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Initial tests of the robustness of the provisional harvest control rule in Canada's Sustainable Fisheries Policy to process and measurement errors using simulated depleted fish populations

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Abstract

Canada's Department of Fisheries and Oceans (DFO) Sustainable Fisheries Framework and the associated Decision Making Framework Incorporating the Precautionary Approach policies (DMF), implemented in 2009, provide a context with potential to improve fisheries management. A Provisional Harvest Control Rule (PHCR) is proposed in the DMF to allow adjustments of the annual total allowable catch based on a scientific assessment of the state of the stock. The DMF defines three spawning stock biomass Zones (Critical, Cautious and Healthy). The PHCR adjusts fishing mortality dependent on the Zone within which the spawning stock biomass is estimated to fall. Elements of the PHCR have been incorporated in the scientific advice and management approaches for a number of Canadian fish stocks. In this study, initial evaluation of the PHCR was carried out on three simulated depleted fish populations with different life histories under a variety of combinations of process error on recruitment and measurement error on spawning stock biomass. The simulations represent "best-case" scenarios because reference points were assumed to be known exactly and the magnitude of the errors was moderate. The simulation results suggested that fish stocks in the Critical Zone should rebuild to the Healthy Zone under the PHCR with high probability (>0.78) irrespective of life history differences and the combinations of process and observations errors. However, the time to rebuild was up to twice as long as it took in the absence of fishing and the PHCR was not effective in ensuring the DMF requirement of a low probability (<0.1) of the population returning to the Cautious Zone. The PHCR was also not effective in keeping fishing mortality below the level that generates maximum sustainable yield when the stock was in the Cautious Zone and subject to measurement error. Variation in the annual catch generated by the PHCR in the simulations increased with increasing process and observation errors to a maximum CV of 0.6, which may be inconsistent with the fishing industry's desire for low variation in annual catch.

Keywords: Sustainable fisheries, harvest control rules, simulation evaluation, performance statistics, precautionary approach

Introduction

In 2009, Canada's Department of Fisheries and Oceans (DFO) introduced the Sustainable Fisheries Framework Policy (SFF; DFO, 2009a) to provide a more rigorous and comprehensive approach to managing Canada's marine fisheries. A key component of this Policy is "A Fishery Decision-Making Framework Incorporating the Precautionary Approach" (DMF; DFO, 2009b) which describes a general fishery decision-making framework for implementing a harvest strategy that complies with the Precautionary Approach (PA) as defined by the United Nations Fish Stocks Agreement (UN, 1995) and by the Food and Agriculture Organization of the United Nations (FAO; FAO, 1995). Central to the Policy's approach is the identification of desirable (target) and undesirable (limit) reference points, and specification of management objectives that avoid limits and achieve targets with regard to spawning stock biomass (*SSB*) and fishing mortality (*F*). The FAO guidelines suggest that this be achieved through decision rules that specify what management action will be taken when specified deviations from operational targets are observed. In practice, following the UN Agreement and FAO guidelines is not mandatory in Canada because the Fisheries Act allows for "ministerial discretion" in all decisions. In most cases, targets have not been defined and probability thresholds and time horizons with respect to management objectives have not been developed for Canadian fish stocks in DFO fishery management plans.

The DMF defines three zones based on stock status (typically measured in units of *SSB*: Healthy, Cautious and Critical Zones (Fig. 1). The Healthy Zone occurs above an Upper Stock Reference (USR). The Target Reference Point (TRP) for a stock is set within this Zone by fishery managers. Below the Healthy Zone is the Cautious Zone, bounded at low stock status by the Limit Reference Point (LRP). Below the LRP is the Critical Zone, which denotes a stock at a critically low level of *SSB*. To prevent a stock from entering the Critical Zone, a reduction in *F* is required when the stock is in the Cautious Zone in order to ensure it rebuilds to the Healthy Zone rather than declining further and entering the Critical Zone. If a stock is already in the Critical Zone, then it must be rebuilt, with high probability (*i.e.*, 75–95%), to the Cautious Zone within 1.5–2 generations. Once in the Cautious Zone, management actions are required to continue to rebuild the stock to the Healthy Zone within an additional 1.5–2 generations. Thus, the total amount of time to rebuild from the Critical Zone to the Healthy Zone could be up to 4 generations in length.

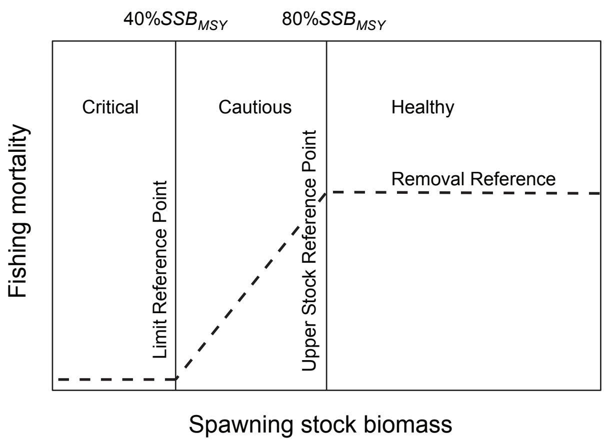

Fig. 1. Elements of the Provisional Harvest Control Rule (PHCR) for the Canada Department of Fisheries and Oceans' (DFO) Fishery Decision Making Framework Incorporating the Precautionary Approach. The Removal Reference denotes the upper limit of fishing mortality (*F*) in each of the three spawning stock biomass (*SSB*) Zones. In the Healthy Zone, *F* must be less than or equal to the *F* that generates maximum sustainable yield (F_{MSY}). *F* must be decreased for a declining stock in the Cautious Zone to ensure a return to the Healthy Zone. In the Critical Zone, *F* must be kept at an absolute minimum. Under the DFO PHCR, the Upper Stock Reference Point is set at 80%SSB_{MSY}, where SSB_{MSY} is the *SSB* consistent with fishing at F_{MSY} and the Limit Reference Point is set at 40%SSB_{MSY}. The Target Reference Point for *SSB* is set at a level within the Healthy Zone by fishery managers.

The DMF introduces a Removal Reference (Fig. 1), typically expressed in terms of *F*, which prescribes the maximum acceptable harvest rate for the stock in each of the three *SSB* Zones. *F* in the Healthy Zone must be less than or equal to the harvest rate associated with maximum sustainable yield (F_{MSY}) and in the Cautious Zone, there must be a progressive decline in *F* with decreasing stock status. A Harvest Control Rule (HCR) determines the change in *F*. Below the LRP, the harvest rate, taking into account discards and landings, must be kept to an absolute minimum. The specific harvest rate required when the stock is below the LPR is undefined in the DMF but subsequent assessments of some stocks have shown that it can include both bycatch and directed fishing.

While the DMF recognises that stock-specific characteristics, such as life history, should be taken into consideration when developing specific HCRs for individual stocks, it also provides guidance on a Provisional Harvest Control Rule (PHCR) as an example of an HCR considered to be generally consistent with the SFF and DMF policies. In keeping with a number of management strategies applied elsewhere (Restrepo and Powers, 1999; Lassen *et al.*, 2014; Shelton and Morgan, 2014), the PHCR is based on *MSY* reference points. Elements of the PHCR have been implemented for a number of Atlantic Canada fish stocks including: Units 1, 2 and 3 Redfish (McAllister and Duplisea, MS 2012; Duplisea *et al.*, MS 2012); 3Pn4RS Atlantic Cod (Duplisea and Fréchet, MS 2009); 3NOPs4VWX+5 Atlantic Halibut (Trzcinski *et al.*, MS 2011); 4VsW Atlantic Cod and 4X5Y Haddock (DFO, 2012); 4VW+4Xmn Pollock (Stone, MS 2012; DFO, 2011a); and 3Ps American Plaice (Morgan *et al.*, MS 2012), as well as Pacific stocks such as Queen Charlotte Sound Pacific Ocean Perch (DFO, 2011b).

Simulation testing of fishery management strategies is widely considered to be good practice to ensure robustness to uncertainty (Deroba and Bence, 2008; 2012; Zhang *et al.*, 2011; Wiedenmann *et al.*, 2013; Punt *et al.*, 2014). However, there has only been limited testing of management strategies on Canadian fish stocks (*e.g.* Cox and Kronlund, 2008; Cleary *et al*., 2010; Shelton and Miller, MS 2009; Miller and Shelton, 2010) and no tests of the likely effectiveness of the PHCR for specific stocks, or more generally, under a range of life histories, process errors and measurement errors. Instead of simulation testing of management strategies, the DMF requires empirical evaluation of the management strategy 6–10 years after implementation. The first of such empirical evaluations has yet to take place and details regarding the approach are not available in the DMF. It is assumed such an evaluation would depend on a review of survey and catch outcomes and stock assessment reconstructions of the population, and that simulation tests of the PHCR on a stock-by-stock basis would augment this empirical evaluation.

The objective of the present study was to evaluate the general performance of the PHCR for three simulated hypothetical fish populations with different life histories and under a range of assumed process and measurement errors. Performance criteria for evaluating the PHCR were developed from the DMF's management objectives with regard to *SSB*, *F* and catch. This study is considered preliminary because it was not stock-specific and did not implement a full closed-loop management strategy evaluation (MSE) that includes simulating the actual stock assessment process; widely acknowledged as the preferred approach, but one that would have to be stock-specific (Cox and Kronlund, 2008; Punt *et al*., 2014).

Materials and Methods

In keeping with the MSE approach, the present study considered both the "true" simulated population and the "perceived" population; the population that would be estimated to exist from the stock assessment, taking into account measurement error (Haltuch *et al*., 2008). The PHCR was applied to the "perceived" population while the performance was measured with respect to the "true" population. Process error was only considered with regard to recruitment and measurement error with regard to *SSB*. The standard deviation of the errors was assumed to not exceed 0.4, which is moderate compared to some other studies (*e.g.* Wetzel and Punt, 2016; Cao *et al*., 2014). Further, it was assumed that reference points required by the PHCR were known exactly.

Provisional harvest control rule

The PHCR defined in the DMF adopted 80%SSB_{MSY} as the USR and 40%SSB_{MSY} as the LRP, where SSB_{MSY} is the spawning stock biomass corresponding to *MSY*. In accordance with the PHCR, the *F* applied to the fishery was determined using the following equations:

When the stock is in the "Healthy Zone",

$$F_y = \lambda F_{MSY}, \tag{1}$$

where λ is a constant ≤ 1.

When the stock is in the "Cautious Zone",

$$F_y = \lambda F_{MSY} \left(\frac{SSB_y - 0.4SSB_{MSY}}{0.8SSB_{MSY} - 0.4SSB_{MSY}}\right). \tag{2}$$

When the stock is in the "Critical Zone",

$$F_y \approx 0. \tag{3}$$

The simulations assumed that $\lambda = 1$ and that $F_y = 0.001$ in the Critical Zone acknowledging that, even with no directed fishing, some amount of bycatch will occur. Note that values of $F_y > 0$ in the Critical Zone create a discontinuity in the HCR at the LRP. Changes to the PHCR to avoid this discontinuity need to be considered if directed fishing is allowed below the LRP.

Simulated populations

Three simulated fish populations representing species with different life history characteristics (Table 1) were constructed in R (R Core Team, 2013). A similar approach was adopted by Wetzel and Punt (2016) in their simulation study of rebuilding strategies for overfished stocks in the U.S.A. and by Wiedenmann *et al*. (2013) in their evaluation of the performance of harvest control rules on data-poor fisheries. Here, Population A represented a slow-growing, long-lived and late-maturing species that reached a large maximum size, Population C was a fast-growing, short-lived and early-maturing species that grew to a small size, and Population B was an intermediate species in terms of growth, longevity and size. In order to ensure consistency with fish life history theory (Roff, 1992; Beverton, 1992; Sterns, 1992; Charnov, 1993; Jensen, 1996), the following approach was adopted. Maximum (terminal) age (*A*) was chosen for each population and then natural mortality rate (*M*) was computed using the empirical equation from Hewitt and Hoenig (2005) where:

$$M = 4.22/A. \tag{4}$$

Based on this value of *M*, values for the von Bertalanffy growth equation parameter, *k*, and age at 50% maturity for a logistic maturation function τ_{50}, were computed for each population such that these values satisfied two life history invariant properties proposed by Jensen (1996):

$$M = 1.5k, \tag{5}$$

and

$$M = 1.65/\tau_{50}. \tag{6}$$

The von Bertalanffy growth equation (Quinn and Deriso, 1999) is:

$$L_a = L_\infty(1-e^{-k(a-a_0)}), \tag{7}$$

where L_a is the length at the beginning of age a in centimeters L_∞, is the asymptotic length and a_0 is the x-intercept of the curve (assumed to be zero for all three simulated populations). Values for L_∞ were chosen in descending magnitude for Populations A, B and C, respectively.

Maturation for males and females combined was

Table 1. Life history properties of the three simulated populations created to test the performance of the Provisional Harvest Control Rule associated with the Sustainable Fisheries Framework policy of Canada's Department of Fisheries and Oceans. Population A was slow-growing and long-lived, Population B was intermediate and Population C was fast-growing and short-lived.

Property	Explanation	Population A	Population B	Population C
A (year)	Maximum age	30	15	5
von Bertalanffy growth				
a_0	Intercept of growth curve	0	0	0
k	Growth rate	0.094	0.187	0.563
L_∞ (cm)	Asymptotic length	150	100	15
Length-weight				
η	Constant	0.00001	0.00001	0.00001
ω	Constant	3	3	3
Maturation				
τ_{50} (year)	Age at 50% maturation	11.692	5.870	1.954
ν	Maturation rate	0.100	0.300	0.800
M	Instantaneous reat of natrual mortality	0.141	0.281	0.844
$SPR_{\mathbf{F=0}}$ (kg per age 1 fish)	Spawner per recruit when fishing mortality is zero	24.753	4.250	0.008
$SPR_{\mathbf{F=Fmsy}}$ (kg per age 1 fish)	Spawner per recruit when fishing mortality gives MSY	13.195	1.631	0.003
$SPR_{\mathbf{F=Fmsy}}/SPR_{\mathbf{F=0}}$	Ratio of spawner per recruit at F=F_{MSY} to spawner per recruit at F=0	0.533	0.384	0.375
h	Steepness parameter for Beverton-Holt stock-recruit relationship	0.5	0.7	0.8
$RPS_{\mathbf{max}}$ (thousands of recruits/ tons of spawners)	Maximum recruits per spawner	0.162	2.196	1895.556
$r_{\mathbf{max}}$	Maximum instantaneous rate of population growth	0.083	0.284	1.202
$F_{\mathbf{MSY}}$	Fishing mortality rate that generates MSY	0.118	0.458	1.767
$F_{\mathbf{20\%SSBmsy}}$	Fishing mortality rate that results in 20% of the SSB that generates MSY	0.286	1.563	7.921
GT (year)	Generation time	18.611	9.350	3.052
Hoenig $M = 4.22/T_{\mathbf{max}}$	Hoenig's equation for caculating M (Hewitt and Hoenig, 2005)	0.141	0.281	0.844
Jensen $M = 1.5*k$	Jensen's equation for calculating M (Jensen, 1996)	0.141	0.281	0.844
Jensen $M = 1.65/\tau_{\mathbf{50}}$	Jensen's second equation for calculating M (Jensen, 1996)	0.141	0.281	0.844

determined by a population-specific logistic function:

$$P_a = 1/(1+e^{-\nu(a-\tau_{50})}), \tag{8}$$

where P_a is the proportion mature-at-age and v is the maturation rate with respect to τ_{50}.

Fish weight was obtained from length data by the following equation:

$$W_a = \eta L_a^{\omega}, \tag{9}$$

where W_a is individual weight in kilograms at age a, L_a is the length in centimeters at age a and η and ω are constants, considered to be population-invariant in this study based on the relatively small amount of variation that occurs across marine fish species (Froese, 2006).

Spawner-per-recruit in the absence of fishing, $SPR_{F=0}$, the expected average lifetime production of spawning biomass from a single age 1 recruit when $F = 0$, was computed as:

$$SPR_{F=0} = \Sigma_{a=1}^{A}(e^{(-M(a-1))} P_a W_a), \tag{10}$$

where A is the maximum (terminal) age, *i.e.*. there is no plus group. The omission of a plus group was justified on the basis of the low survival (2–3%) to age A under M for each population.

SPR at $F = F_{MSY}$ (the fully recruited fishing mortality at MSY) was similarly calculated as:

$$SPR_{F=F_{MSY}} = \Sigma_{a=1}^{A}(e^{(-(M+F_{MSY}S_a)(a-1))} P_a W_a), \tag{11}$$

where S_a is the fishery selectivity-at-age, arbitrarily set equal to P_a.

Recruitment (R, in thousands of fish) at age 1 at the beginning of year y, $N_{1,y}$, in the simulated populations was modelled using a Beverton-Holt stock-recruit function (Quinn and Deriso, 1999) with multiplicative, lognormal, autocorrelated process error ε_{py} standardized to have a mean = 1 (Cadigan, MS 2012), such that:

$$N_{1,y+1} = \frac{\alpha SSB_y}{\beta + SSB_y}\varepsilon_{py} \tag{12}$$

where the spawning biomass at the beginning of year y is given by

$$SSB_y = \Sigma_{a=1}^{A}(N_{a,y} P_a W_a), \tag{13}$$

and where

$$\varepsilon_{py} = e^{\left(\sigma_\phi Z_y - \frac{\sigma^2}{2}\right)},$$

$$Z_y = \phi Z_{y-1} + \delta_y,$$

$$\delta_y \sim N[0,1],$$

and

$$\sigma_\phi = \sigma(1-\phi^2)^{1/2}. \tag{14}$$

Here, σ is the standard deviation of the error on a log scale, δ_y is an annual random normal variable with mean = 0 and standard deviation = 1, and ϕ determined the amount of autocorrelation in the error with $\phi = 0$ resulting in no autocorrelation.

To obtain parameters for the Beverton-Holt model, it was re-parameterized in terms of steepness (h) and virgin biomass (K). Steepness is defined as the fraction of R at K when SSB is reduced to $0.2K$ (Mace and Doonan, 1988). In the re-parameterized formulation,

$$\alpha = \frac{K4h}{SPR_{F=0}(5h-1)} \tag{15}$$

and

$$\beta = \frac{\alpha SPR_{F=0}(\frac{1}{h}-1)}{4}. \tag{16}$$

Steepness cannot be chosen arbitrarily because it depends on life history attributes (Mangel *et al*., 2010). Values of h for the three simulated populations were therefore chosen to be roughly consistent with the relationship between the ratio $\frac{SPR_{F=F_{MSY}}}{SPR_{F=0}}$ and h described in Mangel *et al*. (2013) as well as with empirical values of h estimated for real populations with life histories similar to the three simulated populations given in Myers *et al*. (1999).

A number of additional life history properties were calculated from those described above to further illustrate the differences between the populations (Table 1). Maximum recruits-per- spawner, RPS_{max}, was estimated from the slope at the origin of the stock-recruit curve. The intrinsic rate of natural increase at low population size, r_{max}, was calculated from, RPS_{max}, $SPR_{F=0}$, τ_{50}, and M using the method described in Myers *et al*. (1997). Generation time GT was computed as the weighted mean age where the weights were the age-specific contributions to $SPR_{F=0}$, based on Goodyear (MS 1994).

The population-updating model applied in the simulations was:

$$N_{a+1,y+1} = N_{a,y} e^{-(Fa,y+M)}, \quad (17)$$

where $F_{a,y}$ was fishing mortality-at-age a in year y, obtained by applying selectivity-at-age, S_a, to the value of F_y generated by the PHCR based on the simulated perceived *SSB* as described in the following section.

Applying the PHCR to the simulated populations

The PHCR was applied to the perceived *SSB* at the beginning of year y, SSB^*_y, to generate the perceived fishing mortality F^*_y, from which the corresponding total allowable catch (*TAC*), in tons, was obtained (assuming no implementation error). SSB^*_y differed from the true simulated SSB_y through the introduction of measurement error, so that

$$SSB^*_y = SSB_y \varepsilon_{my}, \quad (18)$$

where ε_{my} is lognormal, autocorrelated, random measurement error obtained using the same equations described above for process error with the subscript changed from to p to m.

F^*_y was age-disaggregated by multiplying by selectivity-at-age, S_a, assumed to be constant, known and equal to P_a, so that

$$F^*_{a,y} = S_a F^*_y. \quad (19)$$

Catch, in thousands of fish at age a in year y, $C_{a,y}$, was computed as

$$C_{a,y} = N^*_{a,y} \,(1 - e^{-(M+F^*_{a,y})}) \frac{F^*_{a,y}}{(F^*_{a,y} + M)} \quad (20)$$

$N^*_{a,y}$ is the perceived numbers at age a at the beginning of year y and was obtained by finding, through iteration, the vector of population numbers-at-age in each year that satisfied

$$SSB^*_y = \Sigma^A_{a=1}(N^*_{a,y} P_a W_a), \quad (21)$$

subject to the constraint that the proportions-at-age in the perceived population was identical to the proportions in the true simulated population, and considering *SSB* to comprise the mature biomass of males and females combined.

The *TAC* given by the PHCR, and therefore the catch, in year y was computed as

$$TAC_y = \Sigma^A_{a=1}(C_{a,y} W_a). \quad (22)$$

Because TAC_y was obtained from the PHCR applied to, SSB^*_y, F_y corresponding to TAC_y will differ from F^*_y generated by the PHCR when measurement error exists.

F_y was found iteratively by satisfying the condition that:

$$TAC_y = \Sigma^A_{a=1}\Big(N_{a,y}\,(1 - e^{-(M+S_a F_y)}) \frac{S_a F_y}{(S_a F_y + M)} W_a\Big). \quad (23)$$

Simulation runs

The PHCR was evaluated for each population over a 50-year time horizon. The initial state of the stock was an equilibrium population with a stable age composition consistent with *SSB* that was 20% of the true SSB_{MSY}, *i.e.* in the middle of the Critical Zone. For each population, two deterministic reference runs of the simulation model were carried out, the first at $F = 0$ (*i.e.* no fishing throughout the 50-year time period) and the second under the application of the PHCR. The PHCR was then applied under stochastic conditions for various values of standard deviation and autocorrelation in process and measurement errors. For each error combination, 1 000 repeats of the simulation were completed to allow performance of the PHCR to be evaluated.

The following runs of the simulation model, totalling 24 each for Populations A, B, and C, were carried out:

- (i) Two deterministic reference runs, under $F = 0$ and under application of the PHCR;
- (ii) Process error-only runs for $\sigma_p = 0.2$ with $\phi_p = 0$, 0.3, 0.6 and 0.9; $\sigma_p = 0.3$ with $\phi_p = 0$ and 0.9; and $\sigma_p = 0.4$ with $\phi_p = 0$ and 0.9;
- (iii) Measurement error-only runs with $\sigma_m = 0.2$ with $\phi_m = 0$, 0.3, 0.6 and 0.9; $\sigma_m = 0.3$ with $\phi_m = 0$ and 0.9; and $\sigma_m = 0.4$ with $\phi_m = 0$ and 0.9;
- (iv) Combined process and measurement error runs with $\sigma = 0.4$ and $\phi = 0.9$ for both errors, $\sigma_p = 0.4$ and $\phi_p = 0.9$ combined with $\sigma_m = 0.2$ and $\phi_m = 0.9$, $\sigma = 0.3$ and $\phi = 0.9$ for both errors, $\sigma_p = 0.3$ and $\phi_p = 0$ combined with $\sigma_m = 0.3$ and $\phi_m = 0$, and $\sigma_p = 0.4$ and $\phi_p = 0$ combined with $\sigma_m = 0.4$ and $\phi_m = 0$.

Performance statistics

Quantitative performance statistics for evaluating the PHCR were derived from the SFF and DMF documents. The following twelve statistics were defined:

(i) TRCZ is the mean time to reach the Cautious Zone across runs;

(ii) PBCC is the mean probability of *SSB* falling in the Critical Zone in any one year, subsequent to reaching the Cautious Zone, across runs;

(iii) TRHZ is the mean time to reach the Healthy Zone across runs;

(iv) PRHZ is the mean probability of reaching the Healthy Zone within the 50-year simulation period across runs;

(v) PBHC is the mean probability of *SSB* falling in the Cautious Zone in any one year, subsequent to reaching the Healthy Zone, across runs;

(vi) PBHL is the mean probability of *SSB* falling in the Critical Zone in any one year, subsequent to reaching the Healthy Zone, across runs;

(vii) PFCM is the mean probability of F exceeding F_{MSY} for years when the stock is in the Cautious Zone, across runs;

(viii) PFA2 is the mean probability of F exceeding $1.2F_{MSY}$ in any year of the 50 year simulation period across runs;

(ix) PFA5 is the mean probability of F exceeding $1.5F_{MSY}$ in any year of the 50-year simulation period across runs;

(x) CV10 is the mean coefficient of variation in the catch over the last 10 years across runs;

(xi) AC50 is the mean of the ratio of catch to MSY over the 50-year simulation period across runs; and

(xii) AC10 is the mean of the ratio of catch to MSY over the last 10 years across runs.

Analysis of performance statistics

Performance statistics for all runs were tabulated. Process error-only and measurement error-only results were plotted to determine the effects of the standard deviation and autocorrelation in the error on performance statistics. Plots covered the range of standard deviation under zero autocorrelation and the range of autocorrelation under $\sigma = 0.2$. Minimum and maximum values for each performance statistic were computed across all simulation runs in which the PHCR was applied, including the deterministic runs, to determine the range of outcomes. Analysis of variance (ANOVA) was carried out on the same data to determine overall significance of the main effects, which included Population (A, B or C) and levels of σ_p, ϕ_p, σ_m, and ϕ_m. A full factorial design was not conducted because all combinations of σ and ϕ for process and measurement error were not evaluated. Because of a balanced design, the order of the main effects did not matter in determining significance. Main effects were considered significant for $p < 0.05$.

Results

Performance statistics for the simulation trials in which the PHCR was applied under deterministic conditions and process error-only (Table 2) measurement error-only (Table 3) and combined process and measurement error (Table 4) showed considerable variability in some cases, dependent on life history and error combination. In other cases, performance statistics were found to be insensitive to the range of errors examined.

Deterministic reference runs

The simulated *SSB* values for each of the three populations, under deterministic conditions with no fishing, illustrated the impact of differences in life history (Fig. 2a, Table 2). Population A grew slowly, reaching the Healthy Zone by year 19. Population B reached the Healthy Zone by year five and Population C reached the Healthy Zone by year three. When fishing took place under the conditions of the PHCR, Population A reached the Healthy Zone by year 34, Population B by year 10, while in Population C there was no change in the time to reach the Healthy Zone (Fig. 2b, Table 2). An inflection in population growth occurred earliest and was only slight in Population A but occurred later and was more evident in Populations B and C (Fig. 2b). The inflections were caused by life history-mediated, lagged impacts on *SSB* as a result of the change in F from a low value in the Critical Zone to increasing F generated by the PHCR with increasing *SSB* in the Cautious Zone. The PHCR resulted in *SSB* eventually stabilizing at SSB_{MSY} in Population B and C, however, for Population A, the 50-year time horizon of the simulation was insufficient for this to occur. In the absence of process and measurement error, the expectation is that the PHCR will lead to recovery to the Healthy Zone for stocks that are in the Critical Zone, irrespective of life history differences. However, depending on life history, the time to rebuild to the Healthy Zone under the PHCR could take up to twice as long as it would take in the absence of fishing.

Process error-only runs

Process error-only runs plotted against σ_p (Fig. 3) and ϕ_p (Fig. 4) illustrate the impact of these two aspects of variability. Recall that process error was only applied to recruitment. There was no effect of σ_p on TRCZ, PBCC,

Table 2. Performance statistics for the Canada's Department of Fisheries and Oceans' Provisional Harvest Control Rule, for three simulated populations under deterministic conditions and process error. A total of 1 000 simulation runs were conducted over a 50-year time horizon for each population (see Table 1 for details of the life history of Populations A, B and C) and error combination. The initial state of the stock was an equilibrium population with a stable age composition consistent with spawning stock biomass (*SSB*) that was 20% of the true spawning stock biomass consistent with maximum sustainable yield (SSB_{MSY}); *i.e.* in the middle of the Critical Zone shown in Figure 1. σ_p is the standard deviation of the process error, ϕ_p is the autocorrelation of the process error, σ_m is the standard deviation of the measurement error ϕ_m, is the autocorrelation of the measurement error. TRCZ is the time to reach the Cautious Zone, PBCC is the probability of reaching the Cautious Zone, PRHZ is the probability of reaching the Healthy Zone, TRHZ is the time to reach the Healthy Zone, PBHC is the probability of returning to the Cautious Zone having reached the Healthy Zone, PBHL is the probability of returning to the Critical Zone having reached the Healthy Zone, PFCM is the probability that fishing mortality (*F*) will exceed the fishing mortality that generates maximum sustainable yield (F_{MSY}) for years when the stock is in the Cautious Zone, PFA2 is the probability that *F* will exceed $1.2F_{MSY}$, PFA5 is the probability *F* will exceed $1.5F_{MSY}$, CV10 is the mean coefficient of variation in the catch over the last 10 years, AC50 is the mean of the ratio of catch to *MSY* over the 50 year simulation time period and AC10 is the mean of the ratio of catch to *MSY* over the last 10 years.

Pop	σ_p	ϕ_p	σ_m	ϕ_m	TRCZ	PBCC	PRHZ	TRHZ	PBHC	PBHL	PFCM	PFA2	PFA5	CV10	AC50	AC10
A[1]	0.0	0.0	0.0	0.0	6.000	0.000	1.000	19.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A	0.0	0.0	0.0	0.0	6.000	0.000	1.000	34.000	0.000	0.000	0.000	0.000	0.000	0.018	0.526	0.875
A	0.2	0.0	0.0	0.0	6.000	0.000	0.995	33.798	0.062	0.000	0.000	0.000	0.000	0.033	0.524	0.875
A	0.2	0.3	0.0	0.0	6.000	0.000	0.992	33.412	0.095	0.000	0.000	0.000	0.000	0.042	0.525	0.878
A	0.2	0.6	0.0	0.0	6.000	0.000	0.974	32.957	0.132	0.000	0.000	0.000	0.000	0.055	0.523	0.872
A	0.2	0.9	0.0	0.0	6.000	0.000	0.845	32.759	0.080	0.000	0.000	0.000	0.000	0.056	0.517	0.871
A	0.3	0.0	0.0	0.0	6.000	0.000	0.980	32.595	0.140	0.000	0.000	0.000	0.000	0.050	0.524	0.873
A	0.3	0.9	0.0	0.0	6.000	0.000	0.804	31.184	0.098	0.000	0.000	0.000	0.000	0.088	0.517	0.876
A	0.4	0.0	0.0	0.0	6.000	0.000	0.979	32.223	0.192	0.000	0.000	0.000	0.000	0.070	0.519	0.871
A	0.4	0.9	0.0	0.0	6.000	<0.001	0.775	30.122	0.118	0.000	0.000	0.000	0.000	0.122	0.507	0.857
B[1]	0.0	0.0	0.0	0.0	3.000	0.000	1.000	5.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
B	0.0	0.0	0.0	0.0	3.000	0.000	1.000	10.000	0.000	0.000	0.000	0.000	0.000	0.000	0.855	0.999
B	0.2	0.0	0.0	0.0	3.000	0.000	1.000	10.689	0.017	0.000	0.000	0.000	0.000	0.060	0.854	0.997
B	0.2	0.3	0.0	0.0	3.000	0.000	1.000	10.831	0.043	0.000	0.000	0.000	0.000	0.074	0.852	0.996
B	0.2	0.6	0.0	0.0	3.000	0.000	1.000	11.178	0.084	0.000	0.000	0.000	0.000	0.085	0.851	0.992
B	0.2	0.9	0.0	0.0	3.000	0.000	0.997	13.175	0.126	0.000	0.000	0.000	0.000	0.072	0.851	1.002
B	0.3	0.0	0.0	0.0	3.000	0.000	1.000	10.818	0.067	0.000	0.000	0.000	0.000	0.094	0.853	0.995
B	0.3	0.9	0.0	0.0	3.000	0.000	0.987	14.296	0.195	0.000	0.000	0.000	0.000	0.115	0.849	0.988
B	0.4	0.0	0.0	0.0	3.000	0.000	1.000	10.911	0.131	0.000	0.000	0.000	0.000	0.132	0.846	0.992
B	0.4	0.9	0.0	0.0	3.000	0.000	0.975	14.889	0.236	0.000	0.000	0.000	0.000	0.165	0.853	0.976
C[1]	0.0	0.0	0.0	0.0	2.000	0.000	1.000	3.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	0.0	0.0	0.0	0.0	2.000	0.000	1.000	3.000	0.000	0.000	0.000	0.000	0.000	0.000	0.962	1.000
C	0.2	0.0	0.0	0.0	2.000	0.000	1.000	3.495	0.044	0.000	0.000	0.000	0.000	0.113	0.960	0.998
C	0.2	0.3	0.0	0.0	2.000	0.000	1.000	3.634	0.072	0.000	0.000	0.000	0.000	0.128	0.960	0.998
C	0.2	0.6	0.0	0.0	2.000	0.000	1.000	3.739	0.112	0.000	0.000	0.000	0.000	0.135	0.960	0.997
C	0.2	0.9	0.0	0.0	2.000	0.000	0.999	4.547	0.151	0.000	0.000	0.000	0.000	0.100	0.958	0.987
C	0.3	0.0	0.0	0.0	2.000	0.000	1.000	3.768	0.124	0.000	0.000	0.000	0.000	0.176	0.959	0.998
C	0.3	0.9	0.0	0.0	2.000	0.000	0.996	5.721	0.236	0.000	0.000	0.000	0.000	0.149	0.967	1.003
C	0.4	0.0	0.0	0.0	2.000	0.000	1.000	3.876	0.200	0.000	0.000	0.000	0.000	0.246	0.949	0.988
C	0.4	0.9	0.0	0.0	2.000	0.000	0.999	6.544	0.301	0.000	0.000	0.000	0.000	0.208	0.963	0.996

[1]$F=0$

PBHL, PFCM, PFA2 and PFA5 (note that where only one line is visible it is because the plots for all three simulated populations were nearly identical). No impact on F-based performance statistics occurred because process error had no impact on the ability of the PHCR to generate the appropriate F in the process error-only simulations. There was no effect of σ_p on PRHZ for Populations B and C. However, for Population A, increasing σ_p negatively affected PRHZ, although the decrease was small (from 1 to <0.98). The effect of σ_p on TRHZ was very small, with a slight decrease with increasing σ_p for Population A and slight increases for Populations B and C. The impact of σ_p on PBHC was substantial with increases from 0 at σ_p = 0 to nearly 0.2 for Populations A and C and greater than 0.1 for Population B at σ_p = 0.4.

Closer examination of the process error runs revealed the reason for less resilience in PBHC with increasing σ_p in Populations A and C compared with B. Population A took more than 30 years, on average, to reach the Healthy Zone and the median *SSB* remained close to the boundary between the Healthy and Cautious Zones for the subsequent 20 years. Consequently, variation in Population A caused by process error resulted in more frequent incursions into the Cautious Zone than would have been the case if median *SSB* were higher and in

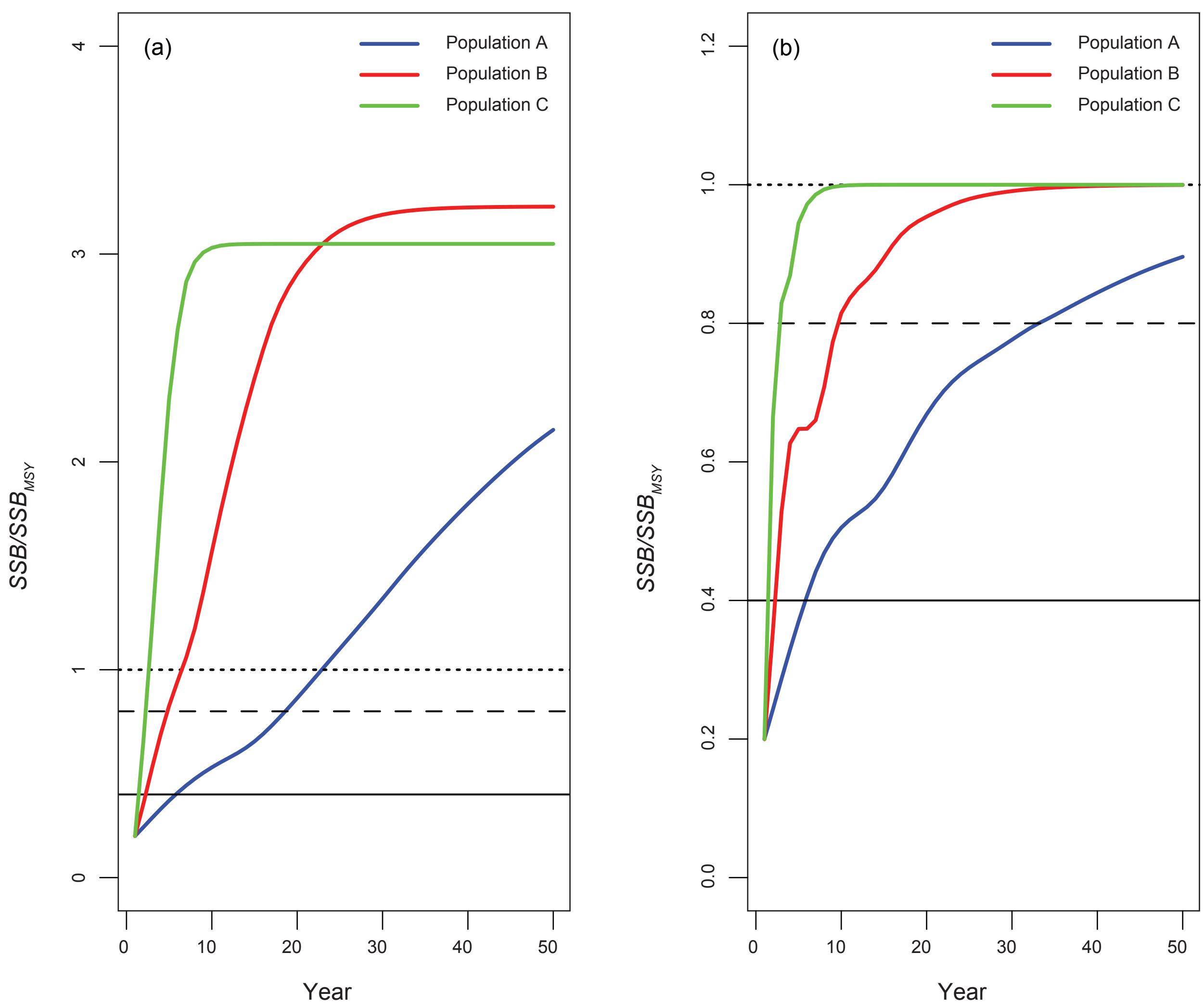

Fig. 2. Results for deterministic reference runs showing *SSB* (expressed as a proportion of SSB_{MSY}) for Population A (blue), B (red) and C (green) in the absence of fishing (a) and under the Provisional Harvest Control Rule (b), with initial *SSB* set in the middle of the Critical Zone at 20%SSB_{MSY}. The life histories of the populations are described in Table 1. The horizontal solid black line corresponds to the Limit Reference Point, the horizontal dashed line corresponds to the Upper Stock Reference Point and the horizontal dotted line corresponds to the spawning stock biomass that generates maximum sustainable yield, SSB_{MSY}.

Table 3. Performance statistics for the PHCR under measurement error (see Table 2 for explanations of the abbreviations).

Pop	σ_p	ϕ_p	σ_m	ϕ_m	TRCZ	PBCC	PRHZ	TRHZ	PBHC	PBHL	PFCM	PFA2	PFA5	CV10	AC50	AC10
A	0.0	0.0	0.2	0.0	6.149	<0.001	1.000	30.768	0.068	0.000	0.198	0.117	0.018	0.300	0.510	0.863
A	0.0	0.0	0.2	0.3	6.121	<0.001	1.000	30.394	0.090	0.000	0.204	0.115	0.018	0.284	0.511	0.863
A	0.0	0.0	0.2	0.6	6.151	<0.001	0.996	30.198	0.105	0.000	0.204	0.111	0.015	0.239	0.511	0.866
A	0.0	0.0	0.2	0.9	6.236	<0.001	0.909	30.920	0.063	0.000	0.206	0.098	0.015	0.142	0.509	0.860
A	0.0	0.0	0.3	0.0	6.397	0.003	1.000	29.643	0.106	0.000	0.225	0.171	0.063	0.459	0.501	0.850
A	0.0	0.0	0.3	0.9	6.531	0.006	0.899	28.878	0.097	0.000	0.229	0.146	0.053	0.238	0.495	0.847
A	0.0	0.0	0.4	0.0	6.669	0.008	1.000	29.399	0.139	0.000	0.245	0.201	0.104	0.614	0.492	0.835
A	0.0	0.0	0.4	0.9	6.911	0.017	0.900	27.628	0.111	0.000	0.243	0.172	0.088	0.334	0.476	0.830
B	0.0	0.0	0.2	0.0	3.000	<0.001	1.000	9.686	0.029	0.000	0.228	0.180	0.038	0.262	0.851	0.997
B	0.0	0.0	0.2	0.3	3.001	<0.001	1.000	9.727	0.039	0.000	0.258	0.177	0.036	0.235	0.850	0.997
B	0.0	0.0	0.2	0.6	3.003	<0.001	1.000	9.881	0.057	0.000	0.293	0.173	0.036	0.187	0.849	0.996
B	0.0	0.0	0.2	0.9	3.008	<0.001	0.997	11.624	0.082	0.000	0.346	0.172	0.036	0.096	0.845	0.990
B	0.0	0.0	0.3	0.0	3.018	0.001	1.000	9.139	0.075	<0.001	0.268	0.240	0.104	0.420	0.847	0.999
B	0.0	0.0	0.3	0.9	3.042	0.003	0.997	11.249	0.124	<0.001	0.397	0.207	0.083	0.161	0.831	0.976
B	0.0	0.0	0.4	0.0	3.051	0.004	1.000	8.930	0.112	<0.001	0.287	0.263	0.146	0.568	0.840	0.992
B	0.0	0.0	0.4	0.9	3.156	0.009	0.996	10.790	0.163	0.002	0.462	0.239	0.129	0.231	0.814	0.958
C	0.0	0.0	0.2	0.0	2.000	<0.001	1.000	3.509	0.090	0.000	0.285	0.234	0.085	0.310	0.958	0.995
C	0.0	0.0	0.2	0.3	2.000	<0.001	1.000	3.571	0.101	0.000	0.415	0.232	0.082	0.259	0.955	0.993
C	0.0	0.0	0.2	0.6	2.000	<0.001	1.000	3.698	0.114	<0.001	0.562	0.228	0.079	0.196	0.951	0.989
C	0.0	0.0	0.2	0.9	2.000	0.001	1.000	4.476	0.129	<0.001	0.608	0.229	0.078	0.091	0.946	0.984
C	0.0	0.0	0.3	0.0	2.000	0.001	1.000	3.521	0.157	0.000	0.279	0.276	0.156	0.477	0.955	0.993
C	0.0	0.0	0.3	0.9	2.000	0.008	1.000	4.630	0.196	0.006	0.669	0.272	0.143	0.151	0.929	0.966
C	0.0	0.0	0.4	0.0	2.003	0.002	1.000	3.509	0.194	<0.001	0.264	0.290	0.194	0.613	0.949	0.988
C	0.0	0.0	0.4	0.9	2.019	0.023	1.000	4.920	0.220	0.018	0.650	0.282	0.179	0.213	0.907	0.942

Table 4. Performance statistics for the PHCR under combined process and measurement error (see Table 2 for explanations of the abbreviations).

Pop	σ_p	ϕ_p	σ_m	ϕ_m	TRCZ	PBCC	PRHZ	TRHZ	PBHC	PBHL	PFCM	PFA2	PFA5	CV10	AC50	AC10
A	0.3	0.9	0.2	0.9	6.271	0.002	0.854	29.803	0.113	0.000	0.160	0.084	0.011	0.200	0.506	0.868
A	0.3	0.0	0.3	0.0	6.383	0.002	1.000	29.691	0.152	0.000	0.225	0.169	0.063	0.470	0.500	0.845
A	0.3	0.9	0.3	0.9	6.519	0.009	0.861	28.993	0.120	<0.001	0.199	0.130	0.045	0.296	0.488	0.841
A	0.4	0.9	0.2	0.9	6.168	0.005	0.809	28.745	0.133	0.000	0.141	0.074	0.011	0.253	0.491	0.839
A	0.4	0.0	0.4	0.0	6.648	0.009	0.995	28.964	0.193	0.000	0.240	0.195	0.103	0.631	0.492	0.837
A	0.4	0.9	0.4	0.9	7.175	0.031	0.835	28.195	0.126	<0.001	0.202	0.151	0.077	0.449	0.463	0.805
B	0.3	0.9	0.2	0.9	3.004	0.001	0.993	12.930	0.210	0.002	0.302	0.141	0.029	0.181	0.841	0.982
B	0.3	0.0	0.3	0.0	3.016	0.002	1.000	9.218	0.127	<0.001	0.279	0.237	0.102	0.446	0.842	0.986
B	0.3	0.9	0.3	0.9	3.042	0.009	0.989	12.102	0.207	0.004	0.372	0.203	0.088	0.239	0.830	0.972
B	0.4	0.9	0.2	0.9	3.000	0.001	0.986	13.808	0.238	0.001	0.249	0.134	0.027	0.232	0.842	0.992
B	0.4	0.0	0.4	0.0	3.058	0.006	1.000	9.029	0.168	0.001	0.281	0.256	0.143	0.602	0.835	0.988
B	0.4	0.9	0.4	0.9	3.171	0.029	0.990	11.946	0.243	0.016	0.368	0.217	0.115	0.360	0.804	0.949
C	0.3	0.9	0.2	0.9	2.000	0.005	1.000	5.455	0.246	0.003	0.452	0.192	0.063	0.209	0.934	0.979
C	0.3	0.0	0.3	0.0	2.000	0.008	1.000	3.604	0.205	0.007	0.279	0.274	0.155	0.527	0.951	0.991
C	0.3	0.9	0.3	0.9	2.000	0.016	0.999	5.224	0.259	0.012	0.506	0.242	0.129	0.259	0.933	0.971
C	0.4	0.9	0.2	0.9	2.000	0.008	0.999	5.682	0.296	0.005	0.369	0.184	0.061	0.264	0.944	0.991
C	0.4	0.0	0.4	0.0	2.005	0.026	1.000	3.630	0.245	0.025	0.280	0.286	0.194	0.679	0.942	0.983
C	0.4	0.9	0.4	0.9	2.016	0.042	0.999	5.628	0.278	0.032	0.488	0.242	0.153	0.369	0.907	0.943

the Healthy Zone. In the case of Population C, although median *SSB* rapidly reached a level close to SSB_{MSY}, the sensitivity to process error was greater because there were only a few age classes available to smooth out the variability. The similarity in responses by Populations A and C was therefore coincidental. Population B reached the Healthy Zone in about 10 years, on average, and median *SSB* reached a level near SSB_{MSY} by year 20. The combination of high median *SSB* and the buffering effect of multiple age classes for Population B resulted in more resilience in terms of the impact of increasing σ_p on PBHC compared to the other two populations. Increasing σ_p resulted in increasing CV10, reaching a level greater than 0.2 for Population A, greater than 0.1 for Population B and greater than 0.5 for Population C, at $\sigma_p = 0.4$. AC50 and AC10 showed slight decreases at high σ_p for all three populations.

There was little or no effect, of increasing ϕ_p on TRCZ, PBCC, PBHL, PFCM, PFA2, PFA5 and AC50 (Fig. 4). There was little effect of ϕ_p on PRHZ for Populations B and C, whereas for Population A the probability decreased from 1 at $\phi_p = 0$ to less than 0.85 at $\phi_p = 0.9$. TRHZ decreased slightly with increasing ϕ_p for Population A, whereas it increased slightly with increasing ϕ_p for Populations B and C. There was generally an increasing

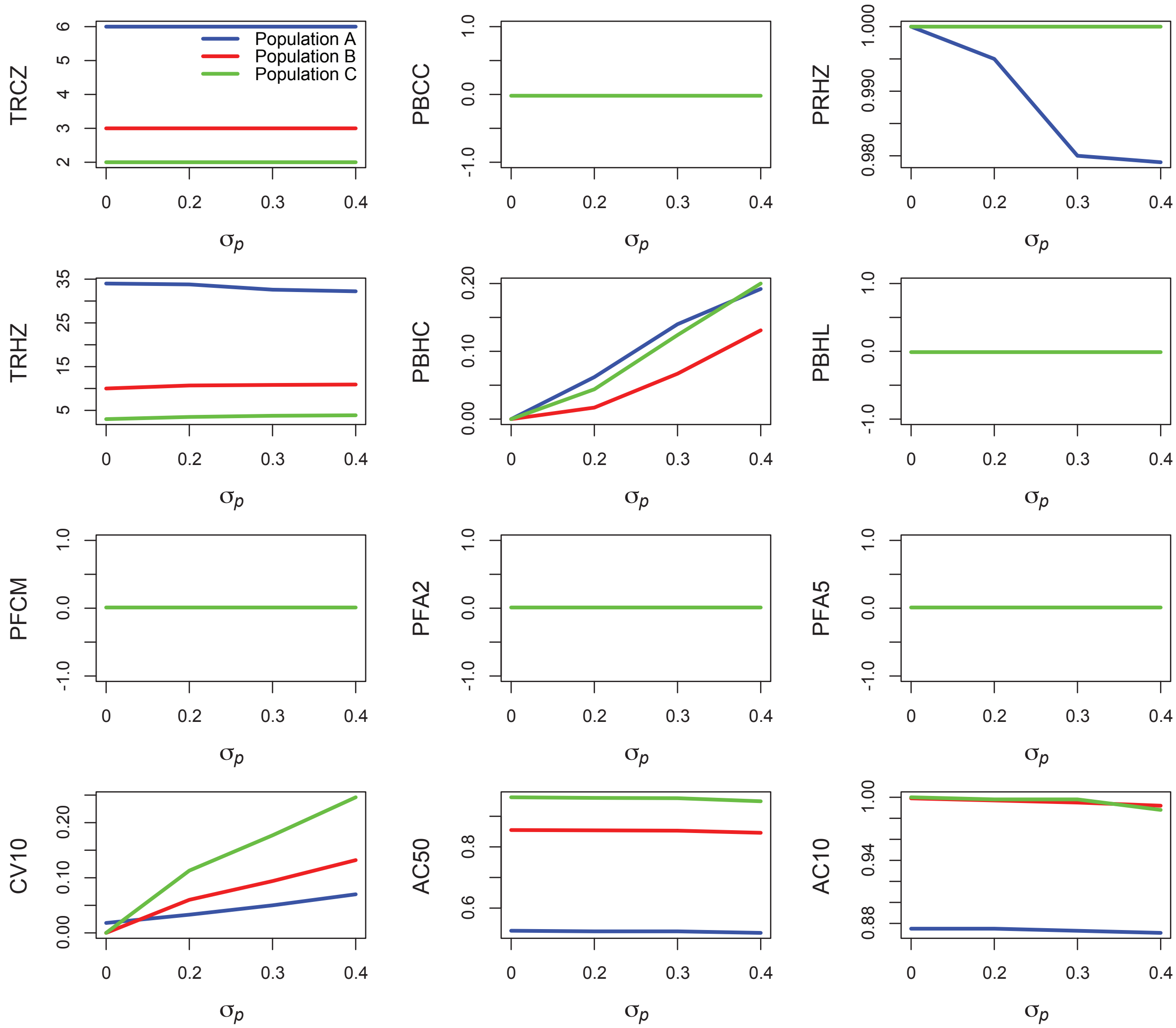

Fig. 3. Effects of the standard deviation of the process error, σ_p, on performance statistics for simulation runs in which the autocorrelation of the process error $\phi_p = 0$ and the standard deviation of the measurement error $\sigma_m = 0$. Refer to Table 2 for explanations of the performance statistics.

trend in PBHC with increasing ϕ_p for all three populations, however at the highest level of ϕ_p there was a decrease in PBHC for Population A. The decrease in PRHZ and PBHC at the highest level of ϕ_p was caused by interaction between highly autocorrelated process error and the slow *SSB* response to change due to the life history of Population A. This changed the shape of the uncertainty envelope in which *SSB* replicates fell such that fewer replicates reached the Healthy Zone while those that did tended to remain in the Healthy Zone. CV10 increased for all three populations with increasing ϕ_p up to $\phi_p = 0.6$ and then declined at $\phi_p = 0.9$ (Populations B and C) or levelled off (Population A). Changes in AC10 in response to increasing ϕ_p were very slight.

Measurement error-only runs

Performance statistics for the simulation trials in which the PHCR was applied under measurement error-only are plotted against σ_m (Fig. 5) and ϕ_m (Fig. 6). Recall that measurement error was only applied to *SSB*. The effect of increasing σ_m was apparent in all the performance statistics, with the exception of PRHZ and PBHL (Fig. 5). However, the effect was very small on TRCZ and AC50. PBCC increased with increasing σ_m for all three populations but remained very small overall. TRHZ decreased slightly with increasing σ_m for Populations A and B. PBHC increased with increasing σ_m in all three populations, from 0 at $\sigma_m = 0$ to nearly 0.2 in Population

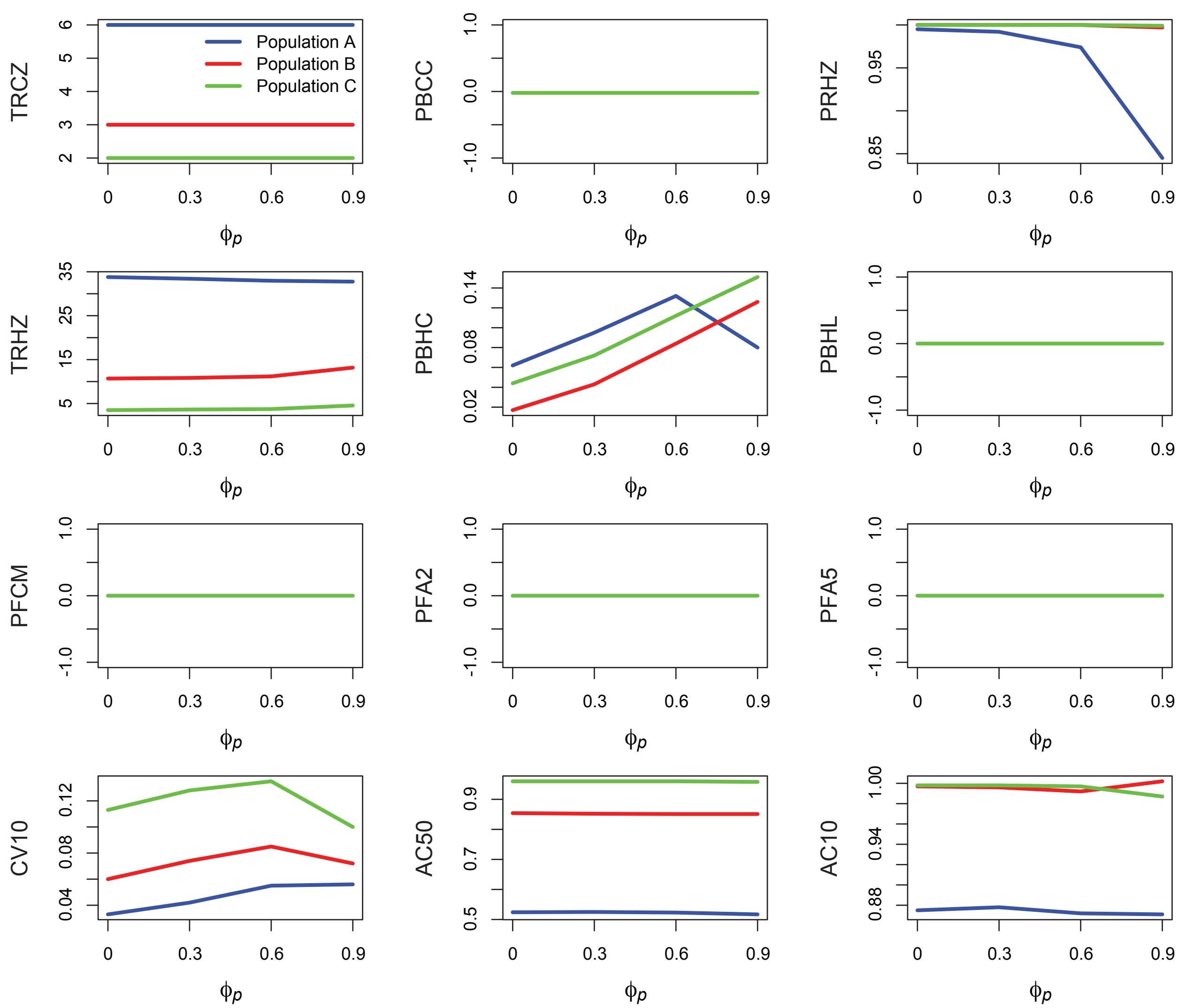

Fig. 4. Effects of autocorrelation in the process error, ϕ_p, on performance statistics for simulation runs in which the standard deviation of the process error $\sigma_p = 0.2$ and standard deviation of the measurement error $\sigma_m = 0$. Refer to Table 2 for explanations of the performance statistics.

C, greater than 0.1 in Population A and about 0.1 in Population B, at $\sigma_m = 0.4$. The three *F*-based performance statistics increased with increasing σ_m and were greatest for Population C, intermediate for Population B and least for Population A. The exception was for PFCM, where the effect on Population C declined at $\sigma_m = 0.3$ and $\sigma_m = 0.4$, ending up below the corresponding value for Population B. Probabilities reached as high as 0.3 for PFA2 and 0.2 for PFA5 in the case of Population C while values for the other populations were lower. CV10 increased with increasing σ_m for all three populations and were around 0.6. AC50 and AC10 decreased slightly with increasing σ_m, particularly in the case of Population A.

An effect of ϕ_m increasing on the performance statistics was most apparent with regard to PBHC, PFCM and CV10 (Fig. 6). PBHC tended to increase with increasing ϕ_m for all three populations with the exception of Population A at $\phi_m = 0.9$ where there was a decrease. There was a corresponding decrease in PRHZ in Population A at $\phi_m = 0.9$. The reason for these decreases in Population A at the highest level of ϕ_m was similar to those observed under process error, although in this case the source of variation was due to changes in *F* which resulted from the PHCR applied to *SSB* observed with autocorrelated measurement error. PFCM increased with increasing ϕ_m for Populations B and C but there was no effect on Population A. CV10 decreased with increasing ϕ_m for all three populations.

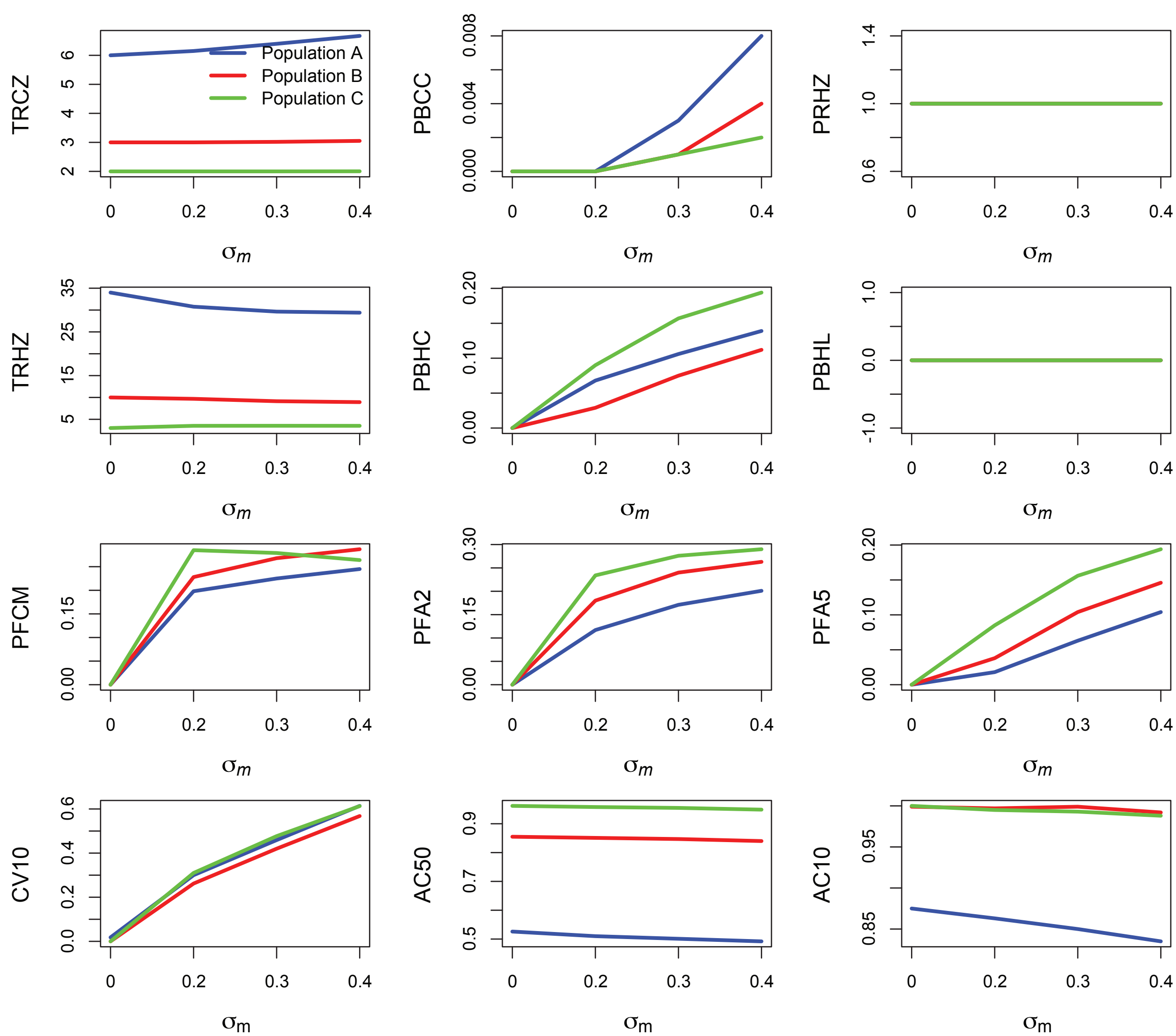

Fig. 5. Effects of the standard deviation of the measurement error, σ_m, on performance statistics for simulation runs in which the autocorrelation of the measurement error $\phi_m = 0$ and the standard deviation of the process error $\sigma_p = 0$. Refer to Table 2 for explanations of the performance statistics.

Minimum and maximum values

Minimum and maximum values for all performance statistics across all runs in which the PHCR was applied (*i.e.*. excluding F = 0 runs; data in Tables 2, 3 and 4) showed that TRCZ had a range of 6.00 to 7.18 years for Population A and less than one year for Populations B and C (Table 5). The range in PBCC was less than 0.05 for all three populations. PRHZ had a minimum that was population dependent, being lowest for Population A (0.78) and highest for Population C (close to 1.0). TRHZ had a wide range, more than 6 years for Population A, about 6 years for Population B and about 3.5 years for Population C. Maximum values for PBHC were close to 0.2 for Population A, close to 0.25 for Population B and about 0.3 for Population C. PBHL had a small range and was less than 0.04 for all three populations. The range in PFCM was population-dependent and was widest for Population C with a maximum of about 0.7 and smallest for Population A with a maximum of about 0.25. Maximum values of PFA2 and PFA5 did not vary much across populations with values of about 0.2 to 0.3 for PFA2 and about 0.1 to 0.2 for PFA5. CV10 had a wide range within each population but with a maximum value that was fairly similar across all three populations (0.6–0.68). Maximum values for AC50 were population-dependent with a narrow range within each population. AC10 had an even narrower range within each population.

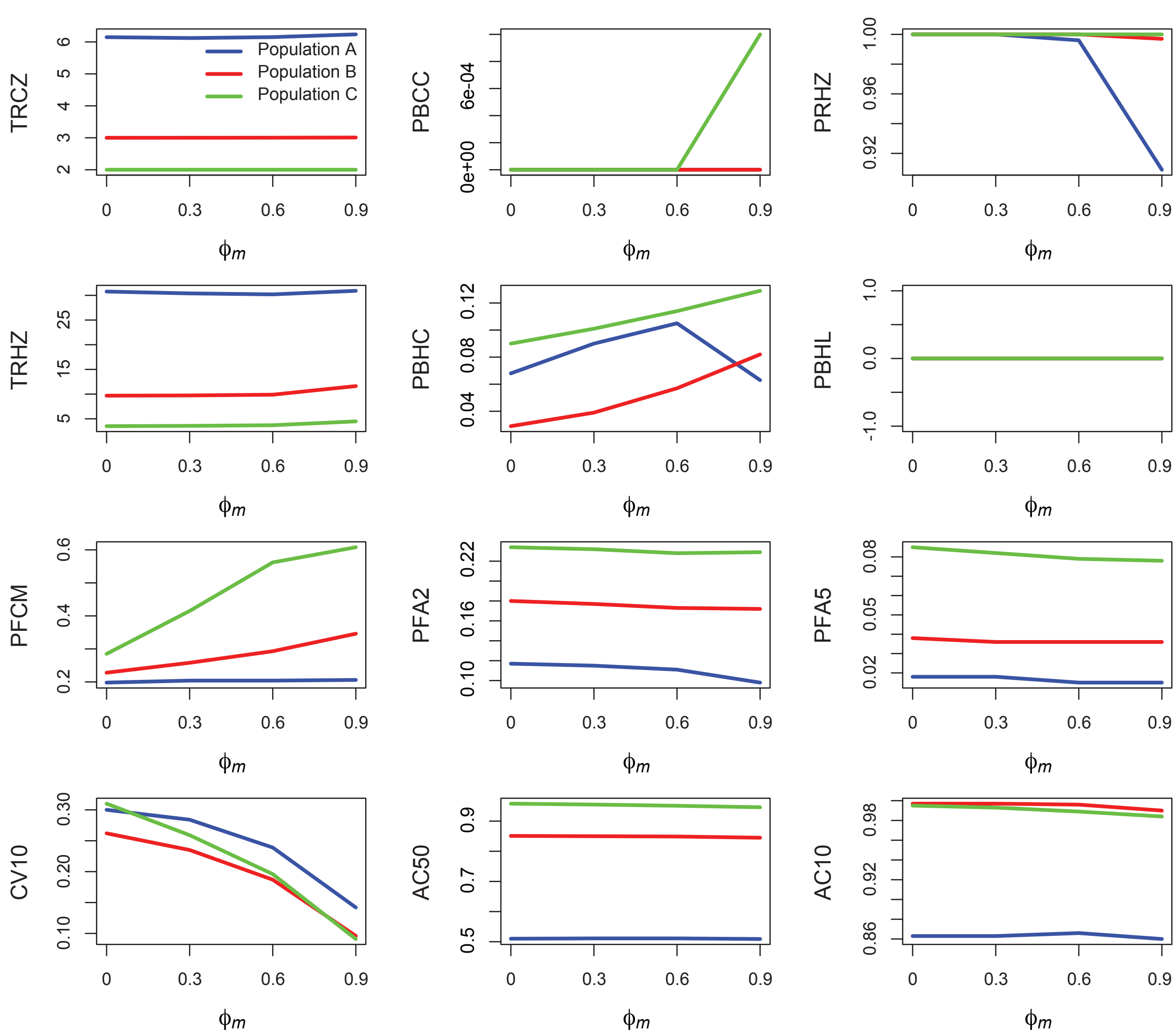

Fig. 6. Effects of the autocorrelation in the measurement error, ϕ_m, on performance statistics for simulation runs in which the standard deviation of the measurement error σ_m = 0.2 and standard deviation of the process error σ_p = 0. Refer to Table 2 for explanations of the performance statistics.

Analysis of variance

ANOVA results for main effects (Table 6) showed that Population was significant for all performance statistics (Tables 3, 4 and 5) with the exception of PBCC. There was a significant effect of σ_p on all performance statistics with the exception of TRCZ and PRHZ. ϕ_p had a significant effect on only five of the performance statistics: PRHZ, PBHC, CV10, AC50 and AC10. The effect of σ_m on the performance statistics was significant in all cases with the exception of PRHZ. ϕ_m had a significant effect on five of the performance statistics: PBCC, PFCM, CV10, AC50 and AC10. A comparison across effects showed that the catch-based performance statistics, CV10, AC50 and AC10 were significantly affected by all five main effects. PBHC was significantly affected by four of the five effects, the effect for ϕ_m being non-significant. PFCM was also significantly affected by four of the five effects, but in this case ϕ_p was non-significant.

Discussion

In this study, initial trials of the robustness of the PHCR were explored under a range of process errors and measurement errors for three simulated depleted populations with different life histories. Life history had a significant effect on nearly all performance statistics selected for evaluating the PHCR. Both process and observation errors, and to a lesser extent autocorrelation in these errors, had significant effects on many of the performance statistics selected. However, in several cases, the range of values obtained under different error combinations was small (<10%). It should be noted that a danger in the application of ANOVA on simulation results is that any variable with a non-zero effect size can be found to be significant if enough simulations are run. Responses for some of the performance statistics were not consistent across populations. This is attributed to life history differences and the relative impact of autocorrelated errors. For example, the decline in PBHC in the slow-growing, long-lived simulated population, at the highest levels of ϕ_p and ϕ_m, was caused by interactions between the lagged response by *SSB* to variation determined by life history and autocorrelation in the errors, which in the case of ϕ_m, was mediated through changes in *F* by the PHCR. The performance of the PHCR would change if time lags in the application of the PHCR were considered. Typically data from $y-1$ is used in year y to provide scientific advice for year $y+1$, resulting in a two-year lag between data for the terminal year and when the catch advice occurs. These lags were not considered in the present study.

The simulation results showed that the DMF objective of rebuilding stocks from the Critical Zone to the Cautious Zone, with a probability of 75% to 95% within 1.5 to 2 generations (DFO, 2009b), was easily achieved for all three populations irrespective of the errors introduced in the simulations. This result occurred because the *TAC* in the simulations was set consistent with a very low *F* of 0.001 when perceived *SSB* was in the Critical Zone. However, such a low F in the Critical Zone may be unrealistic. For example, Cadigan (2015) estimated fully selected *F* for *status quo* catch projections of Northern Cod, a stock well below the LRP, to be 0.124 for his base model, considerably higher than the value of *F* assumed in the simulations run here. The simulation results suggested that fish stocks in the Critical Zone could rebuild to the Healthy Zone under the PHCR with high probability (> 0.78) irrespective of life history differences and the combinations of process and observations errors. However, the amount of time necessary to rebuild under application of the PHCR was up to twice as long

Table 5. Minimum and maximum values for performance statistics across the range of error combinations evaluated in Tables 2–4 for Populations A, B and C (Pop A, B and C). Population A was slow-growing and long-lived, Population C was fast-growing and short-lived and Population B was intermediate (see Table 2 for explanations of abbreviations).

	TRCZ	PBCC	PRHZ	TRHZ	PBHC	PBHL	PFCM	PFA2	PFA5	CV10	AC50	AC10
Pop A												
Min	6.000	0.000	0.775	27.628	0.000	0.000	0.000	0.000	0.000	0.018	0.463	0.805
Max	7.175	0.031	1.000	34.000	0.193	0.000	0.245	0.201	0.104	0.631	0.526	0.878
Pop B												
Min	3.000	0.000	0.975	8.930	0.000	0.000	0.000	0.000	0.000	0.000	0.804	0.949
Max	3.171	0.029	1.000	14.889	0.243	0.016	0.462	0.263	0.146	0.602	0.855	1.002
Pop C												
Min	2.000	0.000	0.996	3.000	0.000	0.000	0.000	0.000	0.000	0.000	0.907	0.942
Max	2.019	0.042	1.000	6.544	0.301	0.032	0.669	0.290	0.194	0.679	0.967	1.003

as it took in the absence of fishing. The DMF (DFO, 2009b) suggested that, for a stock in the Cautious Zone, management actions should rebuild the stock to the Healthy Zone in 1.5 to 2 generations. Combining the amount of time defined for rebuilding to the Cautious Zone and then to the Healthy Zone suggested that a time period of up to 4 generations would be acceptable for a stock to rebuild from the Critical Zone to the Healthy Zone, *i.e.*. between 12 and 74 years for the three simulated stocks considered in the present analysis. Simulation results suggested that the amount of time to rebuild under the PHCR should meet these objectives with high probability despite process and observation errors. However, these rebuilding times may be overly generous. In the United States, federally managed marine fisheries are mandated to rebuild the biomass of overfished stocks to levels that support maximum sustainable yield in as short a time as possible, typically within 10 years, except in cases where the life history characteristics of the stock, environmental conditions or management measures under an international agreement dictate otherwise (Patrick and Cope, 2014). In the simulations, the starting level for all three populations was 20%SSB_{MSY}. Lesser or greater depletion in actual stocks will impact the rebuilding time and, for severely depleted stocks, rebuilding times defined in the DMF may not be met.

Having rebuilt to the Healthy Zone, the simulations found that the PHCR was not effective in ensuring a low probability (<0.1) of preventing the return to the Cautious Zone when recruitment was subject to process error and when the spawning stock size estimates provided to the PHCR were subject to measurement error. The probability of returning to the Cautious Zone increased with increasing standard deviation of both types of errors and, in most cases, with increasing autocorrelation in the errors. The probability was as high as 0.3 in the simulations, depending on the error combination and life history. In some replicates of the simulation at higher levels of process and observation errors and higher autocorrelation in these errors, *SSB* fell from the Healthy Zone to the Cautious Zone and remained in the Cautious Zone for the remainder of the simulation period. Future studies should consider including an additional performance statistic to capture this response. Reducing F in the Healthy Zone to less than F_{MSY} (*i.e.*. $\lambda < 1$) could be explored as a way to reduce this probability. Probabilities for returning to the Cautious Zone were highest for Population C and lowest for Population A, suggesting that the PHCR may need to be adapted to account for life history differences, such that a smaller value of λ is adopted for fast-growing, short-lived species. An additional option that could be explored, irrespective of life history, for reducing the probability of

Table 6. P-values for the main effects of Population (A, B or C, see Table 1 for details regarding the life history of each population), σ_p, ϕ_p, σ_m, and ϕ_m in an analysis of variance applied to the performance statistics resulting from simulations carried out on three populations. The Provisional Harvest Control Rule was applied under a range of process and observation errors and auto-correlation in these errors. σ_p is the standard deviation of the process error, ϕ_p is the autocorrelation of the process error, σ_m is the standard deviation of the measurement error, ϕ_m is the autocorrelation of the measurement error (see Table 2 for explanations of abbreviations). Results not significant at the $p < 0.05$ level are denoted by NS.

Effect	Population	σ_p	ϕ_p	σ_m	ϕ_m
Performance statistic					
TRCZ	<0.0001	NS	NS	<0.0001	NS
PBCC	NS	<0.0001	NS	<0.0001	<0.01
PRHZ	<0.0001	NS	<0.0001	NS	NS
TRHZ	<0.0001	<0.05	NS	<0.05	NS
PBHC	<0.0001	<0.0001	<0.05	<0.001	NS
PBHL	<0.01	<0.05	NS	<0.001	NS
PFCM	<0.0001	<0.0001	NS	<0.0001	<0.001
PFA2	<0.0001	<0.0001	NS	<0.0001	NS
PFA5	<0.0001	<0.0001	NS	<0.0001	NS
CV10	<0.05	<0.0001	<0.0001	<0.0001	<0.0001
AC50	<0.0001	<0.0001	<0.001	<0.0001	<0.0001
AC10	<0.0001	<0.0001	<0.05	<0.0001	<0.0001

returning to the Cautious Zone would be to commence the decrease in F with decreasing SSB at SSB_{MSY} rather than at the USR (80%SSB_{MSY}). On the positive side, there was a very low probability (< 0.05) of a population returning to the Critical Zone under the PHCR once it reached the Cautious Zone.

The PHCR was not effective in keeping F below F_{MSY} in the simulations when the stock was in the Cautious Zone and subject to measurement error, particularly at high levels of autocorrelation. Setting $\lambda < 1$ and commencing the reduction in F with decreasing SSB at SSB_{MSY} rather than at the USR, as suggested above, would reduce the probability of high values of F in the Cautious Zone.

Variation in the annual catch generated by the PHCR in the simulations was high at higher levels of both process error in the population and observation error associated with SSB. This raises concerns that the behaviour of the PHCR may not be consistent with the general desire of the fishing industry to minimize annual catch variation. On the positive side, the PHCR achieved average catches that were close to the MSY level once the stock had recovered, except in the case of the slowest-growing and longest-lived population which was still in the process of recovering towards SSB_{MSY} under the PHCR at the end of the 50-year simulation period.

The results from the simulation trials suggested that, depending on the nature of the errors and the life history of the population, the PHCR with $\lambda = 1$ and the inflection point below which F is reduced (*i.e.*, 80%SSB_{MSY},) may not result in the desired management outcomes of keeping SSB in the Healthy Zone and avoiding high levels of F, particularly in the Cautious Zone. HCRs can be "tuned" to improve the trade-off in performance statistics so as to better achieve management objectives (Rademeyer *et al.*, 2007). Adjusting λ and the inflection point to improve performance would constitute tuning the HCR. However, tuning the HCR requires that management objectives be clearly stated in terms of targets and limits and that measurable quantitative performance statistics be derived from these objectives. Yet, in most cases, targets have not been defined and probability thresholds and time horizons with respect to management objectives have not yet been developed for Canadian fish stocks in DFO fishery management plans.

The performance statistics applied in these initial trials of the PHCR were informed by the DFO SFF and DMF policies, but remain somewhat arbitrary and may not provide the best representation of management objectives associated with the DFO PA and sustainable fisheries policies. Under the PA, some performance statistics may represent imperative conservation outcomes that have to be achieved at the possible expense of less desirable outcomes with respect to fishery-related performance statistics (Miller and Shelton, 2010). An example of an imperative outcome, consistent with the PA, would be a specific probability threshold that must not being exceeded over some specified time horizon with respect to SSB falling into the Critical Zone.

The coupling of HCR decision points with biological reference points (USR and LRP) is not a requirement under the DFO SFF and DMF, and an HCR that uses different SSB decision points (*e.g.* Cox *et al*., 2013), or doesn't use SSB decision points at all (*e.g.* a simple HCR based on relative change in the annual research survey index; Miller and Shelton, 2010), might result in a better trade-off in performance statistics than the PHCR. This could be explored through further simulation studies in which the performance of alternative HCRs is evaluated.

In this study, it was assumed that MSY reference points were known exactly. In practice, they need to be estimated as part of the stock assessment process. This is done either in the initial fitting of the assessment model, or as an additional model fitting exercise applied to estimates of SSB and R obtained from the assessment model. Traditionally, groundfish stock assessments by DFO in Atlantic Canada have been based on Virtual Population Analysis (VPA; Pope, 1972; Quinn and Deriso, 1999) and reference points have been estimated from the fitting of a stock-recruit model to the VPA estimates of SSB and recruitment (*e.g.* Duplisea and Fréchet, MS 2009). This typically results in the "errors-in-variables" problem (Walters and Ludwig, 1981; Ludwig and Walters, 1981; Hilborn and Walters, 1992; and Quinn and Deriso, 1999), which arises because the estimation method does not account for errors in the independent variable, SSB. The consequence of the "errors in variables problem" is that F_{MSY} is typically over-estimated and SSB_{MSY} is typically under-estimated (Hilborn and Walters, 1992). Process error associated with recruitment can also add bias to the estimates of MSY reference points as a consequence of correlation between the residuals around the stock-recruit curve and subsequent SSB (Walters, 1985). These two sources of bias could negatively impact the performance of the PHCR if they are not taken into account. State-space models that explicitly account for both process and measurement errors in the estimation of the population may be capable of providing estimates of MSY reference points that are less biased (Walters and Martell, 2004), however the development of such models for fish stocks in Atlantic Canada is at an early stage (*e.g.* Cadigan, 2015).

The current analysis provides an initial evaluation of the DFO PHCR and suggests some potential weaknesses and changes that could be considered to improve performance. This study represents a "best-case" scenario, and therefore, a minimum test of the robustness of the PHCR with respect to achieving management objectives derived from the DMF. Bias in the stock assessment estimates or non-stationarity in biological or fishery parameters will negatively impact the performance of the PHCR. The level of fishing mortality, whether directed or bycatch, applied when a stock is in the Critical Zone is another important area to explore in future research. The PHCR assumes this is negligible, but this may not be realistic (*e.g.* Cadigan, 2015). The simulation results presented here indicate that rather than simply adopting the PHCR for all stocks, stock-specific HCRs should be developed and tuned to improve performance. However, tuning would require more explicit derivation of quantitative performance statistics to reflect management objectives with respect to both limits and targets, consistent with the DFO SFF and DMF policies.

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