 0.05)	0 (0)	0 (0)	0 (0)	0 (0)
Movement of biomass within stock status zones (begins, ends over one year)				
Healthy to healthy	27 (12)	26 (12)	26 (12)	26 (12)
Healthy to cautious	4 (1)	4 (1)	4 (1)	4 (1)
Healthy to critical	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to cautious	15 (1)	16 (1)	16 (1)	16 (1)
Cautious to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to critical	0 (0)	0 (0)	0 (0)	0 (0)
Critical to cautious	0 (0)	0 (0)	0 (0)	0 (0)
Critical to healthy	0 (0)	0 (0)	0 (0)	0 (0)
Cautious to healthy	4 (1)	4 (1)	4 (1)	4 (1)
PA compliant	✓	✓	✓	✓
Socio-economic criteria				
Number of years fishery is closed	2 (0)	11 (0)	7 (0)	11 (0)
Sum of TAC over years	913,271 (367,516)	928,709 (376,444)	934,090 (377,364)	933,718 (377,395)
Average TAC over all years	18,266 (24,502)	18,574 (25,096)	21,723 (25,158)	18,674 (25,160)
Average TAC when fishery open	19,026 (24501)	23,813 (25,096)	18,682 (25,158)	23,941 (25,160)
Minimum and maximum TAC over years	62 to 54,562 (8,893 to 49,514)	6,311 to 54,518 (10,066 to 49,264)	45 to 54,511 (10,775 to 49,261)	7,089 to 54,517 (10,776 to 49,264)
Average (%) recruitment of commercial biomass	53.9% (62.9%)	55.2% (64.6%)	55.6% (64.9%)	55.6% (64.9%)

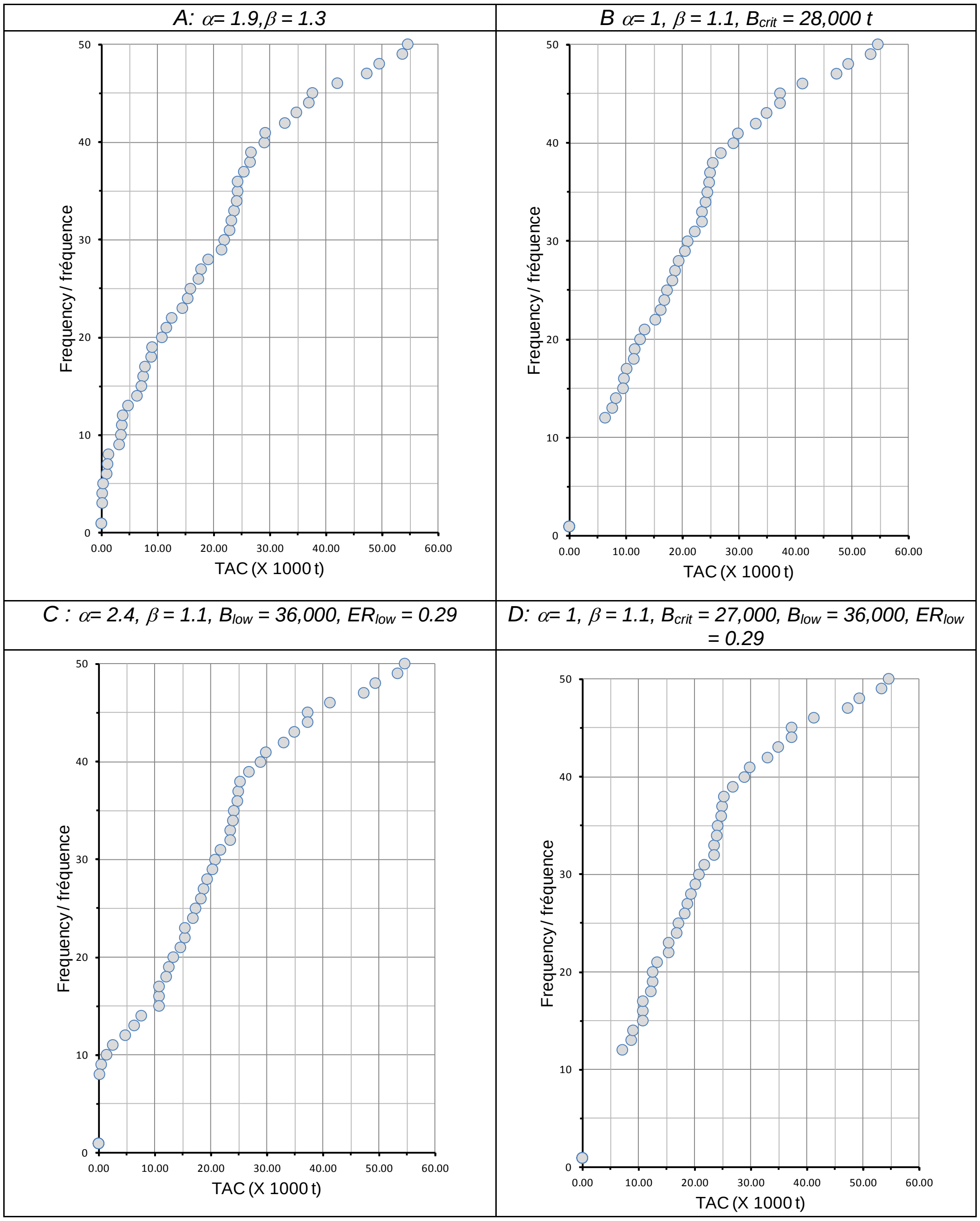
Appendix 4 Table 2. Removal rates and TAC per 1000 t increment of commercial biomass of snow crab for four variants of the harvest decision rules in the cautious zone for the proportional decision rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= B_{lim} is less than 5% in any year. The rules are not stock-trajectory dependent.

	A: α= 1.9,β = 1.3		B: α= 1, β = 1.1, B_{crit} = 28,000 t		C: α= 2.4, β = 1.1, B_{low} = 36,000 t, ER_{low} = 0.29		D: α= 1, β = 1.1, B_{crit} = 27,000 t, B_{low} = 36,000 t, ER_{low} = 0.29	
Biomass (X 1000 t)	ER	TAC (X 1000 t)	ER	TAC (X 1000 t)	ER	TAC (X 1000 t)	ER	TAC (X 1000 t)
10	0	0.0	0	0.0	0	0	0	0
11	0	0.0	0	0.0	0	0	0	0
12	0	0.0	0	0.0	0	0	0	0
13	0	0.0	0	0.0	0	0	0	0
14	0	0.0	0	0.0	0	0	0	0
15	0	0.0	0	0.0	0	0	0	0
16	0	0.0	0	0.0	0	0	0	0
17	0	0.0	0	0.0	0	0	0	0
18	0	0.0	0	0.0	0	0	0	0
19	0	0.0	0	0.0	0	0	0	0
20	0.01	0.2	0	0.0	0	0	0	0
21	0.02	0.4	0	0.0	0	0	0	0
22	0.03	0.7	0	0.0	0	0	0	0
23	0.04	0.9	0	0.0	0	0	0	0
24	0.05	1.2	0	0.0	0	0	0	0
25	0.06	1.5	0	0.0	0.024	0.6	0	0
26	0.07	1.8	0	0.0	0.048	1.3	0	0
27	0.079	2.1	0	0.0	0.073	2.0	0	0
28	0.089	2.5	0	0.0	0.097	2.7	0.201	5.6
29	0.099	2.9	0.185	5.4	0.121	3.5	0.212	6.1
30	0.109	3.3	0.195	5.8	0.145	4.3	0.223	6.7
31	0.119	3.7	0.204	6.3	0.169	5.2	0.234	7.3
32	0.129	4.1	0.214	6.9	0.193	6.2	0.245	7.9
33	0.139	4.6	0.224	7.4	0.217	7.2	0.257	8.5
34	0.149	5.1	0.234	7.9	0.242	8.2	0.268	9.1
35	0.159	5.6	0.243	8.5	0.266	9.3	0.279	9.8
36	0.169	6.1	0.253	9.1	0.290	10.4	0.290	10.4
37	0.179	6.6	0.263	9.7	0.296	10.9	0.296	10.9
38	0.189	7.2	0.273	10.4	0.302	11.5	0.302	11.5
39	0.199	7.8	0.282	11.0	0.308	12.0	0.308	12.0
40	0.209	8.3	0.292	11.7	0.313	12.5	0.313	12.5
41	0.219	9.0	0.302	12.4	0.319	13.1	0.319	13.1
41.4	0.223	9.2	0.306	12.7	0.322	13.3	0.322	13.3
42	0.229	9.6	0.312	13.1	0.325	13.7	0.325	13.7
43	0.238	10.3	0.321	13.8	0.331	14.2	0.331	14.2
44	0.248	10.9	0.331	14.6	0.337	14.8	0.337	14.8
45	0.258	11.6	0.341	15.3	0.343	15.4	0.343	15.4
46	0.268	12.3	0.347	16.0	0.347	16.0	0.347	16.0
47	0.278	13.1	0.349	16.4	0.349	16.4	0.349	16.4
48	0.288	13.8	0.350	16.8	0.350	16.8	0.350	16.8
49	0.298	14.6	0.352	17.3	0.352	17.3	0.352	17.3
50	0.308	15.4	0.354	17.7	0.354	17.7	0.354	17.7
51	0.318	16.2	0.356	18.1	0.356	18.1	0.356	18.1
52	0.328	17.1	0.358	18.6	0.358	18.6	0.358	18.6
53	0.338	17.9	0.359	19.0	0.359	19.0	0.359	19.0
54	0.346	18.7	0.361	19.5	0.361	19.5	0.361	19.5
55	0.348	19.2	0.363	20.0	0.363	20.0	0.363	20.0
56	0.351	19.6	0.365	20.4	0.365	20.4	0.365	20.4
57	0.353	20.1	0.367	20.9	0.367	20.9	0.367	20.9
58	0.355	20.6	0.368	21.4	0.368	21.4	0.368	21.4
59	0.357	21.1	0.370	21.8	0.370	21.8	0.370	21.8

Biomass (X 1000 t)	A: α= 1.9,β = 1.3 ER	A: TAC (X 1000 t)	B: α= 1, β = 1.1, B_{crit} = 28,000 t ER	B: TAC (X 1000 t)	C: α= 2.4, β = 1.1, B_{low} = 36,000 t, ER_{low} = 0.29 ER	C: TAC (X 1000 t)	D: α= 1, β = 1.1, B_{crit} = 27,000 t, B_{low} = 36,000 t, ER_{low} = 0.29 ER	D: TAC (X 1000 t)
60	0.359	21.5	0.372	22.3	0.372	22.3	0.372	22.3
61	0.361	22.0	0.374	22.8	0.374	22.8	0.374	22.8
62	0.363	22.5	0.376	23.3	0.376	23.3	0.376	23.3
63	0.365	23.0	0.377	23.8	0.377	23.8	0.377	23.8
64	0.367	23.5	0.379	24.3	0.379	24.3	0.379	24.3
65	0.369	24.0	0.381	24.8	0.381	24.8	0.381	24.8
66	0.372	24.5	0.383	25.3	0.383	25.3	0.383	25.3
67	0.374	25.0	0.385	25.8	0.385	25.8	0.385	25.8
68	0.376	25.6	0.386	26.3	0.386	26.3	0.386	26.3
69	0.378	26.1	0.388	26.8	0.388	26.8	0.388	26.8
70	0.380	26.6	0.390	27.3	0.390	27.3	0.390	27.3



Appendix 4 Figure 1. Summary performance plots of four variants of the harvest decision rules in the cautious zone combined with the proportional decision rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= Blim is less than 5% in any year. The rules are not stock-trajectory dependent.



Appendix 4 Figure 2. Summary plots of the cumulative TAC over 50 years for four variants of the harvest decision rules in the cautious zone combined with the proportional decision rule in the healthy zone which would be PA compliant based on the probability of residual biomass being <= B_{lim} is less than 5% in any year. The rules are not stock-trajectory dependent.