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A Naive Simulator for a Harvest Control Rule for the West Greenland Fishery for *P. borealis*

by

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Abstract

The Northern shrimp (*Pandalus borealis*) occurs on the continental shelf off West Greenland in NAFO Divisions 0A and 1A–1F in depths between approximately 150 and 600 m. Greenland fishes this stock in Subarea 1, Canada in Div. 0A. In connection with the certification of the Greenland fishery by the Marine Stewardship Council there has been interest in developing a Harvest Control Rule.

A naïve simulator for a Harvest Control Rule based on mortality- and biomass-risk criteria, and its application to a stock with simple Schaefer dynamics and a management system based on a surplus-production model, was written for Microsoft Excel.

Preliminary conclusions were that, as expected, more conservative mortality-risk criteria can ensure a safer mean level of biomass, with some cost in lower catches. Harvest Control Rules in which the mortality risk could be higher when biomass risk was low and vice versa appeared to be no better—if anything worse—than ones in which mortality risk was kept the same. For the stock-dynamic model simulated, limiting the permissible increase or decrease of catches appeared to bear a cost in lower mean biomass and lower mean catch.

Introduction

A fishery consortium has asked the Marine Stewardship Council (MSC) to certify the West Greenland fishery for Northern shrimp as sustainable. *Inter alia*, certification requires that a fishery should be managed according to a Harvest Control Rule (HCR), defined by MSC as 'a set of well-defined pre-agreed rules or actions used for determining a management action in response to changes in indicators of stock status with respect to reference points.'

An initial HCR was included in the first shrimp management plan issued by the Greenland Home Rule Government in 2010. Its provisions included ' '.

1. Bmsy: The probability that the biomass < Bmsy must not exceed 20%. Applies to both scenarios.

2. Blim: The probability that B< Blim must not exceed 1%. Applies to both scenarios.
3. Zmsy:
a) The probability that Z exceeds Zmsy must not exceed 10% Applies in the event of low recruitment rate and small distribution area.
b) The probability that Z exceeds Zmsy must not exceed 15% Applies in the event of high recruitment rate and large distribution area.

There are difficulties in implementing this HCR. The first is that biomass can not be regulated in the short term. The annual stock assessment produces an assessment of stock status, which includes an estimate of the recent past biomass and a projected value for the end of the current year, but current-year quotas could not be changed to satisfy a biomass criterion even if quota changes that would do so were within reach. Fisheries management usually keeps mortality as its short-term objective and seeks to control it in such a way that, in the medium and long term, safe levels of biomass are reconciled with the biggest compatible catches. This initial HCR includes a criterion for the present estimated level of biomass, but makes no provision for the eventuality that it is not met.

A further difficulty is that the mortality-risk levels specified *appear* to be overly conservative and likely to forgo possible catches, maintaining biomass at a level that might, depending on the precision that can be expected of the assessment, be unnecessarily high.

An alternative HCR that did not attempt to regulate biomass risk in the short term was devised. It regulated mortality risk in the short term, acceptable levels depending on the current estimate of biomass risk. If biomass risk at the end of the current (assessment) year is estimated to be greater than an upper breakpoint, the mortality risk associated with the following year's catch must be at a low level; if the estimated biomass risk is lower than a lower breakpoint, the mortality risk can be at a moderately high level, and if the biomass risk is in the middle, a moderate mortality risk can be tolerated.

To get some idea of whether it might work in practice and how it would behave differently with different settings of its control parameters, a naive simulator was built.

Methods

The HCR was imagined to be a process of setting a catch on the basis of a simulated assessment, and then running the stock through a stock-dynamic process, including the catch decided on, to produce a stock status for the following year. I assumed that the biomass could be estimated relative to its MSY level, and that the maximum production, Z, could be estimated independently. The assessment had errors. The biomass was estimated in the simulated assessment:

$$\log(E_t) \sim N\left(\log(B_t), \sigma_{E,t}^2\right)$$

E and *B* being the estimated and true biomasses and the σ_E randomly and independently sampled from a uniform distribution. The assessment's estimate of its own uncertainty, $\hat{\sigma}_E$, was sampled from a narrower uniform distribution. Assessment errors were independent from year to year. The biomass risk estimated by the assessment was

$$R_B = 1 - \Phi\left(\ln(E_t) \big/ \hat{\sigma}_{E,t} \right)$$

Then an allowable mortality risk R_Z could be looked up according to where the biomass risk was with respect to the biomass-risk breakpoints.

The MSY productivity of the stock, i.e. Z_{msy}, was fixed at 20%, but the assessment estimated it with some error:

$$\ln(\hat{Z}_t) \sim N\left(\ln(Z), \sigma_Z^2\right)$$

where σ_Z was sampled from a uniform distribution. The assessment's estimate of its own uncertainty about Z_{msy}, $\hat{\sigma}_Z^2$, was sampled from a narrower uniform distribution. Assessment errors were independent from year to year. Then a catch C_1 could be set that according to the assessment would meet the allowed mortality risk, i.e. such that:

$$R_Z = \Phi\left(\ln\left(C_1 / E\hat{Z}\right) \Big/ \sqrt{\hat{\sigma}_E^2 + \hat{\sigma}_Z^2} \right)$$

Catches were also required to satisfy a condition that the risk of falling below B_{lim}, i.e. 30% of B_{msy}, in the following year would be less than 5%. To calculate this, the present assessed state of the stock was put through the assumed Schaefer stock-dynamic process with zero catch:

$$D_{t+1} = E_t\left(1 + \hat{Z}_t\left(2 - E_t\right)\right)$$

and an approximate uncertainty calculated for D_{t+1}, including a process error. A catch C_2 was then calculated that would have a 5% chance of bringing the biomass below B_{lim}.

The lower of the catches C_1 and C_2 was then taken as a provisional catch. If C_1 was the lower, the provisional catch was adjusted to be no more than *u*% up or *v*% down from the previous advised catch; C_2 was not allowed to be adjusted in this way. The catch was then rounded to the nearest 0.01 (corresponding to about 5% of the average allowable catch) and the stock at its true status was put through the stock-dynamic process with a process error:

$$B_{t+1} = \left(B_t\left(1 + Z\left(2 - B_t\right)\right) - C\right) \cdot \exp\left(\bar{p}_t\right)$$

Process errors were based on random draws from Normal distributions with zero mean and a standard deviation which itself was a random draw from a uniform distribution, but were serially correlated so that

$$\hat{p}_t \sim N\left(0, \sigma_{p_t}^2\right)$$
$$\sigma_{p_t} \sim U\left(L_p, U_p\right)$$
$$\bar{p}_t = \rho \cdot \bar{p}_{t-1} + \left(1 - \rho\right) \cdot \hat{p}_t$$

The simulator was built as an Excel® spreadsheet and run for a thousand years.

Parameter Settings

I considered two qualities of assessment. The imprecise assessment had:

- Limits for true c.v. of estimating biomass: 15 and 25%
- Limits for estimated c.v. of estimating biomass: 10 and 18%
- Limits for true c.v. of estimating Zmsy: 8 and 25%
- Limits for estimated c.v. of estimating Zmsy: 5 and 15%
- Limits for process error c.v.: 10 and 15%
- Process error serial correlation parameter, 66.67%

The precise (or at any rate, more precise) assessment scenario had

- Limits for true c.v. of estimating biomass: 8 and 12%
- Limits for estimated c.v. of estimating biomass: 6 and 10%
- Limits for true c.v. of estimating Zmsy: 6 and 12%
- Limits for estimated c.v. of estimating Zmsy: 5 and 10%
- Limits for process error c.v.: 5 and 7.5%

Process error serial correlation parameter, 33.33%

Biomass risk breakpoints: 30% and 70%; i.e. if biomass risk was less than 30%, the highest mortality risk could be allowed; if it was between 30% and 70% a middling mortality risk, and if it was above 70% the mortality risk had to be at its lowest level.

With no response to biomass risk, three levels of mortality risk were tested: 45, 35 and 25%. To try out the effect of changing the response of the HCR to biomass risk (having already tried out no response), I kept the middling mortality risk fixed at 35% and considered a low-response HCR with mortality risks at 40, 35 and 30%, a middling response at 45, 35 and 25%, and a high level of response at 50, 35 and 20%.

Allowable increase or decrease in catch: 7.5% up or down; 20% up or down.

Performance statistics were: mean and standard deviation of catch; mean biomass; frequency of biomass above, between or below breakpoints.

A more complicated simulator was also built, in which biomass was estimated, as before, with error and (smaller) uncertainty. The simulator then estimated Zmsy as:

$$\hat{Z}_t = \frac{\hat{B}_t + C_{t-1} - \hat{B}_{t-1}}{\hat{B}_{t-1}\left(2 - \hat{B}_{t-1}\right)}$$

and estimated an error variance $\sigma^2_{\hat{Z}t}$ for $\hat{Z}_t$ from the estimated uncertainties of B_t and B_{t-1}. This estimate of $\hat{Z}_t$ was weighted with its estimated precision and smoothed with the foregoing estimates:

$$\overline{Z}_t = \frac{\delta}{\sigma^2_{\hat{Z}t}}\hat{Z}_t + \left(1 - \frac{\delta}{\sigma^2_{\hat{Z}t}}\right)\overline{Z}_{t-1}$$

and an uncertainty for the smoothed value calculated as:

$$\sigma^2_{\overline{Z}t} = \left(\frac{\delta}{\sigma^2_{\hat{Z}t}}\right)^2 \sigma^2_{\hat{Z}t} + \left(1 - \frac{\delta}{\sigma^2_{\hat{Z}t}}\right)^2 \sigma^2_{\overline{Z}(t-1)} + \left(\frac{\delta}{\sigma^2_{\hat{Z}t}}\right)^2 \left(1 - \frac{\delta}{\sigma^2_{\hat{Z}t}}\right)\left(\hat{Z}_t - \overline{Z}_{t-1}\right)^2$$

This could then be used with the current estimate of Z to set a catch level that would respect the required mortality-risk and limit-biomass-risk criteria in the same way as in the simpler simulator.

Results, Discussion and Tentative Conclusions

With the HCR model built as it is, the results are relatively insensitive to the control parameters that I tried changing. The large uncertainties in estimation and the large process error, aggravated by its high correlation, dominate the behaviour of the system. Differences between different HCR strategies are small.

First Draft HCR

	Precise assessment		Imprecise assessment	
Allowable change (up-down, %)	20-20		20-20	
Allowable mortality risk (%)	10	15	10	15
Mean catch	19.5	19.7	19.0	19.1
CV catch	14.4	14.3	21.8	21.9
Serial correlation	32.3	32.3	66.4	65.0
Mean biomass	1.13	1.11	1.20	1.17
Smoothed (/’000)	306	301	550	553

The rather conservative mortality risks of the first draft HCR tend to keep the biomass well above its MSY level, especially if the assessment is imprecise and the tails of the uncertainty distributions therefore long. With imprecise assessments even this conservative HCR makes relatively frequent recommendations for large change in catches and catches are smoothed more than half the time.

Precise assessments
Effect of changing the middle value—no response to biomass risk

	Allowable change in catches (% up–% down)								
	20-20			7.5–7.5			20-7.5		
Mortality risk (%)	45	35	25	45	35	25	45	35	25
Mean catch	19.8	19.9	19.9	19.9	19.8	19.7	19.7	19.9	19.7
CV catch	15.0	14.7	14.4	12.2	11.8	11.5	13.6	13.5	13.1
Serial correlation	32.0	32.2	31.0	31.8	32.1	31.7	33.6	33.9	34.9
Mean biomass	1.01	1.05	1.07	1.01	1.04	1.07	0.94	0.97	1.00
Smoothed (/1000)	311	308	302	684	673	677	554	557	553

With the precise assessment, lowering the allowable mortality risk increases the mean biomass, but not by enough to have much effect on allowable catches. If the catch smoothing is made a lot more aggressive it is more often used; it reduces catches slightly. If catch smoothing is very unsymmetrical, with free increase in catches but smaller decreases allowed, the biomass tends to be driven down and catches are less.

Effect of changing the responsiveness; biomass-risk breakpoints at 30% and 70%

	Allowable change in catches (% up–% down)								
	20-20			7.5–7.5			20-7.5		
Mortality risks %	40-35-30	45-35-25	50-35-20	40-35-30	45-35-25	50-35-20	40-35-30	45-35-25	50-35-20
Mean catch	19.9	20.0	19.8	19.8	19.8	19.7	19.8	19.9	19.8
CV catch	15.2	15.8	16.5	12.5	12.8	13.6	13.8	14.4	15.3
Serial correlation	33.9	33.8	34.2	34.8	33.5	34.2	33.7	33.0	31.8
Mean biomass	1.04	1.04	1.03	1.04	1.03	1.03	0.97	0.97	0.96
Over	479	480	458	465	462	458	320	319	302
Between	220	223	229	204	202	202	200	207	199
Under	301	297	313	331	336	340	480	474	499
Smoothed	336	353	383	702	725	731	578	598	631

Changing the responsiveness of the HCR does not significantly change its performance. But catches become more variable. With aggressive catch smoothing, a responsive HCR is usually trumped by the catch smoothing, and in the sense of increasing catches—if anything, it looks as though catches are less with a responsive HCR. Even if catch smoothing is unsymmetrical, a responsive HCR is little help in maintaining biomass at a safe level.

With all these settings, it was obvious that the biomass risk was relatively seldom between the biomass-risk breakpoints.

Imprecise assessments, variable system.
Effect of changing the middle value

	Allowable change in catches (% up–% down)								
	20-20			7.5–7.5			20-7.5		
Mortality risk (%)	45	35	25	45	35	25	45	35	25
Mean catch	19.8	19.6	19.4	19.4	19.3	19.2	19.0	19.3	19.4
CV catch	24.1	23.6	23.1	21.8	20.3	19.2	27.3	26.4	24.0
Serial correlation	67.3	66.2	66.8	66.0	65.6	67.2	66.6	66.4	66.6
Mean biomass	1.03	1.07	1.12	1.01	1.05	1.10	0.85	0.90	0.95
Smoothed (/1000)	558	559	551	826	825	829	755	753	750

If assessments are imprecise, the tails of the uncertainty distributions are longer, and changes in allowable risks induce greater changes in advised levels. More conservative settings for the HCR have more pronounced effects in raising the mean biomass, but also in reducing catches, than when assessments were precise and the system was not very variable. Aggressive catch smoothing, again, usually trumps the HCR in setting catch levels—the assessment is usually only advising on whether catches should increase or decrease. Aggressive catch smoothing reduces mean biomass and reduces mean catches, but also reduces catch CV. Unsymmetrical catch smoothing, as before, tends to drive the stock to levels below its MSY level, reduces mean catches, and also, on average, increases the catch CV above the level of mild catch smoothing.

Effect of changing the responsiveness

	Allowable change in catches (% up–% down)								
	20-20			7.5–7.5			20-7.5		
Mortality risks %	40-35-30	45-35-25	50-35-20	40-35-30	45-35-25	50-35-20	40-35-30	45-35-25	50-35-20
Mean catch	19.8	19.6	19.6	19.2	19.3	19.1	19.2	19.4	19.3
CV catch	24.2	24.4	25.7	20.5	22.0	23.2	26.9	27.0	28.5
Serial correlation	67.0	65.5	66.6	66.2	65.6	66.8	67.0	66.2	66.6
Mean biomass	1.07	1.06	1.06	1.06	1.04	1.04	0.89	0.90	0.89
Over	468	460	457	448	444	433	261	274	268
Between	207	205	207	184	176	174	163	170	169
Under	325	335	336	368	378	393	576	556	563
Smoothed	578	602	615	836	847	859	763	783	791

With the imprecise assessment it looks as though a responsive HCR, which changes the permissible mortality risk according to the perceived biomass risk, has no positive effect on mean catch or on mean biomass level. It does increase the CV of catch, and is more often overridden by the catch smoothing.

These first experiments seem to show that the system modelled is not very sensitive to the settings of the HCR. Whether the high-risk, low-risk or responsive strategy is chosen, the mean biomass is a few percentage points above the MSY level and the long-term mean catch is a few percentage points below its maximum possible.

The simulator is quite simple and naïve—there are no model errors and it is assumed that the biomass can somehow be estimated relative to its MSY level, and that estimates of MSY, although imprecise, are unbiased.

Preliminary conclusions from these experiments are:

catch smoothing costs. Keeping the change in catch small appears to reduce mean catches and reduces mean biomass—i.e. is less safe. Even worse is unsymmetrical catch smoothing, a policy under which catches can be increased when things look good but cannot be brought down when they don't. Such a policy tends to drive the stock into a hole from which it is eternally trying to climb out.

responsive HCRs aren't so much the good idea that they appear to be at first sight. It looks as though an unresponsive HCR which keeps to a fixed mortality risk regardless of the biomass risk is, under most circumstances, at least as good if not better.

conservative levels of mortality risk do give more safety and higher mean levels of biomass, but carry a cost in lower mean catches. They appear to bring the CV of catch down a little bit. A conservative level of mortality risk looks like something of a palliative to unsymmetrical catch smoothing, reducing its worst effects. The effect of changing mortality risk is greater if assessments are imprecise, less if assessments are precise. Might it therefore be useful to change the allowable mortality risk according to the perceived level of uncertainty associated with the assessment?

Model with MSY estimated from biomass change.

Precise assessments, stable system.
Effect of changing the middle value

	Allowable change in catches (% up–% down)								
	20-20			7.5–7.5			20-7.5		
Mortality risk (%)	45	35	25	45	35	25	45	35	25
Mean catch	20.0	19.8	19.6	19.7	19.7	19.7	19.8	19.8	19.8
CV catch	16.7	16.3	16.3	14.9	14.6	14.2	15.8	15.4	15.1
Serial correlation	34.3	33.6	33.0	33.5	33.2	34.1	34.6	32.2	34.5
Mean biomass	1.03	1.06	1.10	1.02	1.05	1.09	0.96	1.00	1.04
Smoothed (/1000)	311	314	306	700	700	703	563	565	551

Effect of changing the responsiveness

	Allowable change in catches (% up–% down)								
	20-20			7.5–7.5			20-7.5		
Mortality risks %	40-35-30	45-35-25	50-35-20	40-35-30	45-35-25	50-35-20	40-35-30	45-35-25	50-35-20
Mean catch	19.9	19.9	19.8	19.7	19.8	19.7	19.8	19.8	19.7
CV catch	17.4	18.1	19.1	15.0	16.0	16.7	16.0	16.8	17.7
Serial correlation	32.7	32.6	34.0	33.1	33.4	34.4	33.5	34.0	33.5
Mean biomass	1.06	1.05	1.05	1.05	1.04	1.04	0.99	0.98	0.97
Over	523	525	514	504	486	475	370	363	341
Between	219	217	217	193	188	192	213	204	202
Under	258	258	270	303	326	333	418	433	456
Smoothed	357	407	454	730	775	799	610	641	683

This model, with the MSY estimated in the assessment from the change in estimated biomass, is perhaps a small step closer to reality. The series of estimates of MSY has some negative serial correlation, probably because overestimating biomass biases this year's estimate of MSY upwards, but next year's downwards, and vice versa. The series of smoothed estimates has rather large positive serial correlation—perhaps a lesson that assessment errors are persistent.

Results and conclusions are little different from those obtained from the model in which an estimate of the MSY was available independent of the biomass estimates. A more conservative mortality-risk criterion increases mean biomass and therefore the safety level at some cost in catches taken; this cost is lower if catches are aggressively smoothed. Aggressive catch smoothing decreases mean catches and mean biomass, and unsymmetrical catch smoothing does so even more.

A responsive HCR, in which allowable mortality risk varies with the estimated biomass risk, does not perform in any respect better than unresponsive HCRs. With these results in mind, I am inclined to think that an HCR with mortality risk fixed at 35% would be a good place to start in formulating advice for the West Greenland stock of *P. borealis*.