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Journal of Northwest Atlantic Fishery Science

Scientific publications by ICNAF and NAFO have been in existence since ICNAF began in 1949 with the ICNAF Special Publication series dealing with proceedings of scientific symposia. The *ICNAF Research Bulletin* was started in 1964 to provide a means of publishing results of scientific research relevant to ICNAF. The *ICNAF Research Bulletin* was terminated in September 1979 after the issue of Number 14. The first volume of the NAFO *Journal of Northwest Atlantic Fishery Science* was published in December 1980, after NAFO came into force replacing ICNAF in 1979.

The Northwest Atlantic fisheries have a rich history, and a great deal of research has been sponsored and encouraged by NAFO and its predecessor ICNAF. NAFO has been a leader amongst international organizations in the application of science to fishery management and in the regulation of fisheries in areas beyond national jurisdiction. In accordance with its mandate to disseminate information on fisheries research to the scientific community, the Scientific Council of NAFO publishes the *Journal of Northwest Atlantic Fishery Science*, which contains peer-reviewed primary papers, and *NAFO Scientific Council Studies*, which contains unrefereed papers of topical interest and importance to the Scientific Council. Lists of these and other NAFO publications are given on the back of this issue.

Editorial Policy

The Journal provides an international forum for the primary publication of original research papers, with emphasis on environmental, biological, economic and social science aspects of fisheries and their interactions with marine habitats and ecosystems. While the Journal is intended to be regional in scope, papers of general applicability, and methodological and review papers, irrespective of region, are considered. Space is available for notes and letters to the editor to facilitate scientific discussion of published papers. Both practical and theoretical papers are eligible. All papers are peer-reviewed to determine their suitability for primary publication. Associate Editors arrange for the peer-reviews and ensure that the papers accepted for publication meet the high standards required for the Journal. Manuscripts approved for publication are accepted with the understanding that they are not copyrighted, published or submitted elsewhere except in abstract form. There are no page charges.

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Foreword (2017)

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As always, this volume of the journal covers a range of topics representing ongoing research in the northwest Atlantic, including robustness testing of harvest control rules, bycatch in the Georges Bank scallop fishery and developments to improve size selectivity in bottom trawls.

I would like to extend my thanks to all the authors who submitted works in 2017, to the Associate Editors and reviewers who make the production of the journal possible, and to Alexis Pacey, publications manager at the NAFO Secretariat for their support and assistance.

I hope you find this volume enjoyable and informative.

December 2017

Tom Blasdale,

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General Editor Journal of Northwest Atlantic Fisheries Science

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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 "bestcase" 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



Spawning stock biomass

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.

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.

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",

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

When the stock is in the "Critical Zone",

$$F_y \approx 0.$$
 (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 slowgrowing, 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:

$$M = 4.22/A.$$
 (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

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

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

$$L_{a} = L_{\infty} (1 - e^{-k(a - a_{0})}),$$

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.

(7)

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
$L_{\infty}(\mathrm{cm})$	Asymptotic length	150	100	15
Length-weight				
η	Constant	0.00001	0.00001	0.00001
ω	Constant	3	3	3
Maturation				
$ au_{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
$SPR_{F=0}$ (kg per age 1 fish)	Spawner per recruit when fishing mortality is zero	24.753	4.250	0.008
$SPR_{F=Fmsy}$ (kg per age 1 fish)	Spawner per recruit when fishing mortality gives <i>MSY</i>	13.195	1.631	0.003
$SPR_{\rm F=Fmsy}/SPR_{\rm F=0}$	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
<i>RPS</i> _{max} (thousands of recruits/ tons of spawners)	Maximum recruits per spawner	0.162	2.196	1895.556
r' _{max}	Maximum instantaneous rate of population growth	0.083	0.284	1.202
F _{MSY}	Fishing mortality rate that generates MSY	0.118	0.458	1.767
F _{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 $M = 4.22/T_{\text{max}}$	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 $M = 1.65 / \tau_{50}$	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:

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

$$SPR_{F=F_{MSY}} = \sum_{a=1}^{A} (e^{(-(M+F_{MSY}S_a)(a-1))} P_a W_a),$$
(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*, $N_{I,y}$, 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:

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

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

$$SSB_v = \sum_{a=1}^A (N_{a,v} P_a W_a), \tag{13}$$

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

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

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

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:

$$N_{a+1,y+1} = N_{a,y} e^{-(F_{a,y}+M)},$$
(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_{yy}^* 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

$$SSB_{y}^{*} = SSB_{y}\varepsilon_{my}, \tag{18}$$

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 selectivityat-age, S_a , assumed to be constant, known and equal to P_a , so that

$$F_{a,y}^* = S_a F_y^*.$$
 (19)

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

$$C_{a,y} = N_{a,y}^* \left(1 - e^{-(M + F_{a,y}^*)}\right) \frac{F_{a,y}^*}{(F_{a,y}^* + M)}$$
(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

$$SSB_{y}^{*} = \sum_{a=1}^{A} (N_{a,y}^{*} P_{a} W_{a}), \qquad (21)$$

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

$$TAC_y = \sum_{a=1}^{A} (C_{a,y} W_a).$$
(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_{v} was found iteratively by satisfying the condition that:

$$TAC_{y} = \sum_{a=1}^{A} \left(N_{a,y} \left(1 - e^{-(M + S_{a}F_{y})} \right) \frac{S_{a}F_{y}}{(S_{a}F_{y} + M)} W_{a} \right).$$
(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 = 0and 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;
- 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;
- 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 historymediated, 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,

ble 2. Performance statistics for the Canada's Department of Fisheries and Oceans' Provisional Harvest Control Rule, for three simulated populations under determinist conditions and mocess error A total of 1 000 simulation runs were conducted over a 50-vear time horizon for each nonulation (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 spawni stock biomass (<i>SSB</i>) that was 20% of the true spawning stock biomass consistent with maximum sustainable yield (<i>SSB</i> _{MSY}); <i>i.e.</i> in the middle of the Critical Zone show	in Figure 1. σ_{ρ} is the standard deviation of the process error, ϕ_{ρ} is the autocorrelation of the process error, σ_{n} is the standard deviation of the measurement error ϕ_{n} , is to 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 Cautious Zone.	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, PFCM is the probability that fishing mortality (<i>F</i>) will exceed the fishing the fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability that fishing mortality (<i>F</i>) will exceed the fishing the probability (<i>F</i>) will exceed the fishing the probability of the fishing mortality (<i>F</i>) will exceed the fishing the probability (<i>F</i>) will exceed the fishing the probability (<i>F</i>) will exceed the fishing the probability (<i>F</i>) will exceed the fishing the fishing the fishing the fishing the probability (<i>F</i>) will exceed the fishing	mortality that generates maximum sustainable yield (<i>F</i> _{MSY}) for years when the stock is in the Cautious Zone, PFA2 is the probability that <i>F</i> will exceed 1.2 <i>F</i> _{MSY} . PFA5	the probability F will exceed 1.5 F_{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.	
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Pop	σ_p	ϕ_p	σ_m	ϕ_m	TRCZ	PBCC	PRHZ	TRHZ	PBHC	PBHL	PFCM	PFA2	PFA5	CV10	AC50	AC10
\mathbf{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
Bī	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
В	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
В	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
В	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
В	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
В	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
В	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
В	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
В	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
В	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	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
С	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
С	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
С	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
С	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
С	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
С	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
С	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
С	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
С	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
$^{1}F=0$																

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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 $\sigma_p = 0$ to nearly 0.2 for Populations A and C and greater than 0.1 for Population B at $\sigma_p = 0.4$.

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}*.

0.000 0.204 0.115 0.000 0.204 0.111	0.090 0.000 0.204 0.115 0.105 0.000 0.204 0.111	30.394 0.090 0.000 0.204 0.115 30.198 0.105 0.000 0.204 0.111	1.000 30.394 0.090 0.000 0.204 0.115 0.006 20.108 0.105 0.000 0.204 0.111	 <c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><c><p< th=""><th>6.121 <0.001 1.000 30.394 0.090 0.000 0.204 0.115 6.151 <0.001 0.006 20.108 0.106 0.000 0.204 0.115</th><th>0.3 6.121 <0.001 1.000 30.394 0.090 0.000 0.204 0.115</th><th>$\begin{array}{cccccccccccccccccccccccccccccccccccc$</th><th>0.0 0.2 0.3 6.121 <0.001</th> 1.000 30.394 0.090 0.000 0.204 0.115 0.0 0.2 0.6 6.151 <0.001 0.996 30.198 0.105 0.000 0.204 0.111</p<></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c></c>	6.121 <0.001 1.000 30.394 0.090 0.000 0.204 0.115 6.151 <0.001 0.006 20.108 0.106 0.000 0.204 0.115	0.3 6.121 <0.001 1.000 30.394 0.090 0.000 0.204 0.115	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.0 0.2 0.3 6.121 <0.001	0.0 0.0 0.2 0.3 6.121 <0.001 1.000 30.394 0.090 0.000 0.204 0.115
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0.000 0.258 0.1	0.039 0.000 0.258 0.1	9.727 0.039 0.000 0.258 0.1	1.000 9.727 0.039 0.000 0.258 0.1	<0.001 1.000 9.727 0.039 0.000 0.258 0.1	3.001 <0.001 1.000 9.727 0.039 0.000 0.258 0.1	0.3 3.001 <0.001 1.000 9.727 0.039 0.000 0.258 0.1	0.2 0.3 3.001 <0.001 1.000 9.727 0.039 0.000 0.258 0.1	0.0 0.2 0.3 3.001 <0.001 1.000 9.727 0.039 0.000 0.258 0.1	0.0 0.0 0.2 0.3 3.001 <0.001 1.000 9.727 0.039 0.000 0.258 0.1
0.000 0.293 0.1	0.057 0.000 0.293 0.1	9.881 0.057 0.000 0.293 0.1	1.000 9.881 0.057 0.000 0.293 0.1	<0.001 1.000 9.881 0.057 0.000 0.293 0.1	3.003 <0.001 1.000 9.881 0.057 0.000 0.293 0.1	0.6 3.003 <0.001 1.000 9.881 0.057 0.000 0.293 0.1	0.2 0.6 3.003 <0.001 1.000 9.881 0.057 0.000 0.293 0.1	0.0 0.2 0.6 3.003 <0.001 1.000 9.881 0.057 0.000 0.293 0.1	0.0 0.0 0.2 0.6 3.003 <0.001 1.000 9.881 0.057 0.000 0.293 0.1
0.000 0.346 0.17	0.082 0.000 0.346 0.17	11.624 0.082 0.000 0.346 0.17	0.997 11.624 0.082 0.000 0.346 0.17	<0.001 0.997 11.624 0.082 0.000 0.346 0.17	3.008 <0.001 0.997 11.624 0.082 0.000 0.346 0.17	0.9 3.008 <0.001 0.997 11.624 0.082 0.000 0.346 0.17	0.2 0.9 3.008 <0.001 0.997 11.624 0.082 0.000 0.346 0.17	0.0 0.2 0.9 3.008 <0.001 0.997 11.624 0.082 0.000 0.346 0.17	0.0 0.0 0.2 0.9 3.008 <0.001 0.997 11.624 0.082 0.000 0.346 0.17
<0.001 0.268 0.240	0.075 <0.001 0.268 0.240	9.139 0.075 <0.001 0.268 0.240	1.000 9.139 0.075 <0.001 0.268 0.240	0.001 1.000 9.139 0.075 <0.001 0.268 0.24	3.018 0.001 1.000 9.139 0.075 <0.001 0.268 0.24	0.0 3.018 0.001 1.000 9.139 0.075 <0.001 0.268 0.24	0.3 0.0 3.018 0.001 1.000 9.139 0.075 <0.001 0.268 0.24	0.0 0.3 0.0 3.018 0.001 1.000 9.139 0.075 <0.001 0.268 0.24	0.0 0.0 0.3 0.0 3.018 0.001 1.000 9.139 0.075 <0.001 0.268 0.24
<0.001 0.397 0.207	0.124 < 0.001 0.397 0.207	$11.249 \qquad 0.124 \qquad < 0.001 \qquad 0.397 \qquad 0.207$	0.997 11.249 0.124 <0.001 0.397 0.207	0.003 0.997 11.249 0.124 <0.001 0.397 0.207	3.042 0.003 0.997 11.249 0.124 <0.001 0.397 0.207	0.9 3.042 0.003 0.997 11.249 0.124 <0.001 0.397 0.207	0.3 0.9 3.042 0.003 0.997 11.249 0.124 <0.001 0.397 0.207	0.0 0.3 0.9 3.042 0.003 0.997 11.249 0.124 <0.001 0.397 0.207	0.0 0.0 0.3 0.9 3.042 0.003 0.997 11.249 0.124 <0.001 0.397 0.207
<0.001 0.287 0.263	0.112 <0.001 0.287 0.263	8.930 0.112 <0.001 0.287 0.263	1.000 8.930 0.112 <0.001 0.287 0.263	$0.004 \qquad 1.000 \qquad 8.930 \qquad 0.112 \qquad <0.001 \qquad 0.287 \qquad 0.263$	3.051 0.004 1.000 8.930 0.112 <0.001 0.287 0.263	0.0 3.051 0.004 1.000 8.930 0.112 <0.001 0.287 0.263	0.4 0.0 3.051 0.004 1.000 8.930 0.112 <0.011 0.287 0.263	0.0 0.4 0.0 3.051 0.004 1.000 8.930 0.112 <0.011 0.287 0.263	0.0 0.0 0.4 0.0 3.051 0.004 1.000 8.930 0.112 <0.001 0.287 0.263
0.002 0.462 0.239	0.163 0.002 0.462 0.239	10.790 0.163 0.002 0.462 0.239	0.996 10.790 0.163 0.002 0.462 0.239	0.009 0.996 10.790 0.163 0.002 0.462 0.239	3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239	0.9 3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239	0.4 0.9 3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239	0.0 0.4 0.9 3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239	0.0 0.0 0.4 0.9 3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239
0.000 0.285 0.234 0	0.090 0.000 0.285 0.234 0	3.509 0.090 0.000 0.285 0.234 0	1.000 3.509 0.090 0.000 0.285 0.234 0	<0.001 1.000 3.509 0.090 0.000 0.285 0.234 0	2.000 <0.001 1.000 3.509 0.090 0.000 0.285 0.234 0	0.0 2.000 <0.001 1.000 3.509 0.090 0.000 0.285 0.234 0	0.2 0.0 2.000 <0.001 1.000 3.509 0.090 0.000 0.285 0.234 0	0.0 0.2 0.0 2.000 <0.001 1.000 3.509 0.090 0.000 0.285 0.234 0	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
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.090 0.000 0.285 0.254 0. 0.101 0.000 0.415 0.232 0.		1.000 3.571 0.101 0.000 0.000 0.232 0.001 1.000 3.571 0.101 0.000 0.415 0.232 0.01	<0.001 1.000 3.571 0.101 0.000 0.415 0.232 0.	2.000 < 0.001 1.000 3.571 0.101 0.000 0.145 0.232 0. 2.000 < 0.001 1.000 3.571 0.101 0.000 0.415 0.232 0.	0.0 - 2.000 < 0.001 1.000 3.509 0.090 0.000 0.283 0.234 0.00 0.3 2.000 < 0.001 1.000 $3.571 - 0.101 - 0.000 - 0.415 - 0.232 - 0.001 - 0.000 - 0.415 - 0.232 - 0.001 - 0.000 - 0.415 - 0.232 - 0.000 - 0.415 - 0.202 - 0.000 - 0.415 - 0.202 - 0.000 - 0.415 - 0.232 - 0.000 - 0.415 - 0.202 - 0.000 - 0.415 - 0.202 - 0.000 - 0.415 - 0.202 - 0.000 - 0.415 - 0.202 - 0.000 - 0.415 - 0.202 - 0.000 - 0.415 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.000 - 0.202 - 0.202 - 0.000 - 0.202 - 0.000 - 0.000 - 0.000 - 0.000 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.202 - 0.000 - 0.000 - 0.000 - 0.000 - 0.000 - 0.000 - 0.000 $	0.2 0.0 2.000 <0.001 1.000 3.509 0.090 0.000 0.228 0.234 0. 0.2 0.3 2.000 <0.001 1.000 3.571 0.101 0.000 0.415 0.232 0.	0.0 0.2 0.0 2.000 2.000 0.00.0 202.2 0.00.1 1.000 2.00 2.	.0 0.0 0.0 0.2 0.0 2.000 <0.001 1.000 3.50 0.000 0.000 0.223 0.234 0. 0.0 0.0 0.0 0.3 2.000 <0.001 1.000 3.571 0.101 0.000 0.415 0.332 0
0.000 0.415 0.232 0.0	0.101 0.000 0.415 0.232 0.0	3.571 0.101 0.000 0.415 0.232 0.0	1.000 3.571 0.101 0.000 0.415 0.232 0.	<0.001 1.000 3.571 0.101 0.000 0.415 0.232 0.0	2.000 <0.001 1.000 3.571 0.101 0.000 0.415 0.232 0.	0.3 2.000 <0.001 1.000 3.571 0.101 0.000 0.415 0.232 0.0			
0.002 0.462 0.239 0.000 0.285 0.234 0.000 0.415 0.232	0.163 0.002 0.462 0.239 0.090 0.000 0.285 0.234 0.101 0.000 0.415 0.232	10.790 0.163 0.002 0.462 0.239 3.509 0.090 0.000 0.285 0.234 3.571 0.101 0.000 0.415 0.232	0.996 10.790 0.163 0.002 0.462 0.239 1.000 3.509 0.090 0.000 0.285 0.234 1.000 3.571 0.101 0.000 0.415 0.232	0.009 0.996 10.790 0.163 0.002 0.462 0.239 <0.001	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	0.4 0.9 3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239 0.2 0.0 2.000 <0.01	0.0 0.4 0.9 3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239 0.0 0.2 0.0 2.000 <0.01	0.0 0.0 0.4 0.9 3.156 0.009 0.996 10.790 0.163 0.002 0.462 0.239 0.0 0.0 0.2 0.0 2.000 <0.001
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	28.878 0.097 0.000 0.229 29.399 0.1139 0.000 0.245 27.628 0.111 0.000 0.243 9.686 0.029 0.000 0.243 9.727 0.039 0.000 0.258 9.881 0.057 0.000 0.258 9.881 0.057 0.000 0.236 9.139 0.075 0.000 0.246 11.624 0.082 0.000 0.346 9.139 0.075 <0.001 0.268 11.249 0.124 <0.001 0.268 11.249 0.112 <0.001 0.287 8.930 0.112 <0.001 0.287 3.570 0.090 0.000 0.285 3.571 0.101 0.000 0.415	0.899 28.878 0.097 0.000 0.229 1.000 29.399 0.113 0.000 0.245 0.900 27.628 0.111 0.000 0.243 1.000 9.686 0.029 0.000 0.228 1.000 9.727 0.039 0.000 0.228 1.000 9.727 0.039 0.000 0.238 1.000 9.881 0.057 0.000 0.293 0.997 11.624 0.082 0.000 0.346 1.000 9.139 0.075 <0.001 0.268 0.997 11.624 0.075 <0.001 0.268 0.997 11.249 0.124 <0.001 0.268 0.997 11.249 0.124 <0.001 0.287 1.000 8.930 0.112 <0.001 0.287 1.000 3.509 0.090 0.000 0.462 1.000 3.571 0.101 0.000 0.415	0.006 0.899 28.878 0.097 0.000 0.229 0.008 1.000 29.399 0.111 0.000 0.245 0.017 0.900 27.628 0.111 0.000 0.245 <0.001		0.9 6.531 0.006 0.899 28.878 0.097 0.000 0.229 0.0 6.669 0.008 1.000 27.628 0.111 0.000 0.245 0.9 6.911 0.017 0.900 27.628 0.111 0.000 0.243 0.0 3.000 <0.001 1.000 9.7528 0.111 0.000 0.243 0.0 3.001 <0.001 1.000 9.7527 0.039 0.228 0.3 3.001 <0.001 1.000 9.727 0.039 0.228 0.3 3.001 <0.001 1.000 9.727 0.039 0.233 0.9 3.018 0.001 1.000 9.124 0.001 0.268 0.0 3.042 0.001 1.000 9.124 0.001 0.346 0.0 3.042 0.001 1.000 9.124 0.001 0.287 0.001		$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	
$\begin{array}{c} 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\\ 0.000\end{array}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	29.643 0.106 0.000 28.878 0.097 0.000 29.399 0.139 0.000 27.628 0.111 0.000 9.686 0.029 0.000 9.727 0.039 0.000 9.727 0.039 0.000 9.881 0.057 0.000 9.139 0.075 0.000 11.624 0.082 0.000 9.139 0.075 <0.001 11.249 0.124 <0.001 11.249 0.124 <0.001 8.930 0.112 <0.002 3.571 0.101 0.000	1.000 29.643 0.106 0.000 0.899 28.878 0.097 0.000 1.000 29.399 0.139 0.000 1.000 27.628 0.111 0.000 1.000 9.686 0.029 0.000 1.000 9.727 0.039 0.000 1.000 9.727 0.039 0.000 1.000 9.727 0.039 0.000 1.000 9.139 0.057 0.000 0.997 11.624 0.075 <0.001 0.997 11.249 0.124 <0.001 0.997 11.249 0.124 <0.001 0.996 10.790 0.163 0.002 1.000 3.509 0.163 0.002 1.000 3.571 0.101 0.000 1.000 3.571 0.101 0.000	$ \begin{array}{ccccccccccccccccccccccccccccccccccc$	6.397 0.003 1.000 29.643 0.106 0.000 6.531 0.006 0.899 28.878 0.097 0.000 6.669 0.008 1.000 29.399 0.139 0.000 6.911 0.017 0.900 27.628 0.111 0.000 3.001 <0.001 1.000 9.686 0.029 0.000 3.001 <0.001 1.000 9.7627 0.039 0.000 3.003 <0.001 1.000 9.727 0.039 0.000 3.013 <0.001 1.000 9.727 0.039 0.000 3.013 <0.001 1.000 9.727 0.039 0.000 3.018 <0.001 1.000 9.139 0.075 <0.001 3.018 0.001 1.000 9.139 0.075 <0.001 3.018 0.001 1.000 9.139 0.075 <0.001 3.018 0.001 1.000 9.139 0.075 <0.001 3.051 0.003 0.997 11.249 0.124 <0.001 3.051 0.009 0.996 10.790 0.163 0.002 2.000 <0.001 1.000 3.571 0.101 0.000 2.000 <0.001 1.000 3.571 0.101 0.000	0.0 6.397 0.003 1.000 29.643 0.106 0.007 0.000 0.9 6.531 0.006 0.899 28.878 0.097 0.000 0.0 6.669 0.008 1.000 29.3399 0.113 0.000 0.9 6.911 0.017 0.900 27.628 0.111 0.000 0.0 3.000 <0.001 1.000 9.686 0.029 0.000 0.3 3.001 <0.001 1.000 9.7527 0.039 0.000 0.3 3.003 <0.001 1.000 9.737 0.032 0.000 0.3 3.003 <0.001 1.000 9.737 0.033 0.000 0.0 3.003 <0.001 1.000 9.139 0.000 0.000 0.0 3.003 <0.001 1.000 9.139 0.002 0.000 0.0 3.018 0.001	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	
	0.063 0.106 0.097 0.139 0.139 0.139 0.039 0.039 0.037 0.039 0.082 0.082 0.075 0.124 0.112 0.112 0.163 0.163	30.920 0.063 29.643 0.106 28.878 0.097 29.399 0.139 29.586 0.139 9.686 0.029 9.727 0.039 9.727 0.039 9.727 0.039 9.727 0.039 9.727 0.039 9.727 0.039 9.739 0.057 11.624 0.062 9.139 0.075 11.249 0.124 8.930 0.112 10.790 0.163 3.571 0.101	0.909 30.920 0.063 1.000 29.643 0.106 0.899 28.878 0.097 1.000 29.399 0.139 0.900 27.628 0.111 1.000 9.686 0.029 1.000 9.727 0.039 1.000 9.727 0.037 1.000 9.727 0.037 1.000 9.727 0.037 1.000 9.727 0.075 0.997 11.624 0.075 0.997 11.249 0.124 1.000 8.930 0.112 0.996 10.790 0.163 1.000 3.509 0.090 1.000 3.571 0.101	<0.001 0.909 50.920 0.063 0.003 1.000 29.643 0.106 0.006 0.899 28.878 0.097 0.008 1.000 29.5399 0.139 0.017 0.900 27.628 0.111 <0.001 1.000 27.628 0.111 <0.001 1.000 9.686 0.029 <0.001 1.000 9.762 0.039 <0.001 1.000 9.727 0.039 <0.001 1.000 9.727 0.037 <0.001 1.000 9.139 0.057 <0.001 1.000 9.139 0.075 <0.001 1.000 9.139 0.075 0.003 0.997 11.249 0.124 0.003 0.997 11.249 0.124 0.004 1.000 8.930 0.112 0.004 1.000 3.509 0.096 <0.001 1.000 3.509 0.090 <0.001 1.000 3.571 0.101	6.236 <0.001 0.909 50.920 0.063 6.377 0.003 1.000 29.643 0.106 6.531 0.006 0.899 28.878 0.097 6.669 0.008 1.000 29.5399 0.139 6.911 0.017 0.900 27.628 0.111 3.000 <0.001 1.000 9.686 0.029 3.001 <0.001 1.000 9.762 0.039 3.003 <0.001 1.000 9.727 0.039 3.003 <0.001 1.000 9.727 0.039 3.003 <0.001 1.000 9.727 0.039 3.018 0.001 1.000 9.139 0.075 3.042 0.003 0.997 11.249 0.163 3.051 0.003 0.997 11.249 0.163 3.051 0.003 0.996 10.790 0.163 3.051 0.009 0.996 0.090 0.103	0.9 6.236 <0.001 0.909 30.920 0.063 0.0 6.337 0.003 1.000 29.643 0.106 0.0 6.331 0.006 0.899 28.878 0.097 0.0 6.669 0.008 1.000 29.5399 0.139 0.0 6.911 0.017 0.900 28.878 0.097 0.0 6.911 0.017 0.900 29.3399 0.139 0.0 3.000 <0.001 1.000 29.5399 0.139 0.0 3.001 <0.001 1.000 9.686 0.029 0.3 3.001 <0.001 1.000 9.881 0.057 0.9 3.003 <0.001 1.000 9.139 0.075 0.9 3.018 0.001 1.000 9.139 0.075 0.9 3.018 0.001 1.000 9.139 0.0124 0	0.2 0.9 6.236 <0.001 0.909 50.920 0.063 0.3 0.0 6.397 0.003 1.000 29.643 0.106 0.3 0.0 6.391 0.003 1.000 29.643 0.097 0.3 0.0 6.531 0.006 0.899 28.878 0.097 0.4 0.0 6.691 0.008 1.000 29.399 0.139 0.4 0.9 6.911 0.017 0.900 27.628 0.111 0.2 0.0 3.000 <0.001 1.000 9.686 0.029 0.2 0.3 3.001 <0.001 1.000 9.786 0.029 0.2 0.3 3.001 <0.001 1.000 9.737 0.039 0.2 0.6 3.003 <0.001 1.000 9.139 0.075 0.2 0.0 3.003 <0.01 1.000 9.139 0.075 0.2 0.0 3.003 0	0.0 0.2 0.9 6.236 < 0.001 0.909 50.920 0.063 0.063 0.063 0.063 0.063 0.063 0.063 0.067 0.003 0.007 0.097 0.007 0.097 0.007 0.097 0.007 0.097 0.007 0.097 0.007 0.097 0.097 0.097 0.097 0.097 0.097 0.097 0.097 0.097 0.097 0.097 0.097 0.097 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.012 0.02 0.03 0.012 0.03 0.012 0.023 0.013 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 0.023 $0.$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$

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

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Table 4.	Perforn	nance st	atistics	for the I	PHCR under	r combined	process and	measurem	ent error (se	e Table 2 f	or explanati	ons of the a	bbreviation	s).		
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
В	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
В	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
В	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
В	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
В	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
В	0.4	0.9	0.4	0.9	3.171	0.029	066.0	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 $\sigma_m = 0.2$ and standard deviation of the process error $\sigma_p = 0$. 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 slowgrowing, 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, shortlived 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, 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	$\phi_{\scriptscriptstyle m}$
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. Statespace 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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Spatiotemporal patterns of flatfish bycatch in two scallop access areas on Georges Bank

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Abstract

Bycatch is a constraint to the Atlantic sea scallop fishery, the most valuable single-species fishery along the eastern coast of the United States. To characterize trends in the bycatch of three flatfish species, a fishery-independent scallop dredge survey was conducted in two sea scallop access areas (Closed Areas I and II) on Georges Bank from 2011 to 2014. Generalized additive mixed models were used to identify seasonal bycatch hotspots of yellowtail, winter, and windowpane flounder. In all cases, spatially explicit models best fit the data (deviance explained: 47–73%) and provided insight into the spatial distribution underlying the seasonal trends in each area. Modeled catch rates for the three flatfish species suggested localized catches at discrete times of the year. Catches of yellowtail and windowpane flounder were highest in Closed Area II in the fall and winter, respectively. Winter flounder were caught in the highest numbers in Closed Area I during the summer and fall, and were largely absent from catches in Closed Area II. Our results suggest consistent seasonal trends that may help managers identify the optimal times to open the access areas to the scallop fleet in order to reduce flatfish bycatch.

Keywords: catch per unit effort, GAMM, generalized additive mixed models, sea scallop, windowpane flounder, winter flounder, yellowtail flounder

Introduction

The Atlantic sea scallop (*Placopecten magellanicus*) fishery is the most valuable single-species fishery along the eastern coast of the United States (US; van Voorhees, MS 2014). The species is distributed along the northeastern US continental shelf from Cape Hatteras, North Carolina, to Maine, but the bulk of the fishery's effort is concentrated on the productive scallop beds in the mid-Atlantic Bight and on Georges Bank (NEFMC, MS 2014). Since 2004, the resource has been harvested under a rotational

area-based management strategy designed to increase the long-term yield and reproductive potential of the stock by identifying and protecting high-density beds of juvenile scallops from fishing mortality (NEFMC, MS 2003). Under the current plan, the fleet is also given limited access to two static closed areas on Georges Bank (Closed Areas I and II, hereafter also referred to as scallop access areas; Fig. 1) that were established in 1994 to protect spawning habitat of depleted groundfish stocks (Murawski *et al.*, 2000). Although this management strategy has resulted in increased scallop yields (NEFSC,



Fig. 1. Location of fixed survey stations in the sea scallop access areas of Closed Area I (31 stations) and Closed Area II (30 stations) sampled from March 2011 to March 2014.

MS 2010), bycatch of several groundfish species remains a constraint to the fishery, both on Georges Bank and in the mid-Atlantic (O'Keefe and DeCelles, 2013).

In particular, catches of yellowtail flounder (Limanda ferruginea) have impacted the timing, location, and, ultimately, the allowable harvest of sea scallops over the past fifteen years (O'Keefe and DeCelles, 2013). The current regulatory framework mandates a strict accounting of fishery-specific bycatch. If the fleet exceeds its annual catch limit for a given species, accountability measures are implemented (e.g. in-season closures or quota reductions to account for previous overages; Magnuson-Stevens Fishery Conservation and Management Act; USDOC/ NOAA/NMFS, MS 2007). Since 1999, the scallop fleet has been allocated an annual catch limit of Georges Bank yellowtail flounder. Between 1999 and 2009, in-season closures on Georges Bank have occurred several times due to yellowtail overages, resulting in economic losses to the fleet (O'Keefe and DeCelles, 2013). In addition to yellowtail flounder, bycatch of windowpane and winter flounder has also become a management concern in the scallop fishery; an accountability measure for windowpane was recently implemented in the mid-Atlantic (NEFMC, MS 2014). Although accountability measures for flatfish species other than yellowtail are not currently in place for the fishery on Georges Bank, it is plausible they may soon follow.

Given the economic consequences of scallop fishery closures due to yellowtail bycatch (O'Keefe and DeCelles, 2013), numerous efforts to mitigate the fleet's impact on non-target species have been implemented. The fishery funds its own observer program, and has invested heavily in approaches aimed at both reactive (*e.g.* real-time bycatch avoidance; O'Keefe and DeCelles, 2013) and proactive strategies (*e.g.* gear modifications; Davis *et al.*, MS 201) to reduce bycatch. However, the current overfished status of the Georges Bank yellowtail flounder stock (TRAC, MS 2014) and the resulting low annual allocation to the scallop fleet (which was reduced by over 40% in 2014; NEFMC, MS 2014) means that existing

approaches to bycatch reduction may not be sufficient to avoid exceeding catch limits.

Documented seasonal variation in flatfish bycatch rates (Bachman, MS 2009) suggests that targeted time-area closures may be a viable option for the scallop fishery on Georges Bank. Given the relatively stationary nature of scallops (Hart and Chute, 2004) and the migratory patterns of the three flatfish species (Chang et al., 1999; Johnson et al., 1999; Pereira et al., 1999), it is plausible that periods of relative spatial segregation between target and non-target species could be identified based on spatiotemporal patterns in bycatch rates. However, the resolution of the data available is limited. Under the current management strategy, scallop access areas are only open to the fleet during certain periods of designated years, which limits the utility of fishery-dependent data for discerning seasonal trends in bycatch rates. Although the National Marine Fisheries Service-Northeast Fisheries Science Center biannual bottom trawl survey provides a continuous time series of fisheries-independent data for Georges Bank since 1963 (Despres-Patanjo et al., 1988), the survey is not conducted at the spatial resolution or temporal frequency required to assess seasonal patterns in flatfish distributions within the access areas.

To collect the fine-scale, fishery-independent information needed to better understand the spatial and temporal dynamics of flatfish bycatch in the sea scallop fishery in Closed Areas I and II on Georges Bank, a seasonal dredge survey was conducted from 2011–2014. Generalized additive mixed models (Wood, 2006, 2011), which provide a flexible framework for the investigation of spatially continuous, non-linear trends (Swartzman *et al.*, 1992; Augustin *et al.*, 2013), were used to identify spatiotemporal patterns in flatfish bycatch rates. The results are considered in the context of possible timearea management strategies for the Georges Bank scallop access areas.

Materials and Methods

Survey Design

Twenty-nine survey trips were conducted aboard eighteen commercial sea scallop vessels from 2011 to 2014. Survey trips were conducted monthly from March through November of 2011, and every six weeks from January 2012 to March 2014. Sampling locations in Closed Area I and Closed Area II were selected using a fixed station, systematic grid design to ensure uniform spatial coverage of each area (Fig. 1). However, some portions of each closed area could not be sampled due to bottom type (*e.g.* rocky substrate) or high densities of sand dollars (*Echinarachnius parma*). In order to evenly distribute sampling effort to areas with different spatial extents, the distance between stations in each area varied. In Closed Area I (CAI), the 31 stations were separated by 5.4 km east to west and 7.2 km north to south. The 30 stations in Closed Area II (CAII) were separated by 8.6 km east to west and 11.1 km north to south.

On each trip, the vessel was outfitted with two commercial scallop dredges: one standardized 4.6 m wide Turtle Deflector Dredge (TDD) and one 4.6 m wide New Bedford-style dredge, which was supplied by the vessel. Each dredge had 10.2 cm rings and a 25.4 cm mesh twine top, but the TDD had a modified headbale designed to exclude sea turtles (Smolowitz et al., 2012). A more detailed description of the dredges used in this fishery as well as a description of the TDD frame is provided in Smolowitz et al. (2012). Only catch data from the standardized TDD used over the entire course of the survey are presented herein. It is important to note that the large mesh used on commercial scallop dredges has a low selectivity for small flatfish (Legault et al., MS 2010). Thus, the flatfish bycatch rates observed during the course of our survey are considered to be representative only of the portion of the population available and vulnerable to capture in commercial scallop dredges.

At each station, standardized survey protocol specified that the vessel operator pass through the center of each grid cell at some point during the tow; tow direction was left to the discretion of the operator. The target tow duration was 30 minutes, with a minimum acceptable tow time of 20 minutes. Tows shorter than 20 minutes or those with gear or other operational issues were deemed invalid, and the station was resampled until an acceptable tow was completed. Target tow speed was 4.8 knots, and dredges were towed with a 3:1 wire to depth scope. Set-out and haul-back coordinates, depth, sea state, vessel speed, and weather conditions were recorded by the vessel operator. Beginning in May 2011, a temperature (Vemco Minilog) and a temperature-depth logger (Star-Oddi DST milli-TD) were attached to the dredge and programmed to acquire data every 30 seconds.

Following each tow, the catch from each dredge was sorted by species. All yellowtail, winter, and windowpane flounder were counted and measured to the nearest cm. Bycatch rates for each flatfish species in each tow were expressed in terms of catch per unit effort (CPUE) as the ratio of the number of fish caught in the TDD and the time of the tow in minutes; CPUE values for tows that varied around the target tow duration of 30 minutes were scaled accordingly.

Seasonal trends in flatfish catches

Generalized additive mixed models (GAMMs; Wood, 2006, 2011) were used to investigate seasonal changes in the spatial distribution of flatfish catches. There were a large number of tows with zero flatfish catch in both areas (Table 1). Therefore, a Tweedie error distribution (which can accommodate continuous data with many zeros; Tweedie, 1984; Dunn and Smyth, 2005) and a log link function were assumed (Candy 2004; Shono 2008). The Tweedie distribution belongs to the family of exponential dispersion models, which generalize the exponential families used in generalized linear and additive modeling frameworks (Jørgensen 1992). The variance of a Tweedie-distributed random variable, Y, is given by $\operatorname{Var}(Y) = \varphi [E(Y)]^p$, where φ is a dispersion parameter and p is the Tweedie index parameter, which is a constant. When p is equal to 0, 1, or 2, the Tweedie is equivalent to the normal, Poisson, or gamma distribution, respectively. For values of p between 1 and 2, the model is a compound Poisson-gamma distribution. When p is closer to 1, the Tweedie distribution most closely resembles the Poisson and allows for a point mass at 0; as the value of p increases, the Tweedie more closely approximates the gamma (Candy 2004).

Because we were most interested in describing the spatial distribution of catches over the course of the year, we chose to model catch rates as a function of geographic location and month rather than environmental conditions. Additionally, depth and bottom temperature (the two available environmental variables we expected to correlate most highly with catch rates; Swartzman *et al.*, 1992; Hyun *et al.*, 2014) were not collected over the entire course of the survey and were highly correlated with longitude and month, respectively. Preliminary analyses

also indicated that the results of models based on those covariates did not adequately describe the distribution of residuals; they are therefore not presented further here. For model fitting, tow location was estimated as the midpoint of the great circle distance between the start and end points of each tow using the "geosphere" package (Hijmans et al., 2012) in R (R Core Team, 2015). Midpoint coordinates were projected into the universal transverse Mercator coordinate system (UTM zone 19) using the R package "rgdal" (Bivand et al., 2013). Although we used standardized sampling protocols on each survey, different vessels were employed over the course of the study. Therefore, vessel was incorporated as a random effect to account for variability due to differences in vessel handling, engine power, or other technical characteristics of the vessels employed, as well as other inter-vessel differences not accounted for by the covariates of interest (Candy 2004; Augustin et al., 2013).

The response, the CPUE of each flatfish species for tow *j* from vessel $i(y_{ij})$ was modelled as:

$\log(y_{ij}) = \beta_0 + f_1(\text{month}_{ij}, \text{northing}_{ij}, \text{easting}_{ij}) + \beta_1 * \text{year}_{ii} + v_i + \varepsilon_{ij},$

where β_0 is an intercept term; f_i is a smooth function of the covariates associated with vessel *i* and tow *j*; northing and easting are projected tow coordinates; β_i is a coefficient specifying the effect of survey year (note the distinction from calendar year); v_i represents the random effect of vessel; and ε_{ij} is an independently and identically distributed (i.i.d.) error term. It was assumed that $v_i \sim \text{Normal}(0, \sigma_i^2)$ and i.i.d. The incorporation of vessel as a random effect term allows for marginal, "population-level" (*i.e.* vessel-averaged) predictions via integration of v_i out of the conditional CPUE predictions (Candy 2004; Augustin *et al.*, 2013).

Table 1.Number of tows capturing zero yellowtail, winter, and windowpane flounder for all survey
trips and trips by survey year conducted in two scallop access areas on Georges Bank
from March 2011 to March 2014.

Area	Yellowtail	Winter	Windowpane
Closed Area I (<i>n</i> = 849)	517 (61%)	428 (50%)	227 (27%)
2011 (<i>n</i> = 353)	197 (56%)	191 (54%)	105 (30%)
2012 (n = 248)	150 (61%)	114 (46%)	60 (24%)
2013 (<i>n</i> = 248)	170 (69%)	123 (50%)	62 (25%)
Closed Area II ($n = 857$)	145 (17%)	730 (85%)	348 (41%)
2011 (<i>n</i> = 379)	52 (14%)	335 (88%)	153 (40%)
2012 (<i>n</i> = 238)	49 (21%)	191 (80%)	98 (41%)
2013 (<i>n</i> = 240)	44 (18%)	204 (85%)	97 (40%)

Shifts in the spatial distribution of the catch by month are represented by f_{i} , which is a tensor product interaction of a two-dimensional isotropic smooth for location and a one-dimensional smooth for month. The tensor product construction of this interaction term allows for CPUE to be modeled as a smooth function of location and month while being invariant to their relative scaling (Wood, 2006). Thin plate regression splines (Wood, 2006) were used to represent CPUE as a function of geographic coordinates (northing and easting). A cyclic cubic regression spline was used to represent trends in CPUE by month to avoid discontinuities between December and January (Zuur et al., 2009). Catches of winter flounder in CAII were too low (Table 2, Fig. 2; observed CPUE < 4.4 fish per tow in all cases; 3^{rd} quantile = 0.0 fish per tow) and diffuse to se nsibly model in the framework used, as confirmed by residual diagnostics. Therefore, only the results for winter flounder catches in CAI are presented.

Given that stations in CAI and CAII were separated by approximately 100 km, two unique models were constructed for CAI and CAII to avoid smoothing over areas that were not sampled. Simpler models nested within the above equation (*e.g.* models without month, models with the interaction term between geographic location and month replaced by additive effects; see Tables 3-5for the full list of models fitted) were also considered. For each species, the Tweedie index parameter (*p*) was set to the value that maximized the penalized log-likelihood for all model variants (Tables 3-5). All models were fitted via maximum likelihood estimation using the R package "mgcv" (Wood, 2006, 2011).

Model selection and spatial prediction

Model fit was evaluated based on the Akaike Information Criterion (AIC; Akaike, 1973). Interaction and individual



Fig. 2. Catch per unit effort (CPUE; in number of fish per thirty minutes of towing time) of three flounder species in the scallop access areas of **Closed Area I (CAI)** and **II (CAII)** on Georges Bank by month. Note the different axis scales for CPUE in each plot. The axis limits for yellowtail in CAII exclude one large tow in September of 2012 (CPUE = 143 fish per 30 minute tow).

Table 2. Sampling dates, vessel employed, and the median flatfish catch per unit effort (CPUE; expressed as the number of fish caught per thirty-minute tow) for each survey trip conducted from 2011–2014. The range of CPUE for individual stations within each scallop access area is indicated in parentheses below. CAI = Closed Area I; CAII = Closed Area II.

			Yellowtai CF	l Flounder PUE	Winter I CP	Flounder UE	Windowpa CI	ne Flounder PUE
Sar	npling Dates	Vessel	CAI	CAII	CAI	CAII	CAI	CAII
2011	3/9 - 3/15	Arcturus	0.0 (0.0 - 3.0)	4.0 (0.0 - 21.0)	0.0 (0.0 - 1.0)	0.0 (0.0 - 2.0)	2.0 (0.0 - 7.0)	10.5 (0.0 - 126.0)
	4/14 - 4/20	Celtic	0.0 (0.0 – 2.6)	5.0 (0.0 – 18.0)	0.0 (0.0 - 2.9)	0.0 (0.0 - 2.0)	1.1 (0.0 – 5.8)	10.0 (0.0 - 34.0)
	5/11 - 5/17	Westport	1.2 (0.0 – 12.0)	2.0 (0.0 - 15.0)	0.0 (0.0 - 20.0)	0.0 (0.0 – 1.8)	0.0 (0.0 - 4.8)	0.0 (0.0 – 16.0)
	6/1 - 6/7	Liberty	1.5 (0.0 - 8.0)	2.5 (0.0 – 15.0)	1.0 (0.0 – 13.0)	0.0 (0.0 - 1.0)	0.0 (0.0 - 6.0)	0.0 (0.0 - 2.0)
	7/6 - 7/12	Endeavor	1.0 (0.0 - 5.8)	2.5 (0.0 - 20.0)	1.5 (0.0 – 24.0)	0.0 (0.0 - 0.0)	1.0 (0.0 – 10.0)	0.0 (0.0 - 5.0)
	8/15 - 8/21	Regulus	0.0 (0.0 - 6.0)	12.0 (0.0 – 57.8)	2.1 (0.0 – 15.4)	0.0 (0.0 - 2.0)	2.5 (0.0 - 20.1)	0.0 (0.0 – 1.0)
	9/10 - 9/16	Resolution	0.0 (0.0 - 4.0)	10.4 (2.0 – 70.0)	2.0 (0.0 - 48.0)	0.0 (0.0 - 1.0)	1.5 (0.0 – 37.0)	0.0 (0.0 - 0.0)
	10/4 - 10/10	Ranger	0.0 (0.0 - 5.1)	16.0 (3.0 – 47.0)	2.0 (0.0 - 46.5)	0.0 (0.0 - 4.0)	4.0 (0.0 - 26.0)	1.0 (0.0 – 15.0)
	11/29 - 12/5	Horizon	1.0 (0.0 – 9.3)	4.6 (0.0 – 20.7)	1.9 (0.0 – 18.1)	0.0 (0.0 - 1.8)	3.0 (0.0 – 23.1)	3.2 (0.0 – 15.6)
2012	1/4 - 1/10	Wisdom	1.0 (0.0-6.0)	6.0 (0.0 – 25.0)	0.0 (0.0 - 8.0)	0.0 (0.0 - 1.0)	5.0 (0.0 - 23.0)	10.0 (0.0 - 100.0)
	2/16 - 2/22	Venture	0.0 (0.0 –2.0)	2.5 (0.0 - 33.0)	0.0 (0.0 - 3.0)	0.0 (0.0 - 1.0)	3.0 (0.0 - 7.0)	21.0 (0.0 - 73.0)
	3/10 - 3/16	Regulus	0.0 (0.0-3.0)	5.6 (0.0 - 30.0)	0.0 (0.0 - 1.1)	0.0 (0.0 - 0.9)	2.0 (0.0 - 8.2)	16.1 (0.0 – 72.0)
	4/10-4/16	Endeavor	1.0 (0.0-6.0)	8.0 (1.0 – 18.0)	0.0 (0.0 - 2.0)	0.0 (0.0 - 3.0)	2.0 (0.0 - 7.0)	27.0 (1.0 - 70.0)
	5/4 - 5/11	Zibet	2.0 (0.0 –7.7)	3.7 (0.0 – 13.1)	0.0 (0.0 – 9.5)	0.0 (0.0 - 2.9)	1.9 (0.0 - 6.0)	2.9 (0.0 - 32.0)
	6/20 - 6/26	Kayla Rose	0.9 (0.0 -8.4)	1.8 (0.0 – 10.0)	1.2 (0.0 - 8.2)	0.0 (0.0 - 1.0)	0.0 (0.0 - 7.0)	0.0 (0.0 - 4.8)
	8/6 - 8/14	Anticipation	0.0 (0.0 –9.4)	7.9 (0.0 – 45.7)	2.2 (0.0 – 9.4)	0.0 (0.0 - 1.9)	3.0 (0.0 - 33.9)	0.0 (0.0 - 0.0)
	9/25 - 10/1	Liberty	0.0 (0.0 –2.5)	7.8 (0.0 – 143.0)	1.0 (0.0 – 15.3)	0.4 (0.0 - 3.6)	7.6 (0.0 – 34.3)	0.0 (0.0 – 9.1)
	11/3 - 11/12	Horizon	0.0 (0.0-3.9)	5.6 (0.0 - 43.6)	2.8 (0.0 – 14.5)	0.0 (0.0 - 2.9)	4.8 (0.0 - 34.7)	2.3 (0.0 - 22.2)
	12/4 - 12/16	Thor	0.0 (0.0–9.8)	5.6 (0.0 – 43.6)	1.0 (0.0 – 31.6)	0.0 (0.0 – 2.7)	4.1 (0.0 – 28.6)	4.1 (0.0 – 18.0)
2013	1/28 - 2/3	Polaris	0.0 (0.0 - 2.1)	2.0 (0.0 - 44.7)	0.0 (0.0 - 5.3)	0.0 (0.0 - 2.0)	4.0 (0.0 - 15.0)	22.7 (1.0 – 104.7)
	3/15 - 3/23	Vanquish	0.0 (0.0 - 1.3)	0.0 (0.0 – 11.3)	0.0 (0.0 - 0.9)	0.0 (0.0 - 2.0)	2.3 (0.0 – 11.3)	9.1 (1.2 – 63.8)
	4/27 - 5/4	Endeavor	0.0 (0.0 - 3.1)	3.0 (0.0 - 10.0)	0.0 (0.0 – 1.1)	0.0 (0.0 - 2.0)	3.9 (0.0 – 17.0)	11.6 (0.0 – 31.0)
	6/12 - 6/19	Zibet	1.0 (0.0 - 6.2)	1.8 (0.0 - 7.0)	1.1 (0.0 – 13.2)	0.0 (0.0 - 1.0)	1.0 (0.0 – 8.1)	0.0 (0.0 - 7.0)
	7/26 - 8/2	Venture	0.0 (0.0 - 5.1)	4.0 (0.0 – 26.7)	2.2 (0.0 – 25.6)	0.0 (0.0 – 2.1)	1.1 (0.0 - 60.0)	0.0 (0.0 - 8.9)
	9/9 - 9/16	Atlantic	0.0 (0.0 - 10.9)	5.7 (0.0 – 41.7)	1.3 (0.0 – 10.7)	0.0 (0.0 - 3.2)	4.1 (0.0 – 52.6)	0.0 (0.0 – 10.0)

Table 2 cont'd next page

Table 2 cont'd

	10/26 - 11/2	Regulus	0.0 (0.0 - 8.6)	4.4 (0.0 – 26.4)	0.8 (0.0 - 9.0)	0.0 (0.0 - 4.4)	4.0 (0.0 - 31.4)	0.0 (0.0 - 35.2)
	12/10 - 12/18	Vanquish	0.0 (0.0 - 6.9)	2.2 (0.0 – 11.0)	2.1 (0.0 – 13.2)	0.0 (0.0 - 3.1)	5.1 (0.0 – 31.1)	4.4 (0.0 – 24.6)
2014	1/15 - 1/22	Horizon	0.0 (0.0 – 1.2)	3.2 (0.0 - 20.4)	0.0 (0.0 – 2.2)	0.0 (0.0 – 2.1)	7.6 (1.2 – 18.9)	34.1 (0.0 – 95.6)
	3/8-3/15	Liberty	0.0 (0.0 - 1.0)	1.9 (0.0 – 12.0)	0.0 (0.0 – 1.3)	0.0 (0.0 - 1.0)	3.0 (0.0 - 10.0)	29.2 (13.3 – 62.9)

terms were retained in the model if their inclusion resulted in lower AIC values and explained a higher proportion of the deviance. The AIC difference (Δ_i) of each model was calculated based on the lowest observed AIC value (AIC_{min}) as $\Delta_i = AIC_i - AIC_{min}$. Models with $\Delta_i < 2$ were considered indistinguishable in terms of fit (Burnham and Anderson, 2002). Residual plots were examined to assess model fit.

While location and time were included explicitly in the full models, there was still the possibility of unexplained residual correlation. Therefore, model fit was also assessed based on the mean absolute prediction error (MAPE) to corroborate the likelihood-based AIC approach (Augustin *et al.*, 2013). Because the CPUE of each species varied widely over the course of the year, we chose to use the MAPE rather than the root mean square predictive error, which is more sensitive to large values (Willmott and Matsuura, 2005). Observed data were split into ten test sets based on randomly sampling fixed station locations. For each test set, models were fitted to the remaining data. Values predicted for the omitted set were then compared to observed values to estimate predictive error. The MAPE for each set was calculated as:

$$MAPE = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n}$$

The ten resulting MAPE values were then averaged to generate an overall MAPE for each model.

The spatially explicit models used herein produce a smooth surface from which the expected flatfish CPUE can be estimated at any location within the study area. For models that included year as a fixed effect, the reference level was set to the last survey year (2013) for prediction. In instances when the best fitting models included geographic coordinates, prediction areas were roughly bounded based on the distribution of tow midpoints to avoid extrapolation into unsampled areas (Augustin *et al.*, 1998). The expected flatfish CPUE was predicted over a

high resolution grid (10 000 cells in each closed area). As our aim was to identify bycatch hotspots rather than to predict the number of flatfish that would be caught in a given tow, we decided to plot our estimates at this scale to ease interpretation. However, it is important to note that such fine-scale estimates would be prone to bias if used as the basis for field predictions of actual catches.

Results

A total of 1 706 valid tows were completed from March 2011 to March 2014 (Table 2). Over the 29 survey trips, a total of 6852 yellowtail flounder, 1754 winter flounder, and 12 202 windowpane flounder were collected in the TDD. Catches of all three flounder species varied substantially between areas and seasons (Table 2; Fig. 2). Yellowtail and windowpane flounder catches were generally higher in CAII, with the greatest number of yellowtail caught in the fall and windowpane in the winter and spring (Fig. 2). Winter flounder catches were generally low throughout the year in both areas, but were highest in CAI in the summer and fall (Fig. 2). Yellowtail CPUE ranged from 0.0 to 12.0 in CAI and 0.0 to 143.0 in CAII. The CPUE of winter flounder and windowpane ranged from 0.0 to 48.0 and from 0.0 to 60.0 in CAI, respectively. In CAII, CPUE of winter flounder ranged from 0.0 to 4.4 and windowpane from 0.0 to 126.0.

Seasonal trends in flatfish catches

The results of the GAMM analyses provided insight into the spatial distribution underlying the monthly trends in flatfish catches for each area. Variation in the CPUE of all three species was best described by models including the month-location smoother, indicating difference in the spatial distribution of flatfish catches by month (Tables 3–5). In all cases, the best fitting models also included survey year as a factor, suggesting differences in the magnitude of catches between years; however, differences in fit between the models including both survey year and the month-location smoother and those only including the month-location smoother were Table 3. Relative goodness-of-fit for candidate yellowtail flounder catch per unit effort models in the scallop access areas of a) Closed Area I (n = 849) and b) Closed Area II (n = 857) on Georges Bank. Models are ranked from best to worst fitting. Catch per unit effort was expressed as the number of yellowtail caught per thirty-minute tow. The selected Tweedie index parameter value is also indicated. All models included vessel as a random effect.

Model	edf	AIC	Δ_{i}	Deviance Explained	MAPE
f(month, northing, easting) + year	90.20	1801	0	0.49	0.97
f(month, northing, easting)	87.37	1913	112	0.46	0.96
f(northing, easting) + f(month) + year	42.39	2227	426	0.38	1.08
f(northing, easting) + f(month)	39.11	2375	574	0.34	1.01
f(northing, easting) + year	35.85	2437	636	0.32	1.06
f(northing, easting $)$	33.43	2578	777	0.29	1.03
f(month) + year	24.85	3013	1212	0.20	1.14
<i>f</i> (month)	21.36	3206	1405	0.16	1.11
year	19.87	3327	1526	0.14	1.16

a) Tweedie index parameter value = 1.03

b) Tweedie index parameter value = 1.38

Model	edf	AIC	Δ_{i}	Deviance Explained	MAPE
f(month, northing, easting) + year	65.03	4798	0	0.47	4.96
f(month, northing, easting)	66.10	4844	46	0.45	5.09
f(northing, easting) + f(month) + year	33.36	4972	174	0.34	5.12
f(northing, easting) + f(month)	34.99	4991	193	0.33	5.34
f(northing, easting) + year	33.29	5024	226	0.31	5.96
f(northing, easting $)$	30.92	5079	281	0.28	5.84
f(month) + year	20.04	5107	309	0.25	5.51
<i>f</i> (month)	21.42	5126	328	0.24	5.67
year	20.20	5161	363	0.22	6.32

Note: northing and easting = tow midpoint coordinates projected into the universal transverse Mercator coordinate system (zone 19); edf = total model estimated degrees of freedom; AIC = Akaike information criterion rounded to the nearest whole number; Δ_i = AIC difference rounded to the nearest whole number; MAPE = mean absolute predictive error (in number of fish per 30 minute tow). *f* indicates a smooth function; see text for specifics on the types of smooth functions used for each covariate.

generally minimal (Tables 3–5). Model comparisons based on MAPE estimates supported the model selected based on AIC ranking in all cases (Tables 3–5). In general, the selected models explained a large proportion of the observed variance (deviance explained 0.47 to 0.73 for all cases; Tables 3–5), and residual plots indicated that the assumptions and the selected values of the Tweedie index parameter were appropriate.

For yellowtail, model results for both closed areas suggested changes in the distribution and magnitude of bycatch by month (Fig. 3). In CAI, predicted CPUE was generally low in all months (mean CPUE < 2.0 fish per 30 minute tow for all locations) but was highest along

the northwestern boundary from the spring into the fall (Fig. 3a-b). Catches in CAII exhibited greater variation over the year (Fig. 3c-d). The predicted CPUE was relatively low over large portions of CAII, with localized areas of higher catch (CPUE > 15.0) in the eastern portion of CAII during the fall (Fig. 3c-d). Predicted catches in both areas were lower in survey year 2013 than in the previous years (Table 6).

Model results also suggested seasonal changes in the distribution of winter flounder in CAI. Winter flounder were largely absent in predicted catches from February to April (Fig. 4). Predicted catches were highest along the northwestern and southern portions of the area from

July to November (CPUE > 5.0; Fig. 4). The best fitting model suggested that predicted catches in CAI were lower in 2013 than in survey years 2011 and 2012 (Table 6).

Monthly variation in the predicted bycatch of windowpane flounder was greater than for the other two species (Fig. 5). The predicted range of windowpane catches was greater in CAII (CPUE: 0.0–69.9) than CAI (CPUE: 0.0–30.2) but was more episodic in CAII. In CAI, the highest predicted catches occurred in the southeastern portion of the area in the fall (September to December; Fig. 5a-b). The highest predicted catches in CAII occurred from January to April, and were relatively high over almost the entire area surveyed (Fig. 5c-d). From May to August, windowpane bycatch in CAII appeared to be minimal (Fig. 5c-d). Predicted catches in both areas were higher in survey year 2013 than in the previous two survey years (Table 6).

Discussion

The results of our three-year dredge survey revealed considerable spatiotemporal variation in flatfish bycatch both within and between two scallop access areas on Georges Bank. By frequently sampling Closed Areas I and II over an extended period of time, we were able to document localized, seasonal shifts in the bycatch rates of three flatfish species. Our results suggest consistent seasonal patterns in flatfish bycatch that may help managers identify the optimal times to open the access areas to the scallop fleet in order to reduce bycatch of yellowtail, winter, and windowpane flounder.

The selected models for flatfish bycatch explained a high degree of the variability observed over the three years of the survey. This was not surprising given our use of GAMMs, which allow for flexible, non-linear fits to explanatory variables (Wood, 2006). Additionally, by modeling bycatch rates as a function of location, which is inherently correlated with other factors (*e.g.* depth, bottom temperature, prey availability, substrate type), we were able to encompass a myriad of potential mechanistic drivers without explicitly including them in the model structure. While this certainly compromises a more holistic understanding of the observed trends, as well as the long-term predictive power of the models applied herein, we were most interested in identifying seasonal changes to inform management.

Though we did not directly investigate the effect of environmental factors on bycatch, similar studies conducted in other regions may provide insight into the seasonal trends we characterized. Swartzman *et al.* (1992) used spatially-explicit GAMs to investigate inter-annual trends and environmental effects on flatfish catches from trawl survey data in the Bering Sea. They found that models based only on temperature and depth explained nearly as much of the observed variation in the spatial distribution of most species as did the models incorporating geographic

Table 4. Relative goodness-of-fit for candidate winter flounder catch per unit effort models in the scallop access area of Closed Area I (n = 849) on Georges Bank. Models are ranked from best to worst fitting. Catch per unit effort was expressed as the number of winter flounder caught per thirty-minute tow. The selected Tweedie index parameter value is also indicated. All models included vessel as a random effect.

Model	edf	AIC	Δ_{i}	Deviance Explained	MAPE
f(month, northing, easting) + year	64.26	2586	0	0.58	1.74
f(month, northing, easting)	63.08	2590	4	0.57	1.76
f(northing, easting) + f(month) + year	34.40	3009	423	0.36	2.05
f(northing, easting) + f(month)	33.12	3026	440	0.35	2.04
f(month) + year	22.40	3046	460	0.34	2.06
<i>f</i> (month)	21.51	3062	476	0.33	2.04
f(northing, easting) + year	30.92	3429	843	0.17	2.22
f(northing, easting $)$	29.10	3428	842	0.17	2.21
year	19.75	3460	874	0.15	2.21

Tweedie index parameter value = 1.17

Note: northing and easting = tow midpoint coordinates projected into the universal transverse Mercator coordinate system (zone 19); edf = total model estimated degrees of freedom; AIC = Akaike information criterion rounded to the nearest whole number; Δ_i = AIC difference rounded to the nearest whole number; MAPE = mean absolute predictive error (in number of fish per 30 minute tow). *f* indicates a smooth function; see text for specifics on the types of smooth functions used for each covariate.

Table 5. Relative goodness-of-fit for candidate windowpane flounder catch per unit effort models in the scallop access areas of a)
 Closed Area I (n = 849) and b) Closed Area II (n = 857) on Georges Bank. Models are ranked from best to worst fitting. Catch per unit effort was expressed as the number of windowpane flounder caught per thirty-minute tow. The selected Tweedie index parameter value is also indicated. All models included vessel as a random effect.

Model	edf	AIC	Δ_{i}	Deviance Explained	MAPE
f(month, northing, easting) + year	77.00	3787	0	0.61	2.95
f(month, northing, easting)	75.80	3831	44	0.59	2.96
f(northing, easting) + f(month)	33.46	4087	300	0.44	3.17
f(northing, easting) + year	32.94	4153	366	0.41	3.55
f(northing, easting $)$	30.63	4227	440	0.38	3.61
f(northing, easting) + f(month) + year	36.60	4444	657	0.48	3.15
f(month) + year	21.77	4487	700	0.26	3.84
<i>f</i> (month)	21.63	4518	731	0.24	3.92
year	19.75	4640	853	0.18	4.17

a) Tweedie index parameter value = 1.22

b) Tweedie index parameter value = 1.37

Model	edf	AIC	Δ_{i}	Deviance Explained	MAPE
f(month, northing, easting) + year	54.40	4067	0	0.73	7.42
f(month, northing, easting)	52.81	4077	10	0.73	7.45
f(northing, easting) + f(month) + year	34.22	4278	211	0.62	7.59
f(northing, easting) + f(month)	33.54	4280	213	0.62	7.49
f(month) + year	23.02	4356	289	0.57	7.61
<i>f</i> (month)	22.34	4359	292	0.57	7.60
f(northing, easting) + year	27.83	4795	728	0.33	9.68
f(northing, easting $)$	25.90	4806	739	0.32	9.67
year	20.64	4844	777	0.29	9.90

Note: northing and easting = tow midpoint coordinates projected into the universal transverse Mercator coordinate system (zone 19); edf = total model estimated degrees of freedom; AIC = Akaike information criterion; Δ_i = AIC difference; MAPE = mean absolute predictive error (in number of fish per 30 minute tow). *f* indicates a smooth function; see text for specifics on the types of smooth functions used for each covariate.

coordinates. Limited information is available regarding environmental correlates to flatfish catch rates in CAI and CAII, but temperature and depth likely influence the spatial distribution of yellowtail, winter, and windowpane flounder in a similar fashion (Hyun *et al.*, 2014). Habitat type may also be an important factor. Yellowtail and windowpane flounder typically occur on sand or sand-mud substrates (Chang *et al.*, 1999; Johnson *et al.*, 1999), such as those found along the southeastern edge of the access area in CAII (Murawski *et al.*, 2000). Winter flounder occupy sandy substrates as well, but are more often associated with the mixed sand-gravel sediments typical of CAI (Pereira *et al.*, 1999; Murawski *et al.*, 2000).

Alternatively, environmental covariates may operate via indirect effects by modifying the distribution and behavior of prey species, or by influencing the timing of flatfish migration to feeding or spawning grounds (Kotwicki *et al.*, 2005). All three flatfish species are known to make seasonal migrations in response to both abiotic and biotic factors over some portion of their range (Chang *et al.*, 1999; Johnson *et al.*, 1999; Pereira *et al.*, 1999). The survey CPUEs of all three species were relatively low during periods of peak spawning on Georges Bank (yellowtail flounder spawn from May to August, winter flounder from March to May, and windowpane from June to October; O'Brien *et al.*, MS



Fig. 3. Predicted mean spatial variation in yellowtail flounder bycatch in Closed Areas I (a-b) and II (c-d) over the course of the year. The predicted catches at each of the survey stations (31 in Closed Area 1 and 30 in Closed Area II) in each month are also presented to illustrate differences in the timing of peak bycatch within each area (b, d). The black lines denote the boundaries of the access areas. The red dashed line indicates the boundary between US and Canadian territorial waters. Coordinates are expressed in the universal transverse Mercator coordinate system (zone 19). Note that the panels for each closed area are plotted on different scales for ease of interpretation, but that the color of the annual curves (b) and (d) corresponds to the average catches plotted in (a) and (c).

1993), suggesting that neither area serves as a primary spawning ground for the species. Maturity data collected during the course of the survey corroborate this, as few flounder were observed to be in spawning condition (C. Huntsberger, unpublished data).

Whatever the driving mechanisms may be, the spatiotemporal patterns of flatfish bycatch documented herein may be useful in terms of optimizing the harvest of sea scallops while avoiding bycatch, and hence accountability measures, in the Atlantic sea scallop fishery on Georges Bank. It is important to note that our results are only suggestive of relative trends in the availability of flatfish species to the scallop fishery, and are not necessarily related to actual trends in abundance in the two areas surveyed, particularly given the potential impact of large tows on estimated trends (Maunder *et al.*, 2006). However, our results do suggest that predictable seasonal patterns in flatfish bycatch may provide a practical foundation for the formulation of effective time-area management strategies. Based in part on the survey results reported herein, CAII is now closed to the scallop fleet from August through November (NEFMC, MS 2013) in an effort to reduce high rates of yellowtail bycatch.



Fig. 4. Predicted mean spatial variation in winter flounder bycatch in **Closed Area I** over the course of the year. The predicted catches at each of the thirty-one survey stations in each month are also presented to illustrate differences in the timing of peak bycatch in different areas (b). The black lines denote the boundaries of the access area. Coordinates are expressed in the universal transverse Mercator coordinate system (zone 19). Note that the color of the annual curves (b) corresponds to the average catches plotted in (a).

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	Yellov	wtail	Win	ter	Windo	wpane
Survey Year	Value	SE	Value	SE	Value	SE
Closed Area I						
2011	-0.40	0.28	-0.03	0.14	0.67	0.095
2012	-0.99	0.25	-0.22	0.16	0.96	0.11
2013	-1.23	0.18	-0.37	0.15	1.22	0.56
Closed Area II						
2011	1.86	0.07	n/a	n/a	-0.00	0.28
2012	1.54	0.10	n/a	n/a	0.15	0.26
2013	1.18	0.10	n/a	n/a	0.40	0.14

Table 6. Parameter estimates for the factor survey year from the best-fitting flatfish catch per unit effort models for the scallop access areas of **Closed Area I** and **Closed Area II** on Georges Bank.



Fig. 5. Predicted mean spatial variation in windowpane flounder bycatch in Closed Areas I (a-b) and II (c-d) over the course of the year. The predicted catches at each of the survey stations (31 in Closed Area 1 and 30 in Closed Area II) in each month are also presented to illustrate differences in the timing of peak bycatch within each area (b, d). The black lines denote the boundaries of the access areas. The red dashed line indicates the boundary between US and Canadian territorial waters. Coordinates are expressed in the universal transverse Mercator coordinate system (zone 19). Note that the panels for each closed area are plotted on different scales for ease of interpretation, but that the color of the annual curves (b) and (d) corresponds to the average catches plotted in (a) and (c).

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Size selection of Greenland halibut (*Reinhardtius hippoglossoides*) in the Norwegian bottom trawl fishery with a newly developed double grid system.

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Abstract

Greenland halibut (Reinhardtius hippoglossoides) is a commercially important species in the northeast Atlantic trawl fishery. However, direct fishing for it is not allowed and it can only be harvested as bycatch. We investigated for the first time the size selection of Greenland halibut in a newly developed double steel grid system designed for the cod and haddock bottom trawl fishery. In this sorting system the first grid (lower grid) replaced the lifting panel present in the traditional Sort-V single grid system often applied in the fishery. Thus, it contributed to the fish sorting process and simultaneously guided fish to the second grid (upper grid). However, the results showed that nearly all Greenland halibut escapees left through the second grid. The release efficiency of the first grid was estimated to be low, and only 11% of the Greenland halibut entering the grid zone made contact with this grid in a way that provided a size-dependent release probability. In contrast, the estimations showed that all Greenland halibut, still in the gear after the first grid, made contact with the second grid. However, this contact was suboptimal for size selection of most individuals, as the estimated 50% retention length (based on the morphology of Greenland halibut) was below the expected value. Comparison of the release efficiency of the new double grid system relative to that of the grid systems used in the fishery today revealed that the new system did not improve the release of undersized Greenland halibut. Moreover, we found that the existing Sort-V single grid system released significantly more Greenland halibut than the new double grid system.

Keywords: Selectivity; Sorting grid; Grid selectivity; Greenland halibut; Trawl fishery.

Introduction

Greenland halibut or Greenland turbot (Reinhardtius *hippoglossoides*) inhabits the polar regions of the North Atlantic and North Pacific oceans (Sohn et al., 2010). It is considered to be a deep water species because it is commonly harvested at the edge of the continental shelf at depths between 300 and 1000 m. In the northeast Atlantic, Greenland halibut is harvested using gillnets, longlines, demersal seines and trawls. The fishery is regulated by total allowable catches (TAC), vessel quotas, bycatch regulations and minimum landing and mesh sizes. In 2010, the Joint Norwegian-Russian Fisheries Commission agreed on an allocation key for Greenland halibut in which Norway has a share of 51%, Russia 45% and 4% was allocated to third countries. The landings of Greenland halibut from the Northeast Arctic reached 24 297 tonnes in 2016, whereof 57% is harvested

with bottom trawls (ICES 2017, Bakketeig *et al.* 2017). Statistics from the Directorate of Fisheries (2016) show that the total Norwegian landings of Greenland halibut increased by 24% in weight from 12 717 metric tons in 2012 to 16 789 metric tons in 2016 with an increase of nearly 52% in landing prices, and the species is usually more valuable (ϵ/kg) for fishermen than large cod (*Gadus morhua*).

In the trawl fishery, fishermen are only allowed to harvest Greenland halibut as an unavoidable species on a small bycatch quota in the trawl fishery directed for Arctic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and beaked redfish (*Sebastes mentella*). The latter species is caught along the continental shelf from N72° and further north and in depths where Greenland halibut frequently occurs. In the Northern gadoid fisheries, rigid sorting grids have been mandatory in combination with minimum 130 mm (135 mm until 2011) mesh size in the codend since 1997. Fishermen are allowed to use three different grid systems and all have grids with a 55 mm bar spacing: a three-section system called Sort-X that is composed by two steel grids and a canvas section (Larsen and Isaksen, 1993), a double grid section composed by two grids made of plastic (i.e. bars made from fibre-glass) and rubber (Sistiaga et al., 2016), and a single steel grid section called Sort-V (Jørgensen et al., 2006; Herrmann et al., 2013b). Due to the high densities of cod encountered in the Barents Sea bottom trawl fishery new problems arise (Sistiaga et al., 2016; Brinkhof et al., 2017), especially related to blockage of accumulated fish in grid sections, with subsequent reduction in size selectivity and catch control. In an attempt to solve this issue the Norwegian authorities, research institutes and fishermen are testing alternative gear and grid designs that increase the sorting capacity of the grids (Gjøsund et al., 2013; Grimaldo et al., 2015).

Since Greenland halibut is an important bycatch species in the Barents Sea, the potential solutions applied to the trawl gear used to solve the diverse challenges existing in the cod and haddock fisheries today will have direct consequences for its selectivity. Selectivity studies for Greenland halibut can be found in the literature (Boje *et al.*, 1997; Herrmann *et al.*, 2013a; Huse *et al.*, 1999; Lisovsky *et al.*, 2004; Woll *et al.*, 1998), but to the best of our knowledge Herrmann *et al.* (2013a) is the only documentation of the performance of sorting grids for Greenland halibut.

In the present investigation, we studied the performance of a new double steel grid system (Larsen *et al.*, 2016), developed for the cod and haddock directed trawl fishery, to size select Greenland halibut. The new design was based on a Sort-V grid but is built in four panels rather than two. It has approx. 45% bigger cross section area and the lifting panel (Grimaldo *et al.*, 2015) is substituted by a grid (lower grid) following the idea behind the Flexigrid system (See Herrmann *et al.* (2013b) and Sistiaga *et al.* (2016) for further information on the flexigrid design). The aim was to investigate the size selection in this new double steel grid section for Greenland halibut. Specifically our goal was to answer the following questions:

- Does this new grid design provide any change for Greenland halibut size selection compared to the existing grids?
- To what extent does Greenland halibut escape through the first grid (lower grid) of the section?

Materials and Methods

Vessel, time, area and fishing gear

We carried out a small-scale fishing trial on board the Research vessel RV *Helmer Hanssen* (63.8 m LOA and 4080 HP) 6-7 March, 2015. The tests were conducted in well-known fishing grounds off the coast of Finnmark and Troms counties, Norway (N71°30'– E27°30' and N70°30'– E17°20'), where Greenland halibut occurs in this period of the year.

We applied a trawl design commonly used in the Norwegian bottom trawl fisheries, *i.e.* an Alfredo No. 3 two-panel Euronete trawl with wings and belly entirely built in 155mm nominal mesh size (nms) polyethylene (PE) netting. The trawl had a headline of 36.5 m, a fishing line of 19.2 m and 454 meshes of circumference. The trawl system comprised a set of Injector bottom trawl doors (8.0m² and 3.100 kg each), 60 m sweeps, and a 111 m ground gear. Each of the sides of the ground gear had ten 53 cm steel bobbins on a 46 m x 19 mm chain. Both sides of the ground gear were joined by a conventional 19.2 m long rock-hopper built with 53 cm rubber discs, which were attached to the fishing line of the trawl. The headline was equipped with 170 x 200 mm plastic floats. The trawl-system was monitored by various Scanmar-sensors. With the given rig-details we achieved a door spread of 128-133 m, a fishing line spread of ca. 14.5 m, and a headline height of 4.5–5.2 m at towing speeds of 3.5-4.0 knots in 250-320 m of depth.

We used the four-panel section with two steel grids inserted described by Larsen et al. (2016). This grid section was made from 138 mm nms Euroline Premium PE netting (single Ø 8.0 mm twine), was 26 meshes long (instead of 44.5 meshes like the mandatory Sort-V grid sections), and had 104 meshes in circumference (Fig. 1). All four selvedges in the grid section were made of 40 mm Danline PE rope. Exactly at the position where the lifting panel sits in the Sort-V section (Grimaldo et al., 2015), we installed a one-half standard steel grid (Sort-V type) with 55 mm bar spacing, hereafter called the lower grid (outer dimensions: length = $825 \text{ mm} \times \text{width} = 1234 \text{ mm}$). The upper grid was a standard steel grid (Sort-V type) with 55 mm bar spacing (outer dimensions: length = $1650 \text{ mm} \times \text{width} = 1234 \text{ mm}$) (Fig. 2). The lower grid was fixed to the side panels of the section to maintain an inclination angle of approximately 40° (Fig. 3). The back part of the square mesh lifting panel was made of 80 mm Euroline Premium PE netting (single Ø 3.0 mm twine). The square mesh guiding panel behind the upper grid was made of 80 mm (nominal mesh size = nms) Euroline Premium PE netting (single Ø 3.0mm twine). The guiding panel's length was approximately one-half that used in the mandatory sorting grid section to avoid unnecessary extra netting that could influence the water flow, and it was attached with a steeper angle.



Fig. 1: Illustration showing the main dimensions and parts of the modified four-panel grid section.



Fig. 2: Steel grids used in the modified grid section: a lifting grid (left) and a standard Sort-V grid (right).

The section tested in this study differed from the original Sort-V section in two main ways. First, the lifting panel was replaced by the lower grid. Second, the grid section was built in four panels, which increased the space under the upper grid (Fig. 3).



Fig. 3: Photographs of 1:2 scale models of the two-panel Sort-V grid section (left) and the four-panel double steel grid section (right) taken at SINTEF's flume tank in Hirtshals (Denmark). Note the oversized lifting panel (striped white line) and the lack of space under the Sort-V grid in the two-panel section (white circle).

We used a transition diamond mesh section to connect the two-panel trawl belly to the four-panel grid section. It was made using 138 mm nms Euroline Premium PE netting (single \emptyset 8.0 mm twine), and it was 33.5 meshes long (Fig. 4). We used two small-mesh grid covers (GCs) to collect separately fish escaping through respectively the lower and upper sorting grid. The upper grid was covered with a GC made of 52 mm (full mesh size) Euroline Premium PE netting (single Ø 2.4 mm twine) and had a total length of approximately 25 m (Larsen and Isaksen, 1993). The entire GC was reinforced with double 155 mm Euroline Premium PE netting (single Ø 4.0 mm twine) and 7 x 200 mm plastic floats were added along the mid-seam to ensure its inflation. The lower grid was covered with a GC made of 42 mm PA netting of Ø 1.0 mm in the front sections and 52 mm PE netting (single \emptyset 2.2 mm twine) in the aft sections, and had a total length of approximately 15 m. Total chain weights of ca. 15 kg were added along the mid-seam to ensure inflation of it. The installation of the GCs was done following standard procedures described by Larsen and Isaksen, (1993) and Wileman et al., (1996) (Fig. 4).



Fig. 4: Set-up during selectivity experiments with a double steel grid in front of a four-panel codend with small mesh liner. The small circles indicates 200 mm plastic floats attached to grids and the upper cover. The lower cover was inflated by ca. 15 kg chain weights along the cover.

The four-panel diamond-mesh codend used during the experiments was made from Euroline Premium PE netting (Polar Gold), with 138 mm (nominal mesh size) and 8 mm diameter single twine. It was 120 meshes long and had 80 meshes of circumference. All four selvedges were strengthened by 40 mm Danline PE rope. In total 7 round-straps (\emptyset 24 mm PE) were attached on the codend at intervals of 1.2 m. The codend (C) contained a small mesh liner (length = 14 m) constructed of 52 mm (nms) Euroline Premium PE netting (single \emptyset 2.2 mm twine) (Fig. 4).

Greenland halibut from the codend and the GCs were measured to the nearest cm. Subsampling was only carried out for one haul due to the large number of Greenland halibut in the catch. All fish in the haul were counted to calculate the sampling fraction that was later included in the data analyses.

Two Scanmar flow recorders (*i.e.* a speed/symmetry and a grid sensor) were placed in the middle of a rectangular steel frame (1120 mm x 1000 mm) in the centre and $\frac{3}{4}$

down from the top, respectively. The flow measurements were made in front and the aft of the grid section with and without grid covers.

Modeling size selection in the double grid system

For a single 55 mm Sort-V grid system Herrmann *et al.* (2013b) successfully described the size selection of redfish using a *CLogit* size selection model (1), which accounted for that not necessary all fish entering the grid section made contact with the grid:

$$CLogit(l, C, L50, SR) = 1 - C \times (1 - Logit(l, C, L50, SR))$$

= $1 - \frac{C}{1 + exp^{\frac{(SW)}{SR} \times (1 - L50)}}$ (1)

Only the fish contacting the grid obtain a size dependent probability for escaping through it. In the Clogit model. l denotes fish length and parameter C quantifies the assumed fish length independent probability for a fish entering the grid zone to also make contact with it in a way that provides it a length dependent probability for escaping through the grid. Thus, C undertakes a value between 0.0 and 1.0, where a value at 1.0 would mean that every fish entering the grid zone would make contact with the grid. A value at 0.3 on the other hand would mean that only 30% of the fish entering the grid zone would make contact with it. For the fish making contact with the grid the *CLogit* model assumes a traditional *Logit* size selection model (Wileman et al., 1996) defined by the parameters L50 (length at which the fish that makes selectivity contact with the grid has a 50% chance to escape through the grid) and SR (difference between the lengths at which a fish that makes selectivity contact with the grid has 75% and 25% chance of escaping through the grid) Sistiaga et al. (2016) extended this model to describe the size selection to describe the size of cod and haddock in flexigrid double grid system and Larsen et al. (2016) applied the same double grid size selection model for the size selection of redfish in the double grid system investigated in this study. Therefore, we apply the same model (2) in this study to describe the size selection of Greenland halibut in the double grid system:

$$e_{1}(l) = 1.0 - CLogit(l, C_{1}, L50_{1}, SR_{1})$$

$$e_{2}(l) = (1.0 - CLogit(l, C_{2}, L50_{2}, SR_{2})) \times (1.0 - e_{1}(l)) (2)$$

$$r_{comb}(l) = 1.0 - e_{1}(l) - e_{2}(l)$$

For a Greenland halibut of length *l* that enters the double grid section $e_1(l)$ models the length dependent probability for it to escape through the first grid while $e_2(l)$ models the probability for it escaping through the second grid. If the Greenland halibut does not escape through one of the two grids it is still retained after passaging through the grid section for which the probability is described by $r_{comb}(l)$. C_l quantifies the fraction of entering Greenland

halibut that makes contact with the first grid and is subject to a size dependent probability for escapement through it. For those Greenland halibut, $L50_1$ and SR_1 are the contact selectivity parameters assuming a *Logit* size selection model. For the Greenland halibut that reach the zone of the second grid, meaning that they have not previously escaped through the first grid, C_2 quantifies the fraction of fish, which make contact with it and are subject to a size dependent probability for escapement through this grid. For those fish, $L50_2$ and SR_2 are the contact selectivity parameters assuming a Logit size selection model. Thus, the size selectivity in the double grid system is according to equation (2) fully described by the six parameters C_1 , $L50_1$, SR_1 , C_2 , $L50_2$ and SR_2 . The selection properties of the individual grids, grid, and grid₂, is then described by respectively the parameters $(C_1, L50_1, SR_1)$ and $(C_2, L50_2, SR_2)$ following a *CLogit* size selection model (1). The probability for that a Greenland halibut entering the grid section makes contact with at least one of the two grids, C_{comb} , can be expressed by:

$$C_{comb} = C_1 + C_2 - C_1 \times C_2$$
(3)

The overall selectivity parameters for the whole grid section (first and second grid combined: $L50_{comb}$ and SR_{comb}), was estimated based on (2) using the numerical method described in Sistiaga *et al.* (2010).

Estimation of selection parameters for the double grid model

The values for the parameters for the overall selection model (C_1 , $L50_1$, SR_1 , C_2 , $L50_2$, and SR_2) were obtained using Maximum Likelihood (ML) estimation based on the experimental data pooled over hauls *j* (1 to m) by minimizing:

$$-\sum_{l}\sum_{j=1}^{m} \left\{ \frac{n_{acl,lj}}{q_{acl,j}} \times ln(e_{1}(l)) + \frac{n_{ac2,lj}}{q_{ac2,j}} \times ln(e_{2}(l)) + \frac{n_{cl,lj}}{q_{c2,j}} \times ln(e_{2}(l)) \right\}$$

$$(4)$$

where $n_{GCl,lj}$, $n_{GC2,lj}$, and $n_{C,lj}$ denote the numbers of Greenland halibut length measured in haul *j* with length *l* that were collected in the GC for grid 1, the GC for grid 2, and the blinded and non-selective codend, respectively (Fig. 4). $q_{GCl,j}$, $q_{GC2,j}$, and $q_{C,lj}$ denote the length-independent sampling factors length measured in haul *j* for the GC for the first grid, the GC for the second grid, and the blinded codend, respectively.

When estimating size selection in the double grid system by applying equations (2) and (4), the six selectivity parameters are not constrained in values, meaning that they are not value bound to each other. In addition to considering the initial scenario for modeling size selection of Greenland halibut in the double grid system, a number of constrained models were also tested. These constrained models were based on constraining pairwise one or more parameters of the two grids to have the same value. Specifically, because the two grids have identical bar spacing, it is possible that size selection for the Greenland halibut that make contact with the grids would be similar or partly similar. Based on equation (2) with no parameter constraints, we created a family of constrained models in which one or more of the grid selection parameters ($L50_c$, SR_c) of the two grids were given the same value. Ultimately, we ended up considering four different models (Table 1).

Table 1: Description of parameter value constraints in the different models considered. *: unconstrained.

Model ID	$L50_1$ versus $L50_2$	SR_1 versus SR_2
1	*	*
2	Constrained	*
3	*	Constrained
4	Constrained	Constrained

Among the four different potential models described in Table 1, we chose the one with the lowest AIC value (Akaike, 1974). The goodness of fit diagnosis of the model selected to describe the experimental data was based on the *p*-value, model deviance vs. degrees of freedom, and inspection of the model curve's ability to reflect the trends in the data. The ML estimation using equations (4) and (2) requires aggregation of the experimental data over hauls. This results in stronger data to estimate the average size selectivity, but it does not consider between-haul variation in selectivity (Fryer, 1991).

To account correctly for the effect of between-haul variation in the estimation of uncertainty in size selection and for the uncertainty in individual hauls due to sample sizes, we used a double bootstrap method (Millar, 1993). The procedure accounted for uncertainty due to betweenhaul variation in size selection by selecting m hauls with replacement from the m hauls available during each bootstrap repetition (equation 4). Within each resampled haul, the data for each length class were resampled in an inner bootstrap to account for the uncertainty in the size selection in the haul. The resulting data set obtained from each bootstrap repetition was analyzed using equation (2) and (4) as described above. Based on the bootstrap results we estimated the Efron percentile confidence intervals (CIs) (Efron, 1982; Chernick, 2007) for both the estimated parameters in equation (2) and the resulting curves for $e_1(l)$, $e_2(l)$, and $r_{comb}(l)$. We used the software tool SELNET (Herrmann *et al.*, 2012) for the analysis and applied 1000 bootstrap iterations to estimate CIs.

Using the *CLogit* model and inserting the values of the selection parameters for grid 1 (C_1 , $L50_1$, SR_1) and grid 2 (C_2 , $L50_2$, SR_2), we obtained size selection curves for the two grids for stand-alone deployments. By incorporating this estimation into the bootstrapping procedure, we also obtained 95% confidence limits for the grid's stand-alone size selection curves. To determine whether the two selection curves had parts that were significantly different, we checked for overlap between the 95% confidence limits of the two curves. For the estimated selection parameters we used a similar approach to investigate whether the confidence limits overlapped.

Results

Observations of gear

Whether a gear set-up with multiple covers affects the efficiency and stability of the sorting device is always a question. The mean water flow measured in the center of the grid section when the covers were attached was 2.67 ± 0.04 knots. When the covers were removed, the flow at this point increased to 3.26 ± 0.12 knots, meaning that the covers reduced water flow by approximately 20%. Without the covers, the water flow values in front and behind the grids were 3.13 ± 0.12 and 2.89 ± 0.53 knots, respectively, representing a reduction of approximately 7.6%.

Selectivity analyses

We conducted six hauls with a sufficient number of Greenland halibut to be included in the analyses. Table 2 summarizes the catch data for Greenland halibut in those hauls. In all hauls except for haul 3 all Greenland halibut caught were length measured. In haul 3 the catch in the codend was subsampled and 36% of the Greenland Halibut were measured while the rest of the individuals were just counted to calculate the sampling ratio. In total 2446 Greenland halibut were caught and 1634 of them length measured.

The main other species caught in these hauls where haddock (n = 547), redfish (n = 347) and cod (n = 33). This reflect that during the six hauls addressing Greenland halibut size selection, this species was the main catch during those hauls. This is consistent with the bycatch level of Greenland halibut in cod and haddock directed fisheries (Huse *et al.*, 1999).

The four models considered for describing the size selection in the double grid system were evaluated against each other based on their AIC values (Table 3).

The model assuming that both contact selectivity parameters, L50c and SRc, have identical values performed best(*i.e.*, it had the lowest AIC value) (Table 3). This result was not unexpected, as the differences in

Table 2: Greenland halibut catch data for individual hauls (1 to 6). n_{GCl} , n_{GC2} , and n_C denote the numbers of Greenland halibut length measured that were collected in the cover for grid 1, the cover for grid 2, and the blinded codend, respectively (Fig. 4). q_{GCl} , q_{GC2} , and q_C denote the sampling factors specifying the fractions of the Greenland halibut caught being length measured for the cover for the first grid, the cover for the second grid, and the blinded codend, respectively.

Haul ID	n _{GC1}	n _{GC2}	n _c	q_{GCI}	q_{GC2}	q_{C}
1	0	1	19	1.00	1.00	1.00
2	0	5	103	1.00	1.00	1.00
3	13	118	458	1.00	1.00	0.36
4	9	79	609	1.00	1.00	1.00
5	3	19	90	1.00	1.00	1.00
6	1	4	103	1.00	1.00	1.00

Table 3: AIC values for models considered. *: unconstrained.

Model ID	$L50_1$ versus $L50_2$	SR_1 versus SR_2	AIC value
1	*	*	1608.73
2	Constrained	*	1607.15
3	*	Constrained	1606.78
4	Constrained	Constrained	1605.27

selectivity between two grids with identical bar spacing likely would be defined solely by differences in contact probability. Considering the results shown in Table 3, the remaining analyses were carried out using model ID 4. Table 4 summarizes results of the analysis based on this model, and Figure 5 shows plots of the escapement through grid 1 and grid 2 and retention by the codend (with small mesh liner).

Table 1 shows that the selected constrained model ID4 can describe the size selection of Greenland halibut in the double grid system sufficiently well. The *p*-value of 0.99 (Table 4) indicates that the deviation between the fitted model and the experimental rates is likely a coincidence. This premise is further supported by the plots in Figure 5, as the modeled curves in all cases reflect the trends in the experimental data points well without any systematic patterns in the deviations. Thus, we are confident that it is valid to apply model ID4 to describe the size selection of Greenland halibut in the double grid system. From the estimated selection parameters (Table 4) several observations can be made:

i) Only a very limited fraction of the Greenland halibut entering the grid section makes contact

Table 4: Selectivity results and fit statistics for the selected model (model ID 4). Values in parentheses are 95% confidence intervals. *: not defined.

$L50_{combined}$ (cm)	39.45 (*-43.91)
$SR_{combined}$ (cm)	17.35 (*- 22.74)
$L50_l = L50_2 \text{ (cm)}$	38.56 (34.68–53.22)
$SR_1 = SR_2$ (cm)	17.40 (9.23–21.01)
C_{I} (%)	11.30 (3.32–13.03)
C_{2} (%)	100.00 (31.35-100.00)
<i>p</i> -value	0.99
deviance	72.75
DOF	106

with grid 1 in a way that provides a sizedependent probability for escapement through this grid. It is estimated that only 11.30% (3.32%- 13.03%) of the fish do so.

- ii) In contrast, 100% (31.35% 100.00%) of the Greenland halibut reaching the zone of grid 2 actually make contact with it in such a way they have a size-dependent probability of escapement through it.
- iii) The estimated L50c ($L50_1 = L50_2$) for the 55 mm bar spacing grid is 38.56 cm (34.68–53.22 cm), which is low compared to the morphological limit of 77 cm obtained by Herrmann *et al.* (2013a). This indicates that some of the fish making contact with the grid are not optimally orientated for escapement, which is in line with the previous finding regarding grid size selection of Greenland halibut (Herrmann *et al.*, 2013a).

Based on the *CLogit* model with the estimated parameter values in Table 1, Figure 6 plots the estimated size selection of grid 1, grid 2, and both grids combined. Size selection was much higher for grid 2 compared to grid 1, and this difference was due to the low contact probability obtained for the grid 1. Size selection of grid 2 was slightly better than the combined selectivity for both grids, but the difference was not statistically significant. Thus, the contribution of grid 1 to the overall selectivity was limited.

Figure 7 compares the combined Greenland halibut size selection in the double grid system to previous estimates for other grid systems with the same 55 mm bar spacing (Herrmann *et al.*, 2013a). Compared to the Sort-X system, the differences in retention probabilities are only significant in the size range of 52 to 62 cm (first row). Compared to the Sort-V system this difference is significant in the size range of 36 to 77 cm (second row).

For both sets of comparisons, size selection of the new double grid system was poorer than that obtained with the grid systems currently used in the fishery.



Fig. 5: Panels show halibut escapement from grid1 (top), escapement from grid 2 (middle), and the retention by the gear (bottom). White circles represent experimental rates. The black curves are the size selection curves based on model ID4. Black stippled curves represent the 95% confidence limits for the selection curve in each case. The grey curve represents the population of Greenland halibut found in the cover over grid 1, the cover over grid 2, and in the codend, respectively.



Fig. 6: Selectivity of grid 1 (grey light curve), selectivity of grid 2 assuming that the fish reach the grid 2 zone (grey curve), and total selectivity of the grid section (black curve). The stippled lines show the 95% confidence limits for each of the three selection curves. The vertical line indicate the minimum landing size at 45 cm (total) length.



Fig. 7: Comparison of the size selectivity of the new double grid system (black curves) with earlier selectivity results (grey curves) obtained with the Sort-X sorting grid (top) and the Sort-V sorting grid (bottom). The stippled lines show the 95% confidence limits for the selection curves. The vertical lines indicate the minimum landing size at 45 cm (total) length.

Discussion

The regulation mechanisms used in the Norwegian-Russian fishery management is fully described and the effects of them discussed in Gullestad et al. (2015). The background for the Norwegian regulation on Greenland halibut and the intention of the limited bycatch is to avoid closures in the general bottom trawl fishery for groundfish, *i.e.* species like cod, haddock, beaked redfish and partly saithe (Pollachius virens). Due to limited numbers of fish in each haul, it is relatively complicated to do a direct study on the size selectivity on Greenland halibut during the regulated small quota bycatch trawl fishery. We chose an area for the trials where we knew Greenland halibut would occur as an unavoidable bycatch species, but in limited numbers. We tested during experimental fishing the performance of a recently developed double steel grid system to estimate its ability to size select Greenland halibut in the Norwegian bottom trawl fishery targeting cod and haddock. The Greenland halibut bycatch selectivity data were analysed using a constrained version of a newly developed model (Larsen et al., 2016) that included direct quantification of the probability for fish to make selectivity contact with the individual grids. The first (lower) grid was very efficient at guiding all fish towards the upper grid (enhancing contact probability) without attenuating the water flow. However, nearly all of the escaping Greenland halibut escaped through the second (upper) grid. The release efficiency of the first (lower) grid was poor: approximately 11% of the Greenland halibut entering the grid section made contact with this grid in a way that gave it a size-dependent release probability. In contrast, we estimated that all the Greenland halibut still in grid section after the first grid made contact with the second (upper) grid. For most individuals, however, this contact was sub-optimal for size selection, as the estimated 50% retention length was far below what can be expected based on the morphology of Greenland halibut (Herrmann et al., 2013a). The suboptimal contact with the second (upper) grid may result from the strong water flow. The 3.0–3.2 knot water flow through the grid section likely reduced the ability of fish to react to the approaching grid and orient themselves to pass through the bars of the grid and escape. If most fish arriving in the size selection zone in the grid section already are exhausted from swimming during the capture process (Winger et al., 2010), the relative flow (velocity) inside the grid section represents a key factor for effective size sorting (*i.e.*, a higher relative water velocity gives fish less time to maneuver through selective devices). Escapement through the grids can only occur when Greenland halibut (and other species) orient along the grid bars. Fish that contact the grid sideways will in most cases slide along the full length of the grid bars and be unable to escape.

The poorer selectivity estimates for the new double steel grid section relative to those from the mandatory sorting grid sections currently in use (especially the two-panel Sort-V grid) may be the result of the two geometry modifications performed to increase water flow through the grid section (Fig. 3). The larger cross-sectional area of the new double steel grid section probably meant that the fish had less time to orient themselves properly towards the space between the grid bars compared to the twopanel Sort-V section. In the two-panel Sort-V section there is virtually no space between the lower part of the grid and the panel below, which means that fish have to force themselves under it to pass towards the codend and therefore stay in the grid zone for a longer period of time (Fig 3). Gjøsund et al. (2013) found that the relative water flow from the inlet to the outlet of a sorting grid section can be substantially reduced. As a response, scientists, management authorities, and fishermen have focused on developing grid sections with the aim of increasing water flow and fish passage without reducing their selective properties. The transition from a two-panel to a four-panel design improved water flow in a single grid system (Grimaldo et al., 2015). Our measurements showed strong water flow through the tested double grid system, which allows rapid transport of fish towards the codend. This rapid transport avoids the accumulation of fish and grid section clogging observed in other grid systems. However, it seems that the strong water flow through the new grid section negatively affects the size selectivity of Greenland halibut, *i.e.* shifts the L50 value towards smaller fish.

We measured a reduction in the water flow by adding the covers, but due to the few measurements it is not possible to draw a clear conclusion if they affected the size selection process of Greenland halibut compared to hauls without covers. During comparable experiments on size selection, the results were obtained with similar covers (see for example Larsen and Isaksen 1993; Sistiaga *et al.* 2010; Larsen *et al.* 2016). We compared our recent underwater recordings by older ones, and there is an indication of a stronger water flow through the tested (four-panel) grid section than through the earlier two-panel grid configurations as it is clear that fish pass faster through the grid section (personal observations). We therefore find the measured effects on size selectivity with the new grid design reliable.

Some precaution needs to be taken regarding the results obtained in the cruise as our fishing trial is based on only 6 hauls and the amount of Greenland halibut length measured is limited to 1634 (Table 2), which leads to uncertainty in the estimated size selection curves. This also needs to be considered when making conclusions based on the results obtained. However, these uncertainties are reflected in the confidence bands around the size selection curves and parameters that are provided along with the results. Therefore, as long as these confidence bands are considered when making conclusions, the limited number of fish caught and measured in this study should not be a major concern. The numbers of Greenland halibut length measured during the six hauls we used in this study were acceptable for the statistical analyses. Further, it was the main species caught during those hauls where size selectivity for the species was estimated. In the same hauls, we caught 547 haddock, 347 redfish and 33 cod. This demonstrates that during the six hauls, Greenland halibut was the main catch. This also reflects how the limited catches of Greenland halibut caught in the cod and haddock directed fishery often are harvested with a few hauls conducted in fishing areas where Greenland halibut is an abundant species. Therefore, we choose to apply a similar practice to obtain size selective estimates that best reflect how Greenland halibut typically would be harvested in a commercial fishery. Given the limited quota only six hauls were possible to conduct, which is a low number compared to most trawl selectivity studies, but it is a similar amount of hauls as conducted for the only two other selectivity cruises (with respectively four and six hauls), assessing fishing grid size selectivity of Greenland Halibut (Herrmann et al., 2013a). Considering this, the current study contributes with valuable information on size selectivity of Greenland halibut in trawls using sorting grids as long as inference made do not compromise the wideness of the confidence bands for the obtained size selection curve resulting from that this is a small-scale study. The data we achieved during the trials reflect the scenario fish trawlers meet in the area we conducted our trials and from a management point of view we believe it is important to know the size selectivity of Greenland halibut under such conditions.

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No. 16, 1991 (Special Session on Management Under Uncertainties, 5-7 September 1990)	21.00	26.00
No. 15, 1991 (Miscellaneous Selected Papers)	18.00	23.00
No. 14, 1990 (Miscellaneous Selected Papers)	18.00	23.00
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No. 10, 1986 (Miscellaneous Selected Papers)	18.00	23.00
No. 9, 1985 (Special Session on Squids, September 1984)	21.00	26.00
No. 8, 1985 (Miscellaneous Selected Papers)	16.00	21.00
No. 7, 1984 (Miscellaneous Selected Papers)	14.00	19.00
No. 6, 1983 (Miscellaneous Selected Papers)	14.00	19.00
No. 5, 1982 (Symposium on Environmental Conditions in the Northwest Atlantic During 1970–79, September 1981)	14.00	19.00
No. 4, 1982 (Special Session on Remote Sensing September 1981)	14.00	19.00
No. 3, 1982 (Miscellaneous Selected Papers)	12.00	17.00
No. 2, 1982 (Manual on Groundfish Surveys in the Northwest Atlantic)	11.00	16.00
No. 1, 1981 (Miscellaneous Selected Papers)	12.00	17.00

Information for Preparing Manuscripts for NAFO Scientific Publications

Journal of Northwest Atlantic Fishery Science

The Journal is for the primary publication of original practical and theoretical research that is unpublished and is not being submitted for publication elsewhere. While it is intended to be regional in scope, papers of general applicability and methodology may be considered. Space is also provided for notes, letters to the editor and notices. Each paper is assigned to an Associate Editor of the Journal's Editorial Board, and is normally reviewed by two referees regarding suitability as a primary publication.

NAFO Scientific Council Studies

The Studies publishes papers which are of topical interest and importance to the current and future activities of the Scientific Council, but which do not meet the high standards or general applicability required by the Journal. Such papers have usually been presented as research documents at Scientific Council meetings and nominated for publication by the Standing Committee on Publications. Studies papers are not peer reviewed.

Content of Paper

The paper should be in English. The sequence should be: Title, Abstract, Text, References, Tables and Figures.

Title

The paper should start with the title, followed by the name(s), address(es) and emails of the author(s) including professional affiliation, and any related footnotes.

Abstract

An informative concise abstract should be provided along with key words listed alphabetically.

Text

In general, the text should be organized into Introduction, Materials and Methods, Results, Discussion, and Acknowledgements. Authors should be guided by the organization of papers that have been published in the NAFO Journal or Studies.

Introduction should be limited to the purpose and rationale of the study.

Materials and Methods should describe in sufficient detail the materials and methods used, so as to enable other scientists to evaluate or replicate the work.

Results should answer the questions evolving from the purpose of the study in a comprehensive manner and in an orderly and coherent sequence, with supporting tables and figures.

Discussion should explain the main contributions from the study, with appropriate interpretation of the results focusing on the problem or hypothesis. Comparisons with other studies should be included here. Acknowledgements should be limited to the names of individuals who provided significant scientific and technical support, including reviewers, during the preparation of the paper, and the names of agencies which provided financial support.

References

The references cited in the text should be listed alphabetically. References should be mainly restricted to significant published literature. Unpublished documents and data, papers in preparation, and papers awaiting acceptance to other journals, may be cited with full contact addresses as unpublished or personal communications.

Examples:

KING, M. 1995. Fisheries biology, assessment and management. Fishing News Books, UK, 341 p.

- CROWDER, L. B., and S. A. MURAWSKI. 1998. Fisheries by-catch: implications for management. *Fisheries*, 23: 8–16. doi:10.1577/1548-8446(1998)023<0008:FBIFM> 2.0.CO;2
- ÁVILA DE MELO, A. M., D. POWER, and R. ALPOIM. MS 2005. An assessment of the status of the redfish in NAFO Division 3LN, *NAFO SCR Doc.*, No. 52, Serial No. N5138, 19 p.

Text citations of the above would be (King, 1995; Crowder and Murawski, 1998; Ávila de Melo *et al.*, MS 2005). The surnames of two authors may be used in a citation, but *et al.* should be used for more than two authors. The citation of mimeographed reports and meeting documents should contain the abbreviation "MS". Abbreviations of periodicals can be found <u>ftp://ftp.fao.org/fi/asfa/Monitoring_List/MASTER.txt</u>. The Digital Object Identifier (doi) should be included if available. <u>http://www.crossref.org/freeTextQuery/</u> can be used to checked this.

Tables and Figures

All Tables and Figures must be cited in the text. Tables and Figures must be numbered consecutively and correspond with the order of presentation in the text. Figure captions should be included as a separate page. Each table and figure should have a complete concise descriptive caption. Figures should always be submitted in black and white. Colour plots and photographs are acceptable only if colour is essential to the content.

All figures should be submitted as separate files in .eps or .ps format. Photographs, maps and contour plots can also be submitted in high quality .jpg format.

If using excel, open the files in R and save the graphs by right clicking and saving as metafiles or postscript files. If using SlideWrite copy the files as Metafiles (WMF). Do not save them as bitmap files. They are not editable.

Paper Submission

Papers should be submitted online to: <u>http://journal.nafo.int/dnn/Contact</u> OR <u>https://jnafs.</u> <u>scholasticahq.com/</u> If this isn't possible, email the General Editor at: journal@nafo.int