A productivity-susceptibility risk analysis for the effects of fishing on Arctic Char (*Salvelinus alpinus*) stocks from the Nunavut Territory

Marie-Julie Roux* and Ross F. Tallman
Fisheries and Oceans Canada
Central and Arctic Region

*Present address: National Institute of Water and Atmospheric Research, 301 Evans Bay Parade, Greta Point, Wellington, New Zealand
195 Arctic Char
350 FW and Anadromous
Problems

(...) “what needs to be done to address priority gaps”

- **paucity of data**
- **too large a place**
- **too many stocks**

prohibitive time and financial costs to gather standard assessment data
Paucity of data too large a place too many stocks charr diversity

Prohibitive time and financial costs to gather standard assessment data

Makes it difficult to generalize scientific information for the species and related management plans/actions

Background

(... “what needs to be done to address priority gaps”)

Problems
from Gaps to Solutions

solutions for the scientific understanding and management of Arctic charr fisheries

Objective

charr modelling

charr diversity
Life history traits determine stock productivity

- Life history traits:
  - age at maturity \( (R) \)
  - fecundity \( (R) \)
  - growth rate \( (G) \)
  - survival \( (M) \)

- Elements of productivity:
  - \( R \) = reproductive capacity
  - \( G \) = growth
  - \( M \) = mortality = 1 - survival

(productivity \( \approx \) resilience)
Life history traits determine stock productivity

Life history traits
- age at maturity ($R$)
- fecundity ($R$)
- growth rate ($G$)
- survival ($M$)

Elements of productivity
- $R$ = reproductive capacity
- $G$ = growth
- $M$ = mortality = 1-survival

Stable population:

$$R + G = M$$

Population trend = nil (0)

Traits are in balance and the population persists

(Productivity ≈ resilience)
Charr modelling using life history traits

**life history traits**
- AM = age at maturity
- F = fecundity
- GR = growth rate
- Z = instantaneous mortality

**elements of productivity**
- R = reproductive capacity
- G = growth
- M = mortality
Charr modelling using life history traits

**Conceptual approach**

**Life history traits**
- \( AM = \) age at maturity
- \( F = \) fecundity
- \( GR = \) growth rate
- \( Z = \) instantaneous mortality

**Elements of productivity**
- \( R = \) reproductive capacity
- \( G = \) growth
- \( M = \) mortality

\[ H = \text{harvest rate} \]

(Management history and population response information)
Charr modelling using life history traits

**Conceptual approach**

**life history traits**
- AM = age at maturity
- F = fecundity
- GR = growth rate
- Z = instantaneous mortality

**elements of productivity**
- R = reproductive capacity
- G = growth
- M = mortality

**H = harvest rate**
(management history and population response information)

![Diagram](image)

a model using life history traits and harvest rates as input parameters to predict population trends

explore and identify sustainable H range

\[ R + G - M > 0 \]
Charr modelling using life history traits

Conceptual approach

phase 1:
• demonstrate the extent of inter-population variability in life-history traits and how this can be used for evaluating the relative vulnerability of Arctic charr stocks to fishing activities (SEMI-QUANTITATIVE RISK ANALYSIS)

phase 2:
• model development and testing (FULL QUANTITATIVE ANALYSIS)
Risk assessment using life history traits

- a relative (as opposed to absolute) risk assessment method

- based on the principle that population vulnerability to fishing activities depends on:
  - its ability to recover from increased mortality
    \(\text{productivity} \approx \text{resilience}\) (more productive = less vulnerable)
  - the extent of the impacts due to fishing activities
    \(\text{susceptibility} \approx \text{exposure}\) (more exposed = more vulnerable)
not a new method:

• Australian Northern Prawn fishery by-catch spp. (see Stobutzki et al. 2001)

• recently proposed as a semi-quantitative step in a hierarchical ecological risk assessment for the effects of fishing (ERAEF) framework by the Marine Stewardship Council (MSC eco-certification body) (see Hobday et al. 2007)

• currently being evaluated for use in determining the vulnerability of U.S. fisheries by NOAA (see Patrick et al. 2009)

…but has never been experimented on a single-species basis

Productivity-Susceptibility Analysis
STEP 1: define and estimate productivity and susceptibility attributes

Productivity attributes

Susceptibility attributes
Productivity-Susceptibility risk assessment

**STEP 1**: define and estimate productivity and susceptibility attributes

<table>
<thead>
<tr>
<th>Productivity attributes</th>
<th>Susceptibility attributes</th>
</tr>
</thead>
</table>


97 anadromous stocks
(5.5” (139.7 mm) gillnet studies)
Productivity-Susceptibility risk assessment

**STEP 1: Define and estimate productivity and susceptibility attributes**

### Productivity attributes

- **Age at first maturity**
  - Younger age at first maturity = more productive
  - Estimation: first age group with mature fish (all data pooled) or approximated from a linear model using max age as predictor

- **Individual growth rate**
  - Faster growth = more productive
  - Estimation: Brody (K) growth coefficient calculated by fitting von Bertalanffy growth curves to fully recruited age groups* (all 139.7mm gillnet data pooled)

- **Lifespan**
  - Short-lived = more productive
  - Estimation: maximum age observed in the sample (all 139.7mm gillnet data pooled)

- **Mortality**
  - Higher mortality = more productive
  - Estimation: annual mortality estimated from catch curves (catch at age plots) (all 139.7mm gillnet data pooled)
STEP 1: define and estimate productivity and susceptibility attributes

**Susceptibility attributes**
- **Encounterability**: Likelihood that the stock will encounter fishing gear
- **Availability**: Overlap between fishing effort and stock distribution
- **Selectivity**: Potential for the gear to capture/retain fish
- **Estimation**: Distance from nearest human community
  - Ranked high for anadromous stocks
- **Ratio of mean fork length over mesh size (in mm)**
**STEP 2:** rank individual productivity attributes for data quality

**data quality scores = a measure of uncertainty**

<table>
<thead>
<tr>
<th>Data Quality Score</th>
<th>Conditions</th>
</tr>
</thead>
</table>
| 1                  | - sample size is large ($\geq$300).  
- All conditions *a priori* determined for the estimate to be reliable are met.  
- Data is recent and is likely to reflect current state environmental conditions. |
| 2                  | - sample size is large ($\geq$300).  
- All conditions *a priori* determined for the estimate to be reliable are met.  
- Data is not recent and unlikely to reflect current state environmental conditions. |
| 3                  | - Sample size is $<300$ but $>100$  
OR – sample size is $>300$ BUT other conditions *a priori* determined for an estimate to be reliable are not met. |
| 4                  | - Sample size is $<100$  
OR – Sample size is $>100$ BUT other conditions *a priori* determined for an estimate to be reliable are not met. |
| 5                  | Sample size is $<100$ AND other conditions *a priori* determined for an estimate to be reliable are not met.  
Estimate was approximated using life-history information. |
**STEP 3**: rank productivity and susceptibility attributes into tiers corresponding to different levels of risk

**Productivity**
- **attributes**
  - age at first maturity
  - individual growth rate
  - lifespan
  - mortality

**Susceptibility**
- **attributes**
  - encounterability
  - availability
  - selectivity

→ determine a range of values for each attribute
→ divide this range into thirds:

**Productivity**
- **Risk**
  - 1 = Low
  - 2 = Moderate
  - 3 = High
  - 1 = High
  - 2 = Moderate
  - 3 = Low

**Susceptibility**
- **Risk**
  - 1 = Low
  - 2 = Moderate
  - 3 = High
  - 1 = Low
  - 2 = Moderate
  - 3 = High
**Productivity-Susceptibility risk assessment**

**STEP 3**: rank productivity and susceptibility attributes into tiers corresponding to different levels of risk

*Only stocks with values corresponding to data quality scores ≤3 were used to define the observed range*

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Observed Range</th>
<th>Productivity Tiers and Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Age at first maturity</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Growth rate (K)</td>
<td>0.028</td>
<td>0.175</td>
</tr>
<tr>
<td>Lifespan (Age_{max})</td>
<td>12</td>
<td>31</td>
</tr>
<tr>
<td>Mortality</td>
<td>0.17</td>
<td>0.66</td>
</tr>
</tbody>
</table>
STEP 3: rank productivity and susceptibility attributes into tiers corresponding to different levels of risk

<table>
<thead>
<tr>
<th>Susceptibility attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>encounterability scores</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Encounterability scores</th>
<th>3 = High</th>
<th>2.5</th>
<th>2 = Mod</th>
<th>1.5</th>
<th>1 = Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from community (km)</td>
<td>≤ 10</td>
<td>51-60</td>
<td>101-110</td>
<td>151-160</td>
<td>≥ 201</td>
</tr>
</tbody>
</table>
STEP 3: rank productivity and susceptibility attributes into tiers corresponding to different levels of risk

<table>
<thead>
<tr>
<th>Observed range (mean FL)</th>
<th>Observed range (Mean FL / Mesh size)</th>
<th>Gear Selectivity Tiers and Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIN 501</td>
<td>MAX 772</td>
<td>MIN 3.60</td>
</tr>
<tr>
<td>3.60-4.25</td>
<td>4.26-4.90</td>
<td>4.91-5.55</td>
</tr>
</tbody>
</table>
STEP 3: Rank productivity and susceptibility attributes into tiers corresponding to different levels of risk

**Susceptibility attributes**

<table>
<thead>
<tr>
<th>Availability tiers and scores</th>
<th>low=1</th>
<th>moderate=2</th>
<th>high=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>lacustrine+large lake fishery</td>
<td>anadromous+medium size lake fishery</td>
<td>anadromous+river mouth fishery</td>
<td></td>
</tr>
<tr>
<td>anadromous+medium size lake fishery</td>
<td>lacustrine+medium size lake fishery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lacustrine+large lake fishery</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
STEP 4: plot average productivity-susceptibility scores and estimate vulnerability as the Euclidean distance from the origin.

\[ V = \sqrt{(P - 3)^2 + (S - 1)^2} \]
**STEP 5:** average data quality scores into a data quality index

### Productivity attributes

- **Risk**
  - 1 = High
  - 2 = Moderate
  - 3 = Low

### Susceptibility attributes

- **Risk**
  - 1 = High
  - 2 = Moderate
  - 3 = Low

### Productivity-Susceptibility risk assessment

- **High Productivity Low Susceptibility** = least vulnerable
- **Low Productivity High Susceptibility** = most vulnerable

### Overall Data Quality Index

<table>
<thead>
<tr>
<th>LOW (L)</th>
<th>MEDIUM (M)</th>
<th>HIGH (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥3.6</td>
<td>2.1-3.5</td>
<td>≤2</td>
</tr>
</tbody>
</table>

- □ High data quality
- ○ Low data quality
- ◯ Medium data quality
PSA results

Productivity-Susceptibility risk assessment

Kitikmeot Region

Less Vulnerable
(1.27) Arrowsmith River
(1.27) Kellett River
(1.28) Nakoytok River
(1.28) Perry River
(1.47) Becher River

More Vulnerable
(2.06) Freshwater Creek
(2.07) Paliryuak River
(2.08) Hayes River
(2.24) Jayco River
(2.30) Abermethy River
(2.46) Lord Lindsay Lake
Productivity-Susceptibility risk assessment

Kivalliq Region

Less Vulnerable
- 1.09 Stony Point Area
- 1.10 Barbour Bay
- 1.10 Robinhood Bay
- 1.15 Lorillard River
- 1.18 Gore Bay Area
- 1.18 Hanway River
- 1.19 Steep Bank Bay

More Vulnerable
- 2.05 Ross Inlet
- 1.10 Barbour Bay
- 1.10 Robinhood Bay
- 1.15 Lorillard River
- 1.18 Gore Bay Area
- 1.18 Hanway River
- 1.19 Steep Bank Bay

Vulnerable stocks
- 1.23 Pistol Bay
- 1.36 Chesterfield Inlet
- 1.36 Rankin Inlet Area
- 1.36 Ranger Seal Bay

Less Vulnerable stocks
- 1.09 Stony Point Area
- 1.10 Barbour Bay
- 1.10 Robinhood Bay
- 1.15 Lorillard River
- 1.18 Gore Bay Area
- 1.18 Hanway River
- 1.19 Steep Bank Bay

High data quality
- •

Medium data quality
- ○

Low data quality
- □
Productivity-Susceptibility risk assessment

- **Baffin High Region**
- **Less Vulnerable stocks**
  - (1.23) Ikalukjuaq Lake and River
  - (1.30) Tasiroluk Lake
  - (1.41) Kipisa Lake
  - (1.41) Tugaat River
  - (1.42) Ava Inlet
  - (1.42) Nettilling Lake
- **More Vulnerable stocks**
  - (2.14) Ijaruvung Lake
  - (2.14) Kukaluk River
  - (2.15) Ikikeesarjuaq Lake
  - (2.15) Stanwell-Fletcher Lake
  - (2.20) Tarsiujuaq Arm
  - (2.23) Magda River
  - (2.29) Gifford River
  - (2.30) Ivisarik Lake
  - (2.30) Koluktoo Bay
  - (2.30) Naulingiavik Lake
  - (2.35) Hall Lake
  - (2.39) Rowley River
  - (2.41) Ikpikiturjuaq Lake
  - (2.44) Neergaard Lake
  - (2.44) Ravn River
  - (2.50) Hall Beach Area
  - (2.55) Windless River
  - (2.56) Fury and Hecla Strait

- **Vulnerable stocks**

- **More Vulnerable stocks**

- **High data quality**

- **Medium data quality**

- **Low data quality**

- **Less Vulnerable stocks**
Productivity-Susceptibility risk assessment

PSA results

- Less Vulnerable stocks (more sustainable fisheries)
- Vulnerable stocks (sustainable fisheries)
- More Vulnerable stocks (less sustainable fisheries)
Productivity-Susceptibility risk assessment

- 15% of fisheries examined
- 45% of more sustainable fisheries

Less Vulnerable stocks (more sustainable fisheries)
Vulnerable stocks (sustainable fisheries)
More Vulnerable stocks (less sustainable fisheries)
Productivity-Susceptibility risk assessment

- 22% of fisheries examined
- 60% of less sustainable fisheries

Legend:
- Green dot: Less Vulnerable stocks (more sustainable fisheries)
- Orange dot: Vulnerable stocks (sustainable fisheries)
- Red dot: More Vulnerable stocks (less sustainable fisheries)
Productivity-Susceptibility risk assessment

over a broad geographic landscape:

• PSA analysis allows us to distinguish between regions characterized predominantly by less or more vulnerable Arctic charr populations

  prevalence of more vulnerable stocks = greater risk of overfishing
  prevalence of less vulnerable stocks = lower risk of overfishing

Regional differences in stock vulnerability
Productivity-Susceptibility risk assessment

Cambridge Bay Area

PSA results

- More Vulnerable stocks
- Vulnerable stocks
- Less Vulnerable stocks

- High data quality
- Medium data quality
- Low data quality

Jayco  Paliryuak  Ellice  Perry  Halovik  Lauchlan  Ekalluk  Kulgayuk  Palinyuak  Jayco

Productivity

Susceptibility

1.0  1.5  2.0  2.5  3.0

1.0  1.5  2.0  2.5  3.0

High  Low

(High)  (Low)
Yield Calculations

\[ \log L^\infty = 0.044 + 0.9841 \log L_{\text{max}} \] (Froese & Binohlan 2000)

\[ K = -\ln \left(\frac{1-L_{\text{m}}}{L^\infty}\right) / (tm - t0) \] (Froese & Binohan 2003)

\[ M = 1.5K \quad F = Z - M - Z \text{ calculated from catch curve} \] (Jensen 1996)

Biomass = Yield/F

Max Sustainable Production = 0.33 x Z x Biomass
Estimation of Maximum Sustainable Production

<table>
<thead>
<tr>
<th>Stock (harvestable unit)</th>
<th>Location</th>
<th>sample size</th>
<th>sample size</th>
<th>Max Pl Age</th>
<th>Mean Pl Age full size Z</th>
<th>P</th>
<th>S</th>
<th>V</th>
<th>Uln</th>
<th>K</th>
<th>M</th>
<th>F</th>
<th>Yield</th>
<th>Biomass</th>
<th>MSP</th>
<th>Over/Und CCH</th>
<th>PA</th>
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</thead>
<tbody>
<tr>
<td>Ajuakutlik Lake</td>
<td>68.23</td>
<td>82.33</td>
<td>183</td>
<td>140</td>
<td>865</td>
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<tr>
<td>Akajuk Lake</td>
<td>65</td>
<td>71</td>
<td>283</td>
<td>179</td>
<td>814</td>
<td>23</td>
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<tr>
<td>Akittak Lake</td>
<td>63.17</td>
<td>64.05</td>
<td>230</td>
<td>148</td>
<td>867</td>
<td>22</td>
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<td>Angajakutit Lake</td>
<td>65.05</td>
<td>63.42</td>
<td>202</td>
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<tr>
<td>Arrowsmith River</td>
<td>68.23</td>
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<td>460</td>
<td>137</td>
<td>725</td>
<td>21</td>
<td>588</td>
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<td>Arving Lake</td>
<td>61.07</td>
<td>94.04</td>
<td>427</td>
<td>367</td>
<td>790</td>
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<td>Avvak Lake</td>
<td>63.49</td>
<td>71.55</td>
<td>507</td>
<td>449</td>
<td>731</td>
<td>17</td>
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<td>Back River</td>
<td>67.15</td>
<td>95.15</td>
<td>746</td>
<td>297</td>
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<td>19</td>
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<tr>
<td>Baker Foreland Lake</td>
<td>62.55</td>
<td>90.48</td>
<td>881</td>
<td>815</td>
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<tr>
<td>Bautour Bay</td>
<td>63.35</td>
<td>92.14</td>
<td>130</td>
<td>118</td>
<td>684</td>
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<tr>
<td>Brown Inlet</td>
<td>69.29</td>
<td>79.31</td>
<td>207</td>
<td>207</td>
<td>785</td>
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<tr>
<td>Chesterfield Inlet (Fish Bay)</td>
<td>63.19</td>
<td>90.45</td>
<td>903</td>
<td>765</td>
<td>750</td>
<td>13</td>
<td>597</td>
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<tr>
<td>Clyde Area</td>
<td>70.27</td>
<td>68.36</td>
<td>316</td>
<td>269</td>
<td>768</td>
<td>18</td>
<td>508</td>
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<tr>
<td>Coppermine River</td>
<td>67.49</td>
<td>115.04</td>
<td>209</td>
<td>103</td>
<td>913</td>
<td>14</td>
<td>663</td>
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<tr>
<td>Coopersneek River</td>
<td>61.52</td>
<td>93.37</td>
<td>266</td>
<td>208</td>
<td>747</td>
<td>11</td>
<td>647</td>
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<tr>
<td>Corbett Inlet</td>
<td>62.28</td>
<td>92.9</td>
<td>1422</td>
<td>1242</td>
<td>803</td>
<td>14</td>
<td>647</td>
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<tr>
<td>Curtis River (Committee Bay)</td>
<td>67.12</td>
<td>87.28</td>
<td>829</td>
<td>171</td>
<td>794</td>
<td>19</td>
<td>647</td>
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</tr>
<tr>
<td>Diana River</td>
<td>63.25</td>
<td>92.23</td>
<td>627</td>
<td>141</td>
<td>806</td>
<td>13</td>
<td>704</td>
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PA = 0.32 %
### Estimation of Maximum Sustainable Production

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### Notes
- Healthy: Production is below 10% of carrying capacity.
- Critical: Production is between 10% and 20% of carrying capacity.
- Cautionary: Production is between 20% and 40% of carrying capacity.
- Healthy: Production is above 40% of carrying capacity.
Average Harvest relative to Maximum Sustainable Production
Charr modelling using life history traits

- Among population Variability in life history traits is a characteristic of Arctic charr populations in Nunavut
Charr modelling using life history traits

- Among population Variability in life history traits is a characteristic of Arctic charr populations in Nunavut

- Life history traits for a stock can be determined from a single sample of ≈ 200 fish (intermediate data quality) or approximated using life history theory
Charr modelling using life history traits

- Among population Variability in life history traits is a characteristic of Arctic charr populations in Nunavut

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- Life history traits can be used together with a measure of exposure (susceptibility attributes) to determine the relative vulnerability of Arctic charr stocks to fishing activities over a broad geographic landscape and within smaller areas.
• Among population Variability in life history traits is a characteristic of Arctic charr populations in Nunavut

• Life history traits for a stock can be determined from a single sample of ≈ 200 fish (intermediate data quality) or approximated using life history theory

• Life history traits can be used together with a measure of exposure (susceptibility attributes) to determine the relative vulnerability of Arctic charr stocks to fishing activities over a broad geographic landscape and within smaller areas.

soon:
• Life history traits can be used in a quantitative model to explore and identify sustainable harvest rates for a stock and thereby facilitate the formulation of scientific advice for arctic charr in the CNA region.
Gaps → Solutions

solutions gaps for the scientific understanding and management of Arctic charr fisheries

life history traits → charr diversity

exposure

relative risk assessment

full quantitative analysis
Questions?
Acknowledgments

Theresa Carmicheal DFO
YK area office
DFO Nunavut Implementation Fund
Nunavut Wildlife Management Board