Long-term ecological change and associated environmental forcings in critical freshwater habitat for Okanagan Basin Sockeye Salmon (*O. nerka*)

A comparative paleolimnological study of Wenatchee Lake, WA, USA & Osoyoos & Skaha lakes, BC Canada

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North American Sockeye Salmon Status
Paleolimnology:

The reconstruction of lake and river histories using the physical, chemical, and biological information stored in lake sediments

- Provides valuable information on environmental change in lakes, their watersheds, and the atmosphere
- Critical data used to address major environmental issues (i.e. acid rain, eutrophication, climate change)
Paleolimnology:

Reconstructing lake and environmental histories from sediment archives

- Monitoring
- Paleolimnology
- Hours
- Days
- Seasons
- Years
- Decades
- Centuries
- Millennia
Our Objectives

- Reconstruct the trophic ecology of Okanagan and Wenatchee Sockeye nursery ecosystems over the past ~150 years
- Attempt to identify major drivers of ecological change influential to nursery lake productive capacities
- Assess relative sensitivities of nursery ecosystems to ongoing and future drivers
Our Approach

• **Radiometric Dating** \(^{210}\text{Pb}, \, ^{137}\text{Cs}\)

• **Sediment Geochemistry**
  - Sediment elemental chemistry (C/\(N_{\text{molar}}\))
  - Sediment stable isotope ratios (\(\delta^{15}\text{N}, \, \delta^{13}\text{C}\))

• **Lake Trophic Reconstructions**
  - **Primary Production**
    - Fossil algal pigments
    - NIRS chlorophyll \(a\)
    - Diatom microfossils
  - **Secondary Production**
    - Cladoceran zooplankton sub-fossils
    - Chironomid larvae

• **Quantitative Inference of Key Limnological Parameters**
  - Total Phosphorus (diatoms)
  - Dissolved Oxygen (chironomids)
Lake Wenatchee, WA
Algal Production & Nutrients

Algal Pigments

<table>
<thead>
<tr>
<th>Year</th>
<th>Alloanthin (Cryptophytes)</th>
<th>Fucoxanthin (Diatoms, Chrysophytes, Dinophytes)</th>
<th>Zeaxanthin (Cyanobacteria)</th>
<th>Chlorophyll a (All Algae)</th>
<th>Chlorophyll a - VRS</th>
<th>Diatom-Inferred Total Phosphorus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1850</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
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<td>2010</td>
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<td></td>
</tr>
</tbody>
</table>

Approx. Onset of Nutrient Enrichment

Oligotrophic  Mesotrophic
Wenatchee Lake, WA
Secondary Production

Planktonic Cladocera
Benthic Cladocera

Bosmina spp
Daphnia longispina
Daphnia pulex
Alona affinis
Alona quadranularis
Chydorus brevilabris
Zooplankton Fluxes
Bosmina Mucro Length
Diatom-Inferred
Total Phosphorus
Chlorophyll a - VRS
Salmon Escapement

Zooplankton Relative Abundance (%)
(#/cm²/yr)
(µm)
(µg/L TP)
(mg/g dry sed)
(# adults)
Skaha Lake, BC
Algal Production & Nutrients

Algal Pigments

Aloxanthin
(Cryptophytes)

Echininone
(Cyanobacteria)

Lutein
(Cryptophytes)

Chlorophyll a
(All Algae)

Chlorophyll a - VRS

Diatom-Inferred
Total Phosphorus

(Pigments in µg/g organic matter, mg/g dry sediment, and µg/L TP)

(Year)

0 20 40 60 80 100 120

0 20 40

0 240 480 720

0 0.02 0.04 0.06

10 15 20 25


(µg/L TP)

Mesotrophic
Skaha Lake, BC
Algal Production & Nutrients

Algal Pigments

Aloxanthin
(Cryptophytes)

Echininone
(Cyanobacteria)

Lutein
(Chlorophytes)

Chlorophyll a
(All Algae)

Chlorophyll a - VRS

Diatom-Inferred Total Phosphorus

Algal Pigments

(µg/g organic matter) (mg/g dry sediment) (µg/L TP)
Skaha Lake, BC
Algal Production & Nutrients

Algal Pigments

- Aloxanthin
  - (Cryptophytes)
- Echininone
  - (Cyanobacteria)
- Lutein
  - (Chlorophytes)
- Chlorophyll a
  - (All Algae)
- Chlorophyll a - VRS
- Diatom-Inferred Total Phosphorus

Sewage Plant Discharge

Mesotrophic
Skaha Lake, BC
Algal Production & Nutrients

**Algal Pigments**

- **Aloxanthin** (Cryptophytes)
- **Echininone** (Cyanobacteria)
- **Lutein** (Chlorophytes)
- **Chlorophyll a** (All Algae)
- **Chlorophyll a - VRS**
- **Diatom-Inferred Total Phosphorus**

**Sewage Plant Discharge**

**Sewage Plant Rebuild**

**Mesotrophic**
Skaha Lake, BC
Secondary Production
Skaha Lake, BC
Secondary Production

Zooplankton Relative Abundance (%)
D. longispina
D. pulex
C. affinis
C. quadangularis
C. b. brevibasis
Zooplankton Flux
Mucro Length
Diatom-Inferred TP
Chlorophyll a - VRS
Salmon Escapement

Impassable Dam
Osoyoos Lake, BC
North Basin
Algal Production & Nutrients

Algal Pigments

Diatexanthin
(Diatoms, Chrysophytes, Dinophytes)
Echinone
(Cyanobacteria)
Lutein
(Chlorophytes)
Alloxanthin
(Chlorophytes)
Total Chlorophyll
(All Algae)
Diatom-Inferred
Total Phosphorus

Cumming et al. 2015
Osoyoos Lake, BC
North Basin
Algal Production
& Nutrients

Cumming et al. 2015
Osoyoos Lake, BC
South Basin
Algal Production & Nutrients

Algal Pigments

Diatom Pigments
(Diatoms, Chrysophytes, Dinophytes)

Echinonone
(Cyanobacteria)

Lutein
(Chlorophytes)

Alloxanthin
(Cryptophytes)

Total Chlorophyll
(All Algae)

Diatom-Inferred Total Phosphorus

Cumming et al. 2015
Osoyoos Lake, BC
North Basin
Secondary Production

Planktonic Cladocera
Benthic Cladocera

Zooplankton Relative Abundance (%)
(#/cm²/yr) (µm) (µg/L TP) (# adults)

Bosmina spp
Daphnia longispina
Eury cercus spp
Camptocercus spp
Kurzia latissima
Alona affinis
Alona quadrangularis
Alona excisa
Chydrorus breviblasis
Sida crystallina americana
Zooplankton Flux
Bosmina Micro Length
Diatom-Inferred TP
Total Chlorophyll
Salmon Escapement
Osoyoos Lake, BC
North Basin
Secondary Production
Osoyoos Lake, BC
North Basin
Secondary Production

Planktonic Cladocera
Benthic Cladocera

Bosmina spp
daphnia longispina
eury cercus spp
Camptocercus spp
kurzia latissima
Alona affinis
Alona quadrangularis
Alonella excisa
Chydorus brevilabris
sida crystallina americana
zooplankton flux
Bosmina micro length
Diatom Inferred TP
Total Chlorophyll
Salmon Escapement

Zosel Dam (poor passage)
Osoyoos Lake, BC
Chironomid-Inferred Hypolimnetic Oxygen

Simmatis et al. *in review*
Chironomid-Inferred Volume Weighted Hypolimnetic Oxygen (mg/L)

North Basin
South Basin
Salmonid Hypoxic Threshold

Ruggerone 2000

Simmatis et al. in review
Mean monthly global temperature anomalies relative to the 1961-1990 period

Brohan et al. 2006; J. Geophys. Res. 111: D12106
Figure 1  Changes in climate forcing affect the physical environment of lake ecosystems and thereby alter their chemical and biological properties. These changes affect the capacity of lakes to provide ecosystem services. P/E, precipitation to evaporation ratio. Dotted lines indicate positive feedback effects, e.g., via decreased ice cover or the release of greenhouse gases from lakes into the atmosphere.
Internal Nutrient Loading

- **Internal Loading**
  - Release of limiting nutrients from sediment stores (phosphorus (P), ammonia (N))

- **Causes**
  - Oxygen loss at the sediment-water interface
  - Aerobic microbial decomposition of organic matter (e.g. dead algae, plants, animals)

- **Implications**
  - Release of “stored” nutrients from sediments
  - Increased algal and plant growth (first modest, then rapid)
  - Potential for positive feedback/runaway eutrophication
  - Changes to lake ecosystem structure & functioning
# Summary of Climate Change for Thompson / Okanagan in the 2080s

<table>
<thead>
<tr>
<th>Climate Variable</th>
<th>Season</th>
<th>Projected Change from 1961-1990 Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ensemble Median</td>
</tr>
<tr>
<td>Mean Temperature (°C)</td>
<td>Annual</td>
<td>+2.7 °C</td>
</tr>
<tr>
<td>Precipitation (%)</td>
<td>Annual</td>
<td>+8%</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>-10%</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>+11%</td>
</tr>
<tr>
<td>Snowfall* (%)</td>
<td>Winter</td>
<td>-16%</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>-74%</td>
</tr>
<tr>
<td>Growing Degree Days* (degree days)</td>
<td>Annual</td>
<td>+511 degree days</td>
</tr>
<tr>
<td>Heating Degree Days* (degree days)</td>
<td>Annual</td>
<td>-975 degree days</td>
</tr>
<tr>
<td>Frost-Free Days* (days)</td>
<td>Annual</td>
<td>+36 days</td>
</tr>
</tbody>
</table>

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**Temperature** *(Annual)*

**Precipitation** *(Annual)*

**Snowpack** *(Annual)*
SUMMARY

• Okanagan & Wenatchee Basins
  ▪ Broad-scale & diverse FW habitat changes

• Wenatchee Lake
  ▪ Minor lake enrichment
  ▪ Remains oligotrophic

• Osoyoos & Skaha Lakes
  ▪ Cultural eutrophication history
  ▪ New lake “state” induced by eutrophication
  ▪ Likely magnification of eutrophication symptoms by climate change

• Climate Change Futures
  ▪ Winners and losers
  ▪ Osoyoos - Internal loading, hypolimnetic oxygen, surface temps.
Acknowledgements

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Chelan County Public District
Natural Sciences & Engineering Research Council
Okanagan Nation Alliance
Columbia River Intertribal Fish Commission
Fisheries and Oceans Canada

Photo courtesy of N. Fobes
Extra Slides
Jensen et al. 2012; Simmatis et al. *in review*
<table>
<thead>
<tr>
<th>Pigment</th>
<th>Source $^1$</th>
<th>Stability</th>
<th>Affinity</th>
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</thead>
<tbody>
<tr>
<td>$\beta, \beta$-carotene</td>
<td>P,L,t</td>
<td>1</td>
<td><em>Plantae, Algae</em>, some phototrophic bacteria</td>
</tr>
<tr>
<td>$\beta, \alpha$-carotene</td>
<td>P,I</td>
<td>1</td>
<td>Cryptophyta, Chrysophyta, Dinophyta, some Chlorophyta</td>
</tr>
<tr>
<td>$\beta$-isorenieratene $^2$</td>
<td>P</td>
<td>1</td>
<td>Chlorobiaceae (green sulphur bacteria)</td>
</tr>
<tr>
<td>isorenieratene $^2$</td>
<td>P</td>
<td>1</td>
<td>Chlorobiaceae (brown varieties)</td>
</tr>
<tr>
<td>alloxanthin</td>
<td>P</td>
<td>1</td>
<td>Cryptophyta</td>
</tr>
<tr>
<td>fucoxanthin</td>
<td>P,L</td>
<td>2</td>
<td>Dinophyta$^3$, Bacillariophyta, Chrysophyta</td>
</tr>
<tr>
<td>diatoxanthin</td>
<td>P,L,s$^4$</td>
<td>2</td>
<td>Bacillariophyta, Dinophyta, Chrysophyta</td>
</tr>
<tr>
<td>diadinoxanthin</td>
<td>P,L,s$^4$</td>
<td>3</td>
<td>Dinophyta, Bacillariophyta, Chrysophyta, Cryptophyta</td>
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<tr>
<td>dinoxanthin</td>
<td>P</td>
<td>-</td>
<td>Dinophyta</td>
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<tr>
<td>peridinin</td>
<td>P</td>
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<tr>
<td>echinenone</td>
<td>P,I</td>
<td>1</td>
<td>Cyanobacteria</td>
</tr>
<tr>
<td>zeaxanthin</td>
<td>P,I</td>
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<td>Cyanobacteria</td>
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<td>canthaxanthin</td>
<td>P,I</td>
<td>1</td>
<td>colonial Cyanobacteria, herbivore tissues</td>
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<tr>
<td>myxoxanthophyll</td>
<td>P,I</td>
<td>2</td>
<td>colonial Cyanobacteria</td>
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<td>scytonemin$^5$</td>
<td>p,L</td>
<td>-</td>
<td>colonial Cyanobacteria</td>
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<td>oscilaxanthin</td>
<td>P,I</td>
<td>2</td>
<td>Cyanobacteria (Oscillatoriaceae)</td>
</tr>
<tr>
<td>aphanizophyll$^6$</td>
<td>P,I</td>
<td>2</td>
<td>N$_2$-fixing Cyanobacteria (Nostocales)</td>
</tr>
<tr>
<td>lutein</td>
<td>P,L,t</td>
<td>1</td>
<td>Chlorophyta, Euglenophyta, Plantae</td>
</tr>
<tr>
<td>neoxanthin</td>
<td>1</td>
<td>4</td>
<td>Chlorophyta, Euglenophyta, Plantae</td>
</tr>
<tr>
<td>violaxanthin</td>
<td>1</td>
<td>4</td>
<td>Chlorophyta, Euglenophyta, Plantae</td>
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<tr>
<td>okenone$^2$</td>
<td>P</td>
<td>1</td>
<td>purple sulphur bacteria</td>
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<tr>
<td>astaxanthin</td>
<td>P,I</td>
<td>4</td>
<td>invertebrates, N-limited Chlorophyta</td>
</tr>
<tr>
<td>chlorophyll $a$</td>
<td>P,L</td>
<td>3</td>
<td><em>Plantae, Algae</em></td>
</tr>
<tr>
<td>chlorophyll $b$</td>
<td>P,L</td>
<td>2</td>
<td>*Plantae, Chlorophyta, Euglenophyta</td>
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<td>pheophytin $a$</td>
<td>P,L,t,s</td>
<td>1</td>
<td>Chl $a$ derivative (general)</td>
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<tr>
<td>pheophytin $b$</td>
<td>P,L,t,s</td>
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<td>Chl $b$ derivative (general)</td>
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<tr>
<td>pheophorbide $a$</td>
<td>P,I,s</td>
<td>3</td>
<td>Chl $a$ derivative (grazing, senescent diatoms)</td>
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<tr>
<td>pyro-pheo(pigments)</td>
<td>L, S$^{**}$</td>
<td>2</td>
<td>derivatives of $a$ and $b$-phorbins</td>
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<tr>
<td>Chl $c$</td>
<td>P,I</td>
<td>4</td>
<td>Dinophyta, Bacillariophyta, Chrysophyta</td>
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