Individual-based Modeling for Salmonid Management

Roland H. Lamberson
Humboldt State University

http://math.humboldt.edu/~ecomodel/

1

Credits

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

Funding: EPA STAR Grant

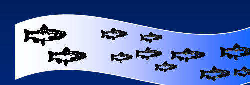
2

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

3

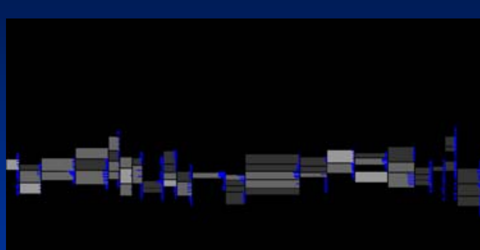
What is an IBM?



- 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

4

What is an IBM? Demo



5

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.

6

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
  - ...

7

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*

8

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.

9

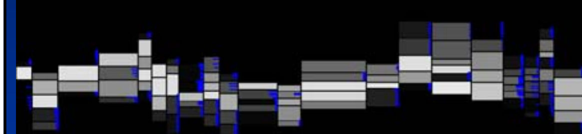
Advantages of IBMs

- 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

10

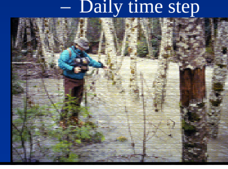
Stream Trout Model

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



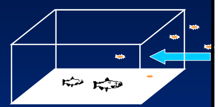
Stream Trout Model

- 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

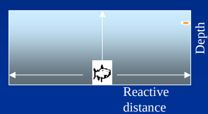
- Drift feeding strategy



  - Food intake per fish:

    Food concentration × velocity × capture area.

Capture area:



13

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

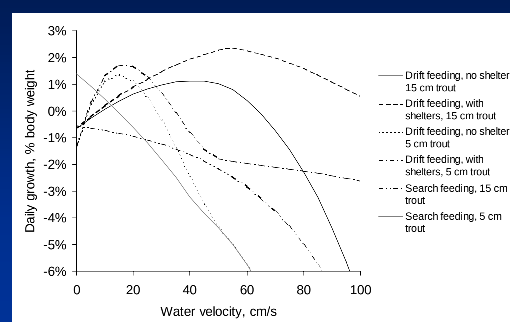
14

Growth Model (bioenergetics)

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

15

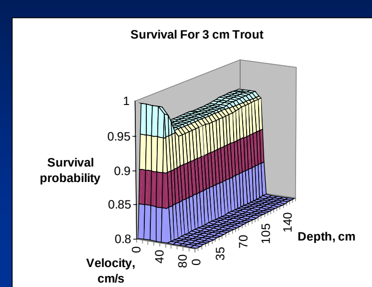
Foraging Model: Growth vs. Velocity, Fish Size, Feeding Strategy



Survival Model

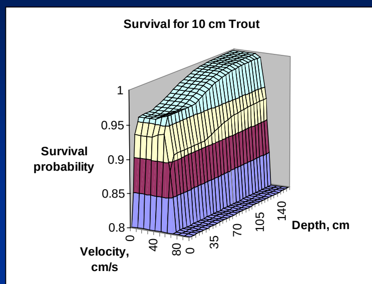
- Survival probabilities:
  - Vary with habitat
  - Depend on fish size, condition
  - Include:
    - Poor condition (starvation)
    - Terrestrial predation
    - Aquatic predation
    - High temperature
    - High velocity (exhaustion)
    - Stranding (low depth)

Survival Model: Overall Risks



18

Survival Model: Overall Risks



19

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

20

Habitat Selection Rules

- Move to the cell that offers highest potential "fitness"
  - (within the radius that fish are assumed to be familiar with)
  - Railsback, S. F., R. H. Lamberson, B. C. Harvey and W. E. Duffy (1999). Movement rules for spatially explicit individual-based models of stream fish. *Ecological Modelling* **123**: 73-89.

21

Habitat Selection: Fitness Measure

- Fish move to cell offering highest fitness
- Key elements of fitness are:
  - Future survival
  - Attaining reproductive size

22

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

23

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

24

Analyzing Individual-based Models

- 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
  - Railsback, S. F. (2001). Getting "results": the pattern-oriented approach to analyzing natural systems with individual-based models. *Natural Resource Modeling* **14**: 465-474.

25

Pattern-Oriented Analysis of inStream

- Validation:
  - Individual level
    - Railsback, S. F. and B. C. Harvey (2002). Analysis of habitat selection rules using an individual-based model. *Ecology* **83**: 1817-1830.
  - Population level
    - Railsback, S. F., B. C. Harvey, R. H. Lamberson, D. E. Lee, N. J. Claasen and S. Yoshihara (2002). Population-level analysis and validation of an individual-based cutthroat trout model. *Natural Resource Modeling* **15**: 83-110.

26

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)

27

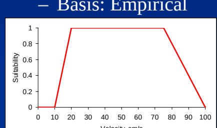
Validation of Habitat Selection Rules: Six Patterns (b)

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

28

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

29

EM vs. HSC Indicators of Habitat Quality

- HSC

  Habitat rating varies only with fish life stage:

  fry, juvenile, adult, spawning

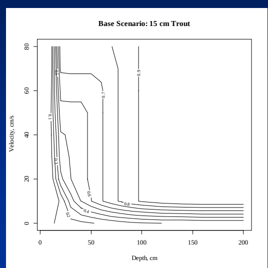
  (occasionally: season)

- EM

  Habitat rating varies with:
  - ↗ Fish size
  - ↗ Fish condition
  - ↗ Temperature & season
  - ↗ Food availability
  - ↗ Cover for hiding, feeding
  - ↗ Other factors affecting growth or survival

30

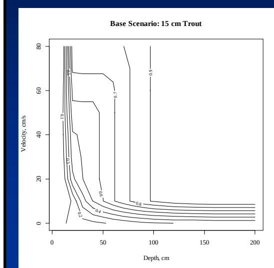
EM as an Indicator of Habitat Quality

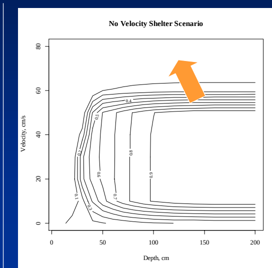


- Adult trout
  - drift feeding
  - using velocity shelter

31

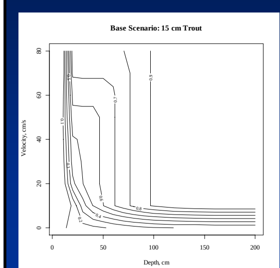
EM as an Indicator of Habitat Quality: With vs. Without Velocity Shelters for Drift Feeding

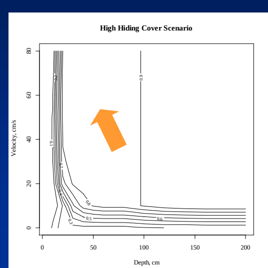




32

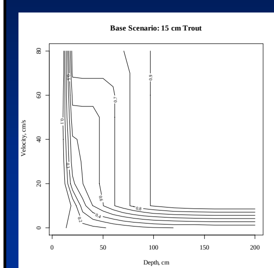
EM as an Indicator of Habitat Quality: Without vs. With Hiding Cover

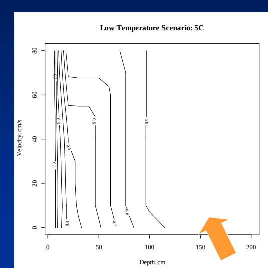




33

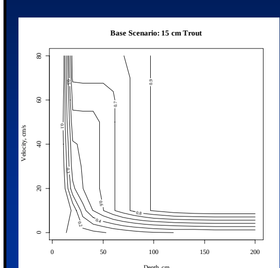
EM as an Indicator of Habitat Quality: 15° vs. 5° Temperature

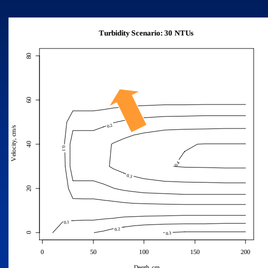




34

EM as an Indicator of Habitat Quality: Low vs. High Turbidity





35

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
  - Railsback, S. F., B. C. Harvey, R. H. Lamberson, D. E. Lee, N. J. Claasen and S. Yoshihara (2002). Population-level analysis and validation of an individual-based cutthroat trout model. *Natural Resource Modeling* **15**: 83-110.

36

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

37

Effect of Habitat Complexity on Population Dynamics

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

38

Effect of Habitat Complexity on Population Dynamics

- Simulation results (2):
  - Size of age 0 and 1 trout *increased* when pools were removed -
    - Abundance decreased, so there was less competition for food
    - Age 1 trout were forced to use faster, shallower habitat where predation risk is higher
      BUT food intake and growth is higher

39

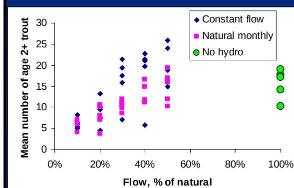
Example IBM Application: Effects of Instream Flow Magnitude & Variability

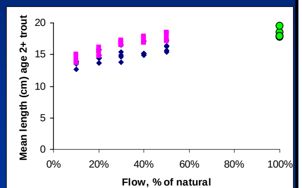
- How does the amount *and timing* of flow affect trout *abundance* and *growth*?
- Site: Little Jones Creek
  (3rd order coastal stream in N. California)
- Scenarios: hypothetical hydropower reservoir
  - Constant flow *vs.* Natural monthly mean flow
- Simulations: 10 years, 5 replicates per scenario

40

Example IBM Application: Effects of Instream Flow Magnitude & Variability

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





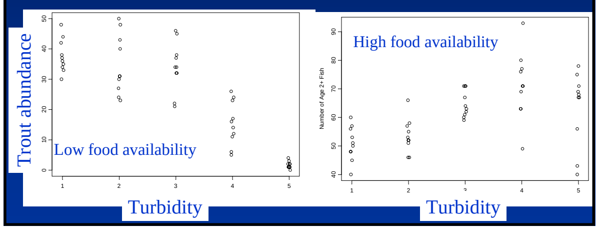
Example Application: Effects of Turbidity

- 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

42

Example Application: Effects of Turbidity

- Result: Interactions between turbidity and food availability are strong



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*.)

44

Habitat Selection vs. Habitat Quality

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

DEN= (# animals using a habitat type) / (area of habitat type)

45

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

46

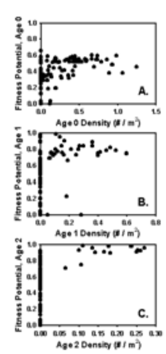
Habitat Selection vs. Habitat Quality

- 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

47

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

49

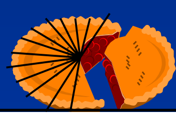
Why is There So Little Relation Between Habitat Selection and Habitat Quality?

- (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

50

Why is There So Little Relation Between Habitat Selection and Habitat Quality?

- (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



51

Why is There So Little Relation Between Habitat Selection and Habitat Quality?

- (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

52

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??

53

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)

54

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

55

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)

56

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

57

Individual-based Modeling for Salmonid Management

Humboldt State University Humboldt Mathematics

http://math.humboldt.edu/~ecomodel/

58