Applying Food Web Models to Fisheries Management

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Biotic Interactions are Essential Elements of Aquatic Habitats

• Physical habitat and water quality define the “potential” for supporting & sustaining species
• That potential will be realized or undermined by biotic processes:
  – Seasonal Food Supply & Access
  – Competition
  – Predation
• Habitat Conservation and Restoration Strategies need to consider food web processes explicitly
Quantifying Trophic Linkages. Interaction Strength may vary among seasons or between life stages

Lake Washington Food Web
Characteristics of Large Western Lakes

• Food web processes very dynamic in Time & Space
  – Prey availability varies spatially and temporally over diel & seasonal cycles
  – Highly mobile consumers move vertically & laterally to feed & satisfy other ecological needs
  – Predator-Prey Size relationships & life stage-specific processes are important

• Non-native Species usurp key ecological roles as: top predators, competitors, prey:
  – Lake trout, Mysids, Kokanee, Brook & Brown trout
  – Bass, Walleye, Shad, Sunfishes, Crayfish
Seasonal Food Web Linkages - Bear Lake Idaho-Utah

**SPRING**
- Terrestrial insects
- Cladocera
- Copepods
- Ephemeroptera
- Chironomus larvae
- Molluscs
- Gastropods
- Cladocerans
- Copepods
- Terrestrial insects

**SUMMER**
- Non-native Lake trout

**FALL**
- Juvenile cutthroat

**WINTER**
- Lake trout
Key Questions

• What processes regulate production and distribution of key species in an aquatic community?
  – Mortality? Predation, Starvation, Disease
  – Growth? Food supply & access, competition
  – Environmental stressors? Temp, O₂, Contaminants

• How do human & natural disturbances disrupt trophic structure & energy pathways?
  – Species invasions/introductions
  – Climate change
  – Land-water use & management
Conceptual Approach

• Identify & Quantify key interactions within a Temporal-Spatial and Ontogenetic framework
• Mechanistically link individual behavior & physiology to structure & function of the ecosystem
• Employ a combination of modeling & directed sampling + the rare experiment
Tools

• Modeling (tightly linked to empirical data)
  – Bioenergetics: Link physiological response of consumers to their [changing] environment
  – Foraging (visual foraging, functional response)
  – Population dynamics

• Field sampling & Analysis to feed the models
  – Temporal-Spatial Distribution
  – Abundance (relative or absolute)
  – Size structure, age & growth
  – Diet, Stable Isotopes, Calorimetry
Bioenergetics Models are useful Ecological Diagnostic Tools

- Quantify trophic linkages & account for variation in diet composition, temperature, & prey quality
- Identify potential ecological bottlenecks through time or space: **Predation, Food Supply, Competition, Thermal regime**
- Model utilizes routine sampling data:
  - diet, growth, distribution, temperature
- Conceptual framework for integrating data, identifying priorities, & managing uncertainty
Bioenergetics Model: An Energy Balance Equation

- **INPUT = OUTPUT**
  - Consumption must balance costs plus Growth
- **Consumption = Waste + Metabolism + Growth**
Temperature-Dependent Energy Budget

Sockeye salmon functions

- Unlimited food
- C_{\text{max}}
- C_{\text{max}} - Waste
- Lower Ration
- Reduce Growth
- Growth
- Increase activity
- Resp. + SDA

Temperature (°C) vs. Rates (g/(g*d))

Temperature Range: 0 to 25°C

Rates Range: 0.00 to 0.25 g/(g*d)
As Ration Declines, Optimal Temperature for Growth Declines

10g Kokanee Prey = 2800 J/g

Thermal tolerance

Temperature

Growth g/(g*d)

100% $C_{max}$

50% $C_{max}$

20% $C_{max}$
Modeling Process

- Diet Composition
- Consumer Growth
- Predator Energy Density
- Prey Energy Density
- Thermal Experience

Bioenergetics Model

\[ C = M + W + G \]

How much food must be \textbf{Consumed} to satisfy observed \textbf{Growth}? or How much \textbf{Growth} given \textbf{Consumption}?

Daily time step

Consumption Estimate
Some Model Applications

• Seasonal Carrying Capacity
• Competition
• Predation Mortality
• Spatial-temporal Growth Potential
• Comparing Net Energetic Benefit among Different Habitats (restoration priority?)
• Effects of Species Introductions
• Effects of Climate Change
• Contaminant Bioaccumulation
• Nutrient Recycling
Lake Washington Applications

• Sockeye hatchery & winter carrying capacity
• Is Predation a serious source of mortality for juvenile salmon in the lake?
  – Sockeye salmon rear in lake for a year
  – ESA-listed Chinook salmon rear/migrate for 1-5 months in lake
• If so, which predators are most important?
  – Species, size, age
  – When is predation most severe?
  – Where does predation occur?
  – What factors alter predation?
Lake Washington Food Web

- **Pelagic community**

- Dotted lines represent unknown interactions
- Width of arrow represents strength of interaction

### Key Species
- **Zooplankton**
- **Peamouth**
- **Juv. chinook**
- **Sucker**
- **Juv. coho**
- **Neomysis**
- **Sockeye**
- **Smelt**
- **Pikeeminnow**
- **Sculpin**
- **Chironomid**
- **Stickleback**
- **Cutthroat**
- **Bass**
- **Scrip**

### Food Web
- Zooplankton feeds on chironomid and peamouth.
- Peamouth preys on chironomid and suckers.
- Juv. chinook feeds on neomysis and smelt.
- Smelt preys on neomysis and peamouth.
- Sockeye preys on smelt and suckers.
- Pikeeminnow preys on suckers and peamouth.
- Sculpin preys on suckers.
- Bass preys on suckers and peamouth.
- Chironomid preys on zooplankton and peamouth.
Early Feeding Demand and Food Supply of Sockeye Salmon Fry

Dave Beauchamp, Chris Sergeant, Mike Mazur
• USGS-WA. Coop. Fish & Wildlife Res. Unit, UW-School of Aquatic & Fisheries Sciences

Kurt Fresh & Dave Seiler
• WDFW

Jenn & Mark Scheuerell, Daniel Schindler, Tom Quinn
• UW- School Aquatic & Fish. Sci.

Funded by Seattle Public Utilities & King County
Sockeye fry migrate from Cedar River to lake during Feb-Apr when food supply is low.

If fry remained aggregated at south end of the lake, localized food limitation could occur.

Will increased hatchery fry output exceed winter carrying capacity?

Study coincided with highest fry production in history.

Where's the food?

Cedar River

Credit: Mike Mazur
Sockeye fry migrate from Cedar River to lake during Feb-Apr when food supply is low.

Food may be limiting on a localized scale.

Will increased hatchery fry output overshoot winter carrying capacity?

OR-Will fry disperse northward to gain access to a larger pool of zooplankton?

Where's the food?

Cedar River

Credit-Mike Mazur
HYDROACOUSTICS
Measures fish density/abundance:
- For different size classes of fish
- At each depth interval
MIDWATER TRAWLING:
- samples species composition by depth
- provides biological data (size, growth, diet)

Thermocline
Fish caught in Midwater Trawl
Help identify what species are detected by SONAR
Zooplankton Sampling

Depth-stratified sampling:
Day: Zooplankton 153 µm
Night: Mysids 500-1000 µm
Model Scenarios: Monthly Food Supply and Demand by Sockeye Fry

Peak feeding Demand by fry In March-April

Peak Demand was 7-12% of Localized Prey biomass

Demand would Increase to 30% if Fry confined to Area 5 only, 60% if no fry Mortality in lake

Observed Fry Distribution 0-30 m, Areas 3-5
Summary

• Winter food supply sufficient to support the projected increase in fry numbers entering the southern end of the lake projected for the expanded hatchery program.

• Management implication: Sockeye hatchery enhancement would not exceed winter carrying capacity of Lake. A major uncertainty removed.

• Future Monitoring Concerns:
  • Interannual variability in zooplankton
  • Dynamics of other planktivores could still create trophic bottlenecks
  • Climate change, other factors affecting zooplankton production
Quantifying Predation Mortality
Lake Washington Applications

• Sockeye hatchery & winter carrying capacity

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  – When is predation most severe?
  – Where does predation occur?
  – What factors alter predation?
Diet & Stable Isotopes in L. Washington: Cutts & Pikeminnow shift from Benthic Inverts to Pelagic Fish w/ increasing size. Perch shift toward Benthic Fish

![Graphs showing isotopic ratios and fish length]

- **Cutthroat Trout**
- **Northern Pikeminnow**
- **Yellow Perch**

**Axes:**
- **Fork Length (mm)**
- **δ¹⁵N (‰)**
- **δ¹³C (‰)**

**Legend:**
- Benthic
- Pelagic
- More Piscivory

**Proportion Benthic Fish and Invertebrates in Diet**

**Proportion Fish in Diet**
HYDROACOUSTICS
DAYLIGHT DISTRIBUTION
Prey fish schooled, deep, or nearshore

Thermocline
Mesotrophic Waters

Day: Fish are active and swimming in the water column.
Dusk: Fish are less active and swim closer to the bottom of the water column.
Night: Fish are mostly at the bottom of the water column.
Daylight:
-Few fish are in the upper water column during daylight except large and very small fish
-Could be in schools, near bottom or near shore

Dusk
-Smolt-sized targets migrate to upper 20 m at dusk

Night
-Smolt-sized targets fully dispersed in upper 20 m at night
-Net samples confirmed that chinook, sockeye, smelt, sticklebacks & cutthroat composed most of the targets
Prey Availability influenced by cyclic odd-even year class
Fluctuations in longfin smelt abundance
Predator Population
Size Structure, Survival & Growth

L. Washington 2005-06
Cutthroat trout
Ages & Length Freq Modes
Confirmed by aging w/ scales

Survival
Cutthroat trout 2005-2006
Annual S = 33%
$r^2 = 0.997$
$P = 0.001$

Size Structure

Size & Growth

Purse seine 2005-2006
Cutthroat trout
Seasonal Size-structured Predation by a standardized Population of 1,000 predators FL > 150 mm (age-2 & older)

**Smaller Cutts** feed mostly on Inverts, YOY Smelt, Sticklebacks & Larval fish

**Larger Cutts** feed heavily on Fish throughout the year: Sticklebacks Smelt Sockeye Other (Sculpin & Perch) Chinook salmon
Northern Pikeminnow
Seasonal Size-structured Predation by a standardized Population of 1,000 predators FL > 200 mm (age-2 & older)
Smaller Pikeminnow feed mostly on Invertebrates, YOY Smelt & other fish
Larger Pikeminnow feed heavily on fish: Smelt Sticklebacks Sockeye Unid. salmonids Other (Sculpin & Perch)
Predator Size – Prey Size Relationships

All Predators 2005-06
Nearshore & Offshore

Predator Fork Length (mm)

0 100 200 300 400 500 600

Prey Standard Length (mm)

0 20 40 60 80 100 120 140 160 180

Smelt
Sockeye
Stickleback
Chinook
Unid. Salmon
Perch
Sculpin

40% Predator FL

Predator Size – Prey Size Relationships
<table>
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<tr>
<th>Year</th>
<th>Species</th>
<th>2005 Mortality</th>
<th>2006 Mortality</th>
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<td>N. Pikeminnow</td>
<td>0.9% Smelt</td>
<td>0.2% Smelt</td>
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<tr>
<td></td>
<td></td>
<td>1.4% Sockeye</td>
<td>0.2% Sockeye</td>
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<tr>
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<td></td>
<td>0.4% Stickleback</td>
<td>1.9% Stickleback</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0% Chinook</td>
<td>0% Chinook</td>
</tr>
<tr>
<td>Cutthroat trout</td>
<td>0.6% Smelt</td>
<td>0.6% Sockeye</td>
<td>1.6% Stickleback</td>
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<tr>
<td></td>
<td>1.1% Chinook</td>
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<td>2005</td>
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<tr>
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<td>N. Pikeminnow</td>
<td>1.1% Chinook</td>
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<td>2006</td>
<td>Cutthroat trout</td>
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<td>0.1% Sockeye</td>
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<tr>
<td></td>
<td></td>
<td>1.9% Stickleback</td>
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<tr>
<td></td>
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<td>0% Chinook</td>
<td>0% Chinook</td>
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</table>
Predation Summary- Lake Washington

• Predators are capable of regulating populations of juvenile salmon and other forage fish
  – 50k - 100k Cutts plus 50k-100k Pikeminnnow would impose severe mortality on most prey populations
• Cutthroat trout & N. Pikeminnow most piscivorous after reaching 300mm FL
• Both predator species exerted similar predation pressure overall, but at different times and in different habitats
  – Cutts: Nearshore during winter, Pelagic Spr-Fall
    – Sticklebacks, Smelt, Sockeye, Chinook
  – Pikeminnow: Nearshore during Spring-Summer
    – Smelt, Sockeye, Sticklebacks
If Predation Mortality is Important, What can Managers Do?

• Assign loss to correct life stage & source:
  – Spp & size of predator, time, and location
  – Is this a population bottleneck?
  – Can habitat efforts overcome this bottleneck or are “upstream” gains undermined by predation here?

• What factors contribute to predation-Can management actions mediate these effects?
  – Predator/competitor control: regain ecological balance
  – Temperature, water quality modification
  – Shoreline/riparian/upland modification
  – Urban Light pollution
  – Fishing regulations, Non-native species mgt.

• Focus effort directly where, when, how needed
Past-Current Applications

- **Washington**: Puget Sound, L. Washington, Sammamish, Ozette, Chelan, Roosevelt, Skagit River
- **Alaska (SE)**: Margaret & Redoubt L., Prince William Sound-Gulf of Alaska
- **Oregon**: L. Billy Chinook
- **California/NV**: L. Tahoe
- **Idaho**: Sawtooth Valley Lakes, Bear L.
- **Utah**: Strawberry Res, Bear L.
- **Montana**: Flathead L.
- **Wyoming**: Yellowstone L.
Flathead Lake - Non-native Introductions:
Lake trout & *Mysis* effects on kokanee

Diagram:
- Lake trout
- Mysis
- Zooplankton
- Kokanee
Flathead Lake Case Study

- Kokanee crashed in mid-1980s: declined from 500k - 1 million adults to <10k, coincident with invasion of *Mysis relicta*
- Non-native Lake trout populations increased 10-fold during 1980s
- Native Bull trout and Westslope cutthroat declined ~10-fold over same period
- In early 1990s, a 5-yr effort to restore kokanee by stocking 800,000 yearlings (>120 mm) in May-June was producing few adults
Predation by Lake Trout in Flathead Lake 1993-1996 Kokanee Restoration

Smaller L. trout Eat less, but More numerous

Mid-size L. trout 500-750 mm FL Imposed highest Mortality on kokanee
Predator-Prey Size Relationship

Lake trout total length (mm)

Prey total length (mm)

- Kokanee
- Whitefishes
- Suckers
- Sculpin
- Yellow perch
- Unidentified

Prey L = 50% Predator L
Seasonal Mortality of Kokanee from Lake Trout Predation

Cumulative mortality

Seasonal mortality of survivors from previous season

85% Predation Mortality in 1st year

Seasonal Mortality of Kokanee from Lake Trout Predation

% mortality

Spring Summer Autumn Winter

Season

Seasonal Mortality of Kokanee from Lake Trout Predation

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Seasonal Mortality of Kokanee from Lake Trout Predation

% mortality

Spring Summer Autumn Winter

Season
Conclusions

• Lake trout predation removed ~85% of the 800,000 yearling kokanee within the first year, and mostly within the first 4 months after stocking

• Hatchery capacity was too limited to produce large enough numbers or sizes of kokanee to overcome the predation demand

• Sensitivity analyses indicated that lake trout populations needed to be reduced by >90% to enable sufficient survival of kokanee under current hatchery capacity

• Kokanee restoration program was terminated as a result
Post-Kokanee Era in Flathead Lake
Size-Structured Seasonal Consumption by Lake Trout

Population consumption (Kg/Season)

Season

Lake whitefish
Pigmy whitefish
Cutthroat trout
Bull trout
Lake trout
Unid. Salmonid
Yellow perch
Other fish
Mysids
Other invert.

Size classes:
100-200 mm
201-375 mm
376-500 mm
501-625 mm
626-750 mm
751-1000 mm

Size-structured Seasonal Predation Rates by Lake Trout
On Fish Prey only

Population consumption (Kg/Season)

Season

Lake whitefish
Pigmy whitefish
Cutthroat trout
Bull trout
Lake trout
Unid. Salmonid
Yellow perch
Other fish

ESA or Sensitive Spp.
Past-Current Applications

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- **Montana**: Flathead L.
- **Wyoming**: Yellowstone L.
Precipitation, freshwater run-off & wind drive coastal currents, salinity, stratification and circulation patterns

Fig. 2. The mean annual cycle of runoff (circles) and the east-west (along-shore) component of wind speed (squares) estimated from Middleton Island (PAMD) measurements.
2001-2004 Gulf of Alaska
Monthly sampling July-Sept/Oct:
Zooplankton, CTD, Fish Diet, Size, Age

PWS
ACC
TRANS
UAF-UW
Divergent Growth & Survival

Growth declined from late June to early July

Survivors grew faster than average juveniles.

Growth of survivors diverged from avg. juveniles during July-Aug

Growth was faster through August during high-survival years

August = “Critical period?” (e.g., Beamish & Mahnken 2001)

Source: Alison Cross
Survival, Growth, Distribution, Diet & Feeding Rate

**GROWTH:**
Larger juveniles = Higher survival

**DISTRIBUTION:**
Higher survival = Earlier, wider dispersal during Aug-Sep

**DIET:**
Diet highly variable among months & Years. Non-Crustaceans Important.

**FEEDING RATE:**
Higher during High Survival Years...

Suggests higher prey availability
Food webs based on small phytoplankton & crustacean zooplankton are long (Summer production system)

1° production
100%

3 - 5 Trophic Steps

0.03% Energy transfer efficiency

Strom et al.
Food webs with small primary producers and cast net feeders are shortened

Pteropods
--Limacina

Larvacean

100%

Two or Three Trophic Steps

1-2% transfer efficiency of energy from 1° prod

Strom et al.
Seasonal Growth Limitations:
- Spr-Cold, Food
- Sum-Food
- Wtr-Food

Effective energy conversion at different growth rates:
- 5000 J/g at 50% C_max
- 3000 J/g at 25% C_max
- 1000 J/g at 0.2-10 g

Juvenile salmon in freshwater or marine habitats
Immature & Adult Salmon at Sea

- High feeding rate in Summer
  60-100% $C_{\text{max}}$

- Fast growth requires high-quality prey

- Thermal tolerance sensitive to ration & prey quality

- Low ration = Low thermal limits for adults

Add >30% Wt in last month

Homeward migration

Temperature

3500-7000 J/g

2800 J/g
Spawning Migration: Energy Depletion & Survival

River Entry- No Feeding
Metabolic losses continue:
Temperature & Activity

Remaining Energy Needed
On Spawning Grounds
60% at Arrival
-15% Gonad + Activity

Death:
Energy depleted down to
45% Energy at River Entry

[Graph showing energy depletion over days after river entry for different temperatures and swim speeds.]