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**Equilibrium estimates of Fmsy and
Bmsy for 3Pn4RS cod**

**Estimations à l'équilibre de Frms et
Brms pour la morue de 3Pn4RS**

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TABLE OF CONTENTS

LIST OF TABLES	iii
LIST OF FIGURES	iii
ABSTRACT	iv
RÉSUMÉ	iv
INTRODUCTION	1
METHODS	2
Projection model	2
Input data	2
Weight, maturity and numbers at age	2
Natural mortality	2
Stock-recruit relationships	3
Results	3
Discussion	4
Interpreting equilibrium F_{msy}	4
F in the healthy zone	5
A proposed PA framework for 3Pn4RS cod	6
Acknowledgements	6
References	7
Annex 1 : ageproR Code	8

LIST OF TABLES

Table 1: Summary of equilibrium reference points for nGSL cod under a range of assumptions for recruitment and natural mortality. HS is the hockey-stock model, NP is the non-parametric smoother model, RandR is randomly sampled recruitment at age 3 from 1974-2012. Full F is the F at Fmsy for the fully selected age classes. Fmsy is the numbers weighted average F for ages 7-9 that gives maximum equilibrium yield (MSY). MSY is the maximum equilibrium yield at Fmsy. Bmsy is the spawning biomass at equilibrium maximum yield. Blim and Busr are the limit and upper stock reference points (Duplisea and Fréchet 2011)..... 15

Table 2: F, exploitation rate and recommended TAC (t) at different SSB (t) following the PA framework laid-out in Figure 5. Exploitation rate = $1-e^{-M}$ 16

LIST OF FIGURES

Figure 1: The precautionary approach to fisheries management as developed in Canada (DFO 2009), developed slightly here to provide names for various elements and key features such as $F_{tar} < F_{lim}$ 17

Figure 2: beta distribution which was used to sample natural mortality values for stochastic projections. The black line is the simple random distribution while the red line is the same distribution sampled with first order temporal autocorrelation of 0.5..... 18

Figure 3: stock-recruitment relationships used in some projections. Recruitment is number of individuals to age 3. From Duplisea and Fréchet (2011). 18

Figure 4: Equilibrium yield and spawning biomass at different levels of fishing mortality calculated assuming a hockey-stick stock recruitment relationship and natural mortality that varies between 0.2 and 0.4. The thick dashed blue line is SSB while the thick solid red line is yield. Blim and Busr are shown as horizontal dashed lines while estimates for Bmsy (upper line) and MSY (lower line) are shown as solid horizontal lines. The vertical solid line is Fmsy. F(7-9) is the numbers weighted average F for ages 7, 8 and 9 while the fully selected F value is shown as a second x-axis on the panel. This is a depiction of Run 5 from Table 1..... 19

Figure 5: a proposed precautionary approach framework for 3Pn4RS cod based on Blim and Busr from Duplisea and Fréchet (2011), Fmsy and Bmsy from equilibrium estimates, F in the healthy zone = $\frac{2}{3}$ Fmsy and F in the critical zone = 0.02 (by catch F in 2011/12). 20

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ABSTRACT

Fmsy and Bmsy reference points for northern Gulf of St Lawrence (3Pn4RS) cod were estimated by projecting an age structured model to equilibrium under different F with various assumptions about stock-recruitment relationship and natural mortality resulting in 21 *a priori* reasonable scenarios. A preferred run was selected from the 21 different scenarios based on criteria related to consistency with previously estimated reference points as well which projection best represented the long-term (equilibrium) potential production of the stock accounting for uncertainty in natural mortality. The selected run was based on projection using a previously established fit of the hockey-stick stock-recruitment model combined with stochastic natural mortality ranging from 0.2-0.4 and a mean of 0.25. The Bmsy value from the preferred run was selected as the biomass target reference point (209,000 t) while $\frac{2}{3}$ Fmsy (0.16) was selected as the F strategy in the healthy zone recognising the F should have a low probability of exceeding Fmsy. The precautionary approach framework suggested for this stock conforms to international norms for PA development

RÉSUMÉ

On a estimé les points de référence Frms et Brms pour la morue du nord du golfe du Saint-Laurent (3Pn4RS) en projetant un modèle structuré par âge à l'équilibre pour différentes valeurs de F avec plusieurs hypothèses concernant la relation stock-recrutement et la mortalité naturelle, ce qui a donné 21 scénarios raisonnables *a priori*. Parmi ces 21 scénarios, on en a retenu un en se fondant sur des critères liés à la cohérence avec les points de référence déjà estimés et sur la projection qui représentait le mieux la production potentielle (équilibre) à long terme du stock compte tenu de l'incertitude relative à la mortalité naturelle. Ce scénario sélectionné reposait sur une projection établie à l'aide d'un ajustement antérieur du modèle Hockey Stick de stock-recrutement combiné à une mortalité naturelle stochastique comprise entre 0,2 et 0,4 et une médiane de 0,25. On a utilisé le point de référence de la cible de la biomasse (209 000 t) comme valeur du Brms pour ce scénario de prédilection et $\frac{2}{3}$ Frms (0,16) puisque la probabilité devrait être faible que la stratégie de pêche F dans la zone saine, compte tenu du taux de mortalité par pêche (F), dépasse le taux Frms. Le cadre de l'approche de précaution suggéré pour ce stock est conforme aux normes internationales en la matière.

INTRODUCTION

Implementations of the precautionary approach (PA) to fisheries management require several reference points (DFO 2009) (Fig 1). The reference points and levels are:

1. biomass limit reference point (Blim)
2. biomass upper stock reference point (Busr)
3. biomass target reference point (Btar)
4. a rule for allowed maximum fishing mortality in the critical zone as a function of spawning biomass (Fcz)
5. a rule for allowed maximum fishing mortality in the cautious zone as a function of spawning biomass (Frap)
6. a rule for target fishing mortality in the healthy zone as a function of spawning biomass (Ftar)
7. a rule for maximum allowed fishing mortality in the healthy zone as a function of biomass (Flim)

For 3Pn4RS cod presently, only Blim has been estimated and accepted as 116 000 t while a Busr of 180 000 t has been proposed by science (Duplisea & Fréchet 2011). Given that current stock state is only about 20 000 t, i.e. well below safe biological levels, the suggestion management action is clear and the development of other points is operationally unnecessary under present conditions. Nevertheless, for the sake of presenting a complete picture of the 3Pn4RS cod PA framework, all the other points and rules in the framework are presented here in the hope that a complete PA framework can aid with management planning and stakeholder buy-in to the PA.

The development of the five missing points depends on the estimate of the fishing mortality giving maximum sustainable yield (Fmsy). Fmsy is an accepted norm as the Flim for PA development (e.g. NAFO 2004). Once the Flim is decided then a target F lower than that can be established via simulation, projection or rule of thumb. Through equilibrium projection one can then determine Bmsy and MSY and Framp can be determined the straight line joining (Blim, Fcz) and (Busr, Ftar). Fcz would be a very small value (perhaps a by catch F in the critical zone) or even 0.

Fmsy for the purpose of PA reference point development requires an estimate that reflects the long term tendency of the stock. As such, the estimate needs to account not only for somatic growth and current recruitment of the stock but what could be considered the long term recruitment potential of the stock as a function of stock size as well as other population parameters such as mortality rate, and maturity and fishing selectivity. One can estimate various reference points such as F0.1 and Fmsy proxies from yield per recruit type of relationships but if there is a positive stock-recruit relationship for a stock they will tend to overestimate long-term (equilibrium) Fmsy because they do not consider the feedback between conserving biomass in the water to increase recruitment and yield later-on.

The goal of the present work was to fill out the remaining reference point estimates for the northern Gulf cod stock using equilibrium projections with a stock-recruitment relationship to determine Fmsy.

METHODS

PROJECTION MODEL

The method for projecting an age-structured model was programmed in R (R Development Core Team 2012). The method used here is similar to AGEPRO in the NOAA fisheries toolbox (NOAA 2012) so the present is called ageproR. Programming agepro in R opens up the flexibility of the R language for development and analysis. Also, AGEPRO tends to be designed mostly for short term stochastic projections for biomass while it is time consuming to re-run AGEPRO many times at different F values to determine equilibrium F_{msy} and B_{msy}. ageproR is more designed for the latter though it can also be used for short term stochastic projections. Not all features of AGEPRO have been implemented in ageproR although its modular structure can incorporate changes relatively easily through addition of new modules/subroutines.

ageproR takes vectors of numbers at age, weight at age in the sea, maturity at age, natural mortality at age and recruitment as a function of spawning stock biomass and projects the numbers vector one year at a time. In addition, a single value for fishing mortality in the fully selected age class can be applied to the stock which is then distributed to different age classes via the partial recruitment (fisheries selectivity). One can determine the yield resulting from this fishing mortality by multiplying number caught at age by the weight at age in the catch. The realised F weighted by numbers in a selected age class range can then be calculated. The code ageproR can be found in Annex 1.

INPUT DATA

Weight, maturity and numbers at age

Weight at age in sea was modelled as the mean weight in January over years from 1974-2012. Likewise weight in the catch was mean weight at age over years from the commercial catch from 1974-2012. Maturity at age was the mean maturity over the observed time series from 1974-2012.

For the purpose of starting off the projection the numbers at age in 2012 were used except in one case. Because all projections were run to equilibrium, the starting numbers at age do not matter as they all converge at the same equilibrium except when using the non-parametric stock recruitment relationship which displays strong depensatory dynamics. The depensation in this relationship is so strong that if starting numbers at age for 2012 (which are very low) are supplied then the stock cannot get out of the depensation pit unless $Z \leq 0.15$. However, if one starts the projection off so that numbers at age are in the upper plateau of the curve stock-recruit curve then equilibrium biomass and F_{msy} values are reasonable. Such is the nature of depensatory curves with depensation pits – they are sensitive to starting conditions this is a characteristic of the concept of the Allee effect and depensation and highlights why we need to be risk averse to their reference points.

Natural mortality

Natural mortality was usually fixed at 0.2, 0.25, 0.3 or 0.4 for projections and was constant over ages. In cases where M was not fixed it was randomly sampled from beta distribution that produced a maximum M value of 0.4 and a minimum of 0.2 with a mean of 0.25 (Fig 2). It was assumed that the very long term tendency for M of this stock would be closer to 0.2 than 0.4

which would probably be necessary to achieve stock size s in the $0.5-1.0 \times 10^6$ t SSB range which is a realistic value for unexploited equilibrium biomass of this stock.

For nGSL cod input M values have ranged from 0.2 – 0.4 with a mean over the time series of 0.3. We assume though that 0.3 may be too high an M value for this stock considering its very long term potential and conditions (e.g. several hundreds of years). The distribution of M values used therefore is considered more indicative of the M experienced by this stock.

In addition to random sampling M from a distribution, autocorrelation in M can be included. The impact of a first order autocorrelation coefficient is to narrow the distribution of M but the mean remains the same. It however can increase variance over the suite of bootstrap runs because the autocorrelation will produce runs of large or small M with greater probability thus projections may explore a larger range of stock space. That is, with autocorrelated M , the tails of the distribution are shorter but when a projection gets into the tail there is a greater probability it will stay there than with non-autocorrelated M .

Stock-recruit relationships

In most cases, recruitment was modelled using one or both of the accepted stock-recruitment relationships (SR) used for determining reference point for nGSL cod (Fig 3) (Duplisea and Fréchet 2011). In the case where an SR was not used, recruitment was randomly sampled from the time series of 1 January numbers at age 3 for the stock (1974-2012). The limit reference point for nGSL cod was determined as the mean reference point from the two stock-recruitment relationships here (116 000 t).

RESULTS

The model was projected to equilibrium (300 years) under a range of assumptions about natural mortality and recruitment. In addition, in one case a different starting year was selected. The results of these deterministic and stochastic projections are summarised in Table 1.

Both the choice of the recruitment model and the value for M had major impacts on the estimates of reference points for the stock. As M increased, F_{msy} decreased at equilibrium. The Hockey-stick model produced reasonable dynamics for these equilibrium projections while the non-parametric model randomly sampled recruitment usually did not produce credible or consistent reference points. The non-parametric model showed strong compensatory dynamics and thus two stable equilibrium points which could be affected by the starting point. For this reason runs 12 and 14 were duplicates of each other except the former started in 1983 when stock biomass was high while the latter started in 2012 when stock biomass was low. The reference points for these runs were very different from each other. Using the non-parametric stock-recruit model with strong compensatory dynamics of the form here may not be suitable for long term equilibrium projection of this sort.

Several runs produced results that were not credible or consistent. That is, they produced equilibrium values for B_{msy} that were less than B_{usr} (runs 4, 6, 17-21). When this results, it suggest that the parameters used in the projection are not consistent with the long term productivity dynamics of the stock. These cases are easily rejected as candidate runs for F_{msy} . Other runs produced F_{msy} estimates that were much greater than natural mortality for the stock (e.g. 0.2-0.4) (runs 6, 7, 12, 17-21). In one run (run 4) the M was so high relative to the recruitment rate that the stock went to near 0. This left run 1-3, 5, 8-11, 13-16 as candidates for reference points estimates for nGSL cod. Only these runs are considered for further analysis.

The natural mortality rates of nGSL cod are not well known or estimated outside of models presently. The most credible means of dealing with this kind of uncertainty is to sample M from a plausible distribution and bootstrap the analysis choosing the median. Runs 5, 16 represent this kind of stochastic projection. Run 5 calculated recruitment from the Hockey stick model and produced an F_{msy} of 0.24, B_{msy} of 209 000 t and MSY of 51 000 t. Run 16 gave a similar B_{msy} but a much larger MSY and F_{msy} suggesting a much more productive stock. Run 16 is probably well representative of the stock under high biomass conditions where the recruitment plateau's regardless of stock size. However, because the runs depicted here represent only those conditions (i.e. by starting the projection at high abundance in 1983), the NP model results are less appropriate for anchor a harvesting strategy that must include the stock productivity under low biomass conditions such as presently while the stock is in the critical zone.

Run 6 is the most plausible candidate which could be used as a basis for determining F_{msy} and B_{msy} (Fig 4). This stochastic equilibrium yield and biomass has a fairly well defined peak in the yield curve around $F=0.24$ and $SSB=208,000$ t which produces an equilibrium yield near 50,000 t annually.

DISCUSSION

INTERPRETING EQUILIBRIUM F_{MSY}

F_{msy} is a key estimate that one needs in order to develop a precautionary approach for stocks that complies with international standards. F_{msy} is internationally accepted as a limit reference point for fishing mortality (FAO 1995) and accordingly, the F_{msy} value, implicitly or explicitly defines the maximum acceptable level of fishing mortality on a stock that is in a relatively healthy state. The policy on the PA in Canada has a harvest control rule that can essentially be anchored by the F strategy in the healthy zone with a linear decrease in F with decreasing SSB to the B_{lim} value (DFO 2009, Fig 1). In order to develop a defensible harvest control rule for nGSL cod, F_{msy} estimated here as the F value at the peak of the equilibrium yield curve.

F_{msy} in practice is estimated in a few different ways which are fundamentally different from each other and can produce very different results: (1) yield per recruit analysis (F_{ypr}) (2) proxy methods based on observed data (3) equilibrium estimates using a stock-recruitment relationship. F_{msy} that fully accounts for all components of production (growth, survival and recruitment) can be estimated using only the third method. Method 1 produces an estimate of F that will maximise the yield from a cohort recognising that there is a tradeoff with the benefit of leaving fish in the water to grow big and the loss of fish over time to natural mortality. Proxy methods generally look at the fishing history of the stock and determine the yields and fishing mortality that did not lead to large changes in stock size and assume that is F_{msy} but depends on the range of F , yield and SSB space the stock has explored and been observed. Equilibrium estimates F_{msy} from models take into account, growth and mortality of the stock as in the first method but additionally recognise recruitment as a component of production which affects long term equilibrium yields. For this reason, F_{msy} can vary widely depending on the stock-recruitment dynamics included and this can interact with natural mortality often in a way that is the opposite of a yield per recruit analysis.

Equilibrium F_{msy} is important to determine for nGSL cod presently as opposed to yield per recruit F_{msy} or a proxy F_{msy} because those two methods (especially the former) are likely to strongly overestimate the F that can be inflicted on the stock. F_{ypr} will always show the characteristic of increasing as M increases. This is because if M is high it benefits yield if fishing

mortality is increased thus removing the fish in catch rather than surrendering them to M. However, consider the fact that if a stock-recruitment relationship exists and then it also becomes advantageous to leave fish in the water to spawn and produce more fish. Equilibrium estimates therefore tradeoff M, F and R and for ranges of M, they tend to show decreasing Fmsy for increasing M because it can still be advantageous for yield over the long term so that they make a contribution to SSB which increases R which in turn increases SSB. Equilibrium projections will always keep Z (F+M) at a level where the stock biomass can move to the most productive part of the SR curve. In a system where we can control only F and not M or R, then F needs to decrease to compensate for large M in order to get Z to a level where the stock can be most productive.

The SR curve used to determine equilibrium Fmsy has a strong impact on the shape of the yield curve. The hockey-stock SR model shows increasing R/S to a certain SSB and then levels off at a particular R regardless of any further increase in SSB. Therefore, the hockey stick model tends to produce an Fmsy that takes the stock biomass to the area near the breakpoint SSB value and once F increases beyond that, there is a rapid decline in both yield and SSB. This point of decline essentially represents the recruitment overfishing point. Other kinds of relationships with more gradual declines from peak R/S will tend to show smoother yield curves. Depensation SR curves can show very drastic changes in the yield curves near the depensation point but the shape of the yield curve will also depend on how R/S varies on either side of the depensation point. In the present analysis, the NP curve is depensatory but shows very little change in R/S with SSB below or above the depensation point. This is essentially a two R regime curve and the stock may never be able to get to the most productive part of the SR relationship if it gets stuck at low SSB even with relatively normal levels of M and no fishing (i.e. if $Z > 0.15$).

Equilibrium estimates of Fmsy are necessary for a PA framework yet they are of a fundamentally different character than most other reference points. Because they are equilibrium and fished systems are never in equilibrium then these points must be considered long term ideals which are unlikely to lead to exactly to the equilibrium result given uncertainties. For the reason that they are ideals, however, the equilibrium conditions should also be considered what is 'normal' averaged over a very long period, e.g. hundreds of years. This kind of projection is therefore also quite different then what would be used use for say 3-5 year projections for the purpose of TAC setting. Shorter term projects should be based on more current conditions rather than long term average conditions.

F IN THE HEALTHY ZONE

The acceptable level of fishing mortality in the healthy zone should be sufficiently less than Fmsy that there is a small chance of F exceeding Fmsy. Ideally such an evaluation takes into account many sources of uncertainty to come up with a robust F strategy. That kind of exercise is demanding however and given that this stock is currently well into the critical zone, this consideration is unlikely to come into play until several years of significant stock growth are observed. In the meantime, a proxy for a robust F strategy in the healthy zone is to use $\frac{2}{3}$ Fmsy. $\frac{2}{3}$ Fmsy is considered a good approximation to F0.1 for demersal stocks (Smith et al 1993). $\frac{2}{3}$ Fmsy is used as a harvest strategy for 3LNO yellowtail flounder (Walsh et al 2002) and it has proven a robust strategy that has helped to rebuild that stock. Fmsy has also been used as the F target (Fpa) for Greenland halibut in ICES areas V and XIV (EC 2003). A slightly more conservative point of $\frac{2}{3}$ MSY rather than $\frac{2}{3}$ Fmsy has been suggested as a default in New Zealand as an appropriate long-term yield for a stock near or above Bmsy (MF 2007). DaRocha (2012) found that $\frac{2}{3}$ Fmsy was close to the economically optimal F target for European hake

captured in mixed fisheries. Clearly, there are good grounds and precedents for F targets in the vicinity of $\frac{2}{3}F_{msy}$ for keeping stocks near B_{msy} without sacrificing much yield below MSY.

Given the uncertainties as to M value and stock-recruitment relationship for this stock over the long term, runs 5 is the most suitable candidate. Other runs that may appear to be credible because they also include random M (Run 16) is based on the inclusion of a strong depensatory stock-recruitment curve but only for conditions in the depensation where stock productivity is relatively high.

Depensation as a concept is not completely neglected in the framework here, however. Depensation has some influence on the setting of B_{lim} as the non-parametric stock-recruitment curve estimate of B_{lim} was averaged with that of the hockey-stick curve. Without the NP curve, the B_{lim} would be 95 000 t. Also for this same reason, it would be wise to consider a thorough re-assessment of this stock should the biomass approach the B_{lim} suggestion from the hockey stock model alone (95 000 t).

Given that $\frac{2}{3}F_{msy}$ has established precedents as an acceptably prudent harvest strategy and that considerations of varying M and stock-recruitment relationship. it is suggested that $\frac{2}{3}F_{msy}$ from Run 5 (e.g. $\frac{2}{3} 0.24$) be used as the F strategy in the healthy zone until the next full re-evaluation of reference points which may include simulation approaches. Given that the stock is well into the critical zone, the estimate for F in the healthy zone is unlikely to have any impact on science-based advice for the stock in the next several years.

A PROPOSED PA FRAMEWORK FOR 3PN4RS COD

Accepting a F_{msy} and B_{msy} value for the stock, a multiplier of F_{msy} as a buffer on that ($\frac{2}{3} F_{msy}$), as well as setting the allowable exploitation rate in the critical zone to be equal to by-catch levels (400 t) at current biomass levels (~20 000 t), i.e. $F=0.02$, then it is possible. A framework is described below based on these considerations with F_{msy} and B_{msy} from run 5.

If the PA framework shown in Fig. 5 is accepted then at B_{lim} the recommended TAC would be about 2 500 t at about 2% exploitation (Table 2). Exploitation rate would then rise to about 15% at B_{usr} where the recommended TAC would be about 27 500 t and about 31 500 t at the target biomass.

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François Grégoire for generously sharing his ideas, input files in NFT and output files from VPA as well as showing me how to use NFT VPA. Dominique Gascon for helping me select appropriate reference points runs with his intuitive understanding of equilibrium PA reference points.

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ANNEX 1 : ageproR Code

```
#####
#####
# Projection of an age structured population with fishing mortality
# Written by Daniel Duplisea, Fisheries and Oceans Canada, Institut
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# December 2012
# Use and distribute as you wish but I can accept no responsibility for any
# consequences
#####

#####
# the most basic projection function. This is the engine of all other
# projections. Other functions loop this one for multiple F scenarios and/or for
# stochastic results and then calculate medians. It is rare that you would want
# to run this function on its own. F=0 will give you an error
#####
ageproR.deter.proj.f= function(start.year=2012, fully.selected=F=1e-12,
  all.mean=T, stochastic.M=F){

  projection.length= ageproR.inputs$projection.length
  # Starting Conditions
  # syp = last data year position. Note that this year can be first data years
  # + age at recruitment at the earliest
  syp= grep(start.year,names(ageproR.inputs$N))
  if (syp<ageproR.inputs$age.at.R) stop(paste("start year selected is too early",
    "earliest year possible = start year + age at recruitment - 1"))
  # end year of the simulation (last data year year + sim length)
  end.year= start.year + projection.length
  # the actual years to be simulated (including the start years which is data)
  years=length((start.year-ageproR.inputs$age.at.R):end.year)

  # data starting conditions
  # numbers at age used to start
  N.start= ageproR.inputs$N[, (syp-ageproR.inputs$age.at.R+1):syp]
  # weight at age used to start,
  WA.sea.start= ageproR.inputs$WA.sea[, (syp-ageproR.inputs$age.at.R+1):syp]
  WA.sea.mean= apply(WA.sea.start,1,mean)
  WA.catch.mean= ageproR.inputs$WA.catch[, (syp-ageproR.inputs$age.at.R+1):syp]
  # ogive used to start, see below if all.mean=T
  ogive.start= ageproR.inputs$ogive[, (syp-ageproR.inputs$age.at.R+1):syp]
  ogive.mean= apply(ogive.start,1,mean)
  # SSB values for starting (used for calculating R)
  SSB.start= apply(N.start*WA.sea.start*ogive.start,2,sum)
  #partial recruitment i.e. fishery selectivity
  PR= ageproR.inputs$PR[,1]
  # the Leslie parameter matrix
  A.base= matrix(0,ncol=ageproR.inputs$number.ages,nrow=ageproR.inputs$number.ages)
  if (all.mean==T){
    # data starting conditions with mean over all years for ogive, weight at age
    WA.sea.mean= apply(ageproR.inputs$WA.sea,1,mean)
    WA.catch.mean= apply(ageproR.inputs$WA.catch,1,mean)
    ogive.mean= apply(ageproR.inputs$ogive,1,mean)
  }

  # output data structures including the data from years used to start the
  # projection: numbers at age data matrix, SSB vector
  sim.N= matrix (nrow= ageproR.inputs$number.ages,
    ncol=projection.length+ageproR.inputs$age.at.R+1)
  sim.N[, (1:ageproR.inputs$age.at.R)] = as.matrix(N.start)
  sim.F= matrix(nrow= ageproR.inputs$number.ages,
    ncol=projection.length+ageproR.inputs$age.at.R+1)
  sim.Ncatch= matrix(nrow= ageproR.inputs$number.ages,
    ncol=projection.length+ageproR.inputs$age.at.R+1)
  N= sim.N[,ageproR.inputs$age.at.R]
  sim.SSB= vector(length=projection.length+ageproR.inputs$age.at.R+1)
  sim.SSB[1:ageproR.inputs$age.at.R]= SSB.start
  sim.landings= vector(length=projection.length+ageproR.inputs$age.at.R+1)
  sim.F.mean= vector(length=projection.length+ageproR.inputs$age.at.R+1)

  if (stochastic.M) M.vals= eval(ageproR.inputs$M.rand) else M.vals=
    rep(ageproR.inputs$M,projection.length+ageproR.inputs$age.at.R+1)

##### PROJECTION LOOP #####
  for (year in (ageproR.inputs$age.at.R+1):years){

    # Recruitment
```

```

R= ageproR.SR.f(SSB=sim.SSB[year-ageproR.inputs$age.at.R+1])
pc.fertility= matrix(R*((N * ogive.mean)/sum(N * ogive.mean))/N,nrow=1)

## fishery removals
# only F strategies presently. TAC can be added easily but need to
# iterate catch equation to convert to F.
if (fully.selected.F>0) F.proj= fully.selected.F else
  F.proj= agepro.hcr.f(SSB)
F.age= F.proj * PR

## Removals: F and M
M= M.vals[year]
N.death= N*(1-exp(-(F.age+M)))
catch= sum((F.age/(F.age+M)) * N.death * WA.catch.mean)

## Combine gains and losses into survival rates - make diagonal in Leslie
# matrix and matrix multiplication to move to next year
survival.rate= 1-N.death/N
diag(A.base)= survival.rate
A= rbind(pc.fertility, A.base[-length(N),])
N= A %*% N

  sim.N[,year]= N
  sim.SSB[year]= sum(N * WA.sea.mean * ogive.mean)
  sim.F[,year]= F.age
  sim.Ncatch[,year]= N.death
  sim.landings[year]= catch
}
# numbers weighted mean F over selected age range
sim.F.mean= apply(sim.F[ageproR.inputs$F.mean.ages-ageproR.inputs$age.at.R,
  (ageproR.inputs$age.at.R+1):years]*sim.N[ageproR.inputs$F.mean.ages-
  ageproR.inputs$age.at.R, (ageproR.inputs$age.at.R+1):years],2,sum)/
  apply(sim.N[ageproR.inputs$F.mean.ages-ageproR.inputs$age.at.R,
  (ageproR.inputs$age.at.R+1):years],2,sum)

# make a record of the M used to document in output list
if (stochastic.M){
  M.record= ageproR.inputs$M.rand
  ageproR.inputs$M="M.rand"
}
M.record= ageproR.inputs$M

# all the object to stick into the output list. Includes the simulation
# results and summary results
all.out= list(year=(start.year-ageproR.inputs$age.at.R):end.year, N=sim.N, SSB=
  sim.SSB, FatA= sim.F, Catch.N= sim.Ncatch, landings= sim.landings, F.mean=
  sim.F.mean, M=M.record, params= ageproR.inputs, SR.model= ageproR.SR.f)
all.out
}

#####
# Stock-recruitment model. Random R and non-parametric models are commented-
# out. The hockey stick is the main model. If you want to program uncertainty
# into the SR model you should do it here. This is a bit different than other
# kinds of uncertainty which can be selected as switches but this is because
# the SR model needs to be called on each time-step and if-then statements make
# the stochastic process much slower
#####
ageproR.SR.f= function(SSB){
# hockey stick SR curve
HS.breakpoint= c(190156.0, 109505.9)
slope= HS.breakpoint[2] / HS.breakpoint[1]
R= SSB * slope
R[SSB > HS.breakpoint[1]]= HS.breakpoint[2]
R
}

#ageproR.SR.f= function(SSB){
# R from observed R at age 3
# R= sample(as.numeric(ageproR.inputs$N[1,]),1)
# R
#}

# non parametric smoother SR curve
#setwd("C:/Documents and Settings/duplisead/Desktop/agepro")
#setwd("C:/Users/daniel/Google Drive/agepro")

#load ("NP.bin")
#ageproR.SR.f= function(SSB){
# non-parametric model. you need the non-parametric model fit object in
# your workspace for this to work. (see Duplisea and Frechet 2009)
# R= predict(NP,SSB)$y

```

```

# R
#}

ageproR.SR.f= function(SSB){
# #randomly select either the HS or NP R estimate at each time step
# HS.breakpoint= c(190156.0, 109505.9)
# slope= HS.breakpoint[2] / HS.breakpoint[1]
# R.HS= SSB * slope
# R.HS[SSB > HS.breakpoint[1]]= HS.breakpoint[2]
# R.NP= predict(NP,SSB)$y
# R= sample(c(R.HS,R.NP),1)
# R
#}

#####
# sample M from a beta distribution with cutoffs
#####
ageproR.M.beta.f= function(N.points,a,b,min.M,max.M,autocor.coef){
  M.vec= rbeta(N.points,a,b)+min.M
  M.vec[M.vec>max.M]= max.M
  M.vec= ageproR.autocor.M.f(M.vec,autocor.coef)
  M.vec
}

#####
# put an autocorrelation signal in randomly sampled M values
#####
ageproR.autocor.M.f= function(M.vals, AC){
  # M.vals is the temporal series of random M values
  # AC is the first order autocorrelation strength (0-1)

  AC.series=vector()
  M= M.vals[1]
  AC.series[1]= M
  counter=2
  for (i in M.vals[-1]){
    M= M*AC + M.vals[counter]*(1-AC)
    AC.series[counter]= M
    counter= counter+1
  }
  AC.series
}

#####
# run the deterministic projection to over a range of F values.
# if you want equilibrium estimates you need to run it for many
# years. 300 is a good number but it usually converges well before then
# F.range is a vector. F=0 will give you an error
#####
ageproR.deter.yield.curve.f= function(F.range=c(seq(.0001,.7,length=60)),
  start.year=2012,all.mean=T){
  agepro.Fmsy= matrix(nrow= length(F.range),ncol=4)
  agepro.Fmsy[,1]= F.range
  counter=1
  for(F.val in F.range){
    sims= ageproR.deter.proj.f(start.year=start.year, all.mean=all.mean,
      fully.selected=F.val, stochastic.M=F)
    #select the realised F in the last simulated year (i.e. at equilibrium)
    agepro.Fmsy[counter,2]= rev(sims$F.mean)[1]
    agepro.Fmsy[counter,3]= rev(sims$landings)[1] #catch at equil
    agepro.Fmsy[counter,4]= rev(sims$SSB)[1] #SSB at equil
    counter= counter+1
  }
  agepro.Fmsy= as.data.frame(agepro.Fmsy)
  names(agepro.Fmsy)= c("F.fs","Pages","catch","SSB")
  agepro.Fmsy
}

#####
# The stochastic implementation of the yield curve. It loops the projection for
# MC.N number of bootstraps
#####
ageproR.stoch.yield.curve.f= function(F.range=c(seq(.0001,1,length=40)),
  MC.N=300,stochastic.M=T, start.year=2012, all.mean=T, descriptor=""){

  # a matrix to hold median values from MC runs
  agepro.Fmsy= matrix(nrow= length(F.range),ncol=4)
  agepro.Fmsy[,1]= F.range
  # an array to hold 100 quantile values from the MC runs
  agepro.Fmsy.quantiles= array(dim=c(length(F.range),101,3))
  agepro.Fmsy.quantiles[,1,]= F.range

```

```

counter=1
for(F.val in F.range){
  F.vals= vector(length=MC.N)
  land.vals= vector(length=MC.N)
  SSB.vals= vector(length=MC.N)
  for (MC.run in 1:MC.N){
    Fmsy.runs= ageproR.deter.proj.f(start.year=start.year,fully.selected.F=
      F.val,all.mean=all.mean, stochastic.M=stochastic.M)
    F.vals[MC.run]= rev(Fmsy.runs$F.mean)[1]
    land.vals[MC.run]= rev(Fmsy.runs$landings)[1]
    SSB.vals[MC.run]= rev(Fmsy.runs$SSB)[1]
  }
  # put the output into matrix and array. It is redundant to put the median
  # in a separate matrix when it is the 0.5 quantile in the array but for the
  # sake of having a more comprehensible output list it is done this way.
  agepro.Fmsy[counter,2]= median(F.vals)
  agepro.Fmsy[counter,3]= median(land.vals)
  agepro.Fmsy[counter,4]= median(SSB.vals)
  agepro.Fmsy.quantiles[counter,2:101,1]= quantile(F.vals,(1:100)/100)
  agepro.Fmsy.quantiles[counter,2:101,2]= quantile(land.vals,(1:100)/100)
  agepro.Fmsy.quantiles[counter,2:101,3]= quantile(SSB.vals,(1:100)/100)
  counter= counter+1
}
agepro.Fmsy= as.data.frame(agepro.Fmsy)
names(agepro.Fmsy)= c("F.fs","Fages","catch","SSB")
dimnames(agepro.Fmsy.quantiles)=list(paste("F",round(F.range,3),sep=""),
  c("F.full",paste("Q",(1:100)/100,sep="")),c("Fvals","landings","SSB"))
# median values for MSY, Fmsy, Bmsy and fully selected F
vals.median= agepro.Fmsy[match(max(agepro.Fmsy$catch),agepro.Fmsy$catch),]
# position in the array of distribution MSY based values
position.MSY= match(max(agepro.Fmsy.quantiles[,51,2]),
  agepro.Fmsy.quantiles[,51,2])
# the distributions of Fmsy, MSY and Bmsy
Fmsy.dist= agepro.Fmsy.quantiles[position.MSY,-1,1]
MSY.dist= agepro.Fmsy.quantiles[position.MSY,-1,2]
SSB.dist= agepro.Fmsy.quantiles[position.MSY,-1,3]
result= list(descriptor=descriptor, median.vals= agepro.Fmsy, quantile.vals=
  agepro.Fmsy.quantiles, params= ageproR.inputs, SR.model= ageproR.SR.f,
  M.vals= Fmsy.runs$M, ref.pts.medians= vals.median, Fmsy.dist=Fmsy.dist,
  MSY.dist=MSY.dist, SSB.dist=SSB.dist, MC.N= MC.N)
result
}

```

```

#####
#####
# Projection of an age structured population with fishing mortality
# Written by Daniel Duplisea, Fisheries and Oceans Canada, Institut
# Maurice-Lamontagne, Mont-Joli, QC G0J 1Z0
# daniel.duplisea@dfo-mpo.gc.ca
# December 2012
# Use and distribute as you wish but I can accept no reponsibility for any
# consequences
#####

#####
#plots the result of a simple projection, SSB vs year. The only use of this
# function generally is to determine how far you need to project to reach
# equilibrium and adjust the projection length for stochastic projs accordingly
#####
ageproR.plot.proj.f= function(deter.proj.result){
  plot(deter.proj.result$year,deter.proj.result$SSB, type="p", xlab="Year",
       ylab="SSB (t)", pch=20)
}

#####
# plot yield curve for different deterministic F values. It plots yield and
# SSB as a function of numbers average F
#####
ageproR.plot.deter.yield.curve.f= function(deter.yield.result, top.xaxis=T){
  F.label= paste("F (",min(ageproR.inputs$F.mean.ages),"-",max(ageproR.inputs$
  F.mean.ages),")",sep="")
  matplot(deter.yield.result[,2],deter.yield.result[,3:4],axes=T,lab=c(5,5,7),
         lwd=3,type="l",col=c("red","blue"),lty=c(1,2), xlab=F.label,
         ylab="Equilibrium yield & SSB (t)")
  legend("topright",legend=c("Yield","SSB"),col=c("red","blue"),lty=c(1,2),lwd=2)
  vals= deter.yield.result[match(max(deter.yield.result$catch),
  deter.yield.result$catch),]
  abline(v=vals[2])
  abline(h=vals[3])
  abline(h=vals[4])
  abline(h=ageproR.inputs$Blim, col="red",lty=2)
  abline(h=ageproR.inputs$Busr, col="red",lty=2)
  # this puts a second x axis at the top showing the fully selected F value
  # at the same tick position as on the lower x-axis
  if (top.xaxis){
    ticks= seq(0,round(max(deter.yield.result[,2]),1),length=5)
    tmp= lm(deter.yield.result[,1]~deter.yield.result[,2])
    tick.labs= round(coef(tmp)[1]+ ticks*coef(tmp)[2],2)
    tick.labs[tick.labs<0]=0
    axis(side=3,at=ticks, labels=tick.labs)
    mtext("Fully selected F",side=3,line=2.2)
  }
}

#####
# plots the stochastic yield curve
#####
ageproR.plot.stoch.yield.curve.f= function(proj.output,top.xaxis=T, error.box=T){
  median.vals.plot= proj.output$median.vals
  matplot(median.vals.plot[,2],median.vals.plot[,3:4],lwd=3,type="l",col=
  c("red","blue"),lty=c(1,2), xlab="F(ages 7-9)",
  ylab="Equilibrium yield & SSB")
  legend("topright",legend=c("Yield","SSB"),col=c("red","blue"),lty=c(1,2),lwd=2)
  vals= proj.output$ref.pts.medians
  abline(v=vals[2])
  abline(h=vals[3])
  abline(h=vals[4])
  abline(h=ageproR.inputs$Blim, col="red",lty=2)
  abline(h=ageproR.inputs$Busr, col="red",lty=2)
  if (top.xaxis){
    # this puts a second x axis at the top showing the fully selected F value
    # at the same tick position as on the lower x-axis
    ticks= seq(0,round(max(median.vals.plot[,2]),1),length=5)
    tmp= lm(median.vals.plot[,1]~median.vals.plot[,2])
    tick.labs= round(coef(tmp)[1]+ ticks*coef(tmp)[2],2)
    tick.labs[tick.labs<0]=0
    axis(side=3,at=ticks, labels=tick.labs)
    mtext("Fully selected F",side=3,line=2.2)
  }
}

```

```
# this plots all the quantiles around the median for both Fmsy and Yield on
# the plot as a box with actual quantiles as the shaky line through the box
if (error.box){
  lines(proj.output$Fmsy.dist,proj.output$MSY.dist)
  coords= c(min(proj.output$Fmsy.dist), min(proj.output$MSY.dist),
            max(proj.output$Fmsy.dist),max(proj.output$MSY.dist))
  rect(coords[1],coords[2],coords[3],coords[4])
  }
}
```

```

#####
#####
# Projection of an age structured population with fishing mortality
# Written by Daniel Duplisea, Fisheries and Oceans Canada, Institut
# Maurice-Lamontagne, Mont-Joli, QC G0J 1Z0
# daniel.duplisea@dfo-mpo.gc.ca
# December 2012
# Use and distribute as you wish but I can accept no reponsibility for any
# consequences
#####

#####
# Parameters required to do age based projection
# note that all the parameters in this list may not be used in the projection.
# Typically the units are *1000 for numbers, kg for weight at age, metric tonnes
# for stock biomass and rates are per year. You should change parameters here
# because several functions keep a history of the run parameters by copying
# this list into the output object.
#####
ageproR.inputs=list()

# length of the projection in years
ageproR.inputs$projection.length=300

# starting population numbers at age size 1 Jan
ageproR.inputs$N=read.csv("NatA.csv",sep = ",",header=T)

# weight at age, Kg, in the survey or the sea, used for SSB calculation
ageproR.inputs$WA.sea= read.csv("WatAsea.csv",sep = ",",header=T)

# Weight at age, Kg in the catch, used for landings and turning a TAC into
# numbers at age (also with selectivity - PR)
ageproR.inputs$WA.catch= read.csv("WatAcatch.csv",sep = ",",header=T)

# maturity ogive: proportion mature by biomass in age class
ageproR.inputs$ogive= read.csv("ogive.csv",sep = ",",header=T)

# number of age groups
ageproR.inputs$number.ages= nrow(ageproR.inputs$N)

# first age (age at recruitment)
ageproR.inputs$age.at.R= 3

# M at age. If one scalar then same over all ages. Can be a vector
ageproR.inputs$M= 0.25

# Random M sampled from a beta. If no autocorrelation then set autocor.coef.M=0
ageproR.inputs$a= 1.6 #parameter of the call to the beta function
ageproR.inputs$b= 30 #parameter of the call to the beta function
ageproR.inputs$min.M= 0.2 #minimum M allowed
ageproR.inputs$max.M= 0.4 #maximum M allowed
ageproR.inputs$autocor.coef.M= 0.5
ageproR.inputs$M.rand= call("ageproR.M.beta.f",ageproR.inputs$projection.length+
ageproR.inputs$age.at.R+1,ageproR.inputs$a,ageproR.inputs$b,
ageproR.inputs$min.M,ageproR.inputs$max.M, ageproR.inputs$autocor.coef.M)

# partial recruitment, ie. selectivity of fishery (all fleets)
# column 1 is acutal value from assessment (2012 NFT adapt), column 2 is
# flat topped version
ageproR.inputs$PR= cbind(c(0.0011,0.0438,0.2239,0.5865,0.9671,1,1,0.9722,
0.9283,0.8551,0.9283),c(0.0011,0.0438,0.2239,0.5865,0.9671,1,1,1,1,1))

# ages used for numbers weighted overall F calculation
ageproR.inputs$F.mean.ages= 7:9

# reference points: Blim=limit, Busr=upper stock reference, Btar=target,
# Bdetect=detection limit
ageproR.inputs$Blim=116000
ageproR.inputs$Busr=180000
ageproR.inputs$Btar=220000
ageproR.inputs$Bdetect=1000

```

Table 1: Summary of equilibrium reference points for nGSL cod under a range of assumptions for recruitment and natural mortality. HS is the hockey-stock model, NP is the non-parametric smoother model, RandR is randomly sampled recruitment at age 3 from 1974-2012. Full F is the F at Fmsy for the fully selected age classes. Fmsy is the numbers weighted average F for ages 7-9 that gives maximum equilibrium yield (MSY). MSY is the maximum equilibrium yield at Fmsy. Bmsy is the spawning biomass at equilibrium maximum yield. Blim and Busr are the limit and upper stock reference points (Duplisea and Fréchet 2011).

Run number	SR	M	start year	Full F	Fmsy	MSY	Bmsy	2/3 Fmsy	Blim	Busr
1	HS	0.2	2012	0.46	0.36	72189	203908	0.24	116000	180000
2	HS	0.25	2012	0.33	0.26	51991	199070	0.17	116000	180000
3	HS	0.3	2012	0.18	0.14	30487	209099	0.09	116000	180000
4	HS	0.4	2012	0.03	0.02	17	820	0.01	116000	180000
5	HS	0.2-0.4	2012	0.31	0.24	50971	208928	0.16	116000	180000
6	NP	0.15	2012	0.62	0.47	11153	24390	0.32	116000	180000
7	NP	0.2	1983	0.74	0.56	95568	187144	0.37	116000	180000
8	NP	0.25	1983	0.56	0.43	74997	186109	0.29	116000	180000
9	NP	0.3	1983	0.38	0.30	54566	190333	0.20	116000	180000
10	NP	0.4	1983	0.10	0.08	15530	191461	0.05	116000	180000
11	NP	0.2-0.4	1983	0.51	0.39	72161	193174	0.26	116000	180000
12	HS-NP	0.2	1983	0.74	0.56	95568	187144	0.37	116000	180000
13	HS-NP	0.25	1983	0.56	0.43	74997	186109	0.29	116000	180000
14	HS-NP	0.3	1983	0.38	0.30	54566	190333	0.20	116000	180000
15	HS-NP	0.4	1983	0.10	0.08	15530	191461	0.05	116000	180000
16	HS-NP	0.2-0.4	1983	0.51	0.39	72081	192944	0.26	116000	180000
17	Rand-R	0.2	2012	1.28	0.95	44628	60830	0.64	116000	180000
18	Rand-R	0.25	2012	1.30	0.96	37092	51205	0.64	116000	180000
19	Rand-R	0.3	2012	1.26	0.93	30819	44887	0.62	116000	180000
20	Rand-R	0.4	2012	1.26	0.92	21795	33639	0.61	116000	180000
21	Rand-R	0.2-0.4	2012	1.26	0.92	21795	33639	0.61	116000	180000

Table 2: F , exploitation rate and recommended TAC (t) at different SSB (t) following the PA framework laid-out in Figure 5. Exploitation rate = $1-e^{-M}$.

SSB	F	Exploitation rate	TAC
116000	0.02	0.02	2500
120000	0.03	0.03	3500
125000	0.04	0.04	5000
130000	0.05	0.05	6500
135000	0.06	0.06	8000
140000	0.07	0.07	10000
145000	0.08	0.08	11500
150000	0.09	0.09	13500
155000	0.11	0.10	15500
160000	0.12	0.11	17500
165000	0.13	0.12	20000
170000	0.14	0.13	22000
175000	0.15	0.14	24500
180000	0.16	0.15	27000
185000	0.16	0.15	27500
190000	0.16	0.15	28500
195000	0.16	0.15	29000
200000	0.16	0.15	30000
205000	0.16	0.15	30500
210000	0.16	0.15	31500
215000	0.16	0.15	32000
220000	0.16	0.15	32500
225000	0.16	0.15	33500
230000	0.16	0.15	34000
235000	0.16	0.15	35000
240000	0.16	0.15	35500
245000	0.16	0.15	36500
250000	0.16	0.15	37000

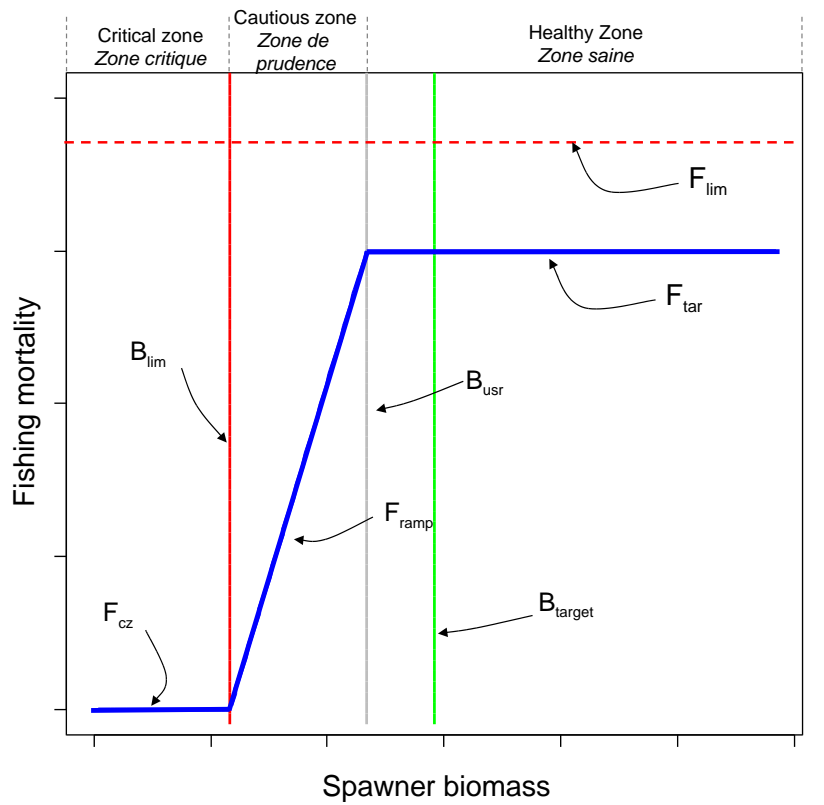


Figure 1: The precautionary approach to fisheries management as developed in Canada (DFO 2009), developed slightly here to provide names for various elements and key features such as $F_{tar} < F_{lim}$.

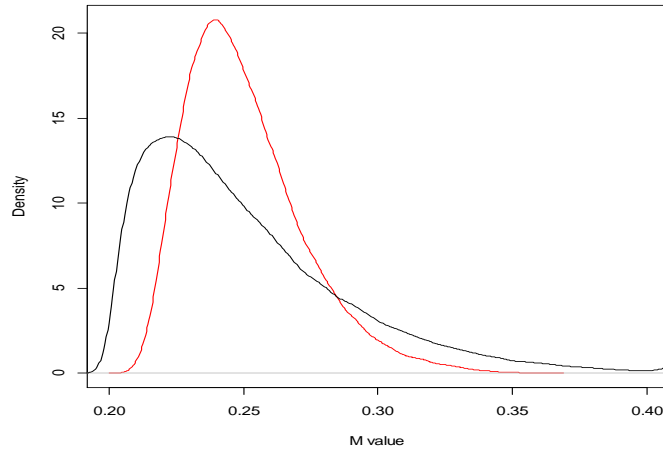


Figure 2: beta distribution which was used to sample natural mortality values for stochastic projections. The black line is the simple random distribution while the red line is the same distribution sampled with first order temporal autocorrelation of 0.5.

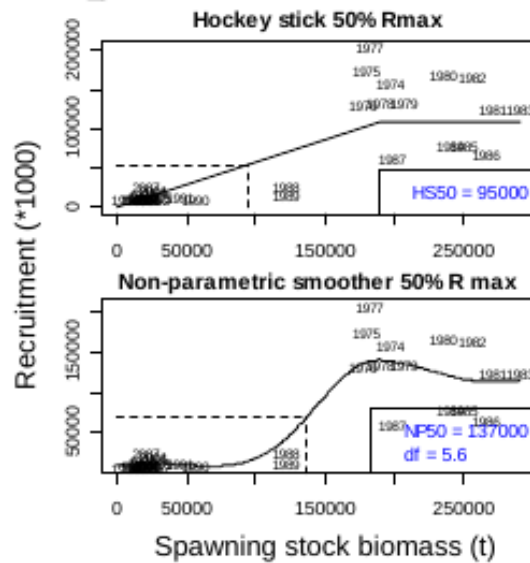


Figure 3: stock-recruitment relationships used in some projections. Recruitment is number of individuals to age 3. From Duplisea and Fréchet (2011).

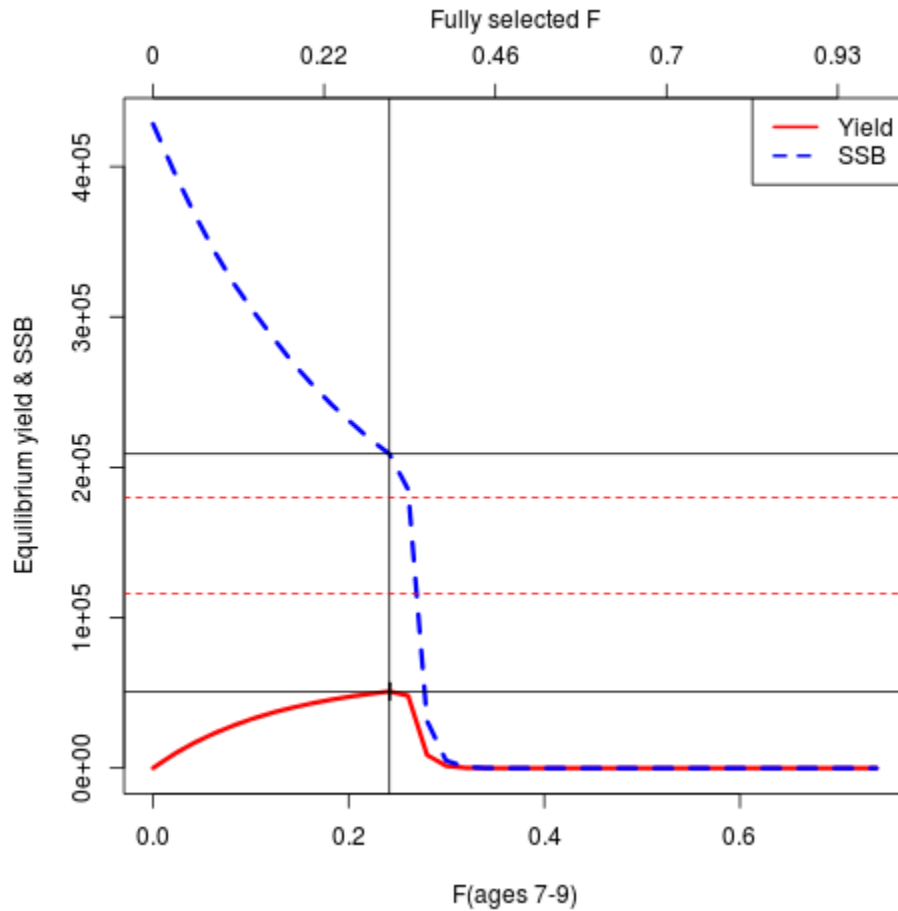


Figure 4: Equilibrium yield and spawning biomass at different levels of fishing mortality calculated assuming a hockey-stick stock recruitment relationship and natural mortality that varies between 0.2 and 0.4. The thick dashed blue line is SSB while the thick solid red line is yield. B_{lim} and B_{usr} are shown as horizontal dashed lines while estimates for B_{msy} (upper line) and MSY (lower line) are shown as solid horizontal lines. The vertical solid line is F_{msy} . $F(7-9)$ is the numbers weighted average F for ages 7, 8 and 9 while the fully selected F value is shown as a second x-axis on the panel. This is a depiction of Run 5 from Table 1.

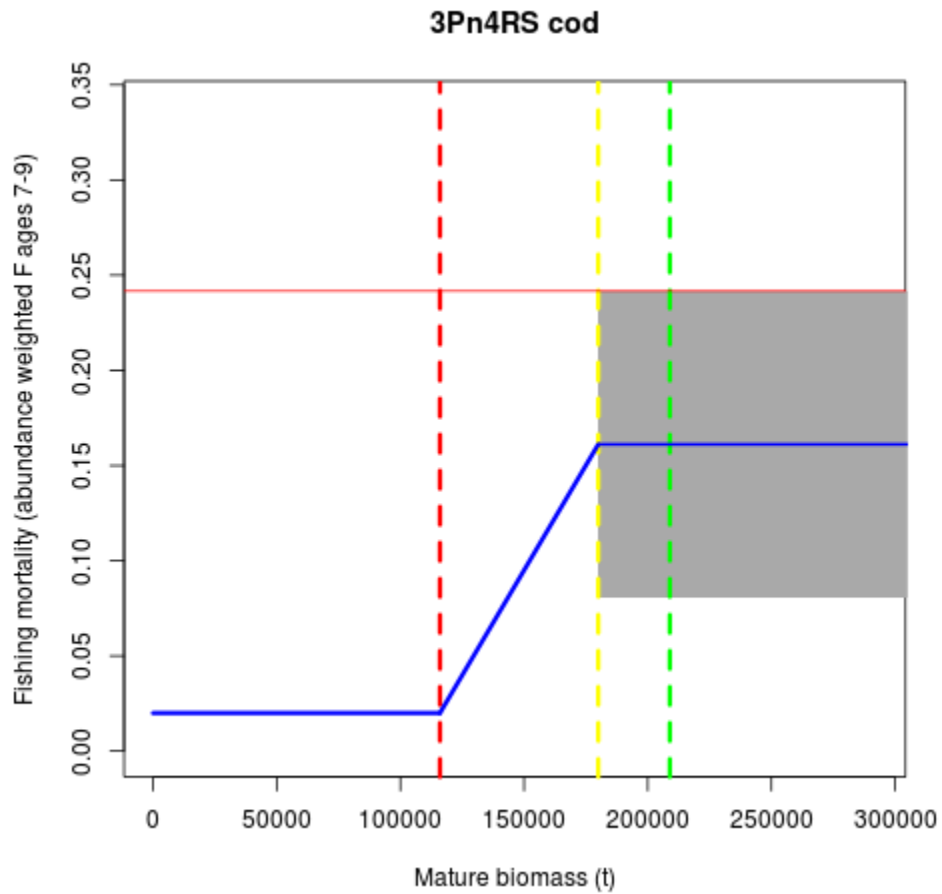


Figure 5: a proposed precautionary approach framework for 3Pn4RS cod based on B_{lim} and B_{usr} from Duplisea and Fréchet (2011), F_{msy} and B_{msy} from equilibrium estimates, F in the healthy zone = $\frac{2}{3} F_{msy}$ and F in the critical zone = 0.02 (by catch F in 2011/12).