**Proposed Size-based Population Model to Southern Gulf of Saint Lawrence Snow Crab**

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**INTRODUCTION**

**Population Models:**

Population models are mathematical constructs that attempt to quantitatively describe how abundance indices are observed to vary over time. When successfully applied, these models are able to capture essential processes driving variations in abundance data, providing insight on underlying biological processes, the impact of fishing activities, and can be used to predict future dynamics of the population.

In this report, we present a size-based population model of the annual dynamics of the Southern Gulf of Saint Lawrence snow crab population. Though size-based, crab are partitioned by instar, i.e. the number of benthic moults crab have undergone, allowing for the specification of biological effects based on instar, as well as on size or year. Instars are identified within the model using a structured growth process which models the expected growth-at-moult between successive instars as well as its variation.

Biological processes included in the model are growth-at-moult, population recruitment, natural and fishing-related mortality (males only), skip-moulting probabilities and moult-to-maturity probabilities. Sampling-related processes are incorporated in the form of survey trawl size-selectivity curves as well as global year effects, intended to shed light on suspected annual differences in survey catchability, which have been associated with vessel changes, as well as other survey sampling changes.

For the purposes of this study, the snow crab population is assumed to be closed, which is a reasonable assumption as the stock is largely bounded by the Gaspé Pensinsula to the North, Cape Breton Island to the Southeast, and the deep warm waters of the Laurentian Channel between the two, though limited movement of crab along the margins of Gaspé and Cape Breton are known to occur.

**Mise-en-garde:**

Population models such as those presented here are often over-parameterized, meaning that in some way the amount of information being estimated exceeds the inherent information content of the data. As such, such analyses often yield multiple solutions, representing potentially very different biological states, but are able to fit the data to a similar degree. Thus during model development, external biological information or assumptions are often imposed to constrain the parameter space to solutions that are more consistent with biological knowledge.

As such population model development is generally a protracted iterative process requiring many revisions in response to suites of model diagnostics, including residual analyses, predictive tests, cross-validations, as well as comparing outputs with known biological or fishery quantities. From this process, the robustness of model outputs under changing assumptions can become known.

In this context, the model described here is not presented as a *fait accompli*, but rather as a presentation of the prototype model, which hopefully finds the right balance of simplicity and complexity to provide, in the short-term, improvements in:

* the retroactive estimation and prediction of annual variations in skip-moulting and moult-to-maturity probabilities.
* the prediction of future population dynamics, specifically fishery recruitment.
* relative catchability estimates between different survey years, or survey vessels, which may provide a means of retroactively standardizing the snow crab survey abundance and biomass time series.

As side-benefits, the proposed modeling framework may also be expected to yield:

* estimates of annual growth estimates, in the form of mean instar size estimates.
* fishery-independent estimates of fishing mortality, including discard mortality.
* a basis for modeling spatially-referenced stock dynamics.

**DATA**

Size-frequency data from the 2006 to 2020 snow crab surveys were used as population model inputs. Survey years 2006 to 2020 were chosen because the distribution of sampling stations were spatial homogenous over this period. Size-frequencies were standardized by swept area for each tow and then simply averaged by survey year, sex and morphometric maturity. For survey years 2006 to 2011, which had a different grid stratification with multiple stations per grid, size-frequencies were first averaged by grid, then averaged over entire survey. Snow crab size is the carapace width, as measured by Vernier calipers by on-board samplers. Though not used directly in the model, shell condition serves as a basis for distinguishing between crab that are moulted in the survey year and those that moulted in previous years. Due to known issues with the consistency of shell condition identification between years and samplers, skip-moulters and new matures were estimated solely from the model inputs.

In addition to the above grid size change sampling design, the survey area was expanded from ~44000 km2 in 2011 to ~57800 km2 in 2012. Sampling stations remained largely fixed from 2006 to 2011. Entirely new sets of random stations were generated for both the 2012 and 2013 surveys. From 2013 onward, stations were often held fixed from year to year, but the practice of moving stations in response to trawl damage has meant that, as of 2020, almost half of the original survey stations in 2013 have been moved. Three survey vessels have been used from 2006, the first is the CFV Marco-Michel from 2006 to 2012, the second is the CFV Jean Mathieu from 2013 to 2018, and the third is the CFV Avalon Voyager II.

**MODEL**

**Description:**

In the literature, benthic stages of snow crab instars are numbered using roman numerals, with I representing the first stage after the megalopses larvae have settled on the bottom and moulted. For both sexes, instars I to VIII are considered sexually immature and characterized by high relative growth rates. Adolescence begins with the onset of gonadal development at instar VIII, which is characterized by lower relative growth rates. Sexual maturity, in the form of a terminal moult accompanied by characteristic morphometric changes, attained at instars IX or larger. The vast majority of female snow crabs reach sexual maturity at instars IX and X.

Females growing to instar XI and larger were considered as being too rare an occurrence to be considered in the analysis. Mature male snow crab moult to maturity over a much wider size range, from instars IX to XIII. Instar XIV males were considered as relatively rare and not considered in the model. It follows that instar X in females and instar XII in males were the largest adolescent instars.

Growth in the model is a combination of two separate processes: one which specifies the probability of moulting from one instar to the next, and the other which specifies the predicted increase in size and its variation when moulting.

Two moulting processes were considered. Sexual maturation was modelled as the proportions of crab that undergo the terminal moult to maturity by instar and year. Although the probability of moulting to maturity for the largest adolescent instars, i.e. instar IX in females and XII in males, was considered to be 1, instars VIII in females and instars VIII-XI in males show variable proportions from year-to-year. Skip-moulting was only considered for adolescent males, was similarly modelled by instar and year. Moulting was considered to occur annually all instars.

Although the odd instar I, II and III do appear in survey catches, only instar IV crab are present in sufficient amounts to be analyzed by the model. For practical reasons, annual recruitment to the population was defined as the abundance of instar IV.

**Specification:**

Mean sizes for successive instars were defined iteratively as follows, allowing for known differences in growth trends between immature and adolescent crab:

, for

, for

where is the mean size for the *k*th instar, and are Hiatt slope and intercept parameters, respectively for immature crab, with and being the corresponding adolescent phase parameters. Instar standard errors were similarly defined, but allow for additional error inflation in the form of two positive parameters and :

, for

, for

Growth for mature crab was modified slightly by including an additive term :

Based on biological considerations, we expect that .

Population dynamics equations define the relationships between instars between years. They were based on the following assumptions:

* For each sex, there is a largest adolescent instar at which all individuals either skip-moult or moult to maturity the following year. This instar is IX for female crab and XII for male crab.
* Skip-moulting crab only occur in male adolescent crab instars IX or larger.
* Skip-moulters moult to maturity the following year.
* Only instars IX and X constitute matures in female crab, and instars IX, X, XI, XII and XIII in male crab.

With indxing the survey year and indexing the instar, the population dynamics equations are as follows:

with the superscripts representing regular immatures, representing immatures which have skipped the previous moult, representing new mature recruits, representing residuals (i.e. old-shelled) matures and representing all matures, i.e. the sum of recruits and residuals. **Table 1** shows a summary of the variables used in the population dynamics equations.

**Table 1**: Descriptions of population model variables.

|  |  |
| --- | --- |
| Variable | Description |
|  | Population number of immature crab. |
|  | Population number skip-moulters. |
|  | Population number of new mature recruits. |
|  | Population number of old mature residuals. |
|  | Population number of total mature crab. |
|  | Proportion of immature crab mortality. |
|  | Proportion of mature crab mortality. |
|  | Proportion of immature crab which skip a moult. |
|  | Proportion of immature crab that moult to maturity. |

The selectivity function is size-based and follows a logistic equation of the type:

where is a scale parameter and is the size at 50% of maximum catchability.

Instar sizes were assumed to follow a Gaussian distribution curve with above-described mean and error. The predicted abundance for a given size and year was defined as:

where indexes instar, represents crab size, is the Gaussian probability density function, and the quantities , , , and are population estimates of immature crab, skip-moulted immature crab, mature recruitment and old-shelled matures, respectively.

The likelihood function for the observed counts were treated as Poisson random variates:

**RESULTS**

**Females:**

**Mortality:**

* 4.5% by instar among immatures and adolescent,
* 4.3% new new matures, 10.3% annually for older matures.

**DISCUSSION**

**Issues:**

* However, inference for larger instars is generally more uncertain owing to increasing variability in growth during adolescence, which resulting in size overlap between successive instars at these stages.
* At 35%, mortality for mature recruits seems high.
* Trawl selectivity function states that selectivity at ~45 mm is the same as that at 80mm, may need to allow for asymmetry about the inflection point.

**FIGURES**

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**Figure 1**: Estimated survey size-structured abundance for immature and adolescent (red lines) and new mature recruits (green lines) and total mature female snow crab (blue lines). Observed size-frequencies are shown as jagged lines following the same colour scheme.

**Survey Size-Distributions:**

* Survey size-frequency distributions for female snow crab are shown in Figure 1, along with predicted immature and adolescent densities, new mature recruit densities, and old-shelled from the population model.
* The fits were generally good, with instar abundances for smaller sizes generally lining up well with observations.
* Despite not having new mature recruits identified in the data, the overall predicted abundance from the model compared surprisingly well with observations based on shell condition identifications.

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**Figure 2**: Size-selectivity curve showing the estimated proportion of female snow crab caught by the survey trawl from 2006 to 2020, based on the population model.

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**Figure 3**: Scaled year effects for female snow crab as estimated from the population model. A value of 1 indicates scales comparable to the 2020 survey.

**Year effects:**

* Estimated year effects are shown in Figure X. Estimates from 2006 to 2012 were around 1.4, ranging from 1.18 in 2009 to 1.79 in 2010. This period corresponds to the surveys performed by the CFV Marco Michel.
* The series corresponding to CFV Jean Mathieu were much lower, ranging from 0.79 to 0.88 from 2013 to 2018.
* The values for the CFV Avalon Voyager II were 1.155 in 2019, representing a 42% increase from 2018.
* The year effect decreased by 13% from 2019 to the 2020 reference survey.

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**Figure 4:** Population abundance of immature and mature female snow crab by year and maturity, as estimated from the population model.

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**Figure 5:** Population abundance of immature and mature female snow crab by year, instar and maturity as estimated from the population model.