Individual-based Modeling for Salmonid Management

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Presentation Objectives

• inSTREAM our individual-based trout model
• Advantages of IBMs for modeling fish population response to stressors
• Example applications of our stream trout IBM to management research and decision-making

What is an IBM?

• A model of the environment
  • Models of individual animals
    – The mechanisms by which the environment affects an individual
    – The mechanisms by which individuals interact
    – The behaviors individuals use to adapt to their environment and each other
  • Population responses that emerge from individual behaviors

Why an Individual-based Model?

• IBM’s resolve the two fundamental dilemmas of modeling:
  – Models usually assume many individual organisms can be described by a single variable like population size or biomass. IBM’s provide for individuals and their differences.
  – Most models don’­t distinguish between organisms’ locations. IBM’s provide for distinctive interactions with neighboring individuals and the local environment.

Credits

• Research collaborators:
  – Steve Railsback, Lang, Railsback, and Associates
  – Bret Harvey, USFS Redwood Sciences Lab
  – Software: Steve Jackson, Jackson Scientific Computing

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Advantages of IBMs for Modeling Fish Population Response to Stressors

- Complex, cumulative effects can be simulated:
  - Base flow
  - High and low flows: timing and magnitude
  - Temperature
  - Turbidity
  - Losses of individuals (angler harvest, diversion entrainment)
  - Food production
  - Reproduction, recruitment
  - Species interactions: competition, predation
  - ... 

Advantages of IBMs for Modeling Response to Stressors

- Complex, cumulative effects can be simulated:
  - These complex interactions emerge from individual-level mechanisms
  - instead of having to be foreseen and built into a model
  - you just have to model how stressors affect individuals

Advantages of IBMs

- IBMs are testable in many ways
  - They can produce many kinds of predictions that can be tested with many kinds of data
    - Habitat selection patterns over space, time, flow...
    - Statistical properties of population (size, abundance)
    - Trends in abundance with environmental factors
    - etc.

Advantages of IBMs

- IBMs provide a way out of the complexity - uncertainty dilemma:
  - A well-designed IBM is a collection of simple submodels for separate processes at the individual level
  - Each submodel can be parameterized and tested with all the information available for its process
  - Yet IBMs can simulate complex population level responses

Stream Trout Model

- Habitat is modeled as rectangular cells
- External hydraulic model simulates how depth, velocity vary with flow

Stream Trout Model

- Habitat:
  - Water depths and velocities
  - Temperature, turbidity
  - Food availability
  - Daily time step
- Fish:
  - Habitat selection (choosing the best cell)
  - Feeding and growth
  - Mortality
  - Spawning & incubation
Feeding Model

- Drift feeding strategy
  - Food intake per fish:
    \[ \text{Food concentration} \times \text{velocity} \times \text{capture area} \]
  - Capture area:

Feeding Model

- Food intake varies between drift and search feeding strategies
  - Relative advantages depend on flow, fish size, habitat
- Food intake can be limited by competition (food consumed by bigger fish)
- Each fish picks the feeding strategy offering highest growth
  - Preferred strategy can vary among cells

Growth Model (bioenergetics)

- Growth = Food intake - metabolic costs
  - Metabolic costs:
    - increase with swimming speed
    - increase with temperature

Foraging Model: Growth vs. Velocity, Fish Size, Feeding Strategy

Survival Model

- Survival probabilities:
  - Vary with habitat
  - Depend on fish size, condition
  - Include:
    - Poor condition (starvation)
    - Terrestrial predation
    - Aquatic predation
    - High temperature
    - High velocity (exhaustion)
    - Stranding (low depth)

Survival Model: Overall Risks
Survival Model: Overall Risks

Habitat Selection: Overview

• Habitat selection is critical:
  – Moving is the primary way fish adapt to changing conditions

• Our approach assumes fish use behaviors that evolved to maximize fitness

Habitat Selection Rules

• Move to the cell that offers highest potential “fitness”
  – (within the radius that fish are assumed to be familiar with)


Habitat Selection: Fitness Measure

• Fish move to cell offering highest fitness

• Key elements of fitness are:
  – Future survival
  – Attaining reproductive size

Habitat Selection: Summary

How a Fish Rates A Potential Destination Cell

• Considers:
  – Potential growth in cell (function of habitat, competition)
  – Mortality risks in cell (function of habitat)
  – Its own size and condition

• Probability of surviving for 90 days in the cell?
  – Assuming today’s conditions persist for the 90 days

• How close to reproductive size after 90 d in the cell?
• Rating = Survival probability × fraction of reproductive size

Habitat Selection

• Many realistic behaviors emerge:
  – Normal conditions: territory-like spacing
  – Short-term risk: fish ignore food and avoid the risk
  – Hungry fish take more chances to get food (and often get eaten)
  – Conditions like temperature, food availability, fish density affect habitat choice
The "pattern-oriented" analysis approach:

- Test specific processes of an IBM by whether it reproduces a wide range of behaviors that emerge from the process
- Test a complete IBM by whether it reproduces a wide range of observed population-level patterns


Validation:

- Individual level
- Population level

Validation of Habitat Selection Rules: Six Patterns (a)

- Feeding hierarchies
- Movement to channel margin during high flow
- Juveniles respond to competing species by using less optimal habitat (higher velocities)

Validation of Habitat Selection Rules: Six Patterns (b)

- Juveniles respond to predatory fish by using shallower, faster habitat
- Use of higher velocities in warmer seasons
- Habitat shift in response to reduced food

Expected Reproductive Maturity vs. Habitat Suitability Criteria as Indicators of Habitat Quality

- PHABSIM habitat suitability criteria (HSC)
  - Basis: Empirical
- Expected Reproductive Maturity (EM)
  - Basis: Mechanistic models of feeding, mortality risks, fitness

EM vs. HSC Indicators of Habitat Quality

- HSC
  - Habitat rating varies only with fish life stage:
    - fry, juvenile, adult, spawning
    - (occasionally: season)
- EM
  - Habitat rating varies with:
    - Fish size
    - Fish condition
    - Temperature & season
    - Food availability
    - Cover for hiding, feeding
    - Other factors affecting growth or survival
EM as an Indicator of Habitat Quality

- Adult trout
  - drift feeding
  - using velocity shelter

EM as an Indicator of Habitat Quality:
With vs. Without Velocity Shelters for Drift Feeding

EM as an Indicator of Habitat Quality:
Without vs. With Hiding Cover

EM as an Indicator of Habitat Quality:
15° vs. 5° Temperature

Example Use of IBM for Management Research:
Effect of Habitat Complexity on Population Dynamics

- Observed pattern: When deep pools are eliminated, a lower abundance of large trout results:
  - Bisson & Sedell (1984) observed fewer pools & fewer large trout in clearcuts

- Simulation experiment:
  - Simulate populations over 5 years with, without pool habitat in the model
Effect of Habitat Complexity on Population Dynamics

• Simulation results (1):
  – Abundance of all age classes was lower when pools were removed
  – Impact was greatest on oldest age class
  – Terrestrial predation caused the lower abundance - pools provide shelter from terrestrial predators

Effect of Habitat Complexity on Population Dynamics

• Simulation results (2):
  – Size of age 0 and 1 trout increased when pools were removed - Why??

Example IBM Application: Effects of Instream Flow Magnitude & Variability

• How does the amount and timing of flow affect trout abundance and growth?
• Site: Little Jones Creek (3rd order coastal stream in N. California)
• Scenarios: hypothetical hydropower reservoir
  – Constant flow vs. Natural monthly mean flow
• Simulations: 10 years, 5 replicates per scenario

Example Application: Effects of Turbidity

• How does the amount and timing of flow affect trout abundance and growth?

Example IBM Application: Effects of Instream Flow Magnitude & Variability

• Turbidity decreases feeding ability, but decreases predation risk
  What are the population-level consequences?

• Site: Little Jones Creek
• Five turbidity scenarios:
  – Turbidity = x Q
  – Five values of x: very clear to very turbid streams
Example Application: Effects of Turbidity

- Result: Interactions between turbidity and food availability are strong

Scenario

Number of Age 2+ Fish

12345

0 1 0 2 0 3 0 4 0 5 0

Example Use of IBM for Management Research: Habitat Selection vs. Habitat Quality

- Theory to be tested: The habitat that animals use most often is the best habitat
  - This assumption is the basis for many management models
  - It is widely questioned but very difficult to test in the field
  - "Relations between habitat quality and habitat selection in a virtual trout population." Railsback, S.F., H. B. Stauffer, and B. C. Harvey. (to appear in Ecological Applications.)

Habitat Selection vs. Habitat Quality

- "Habitat Selection" = the observed choice of habitat
- DEN is evaluated as observed animal density

\[ \text{DEN} = \frac{\text{(# animals using a habitat type)}}{\text{(area of habitat type)}} \]

Habitat Selection vs. Habitat Quality

- "Habitat Quality" or Fitness Potential (FP) = the fitness provided to an animal by a habitat type, in the absence of competition
  - “Preference”: the habitat a fish selects in absence of competitors
  - In our IBM:
    - We know the FP of each habitat cell because we programmed it
    - FP varies among habitat cells with water depth, velocity, feeding shelter, hiding shelter

Habitat Selection vs. Habitat Quality

- The experiment:
  - Observe DEN (fish density) in each habitat cell (snapshot)
  - Calculate FP for each cell
  - Examine: How well does DEN predict FP?
    - (What can you learn about the quality of habitat by observing the habitat that animals use?)
  - Three ages of trout examined separately

What Does Habitat Selection Tell You about Habitat Quality?? Not much!

- Cells with high density usually are fairly high quality
- Many high quality cells have zero fish
- There is no predictive relationship between observed fish density and habitat quality
Management Research with the IBM: Why is There So Little Relation Between Habitat Selection and Habitat Quality?

• (1) Competition:
  – Smaller trout don’t use the habitat that is best for them because they are excluded by larger fish

• (2) Unused and unknown habitat:
  – Good habitat for large trout may be vacant because there are not enough trout to use it all
  – Trout may not use the best available habitat because it is too far away to know about

• (3) Cells where food is plentiful but hard to catch can support more fish at lower fitness:
  – Example: Cells with high velocity
  – Each fish can catch less food than optimal
  – Because each fish gets less of the food, more fish can share the cell

• (4) Cells where food is plentiful but mortality risks are high can support more fish at lower fitness:
  – Density is high because there is plenty of food but
  – Fitness is low because mortality risk are high

Habitat Selection vs. Habitat Quality

• Conclusions:
  – Observed patterns of habitat selection by animals tell us little about how good the habitat is
  – But does this mean models based on habitat selection are worthless??

Are There Problems with Models Based on Habitat Selection?

• A second simulation experiment:
  – A good habitat selection model can be a useful predictor of population response over short times
    • When habitat modifications are small
    • And it is a dominant species or life stage
  – BUT:
    • Habitat selection models have fundamental problems
      (mainly: neglecting that habitat selection varies over time)
Conclusions: Key advantages of IBMs for assessing impacts of multiple stressors on fish

• IBMs can be used to address more questions that are difficult to address with other modeling approaches

• IBMs can be more credible than alternatives
  – More testable
  – Able to simulate complex responses to many stressors without high parameter uncertainty

Conclusions: Potential Limitations of IBMs

• Computation: There is a limit to how many fish / how much habitat we can simulate (overcome with bigger computers, clusters?)

• Models for new groups of fish can be expensive to build

• Expertise: Few biologists are familiar with IBMs (or the mechanistic, individual-based view of ecology)

• Acceptance by managers: IBMs are unfamiliar, not as simplistic as alternative approaches

  • We haven’t done anadromy yet (but have put a lot of work into concepts and software)

Conclusions: Our Status

• Continued evolution, application of the trout model
  – Diel shifts in habitat & activity: feeding vs. hiding
  – Sub-daily time steps and fluctuating flows

• Interest in new applications of our salmonid IBMs
  – Instream flow assessment
  – Assessment of restoration activities …
  – Regional stressor-response applications

• Development of new models (juvenile Colorado pikeminnow)

• Development & publication of theory & software

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