Growth and survival of forage fish and juvenile salmon in response to oceanographic variability in the northern California Current, including the Salish Sea

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Puget Sound Nutrient Forum July 16, 2018
Trends in Nutrient Over-Enrichment in Puget Sound

• Physiological and behavioral changes in salmonids and forage fish in response to low DO conditions in the marine environment

• Marine food web changes in response to shifts in marine water quality
Outline

- Current understanding of salmon and forage fish marine survival
- Factors affecting food web and growth
- Climate change impacts in the North Pacific
- Examples from Puget Sound
A critical period in the life history of Pacific salmonids when mortality is high and variable.

Pearcy 1992; Beamish 2018
Sampling of Juvenile Pacific Salmon 1998-2017

- Juvenile salmon ecology studied for the past 20 years
- Understand marine growth, migration, and survival
- Informs salmon conservation, recovery, harvest management
- Early warning *indicators* of ocean conditions that affect salmon survival
Pacific Decadal Oscillation (PDO)

Positive Phase = Warm, **bad** for salmon
Negative Phase = Cool, **good** for salmon

Marine Heatwave 2014 – 2016

Most (<5%) salmon that enter the ocean do not survive. Why? Prey quality, availability, competition, predators, disease
PDO and Copepods

Cool Phase ➔
Transport of boreal coastal copepods into NCC from Gulf of Alaska

Warm Phase ➔
Transport of subtropical copepods into NCC from Transition Zone offshore

www.nwfsc.noaa.gov
Growth positively related to abundance of cold water copepods

Ontogenetic shift in diet upon ocean entry

Larger size or faster growth may have an advantage: “bigger-is-better” and “growth-mortality” hypotheses

Anderson 1988; Miller et al. 1988; Brodeur et al. 1991; Litz et al. 2017
Both $\delta^{13}C$ and $\delta^{15}N$ *increase* through time as salmon begin feeding more heavily on forage fish.
Chinook salmon size-at-age is changing along the west coast

- Size-selective harvest
- Environmental changes that affect growth and mortality
- Hatchery practices – density dependent effects
- Increased competition
- Predation by marine mammals

Ohlberger et al. 2018
Typical El Niño and La Niña patterns

Bad for PNW Salmon

Good for PNW Salmon
Variations in salmon marine survival correlates with variations in ocean conditions

Peterson et al. 2014
<table>
<thead>
<tr>
<th>Year</th>
<th>Ecosystem Indicators</th>
<th>PDO (Sum Dec-Mar)</th>
<th>PDO (Sum May-Sept)</th>
<th>OI (Average Jan-June)</th>
<th>66/66 SST (°C; May-Sept)</th>
<th>Upper 20 m T (°C; Nov-Mar)</th>
<th>Upper 20 m T (°C; May-Sept)</th>
<th>Deep temperature (°C; May-Sept)</th>
<th>Deep salinity (May-Sept)</th>
<th>Copepod richness anom. (no. species; May-Sept)</th>
<th>N. copepod biomass anom. (mg C m$^{-3}$; May-Sept)</th>
<th>S. copepod biomass anom. (mg C m$^{-3}$; May-Sept)</th>
<th>Biological transition (day of year)</th>
<th>Ichthyoplankton biomass (log (mg C 1000 m$^{-3}$); Jan-Mar)</th>
<th>Ichthyoplankton community index (PCO axis 1 scores; Jan-Mar)</th>
<th>Chinook salmon juvenile catches (no. km$^{-1}$; June)</th>
<th>Coho salmon juvenile catches (no. km$^{-1}$; June)</th>
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**Salmon Indicators 1998 - 2017: Bad ➔ Good**

**Regional biological indices**

- **Regional physical indices**
- **Basin-scale physical indices**

**Mean of ranks**: 17.1  7.0  5.8  6.9  5.8  12.4  15.1  16.2  10.9  6.9  2.7  8.5  12.2  8.2  6.5  7.6  12.3  15.9  16.4  13.9

**Rank of the mean rank**: 20  6  2  5  2  14  16  18  11  10  1  9  12  8  4  7  13  17  19  15

**1998 = Worst Score**

**2008 = Best Score**
Survival associated with physical and biological indicators

PCA
- Basin Scale
- Regional
- Growth/Feeding
- Predation/Disease
- Cohort Abundance

Burke et al. 2013
Puget Sound Indicators

- NOAA IEA Salmon Indicators
- Puget Sound Partnership
- Long Live The Kings Salish Sea Marine Survival Project
Blob forms

El Niño forms

La Niña forms

+3°C

Bond et al. 2015
### Biological Responses to the Warm Ocean

#### 2015
- Harmful algal blooms shut down crab and clam fisheries CA – AK
- Reductions in zooplankton and changes to jellyfish community
- Tropical fish caught in the PNW
- Whales feeding in estuaries

#### 2016
- Pelagic red crabs wash ashore
- Food web changes continue
- Anchovy increase in Salish Sea
- Whales nearshore; entangled in fishing lines

#### 2017
- Pyrosomes explode in N Pacific
- Sea bird die offs in Bering Sea
- Pacific cod collapse in Gulf of AK
- Sea lion abundance increasing in PNW

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Unusual salmon observations in 2015

- Interior Fraser & Puget Sound coho extremely low abundance, small body size, and low fecundity
- Columbia & Oregon coast coho lowest returns since 1990s
- Oregon coast Chinook returns high
- Extremely low downstream survival Central Valley Chinook & steelhead (drought)

Bristol Bay sockeye ocean age 3 adults extremely small body size
Alaska pinks: lowest returns in memory

Unusual salmon observations in 2016

Fraser sockeye lowest on record

High chum returns WA & OR coasts, Columbia

Fraser chum highest in 20 years
Bristol Bay sockeye: top 5 runs since 1952
59.5 million

Fraser sockeye:
2nd lowest in last 70 years

Lowest steelhead returns on record to OR Coast

Fishery closures for Chinook from CA to BC

Highest chum harvest ever in Alaska

Fraser and PS pinks: lowest run in decades

Unusual salmon observations in 2017
Impacts of climate change on fisheries and aquaculture

Coastal sites where nutrients have caused $O_2$ declines <2 mg l$^{-1}$

Median change in surface pH from 1850 – 2100 = 0.2-0.3
Species on the west coast have highest projected magnitude shift in distribution: >1000 km

- Extreme events more frequent
- Warming waters
- Ocean acidification
- Low dissolved oxygen
- Spatial and temporal shifts

Holsman et al. 2018; Morley et al. 2018
Impacts of ocean acidification on marine fish

- Increased fish-killing harmful algae
- Direct effects:
  - behavioral disruption
  - increased boldness?
- Indirect effects:
  - shell-forming zooplankton
  - fecundity


*Heterosigma akashiwo* bloom in northern Puget Sound
(Photo: V. Trainer)
June 2007 – 2016
Minimum Oxygen

Low DO (<1.4 ml l⁻¹) related to climate events

Decreased solubility + increased stratification = reduced subsurface ventilation

C. Morgan, OSU
Restricted range of common demersal fish

- Synergistic effects from changes in temperature, ocean acidification and reduced DO
- Flatfishes, roundfishes, and shelf rockfishes will move away from areas with severe hypoxia

Keller et al. 2017
Impacts of declining DO on marine fish

- Increased mortality
- Physiological impairment
- Displacement out of hypoxic waters
- Habitat compression
- Altered predator-prey relationships
- Changes in foraging dynamics

Keller et al. 2017
Bioenergetics Model:

\[ C = (R + A + S) + (F + U) + (\Delta B) \]
Optimal DO and temperature range for salmon growth

<table>
<thead>
<tr>
<th>Level of Effect</th>
<th>DO (mg l⁻¹)</th>
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Optimal Range: 9 – 16 °C

Carter 2005; Beauchamp 2009
Physiological Studies

- Preferred range: 12 - 15° C
- Physiological Stress: >16 – 18° C
- Lethal Temperature: >21 - 28° C

Enhanced CO₂ and Hypoxia

- Thermal tolerance is narrowed
- Metabolic scope reduced

Pörtner et al. 2005
Increased anchovy abundance in Puget Sound 2014-2016

- Surveys conducted by WDFW in 2016
- Anchovy present in all major basins
- Largest catches in South Sound in Oct/Dec
- Larval/post-larval catches in Skagit Bay
- Benefits resident salmon

Duguid et al. 2018
Reports of mass die-offs:

South Sound:
- Case Inlet
- Carr Inlet

Central Sound:
- Elliott Bay
- Eagle Harbor
  - Southern Hood Canal
  - Whidbey Basin
  - Padilla Bay
  - Discovery Bay
  - Bellingham Bay

D. Lowry, WDFW
Causes of mass die-offs

- Warm water and/or low DO
- Shallow bays
- Summer
- Large tidal exchanges
- No indication of Viral Hemorrhagic Septicemia (VHS)
- Herding behavior by marine mammals
Summary

• Puget Sound is part of the larger Salish Sea and impacted by physical and biological interactions occurring at larger scales
• Reduced DO must be considered along with synergistic effects of increased temperature and ocean acidification
• Climate change impacts impacting the physiology (aerobic capacity, metabolism, etc.) and behavior of marine fish will also affect phenology (timing), spatial range, and ecological interactions (predator-prey interactions)
• Require better understanding of capacity for species to adapt
Acknowledgements

**WDFW**
- Dayv Lowry
- Todd Sandell
- Lisa Hillier

**OSU**
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- Jessica Miller
- Jen Fisher

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- Brian Burke