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Modeling potential population-level impacts of localized oil spills on Puget Sound Pacific herring stocks

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Modeling Potential Population-level Impacts of Oil Spills on Puget Sound Pacific Herring Stocks

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The developing heart is a primary target organ for crude oil

- Developmental cardiotoxicity is a well-studied crude oil injury phenotype in herring and other fish species
- Injury occurs over a gradient of severity, from mild bradycardia to arrhythmias, conduction blockade, and severe heart failure
Low-level oil exposures slow the heartbeat
(embryonic Pacific herring)

The consequence of bradycardia: ineffective cardiovascular circulation

Incardona et al., 2009, *Environmental Science and Technology*, 43:201
Juvenile

Adult

YOY

Cardiorespiratory Function

Lipid dynamics and Energy Reserves

Crude Oil Exposure

Individual-Based Effects Pathways

Maximum Age 9-11
Minimum Age at First Reproduction 2
Annual Reproduction

YOY – Young of the year. Encompasses embryo through hatch through first winter.

Lipid Dynamics and Energy Reserves is a Novel Pathway
Injury

Embryos/larvae
Dissolved oil
(above LC)
- Reduced hatch rate
- Acute lethality
- Surviving embryos show sublethal effects
  - Delayed mortality in juveniles/adults

Embryos/larvae
Dissolved oil
(below LC, above cardiotoxic EC)
- Delayed mortality in juveniles/adults
  - Heart form/function
  - Swimming performance
  - Immune system, disease susceptibility
  - Metabolic rate

Embryos/larvae
Dissolved oil
(below EC)
- No injury

Embryos/larvae
Dissolved oil + UV
- Reduced hatch rate
- Acute lethality
- Tissue narcosis

Not to scale
Pacific Herring Life History
First Year Survival

Key Events
- Fertilization
- Hatch
- Larval Drift
- Free Feeding & Metamorphosis
- Summer Growth
- Winter Fast

Limiting Factors
- Natural
  - Predation
  - Advection to nursery areas
  - Temperature, prey density
  - Prey availability, predation

- Oil-Induced
  - Yolk Conversion
  - Yolk Conversion
  - Swimming & prey capture, Growth & energy storage
  - Stored energy use, Swimming & prey capture
Lessons Learned from Puget Sound Herring studies (Landis & Bryant 2010, Siple & Francis 2016)

- Models sensitive to first year survival, but exact rates highly variable and often combined with other recruitment factors
- Demographic rates specific to regions
- Stocks behave independently

Siple & Francis 2016
Age-structured population model for local stocks

Regional Stock-Specific Demographics in Puget Sound
- 2 Increasing Stocks: Quilcene Bay & Holmes Harbor
- 2 Decreasing Stocks: Port Gamble & Skagit Bay

Estimated Age-specific Survival and Reproductive rates from WDFW Acoustic Data for Each Stock

Oil Exposure Impacts first year survival

Pacific Herring
Mean population growth rates ($\lambda$), standard deviations, and the percent change in $\lambda$ for mortality to first year herring (S1).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>% change in $\lambda$ from % S1 mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda$ mean</td>
<td>std</td>
</tr>
<tr>
<td>Quilcene Bay</td>
<td>1.51</td>
<td>0.50</td>
</tr>
<tr>
<td>Port Gamble</td>
<td>0.84</td>
<td>0.20</td>
</tr>
<tr>
<td>Holmes Harbor</td>
<td>1.45</td>
<td>0.46</td>
</tr>
<tr>
<td>Skagit Bay</td>
<td>0.81</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Values in italics exceed the percent of one standard deviation of the output.
## Herring Stock Oil Exposure Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Model run year(s) exposed</th>
<th>Mortality impact to first year survival each year</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 50 y5 1d</td>
<td>5</td>
<td>50%</td>
</tr>
<tr>
<td>S1 50 y5 2d</td>
<td>5 &amp; 6</td>
<td>50% &amp; 50%</td>
</tr>
<tr>
<td>S1 90 y5 1d</td>
<td>5</td>
<td>90%</td>
</tr>
<tr>
<td>S1 90 50 y5 d2</td>
<td>5 &amp; 6</td>
<td>90% &amp; 50%</td>
</tr>
<tr>
<td>S1 5040302010y5d5</td>
<td>5, 6, 7, 8, 9</td>
<td>50%, 40%, 30%, 20%, 10%</td>
</tr>
<tr>
<td>S1 9070503010y5d5</td>
<td>5, 6, 7, 8, 9</td>
<td>90%, 70%, 50%, 30%, 10%</td>
</tr>
<tr>
<td>S1908070605040302010y5d9</td>
<td>5, 6, 7, 8, 9, 10, 11, 12, 13</td>
<td>90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%</td>
</tr>
</tbody>
</table>
Localized Oil Spill for 4 Puget Sound Stocks

Quilcene Bay

Holmes Harbor

Port Gamble

Skagit Bay

Percent of Control Abundance

Percent Baseline Abundance

year

Percent baseline abundance

year
### Time to extinction (years) for Skagit Bay and Port Gamble stocks

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Skagit Bay</th>
<th></th>
<th>Port Gamble</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>median</td>
<td>min</td>
<td>mean (std)</td>
<td>median</td>
</tr>
<tr>
<td>baseline</td>
<td>65</td>
<td>34</td>
<td>66(13)</td>
<td>73</td>
</tr>
<tr>
<td>S1 50 y5 1d</td>
<td>64</td>
<td>32</td>
<td>65(13)</td>
<td>72</td>
</tr>
<tr>
<td>S1 50y5 2d</td>
<td>63</td>
<td>32</td>
<td>64(13)</td>
<td>70</td>
</tr>
<tr>
<td>S1 90 y5 1d</td>
<td>64</td>
<td>37</td>
<td>64(12)</td>
<td>71</td>
</tr>
<tr>
<td>S1 90 50 y5 d2</td>
<td>62</td>
<td>34</td>
<td>63(13)</td>
<td>69</td>
</tr>
<tr>
<td>S1 5040302010y5d5</td>
<td>62</td>
<td>37</td>
<td>63(12)</td>
<td>70</td>
</tr>
<tr>
<td>S1 9070503010y5d5</td>
<td>60</td>
<td>33</td>
<td>60(12)</td>
<td>67</td>
</tr>
<tr>
<td>S1909870605040302010y5d9</td>
<td>54</td>
<td>27</td>
<td>55(12)</td>
<td>61</td>
</tr>
</tbody>
</table>
Modeling Conclusions

• Adverse Outcome Pathways of cardiac function and lipid/energy dynamics may lead to delayed mortality

• Delayed mortality on young of the year could link to loss of productivity and population-level effects

• Natural variability in herring demographic rates may hinder observation of effects in the field

• Duration and scale of spill effects important in observing population-level impacts

• Migration between stocks could result in metapopulation dynamics that influence the scope of localized spills

• Additional data on toxic impacts to juvenile and adult herring will be important in determining population-level effects
Non-model Methods for Estimating Impact

• Consistent acoustic monitoring to establish trends in age structure, survival rates and recruitment

• Post spill field assessments to determine exposure concentrations in spawning habitat and herring eggs or larval and compare to toxicity thresholds for acute mortality and sublethal effects

• Collection of herring embryos, larvae, or juveniles to determine the proportion showing specific phenotypes (e.g., cardiac edema) or gene regulation patterns indicative of changes in individual fitness (via swimming ability, immune function, or lipid metabolism)
Thank You
Localized Oil Spill for 2 Puget Sound Stocks Connected by 5% Migration
Localized Oil Spill during Spawning Season
Exposure to Adult Spawners and Developing Embryos

Quilicene comparison of S1 and S1+adult effects

Percent of Control Abundance

year

S1 90% to 10% 5y
S1 90% to 10% 5y SA805050
S1 90% to 10% y9
S190to109yS21SA805050