Fifteen years modeling fish population response to river management: Lessons learned and strategies for success

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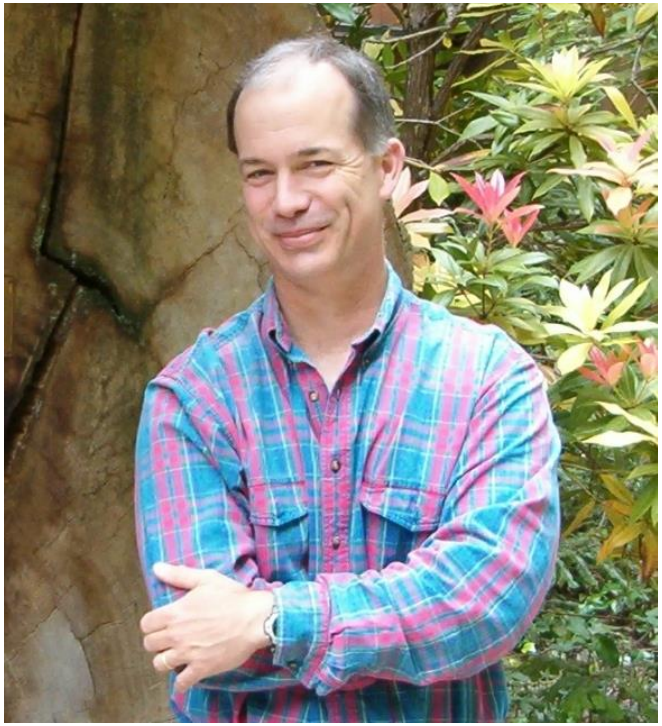
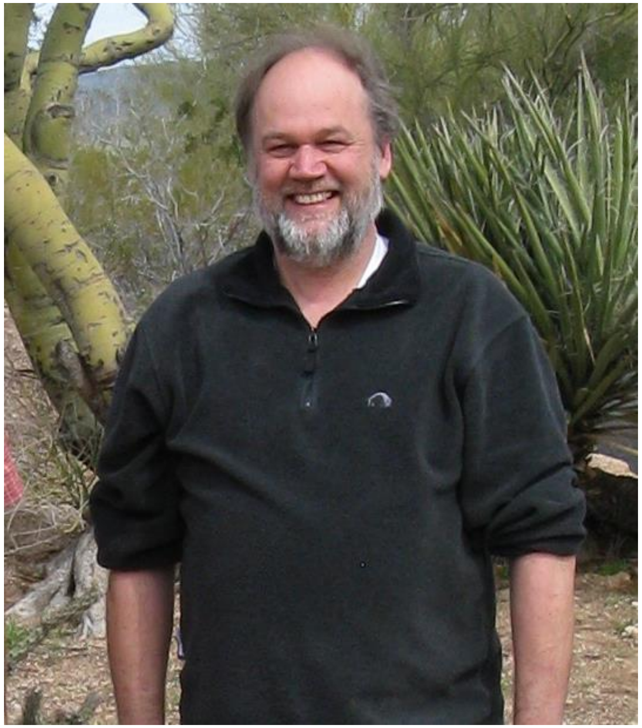
www.humboldt.edu/ecomodel

Acknowledgements





- Bret C. Harvey
  Fish ecologist
  US Forest Service

- Volker Grimm
  Helmholtz Centre for
  Environmental Research
  Leipzig, Germany

Overview

- Why we use individual-based models of trout and salmon
- History of the *inSTREAM* and *inSALMO* models
- Lessons learned about designing and implementing multi-scale models

Our original goal: Predict trout population response to river management

- How do changes in
  - Flow, temperature, and turbidity regimes
  - Channel shape
  - Hiding and feeding cover
  - Stocking, harvest
  - etc.
- affect trout and salmon populations?
- Models are required because experiments are impractical

Conventional methods

- “Habitat selection models”
  - The habitat where you see the most fish must be good habitat,
  - So provide a flow that maximizes this “selected” habitat
- Temperature: Threshold models
  - Temperature < 25° C avoids acute mortality
  - Temperature < 20° C avoids chronic effects

Conventional models do not:

- Consider variation over time
- Integrate cumulative effects of flow, temperature, etc.
- Integrate effects across life stages, species
- Make testable predictions of population response

17 years ago...

Individual-based model of sympatric populations of brown and rainbow trout for instream flow assessment: model description and calibration

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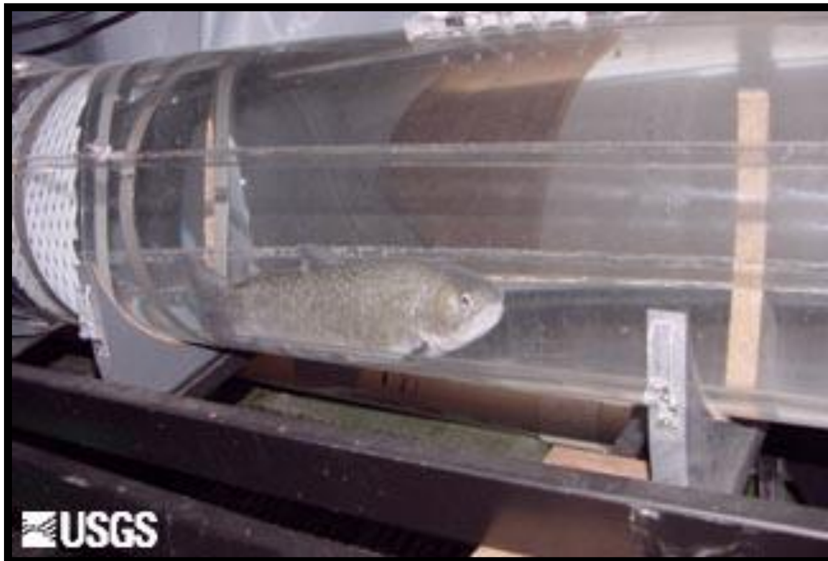
Received 30 July 1997; accepted 18 February 1998

Why Individual-based Models?

- Fish population responses *emerge* from models of individual behavior, growth, survival, reproduction
  - We can model the population if we capture the essential characteristics of individuals & habitat

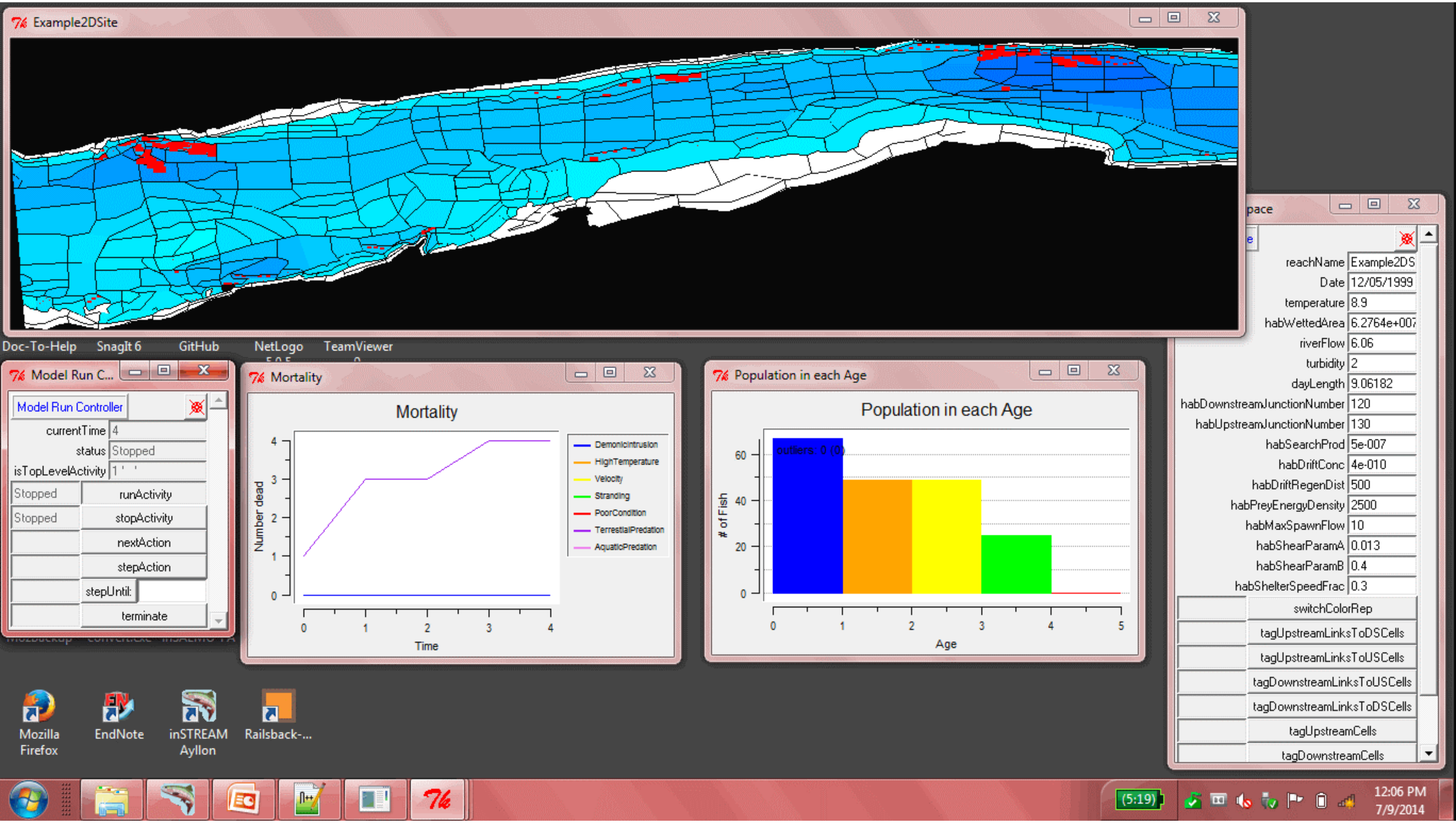


Why Individual-based Models?

- Simulating daily effects of flow, temperature, etc., allows prediction of

  – *cumulative* effects of

  – *dynamic* habitat variables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Model Run Controller
currentTime 4
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nextAction
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Mortality
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HighTemperature
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temperature 8.9
habWettedArea 6.2764e+007
riverFlow 6.06
turbidity 2
dayLength 9.06182
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habUpstreamJunctionNumber 130
habSearchProd 5e-007
habDriftConc 4e-010
habDriftRegenDist 500
habPreyEnergyDensity 2500
habMaxSpawnFlow 10
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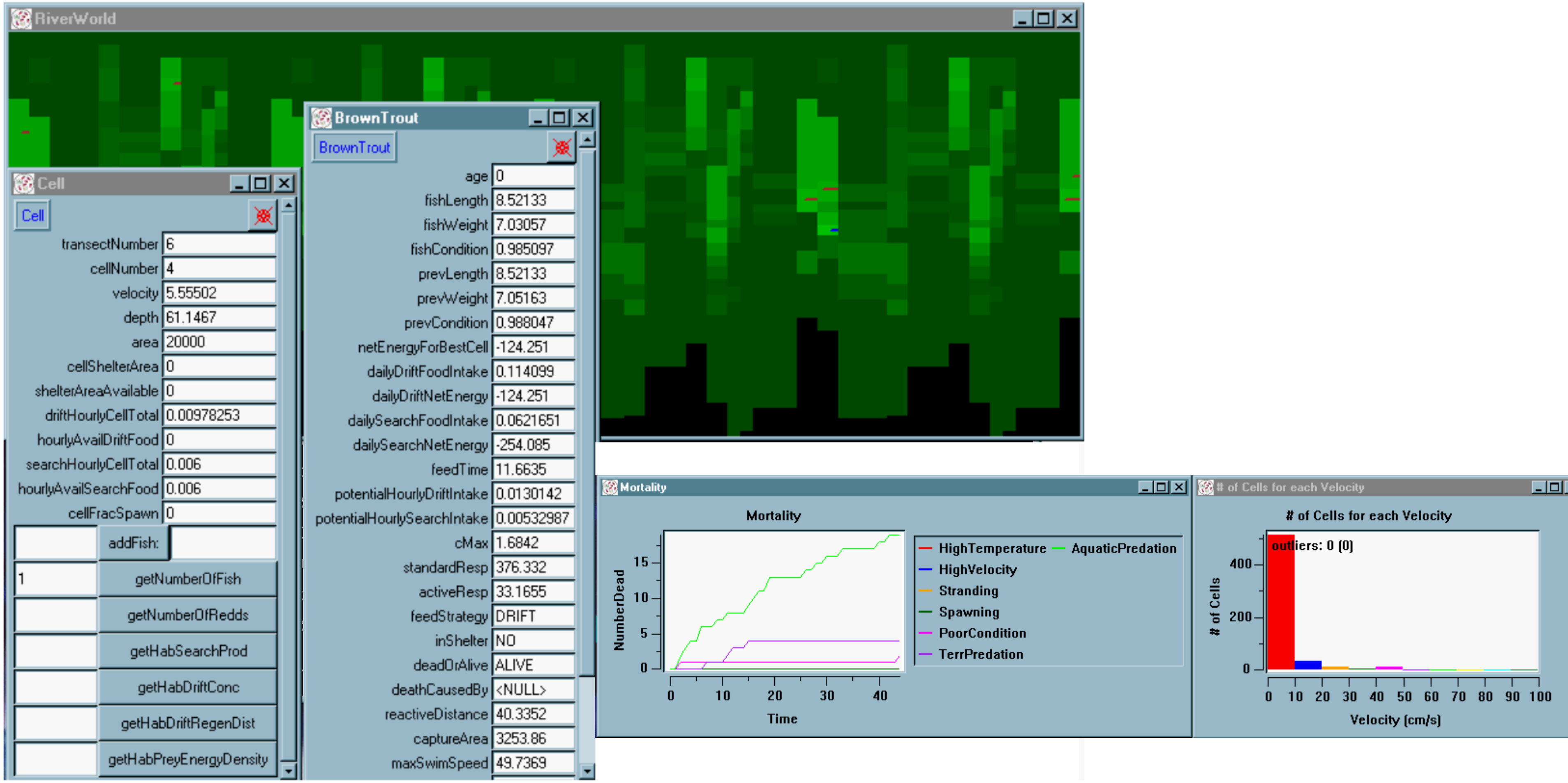
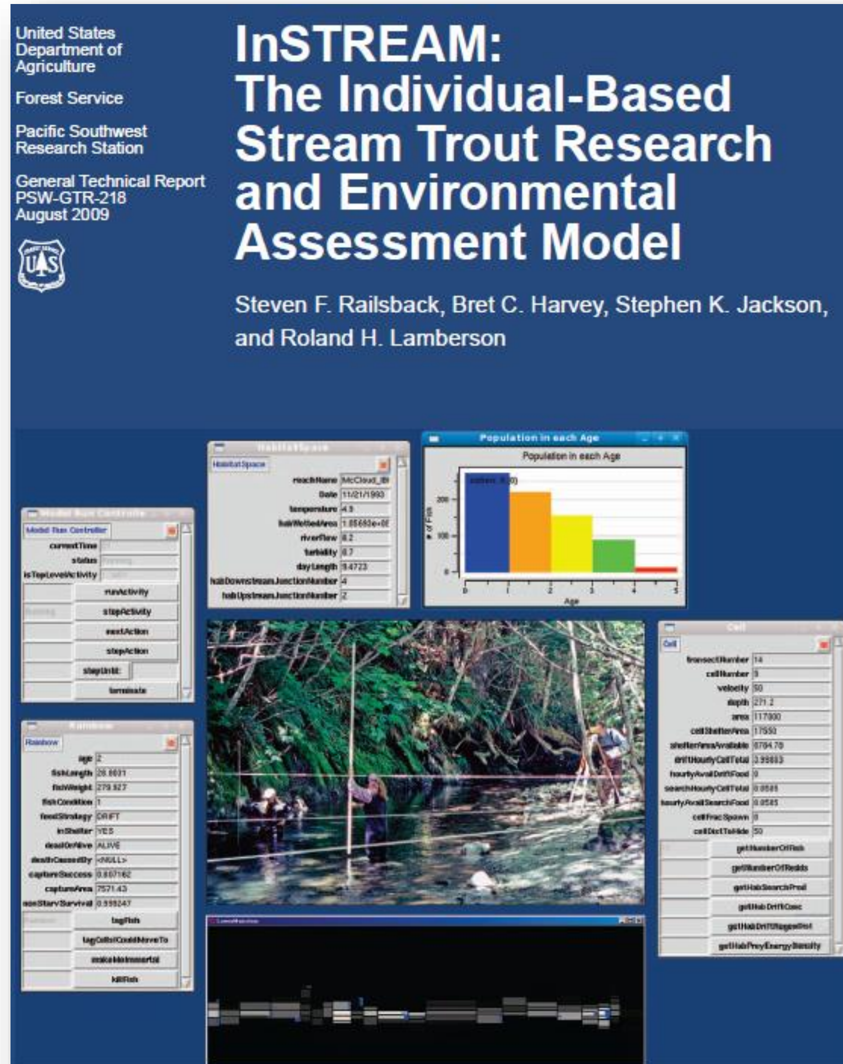
inSTREAM version 1
1999



inSTREAM 4 (2009)

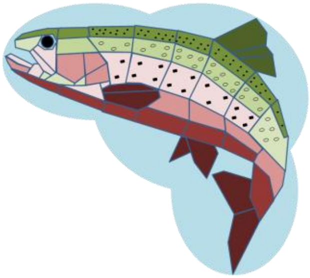
- US EPA grant to release inSTREAM as a public decision-support tool

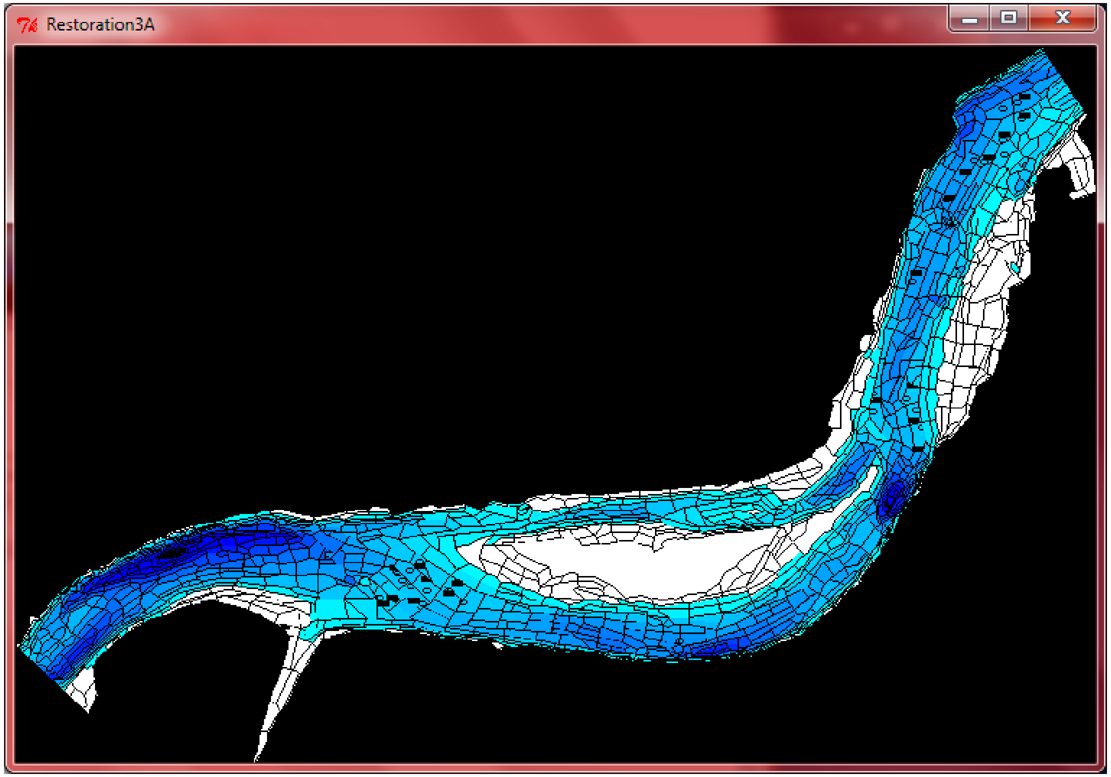


inSTREAM 5.0
Two-dimensional habitat (2013)

- Modern river hydraulic models allow more realistic representation of habitat

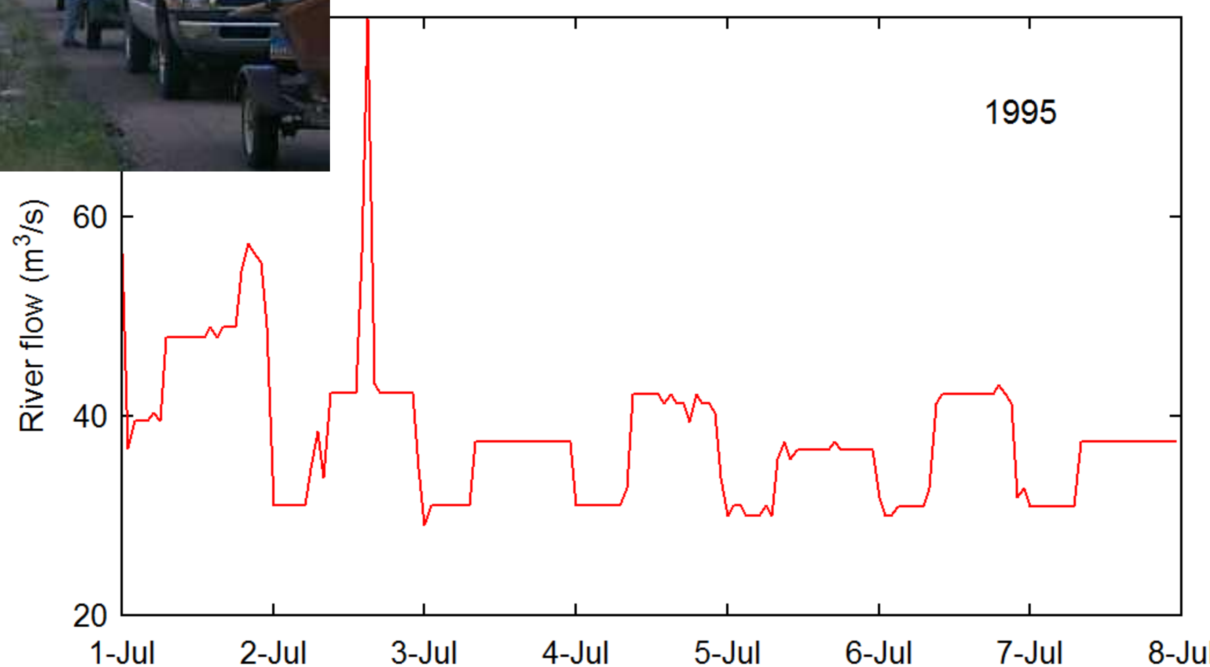
- And:
  – Graphical user interface
  – A logo!



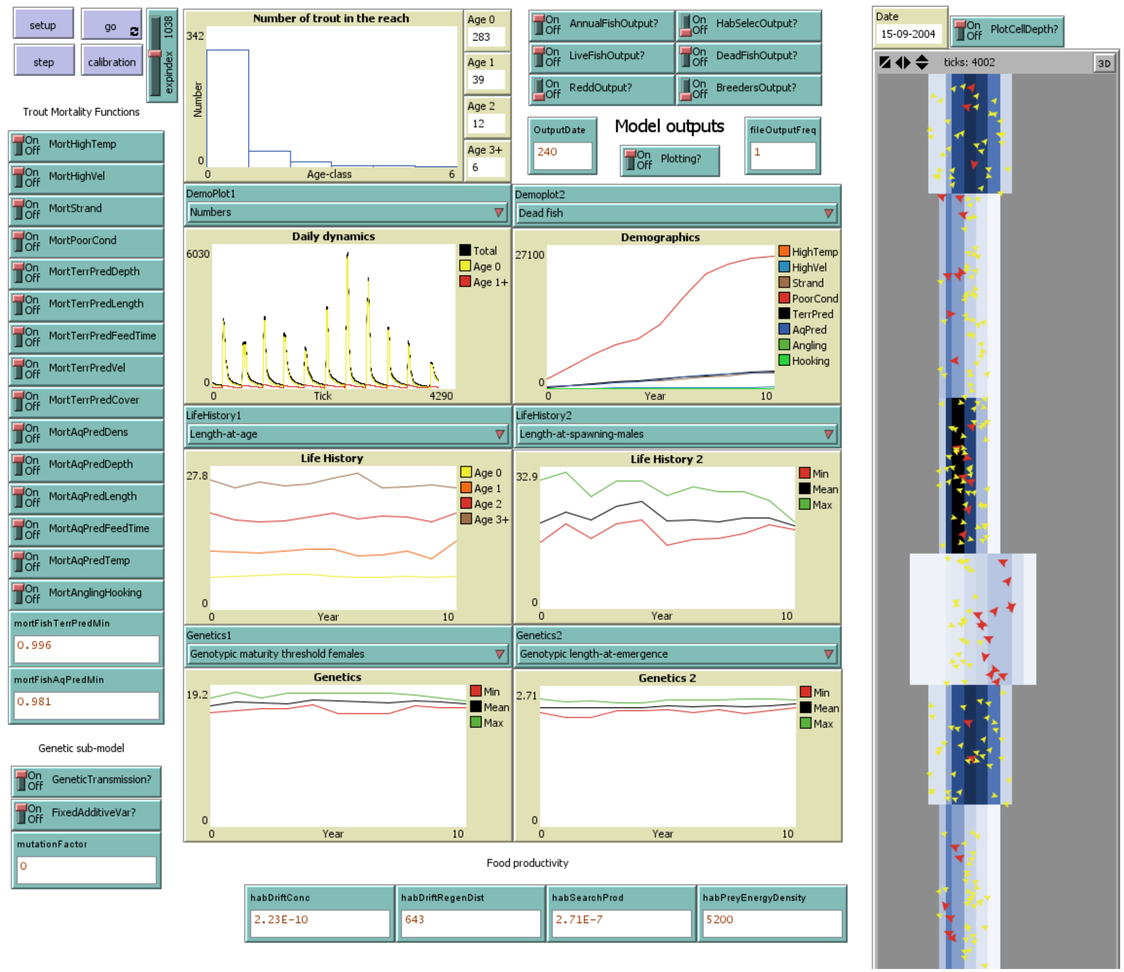


inSTREAM versions 3, 6: Peaking hydropower

- Hourly time step
- Fish decide whether to feed or hide, during day vs. night



2014: inSTREAM in NetLogo, with genetic evolution



- Daniel Ayllón Fernández

inSALMO (2012)

- We spend $$$ restoring salmon habitat...
  – Is it worthwhile?
  – What restoration actions are most effective?

1999-2015

- Eight major versions
- Integrated field & laboratory research program
- ~19 journal articles
- Research and management applications at ~40 sites

inSTREAM and inSALMO are large, complex, uncertain models, but they:

- Make many testable predictions of how trout and salmon populations respond to habitat alteration
- Can address many questions
- Have many indicators of credibility (validation, publications, application record)

- Stimulated much thinking about multi-scale modeling in general

What have we learned?

- The importance of keeping it simple—
  but not *too* simple
  - "Pattern-oriented modeling" to design models
- How to develop theory for agent behaviors
  - Hypothesize and test adaptive traits
- Validation is not so straightforward
- Complex models can produce general understanding

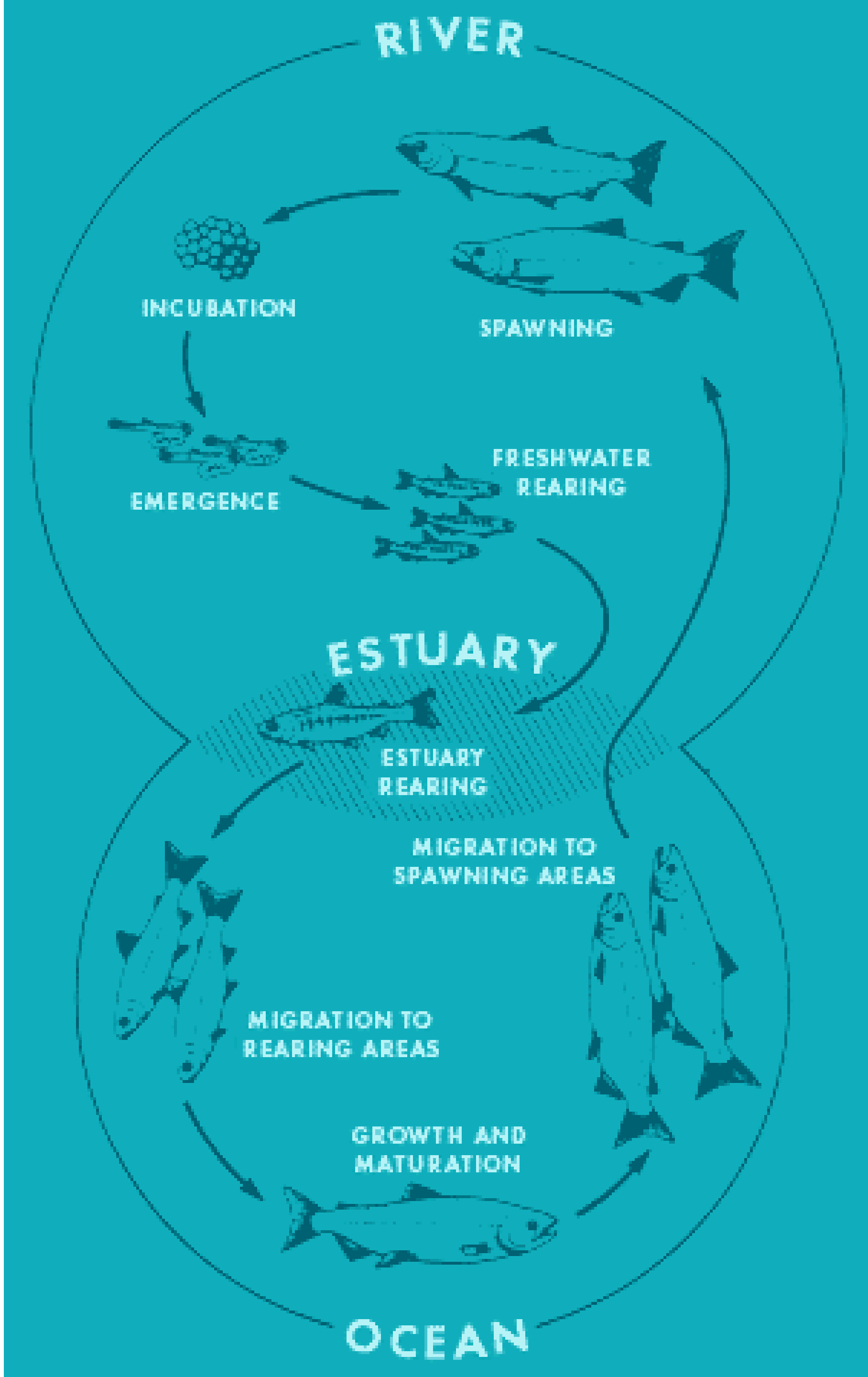
Keeping it simple

- *An example*

The Sacramento River Chinook salmon IBM (ca. 2000)

- Objective: Develop a management model for Chinook salmon in the Sacramento River basin

Chinook salmon life cycle



www.fish.washington.edu

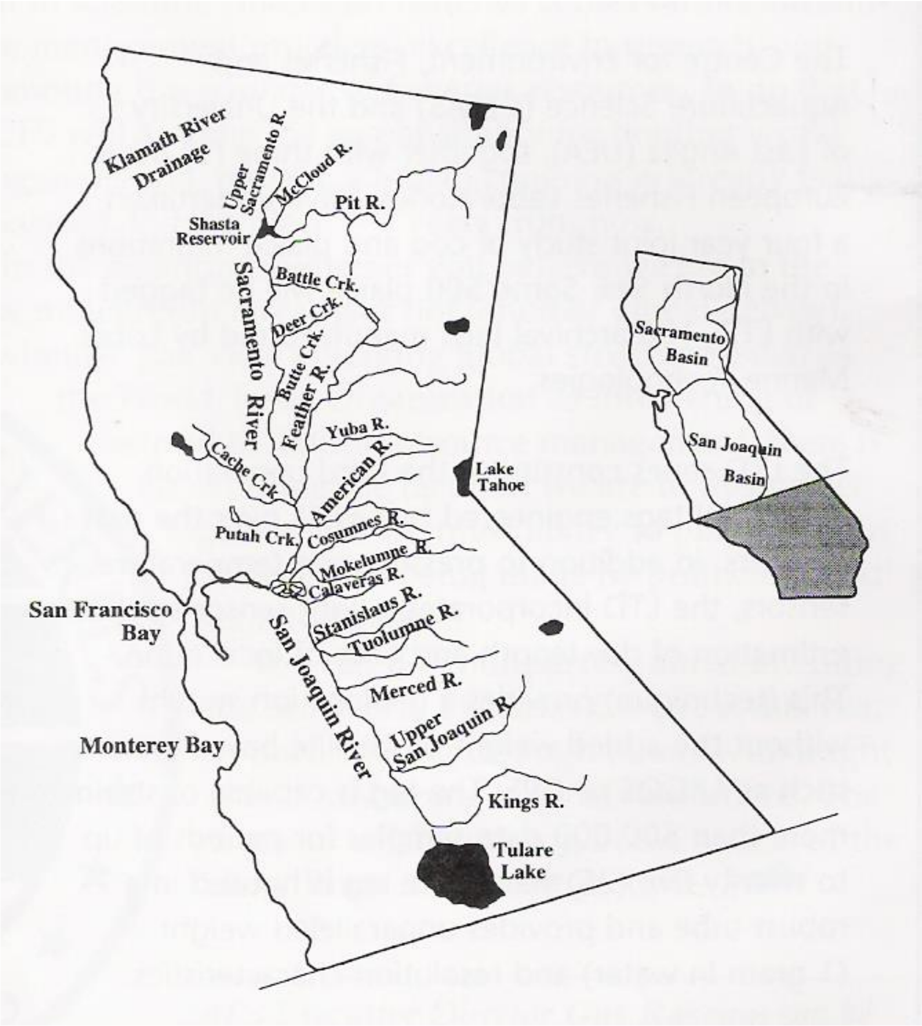
Sacramento River Chinook salmon

- There are actually 4 separate “races” of chinook salmon
  – Fall, late fall, spring, winter

- The races have different behaviors and are managed separately

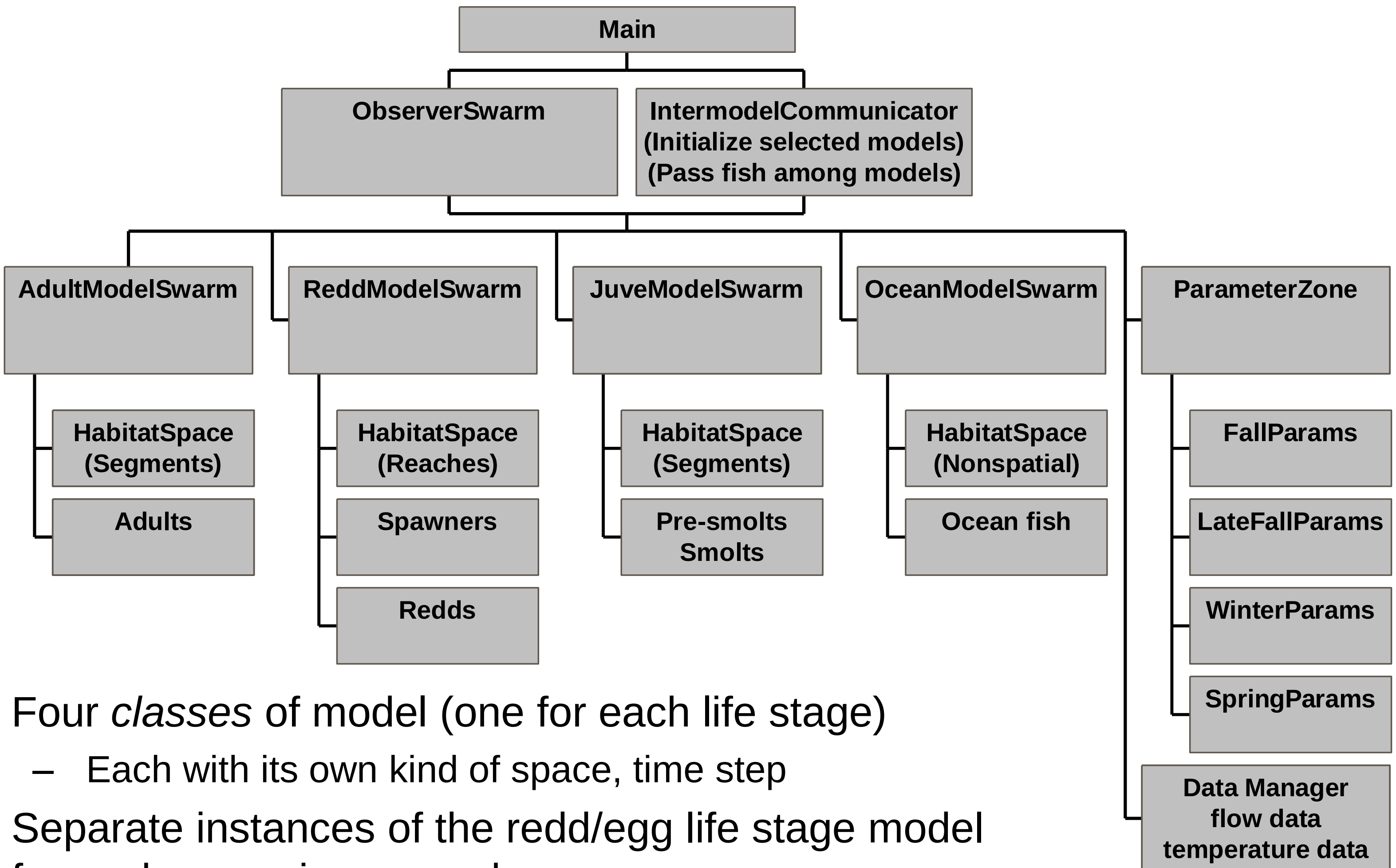
Sacramento River salmon

- Salmon spawn in many different rivers
  - Each “run” has its own timing
  - Each spawning river has its own environmental conditions and stressors



Yoshiyama et al. 2000. Fisheries **25(2)**:6-20.

The Sacramento River salmon model (the gnarliest fish model ever?)



- Four *classes* of model (one for each life stage)
  - Each with its own kind of space, time step
- Separate instances of the redd/egg life stage model for each spawning ground
- Separate parameter values for each race

Because it modeled the whole life cycle, this salmon model was:

- Too complex to
  - parameterize
  - calibrate
  - understand

- Yet too simple to solve any specific problems

- Doomed to failure (and repetition)

Salmon model: Lessons learned

- If someone asks you to build a model of a complicated system, *run away!*

- If your grad student starts to build a model of a complicated system, *stop him/her now!*

- *Instead, we model a specific* problem *of a complex system*

Keeping it as simple as possible... but no simpler

- Models that are too simple, with too little behavior, are boring...
  - you don’t get out more than you put in
  - you can’t solve many problems

- How to find the right level of complexity??

Finding the right level of complexity

- Filter 1: A clear, specific problem (or set of problems) about a real system
  - Include stuff (entities, processes, variables...) only if you think it is *absolutely necessary* to understand the problem
  - But for multi-scale models, this filter is not sufficient...

Filter 2: Pattern-oriented modeling

Phase 1: Patterns for model design

- Identify a set of *observed patterns* that characterize the real system with respect to the problem being modeled
  - Occur at the same scales
  - Driven by the same processes
  - Multiple, qualitative responses to the same drivers

  - (If the model *did not* reproduce these patterns, then it should not be trusted to solve the problem)

Filter 2: Pattern-oriented modeling Phase 1: Patterns for model design

- Identify a set of *observed patterns* that characterize the real system with respect to the problem being modeled

- Add stuff that makes it *possible* for the patterns to emerge from the model
  - – Dimensions, scales
  - – Entities, variables
  - – Processes, behaviors

Pattern-oriented model design...
It works!!

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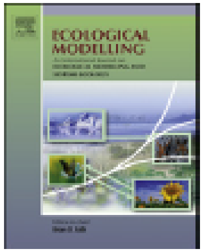
Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel



Pattern-oriented modeling of bird foraging and pest control in coffee farms

Steven F. Railsback[a,*], Matthew D. Johnson[b]

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[b] Department of Wildlife, Humboldt State University, Arcata, CA 95521, USA

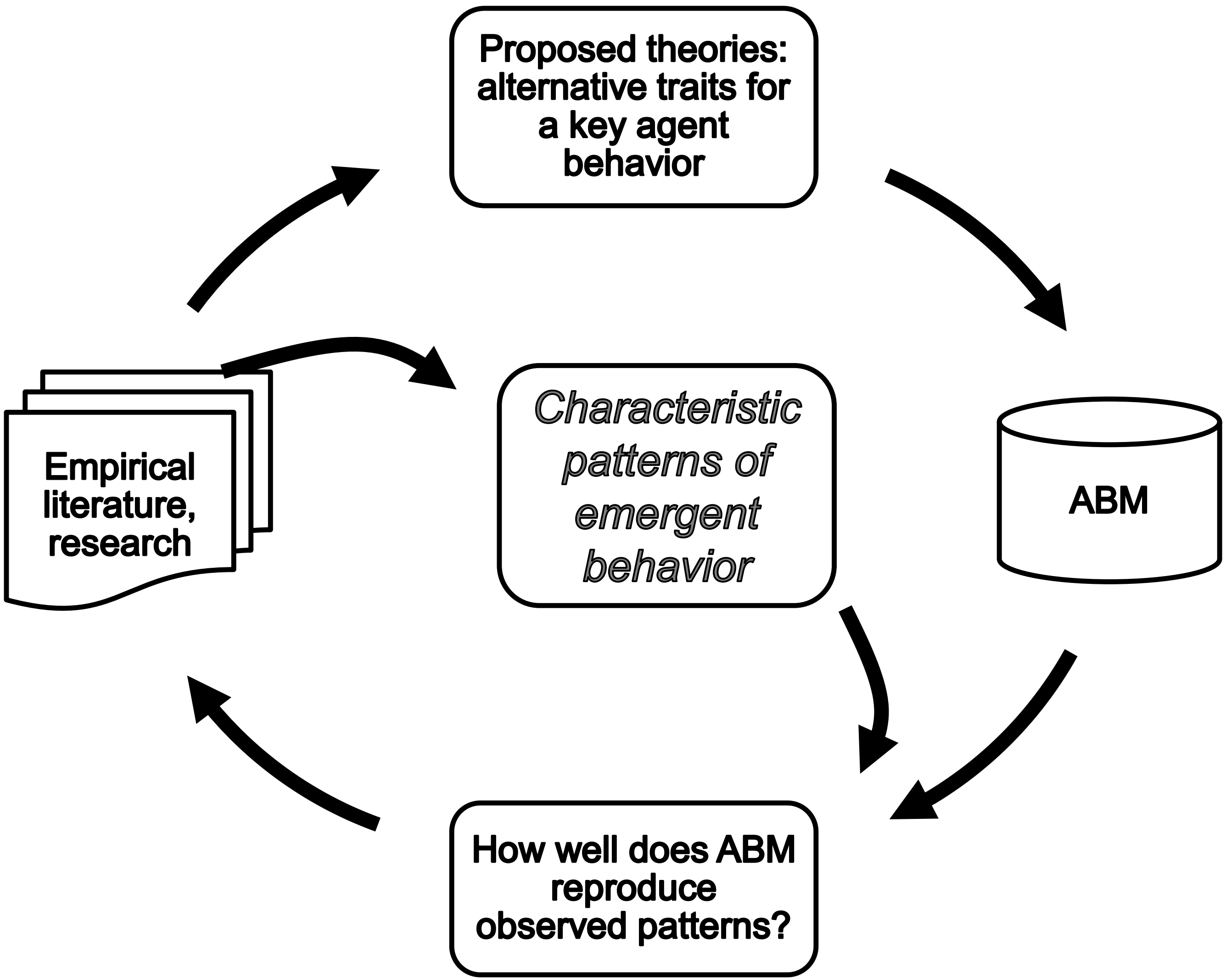
Lessons (2): Modeling agent behavior

- The whole idea of individual-based models is to represent how system properties emerge from individual behavior
  - (and how behavior responds to the system)
- So... how??

Theory in individual-based science is *across-level*

- Models of what *individuals* do that explain *system* dynamics
  - (Capture enough essence of individual behavior to model the system)
  - How??

Pattern-oriented modeling, Phase 2: The theory development cycle



How do individual trout adapt to changes in habitat?

- #1: By changing where they feed ("habitat selection")

- Trout are usually "sit and wait" predators: they stay in one place and wait for food to drift past

  When conditions change, they move to a new feeding place

Habitat selection: A tradeoff between mortality risk and energy intake

Theory for habitat selection
Classical approaches

- Maximize growth
  - But avoiding mortality is clearly important
  - Growth ≠ fitness (why grow when you're already big enough to reproduce?)
  - (Too simplistic)

Theory for habitat selection
Classical approaches

- State-based optimization:
  Find the sequence of habitat patches over time that maximizes expected future reproductive output
  - Combines effects of growth and mortality
  - Clear theoretical meaning

  - But impossible to solve in an IBM (an *individual-level* approach, not *across-level*)

"State- and Prediction-based Theory" for habitat selection

- Choose the habitat that provides the highest expected probability of surviving *predation* and *starvation* for the next 90 days

- Using a simple prediction:
  today's conditions persist over the 90 days

- Repeat this decision every day

“Pattern-oriented” test of SPT for habitat selection in trout

- We identified six “characteristic patterns” of how trout adapt their habitat choice

- Could the IBM reproduce these patterns?
  - Using the “SPT” theory
  - Using two alternative hypotheses for individual decisions

Railsback and Harvey. 2002. Ecology 83:1817-1830.

"Pattern-oriented" test of SPT for habitat selection in trout

Observed pattern	Maximize growth	Maximize survival	SPT: Maximize expected survival
Response to high flow	✓	✓	✓
Hierarchical feeding	✓		✓
Competitor-induced shift	✓		✓
Predator-induced shift		✓	✓
Higher velocity at higher temperatures			✓
Response to reduced food			✓

Railsback and Harvey. 2002. Ecology 83:1817-1830.

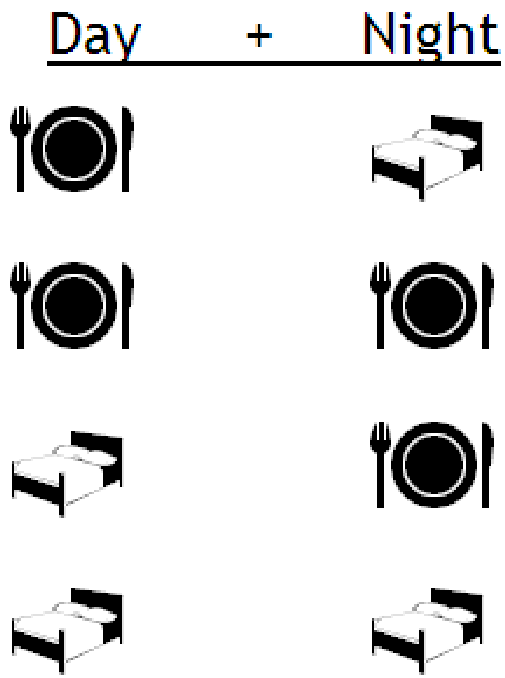
OK, that was easy... Let's try *really* complex behavior

- Real trout select *activity* as well as habitat…adaptively switch between daytime and night feeding

  Can we add this second adaptive behavior?

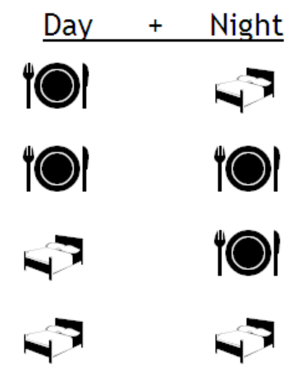
Diel Selection of Habitat *and* Activity

- The decision: choose a good *combination* of feeding and hiding, during day and night:



Additional Complexities

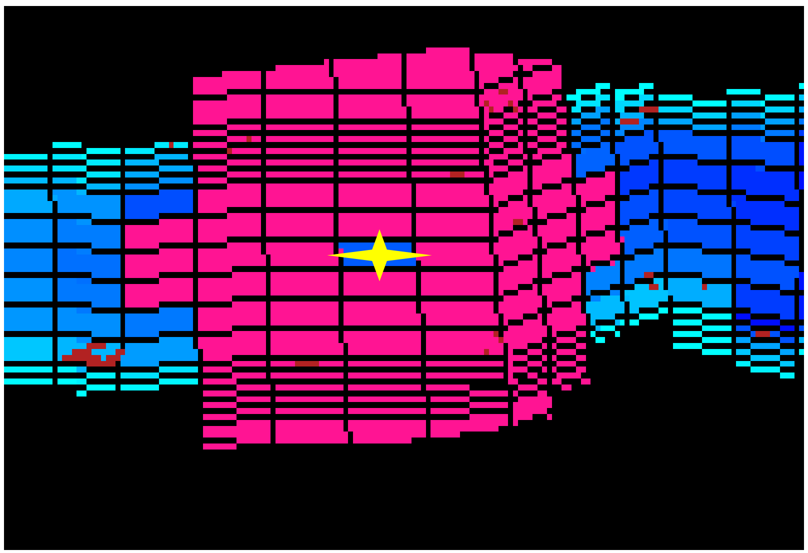
- Growth and mortality risk vary with (time, space, individuals) *and*:



  - Day vs. night
    - Lower feeding success at night
    - Lower predation risk at night
  - Activity
    - Negative growth when hiding
    - Much lower predation risk when hiding

Diel Selection of Habitat and Activity

- Evaluate each combination of day and night activity for each habitat cell



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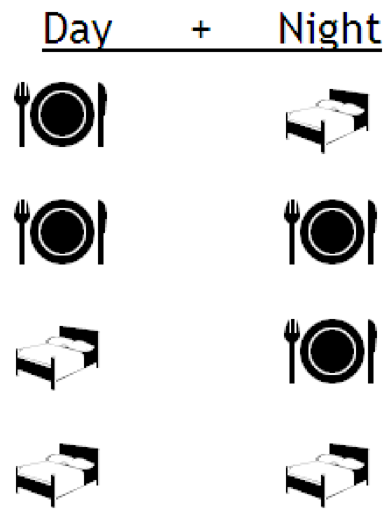


- Select the combination that provides highest expected survival over the time horizon

Pattern-oriented Analysis of the Theory

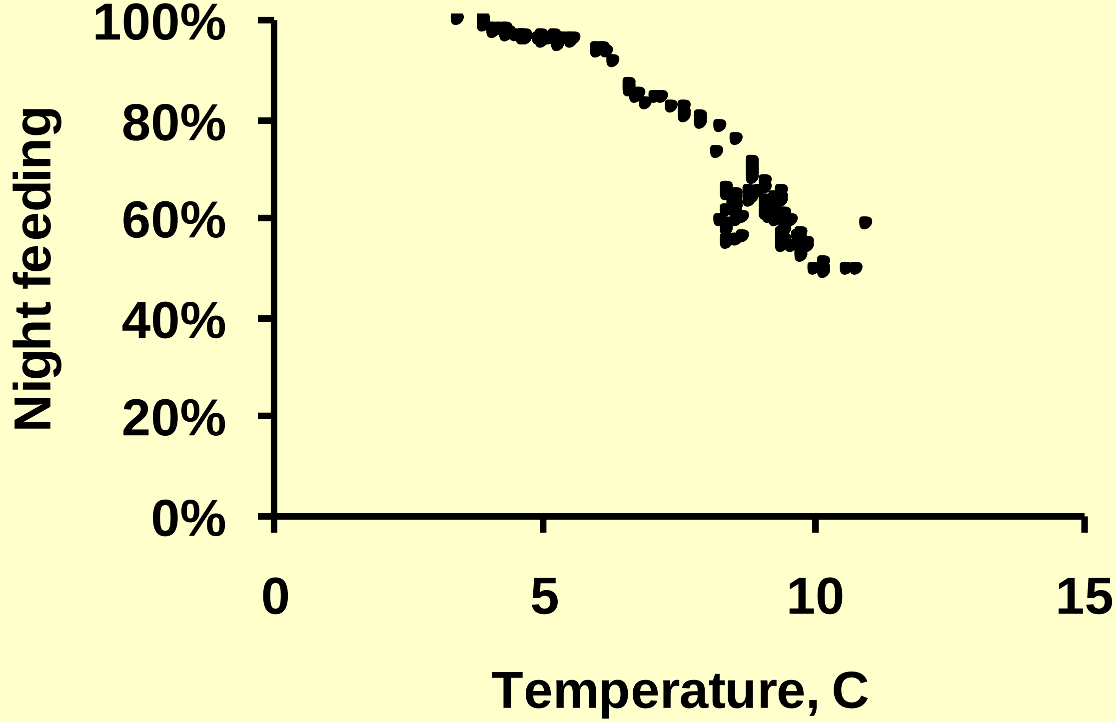
- Many patterns of diel habitat selection in trout have been observed, in the lab and field

- Are these patterns reproduced in the IBM?

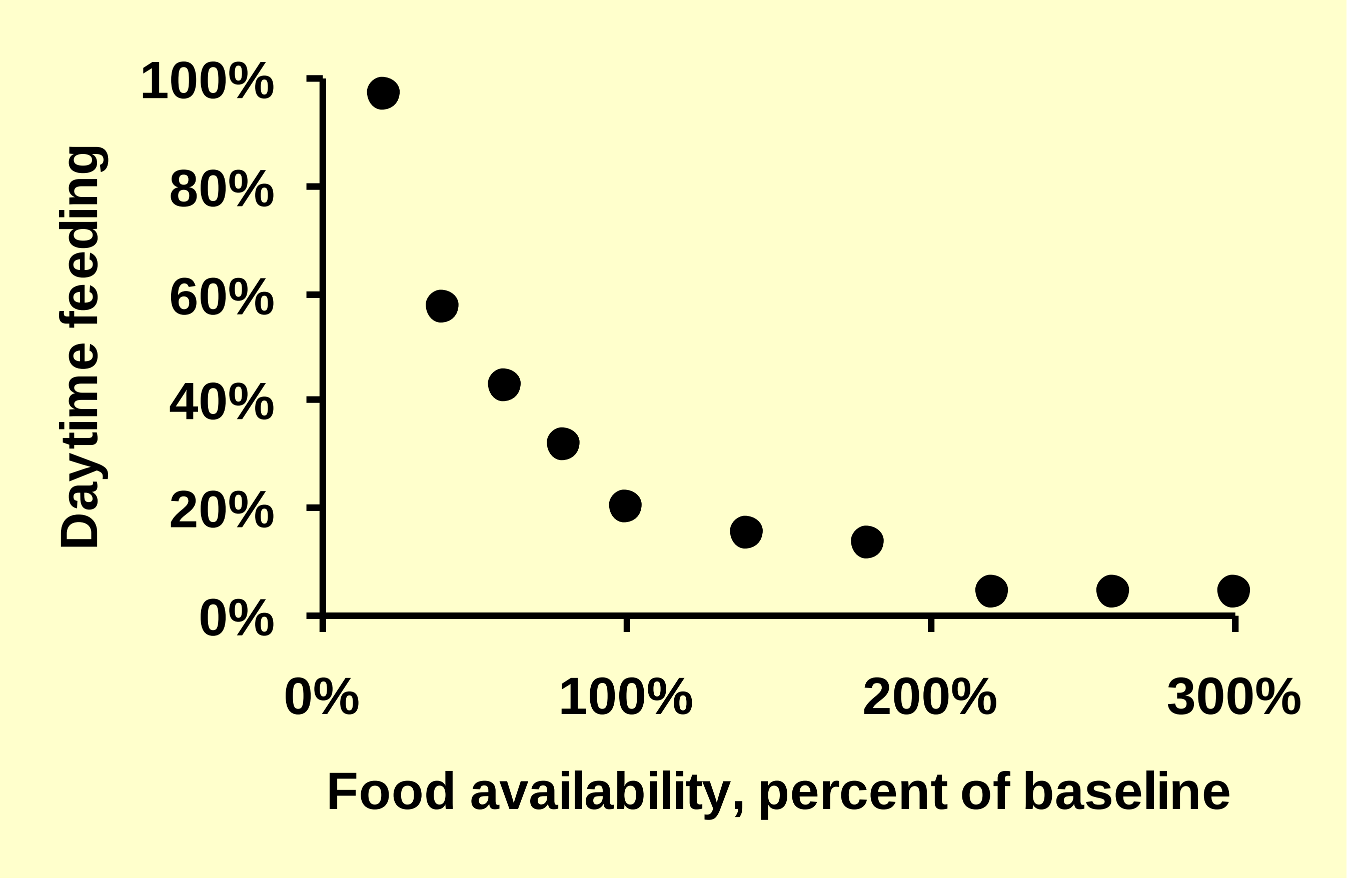
Railsback, Harvey, et al. 2005. Tests of theory for diel variation in salmonid feeding activity and habitat use. Ecology **86**:947-959.

Observed Pattern (1)
More night feeding when temperature is low

- Reduced metabolism allows fish to meet energy needs by feeding at night



Observed Pattern (2)
More daytime feeding when food is scarce



Other observed patterns reproduced by the theory:

- Feeding fish use shallower habitat at night
- Fish feed closer together at night
- Competition from larger fish increases daytime feeding

Another example:
Bird foraging in the coffee farm model

Patterns	Random	Optimal departure	Optimal destination- short distance	Optimal destination- long distance
1) Pest reduction by birds	✓	✓	✓	✓
2) Infestation higher in sun coffee	✓	✓	✓	✓
3) Bird densities higher in shade coffee		✓	✓	✓
4) Bird effect increases with infestation rate	✓	✓	✓	✓
5) Higher bird density during food irruptions			✓	✓
6) Bird density varies with food availability	✓	✓	✓	✓
8) Log-normal movement distance distribution	✓		✓	

Lessons (3): Validation is a sticky issue

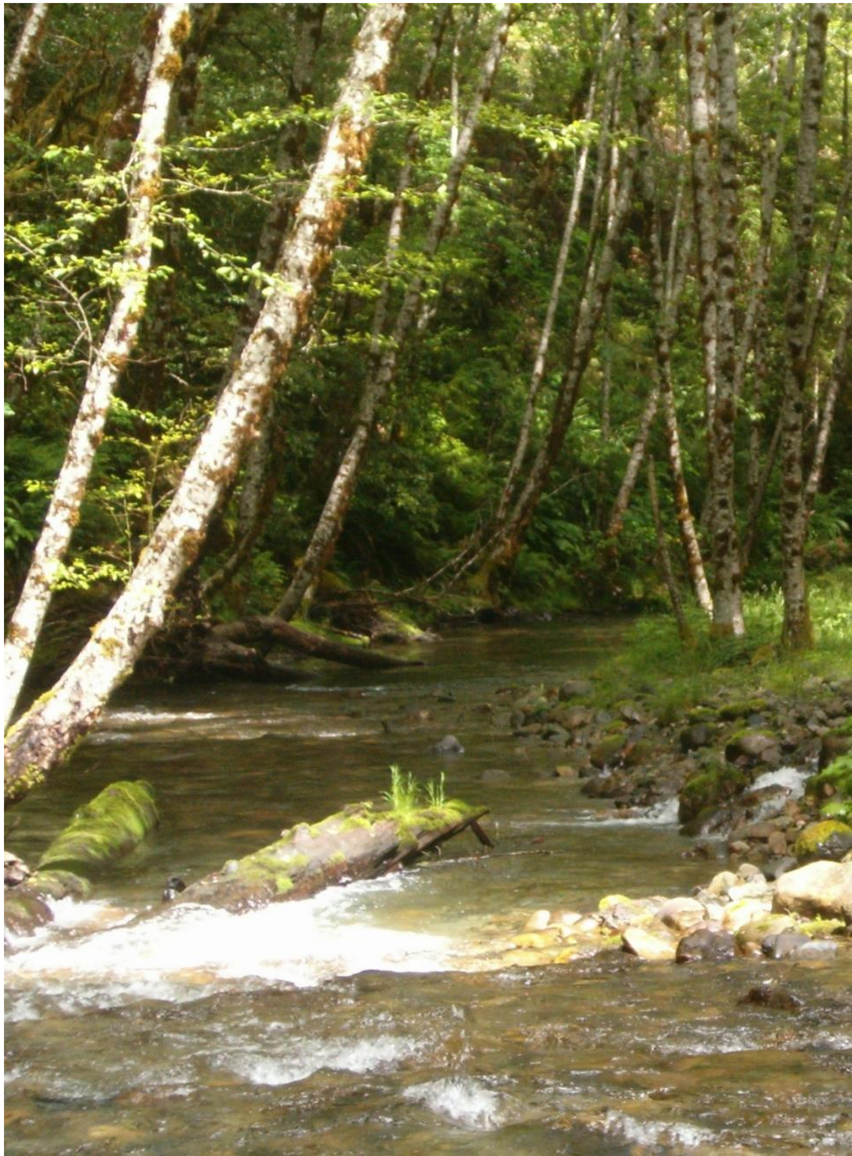
- Sponsors, users, reviewers want to see "validation"

- One advantage (?) of IBMs is that they can make many testable predictions

Our sad validation story

- Attempt 1: An undisturbed study site

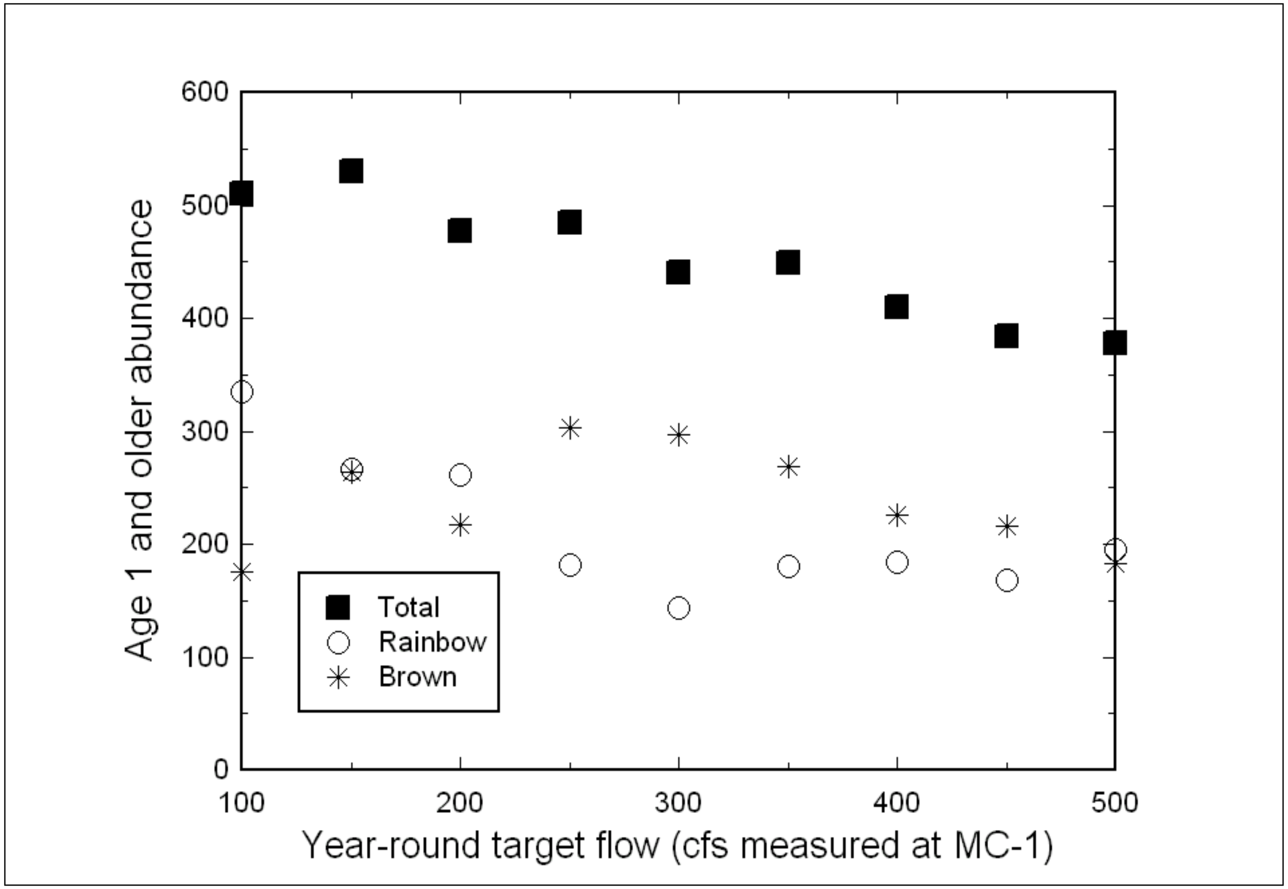
  ... where nothing ever happens



Our sad validation story: Attempt 2

- McCloud River Hydropower Licensing

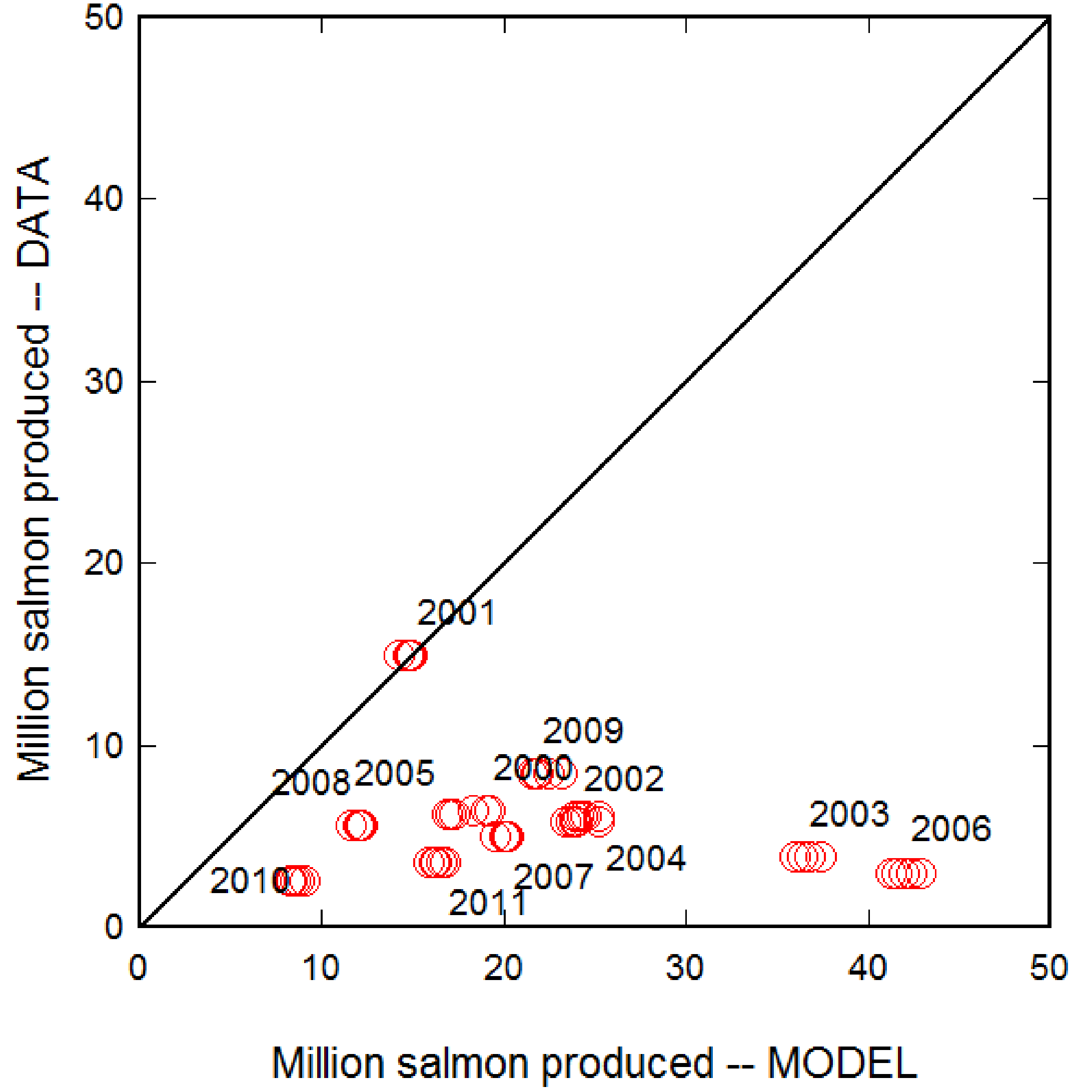
Our sad validation story: McCloud River



- Recommendation: Don’t change the flow!

Validation attempt 3: Clear Creek salmon

- Uncertain field data
- Events and processes not in the model



Some validation:
Controlled studies on small streams

Lessons on validation (1): Validate the model “bottom up”

- Focus first on testing submodels
  - especially for individual behavior

  - (*theory development*)

Lessons on validation (2): Limit expectations

- Even if your model predicts many kinds of response to many inputs, it is still a model...

  - You do not want it to include everything that affects the real system!

- Hence, it will never reproduce all observations

Lessons on validation (2): Limit expectations

- Even if your model predicts many kinds of response to many inputs, it is still a model...
  - You do not want it to include everything that affects the real system!
- Hence, it will never reproduce all observations
  (Or: if it could, then it would be too complex to be useful)

Lessons on validation (3): Failed validation is a research opportunity

Exploring the Persistence of Stream-Dwelling Trout Populations under Alternative Real-World Turbidity Regimes with an Individual-Based Model

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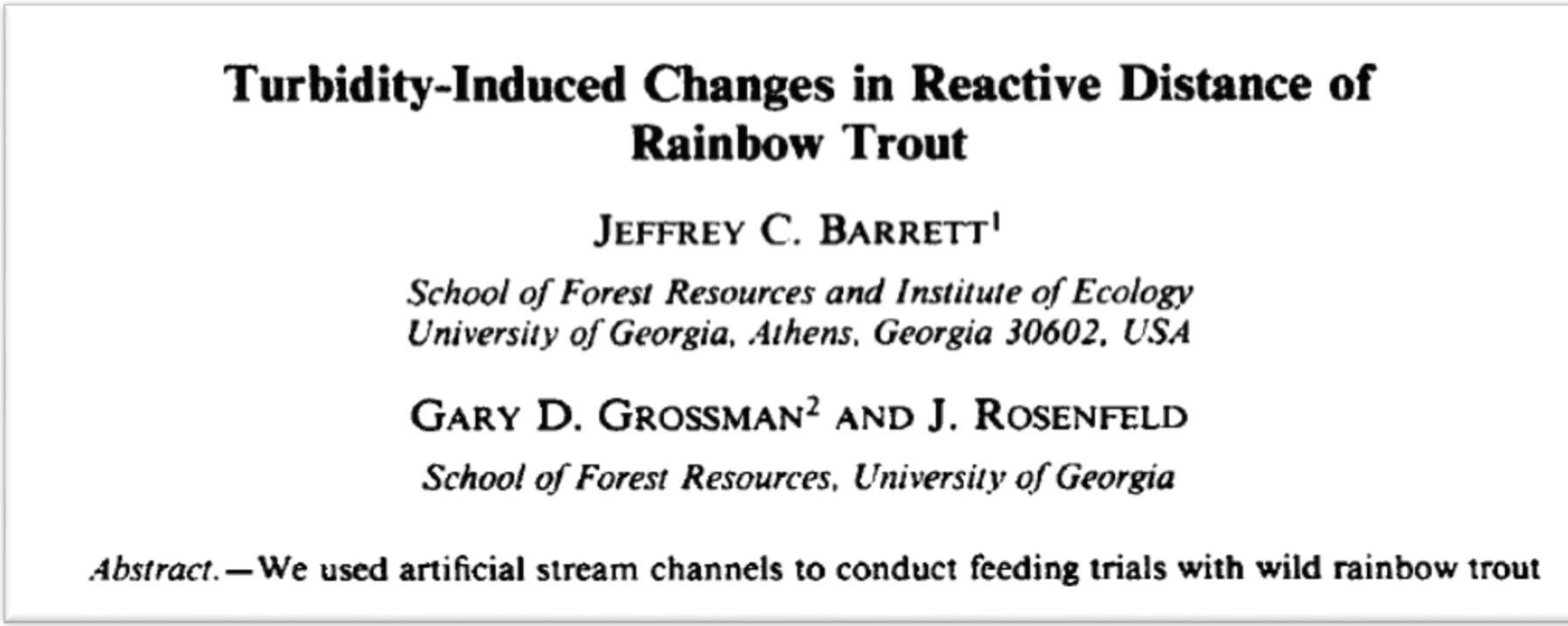
Lang, Railsback, and Associates, 250 California Avenue, Arcata, California 95521, USA

Abstract.—We explored the effects of elevated turbidity on stream-resident populations of coastal cutthroat trout *Oncorhynchus clarkii clarkii* using a spatially explicit individual-based model. Turbidity regimes were

The effect of turbidity on trout ability to catch drifting food is well-understood



Turbidity-Induced Changes in Reactive Distance of Rainbow Trout

JEFFREY C. BARRETT[1]

School of Forest Resources and Institute of Ecology University of Georgia, Athens, Georgia 30602, USA

GARY D. GROSSMAN[2] AND J. ROSENFELD

School of Forest Resources, University of Georgia

Abstract.—We used artificial stream channels to conduct feeding trials with wild rainbow trout

Barrett et al. 1992, Transactions of the American Fisheries Society

inSTREAM results

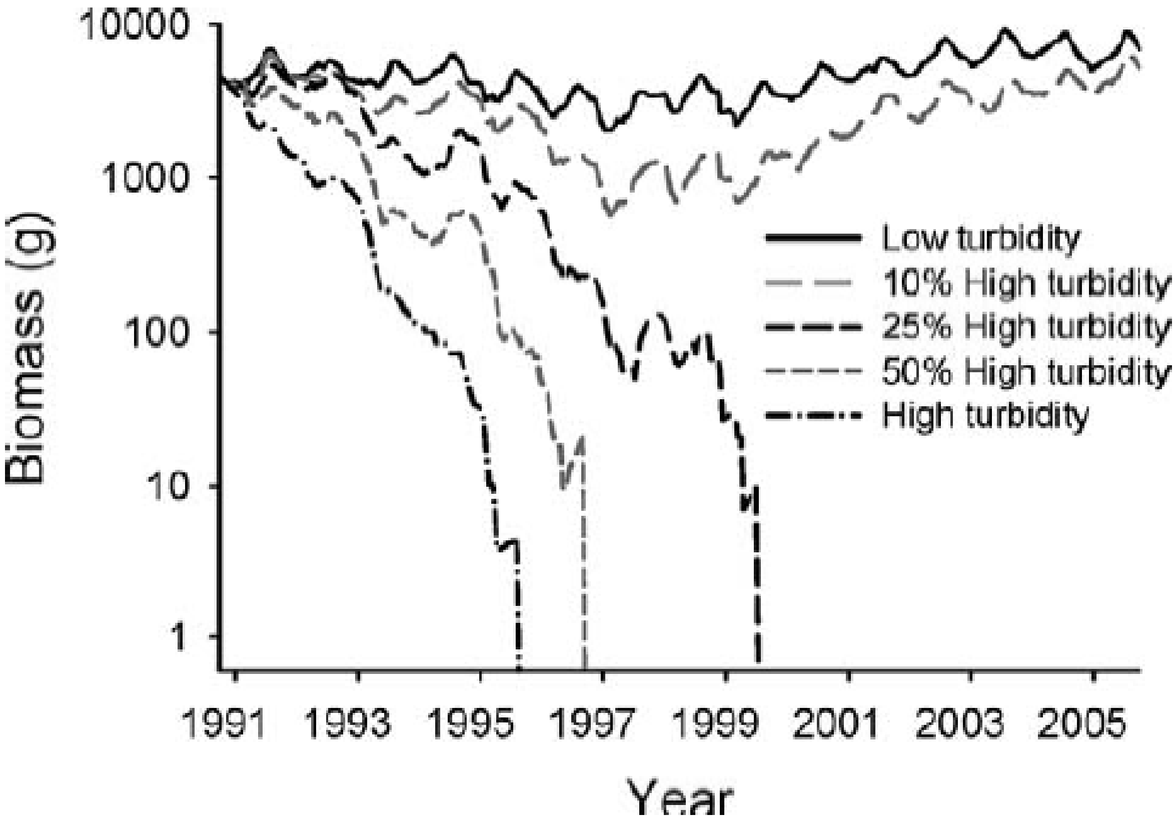


FIGURE 6.—Individual-based model results for total fish biomass of a simulated coastal cutthroat trout population under a drift-based food calibration and five different turbidity

Why did inSTREAM fail in predicting population response to high turbidity?

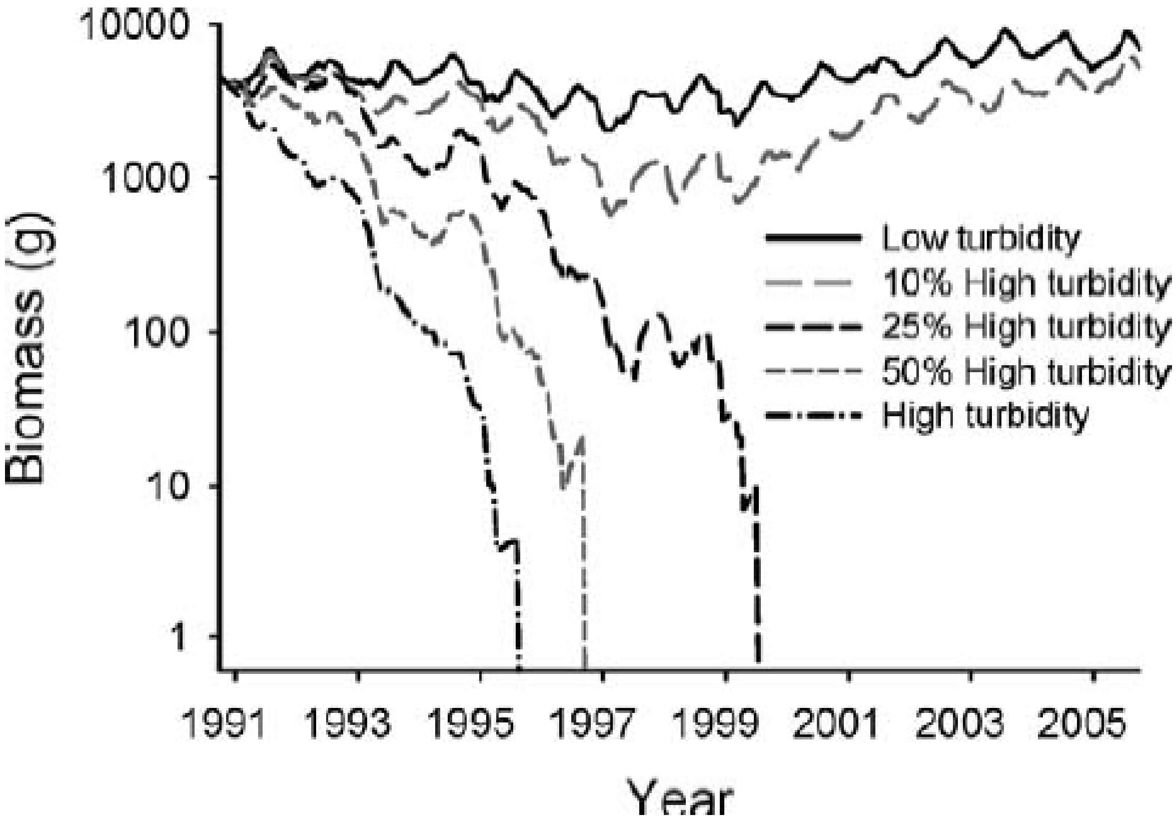


FIGURE 6.—Individual-based model results for total fish biomass of a simulated coastal cutthroat trout population under a drift-based food calibration and five different turbidity

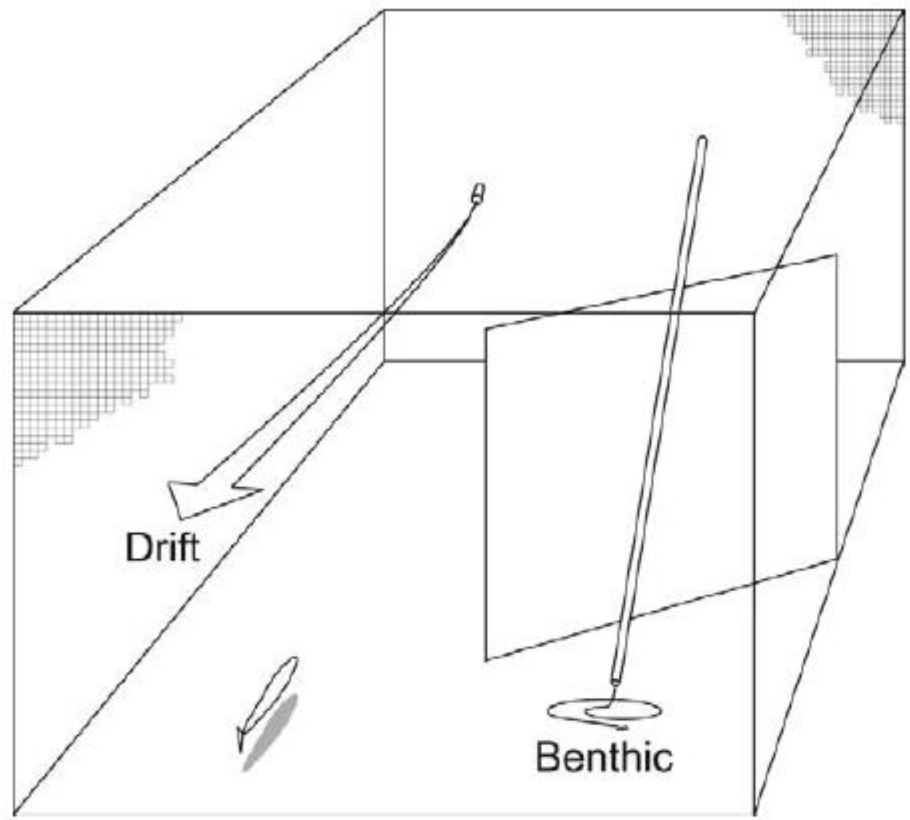
"The results highlight the need for better understanding of patterns in the availability of food under turbid conditions and the capability of stream salmonids to use nonvisual cues in feeding."

How do trout stay alive at high turbidity?

How do trout stay alive at high turbidity?

In the laboratory, trout switched to feeding off the bottom as turbidity increased

(A new understanding of salmonid feeding resulting from the failed simulations)



Harvey and White. 2008. Use of benthic prey by salmonids under turbid conditions in a laboratory stream. Transactions of the American Fisheries Society **137:1756-1763.**

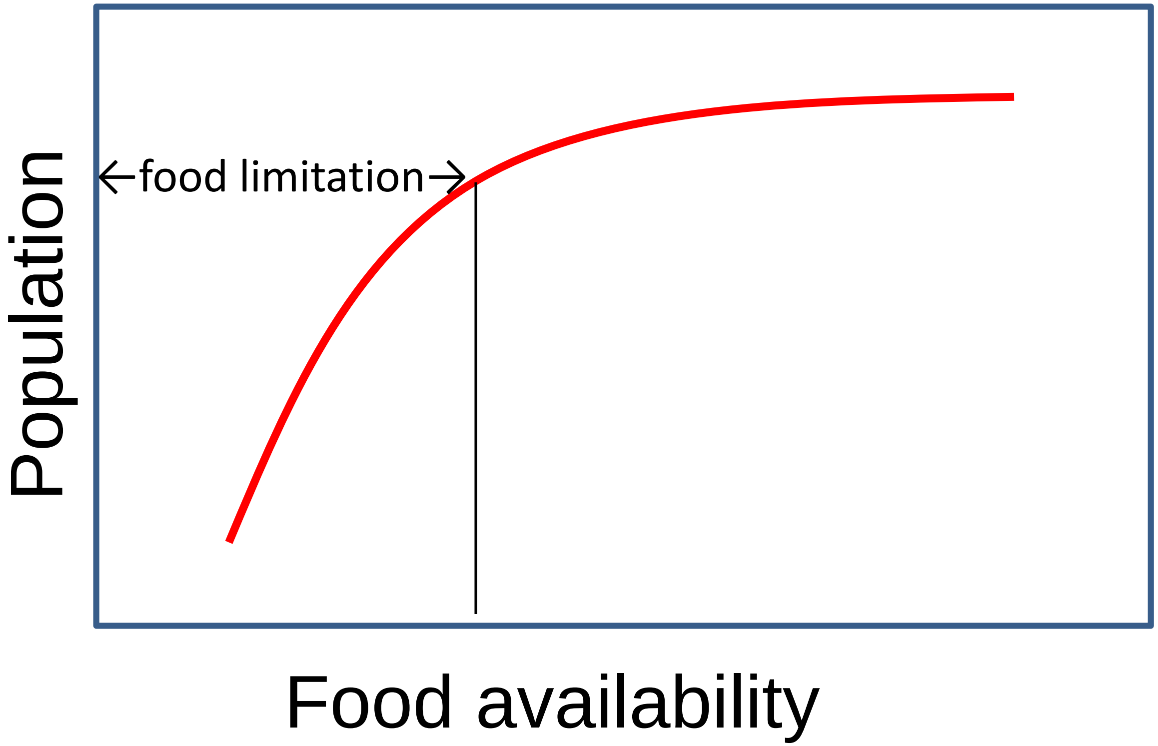
Lessons (4): Multi-scale models can produce general understanding

- Once pattern-oriented modeling shows that a model captures essential mechanisms of the real system,

  we can use it as a virtual laboratory...

  often to show that what “everyone knows” is wrong

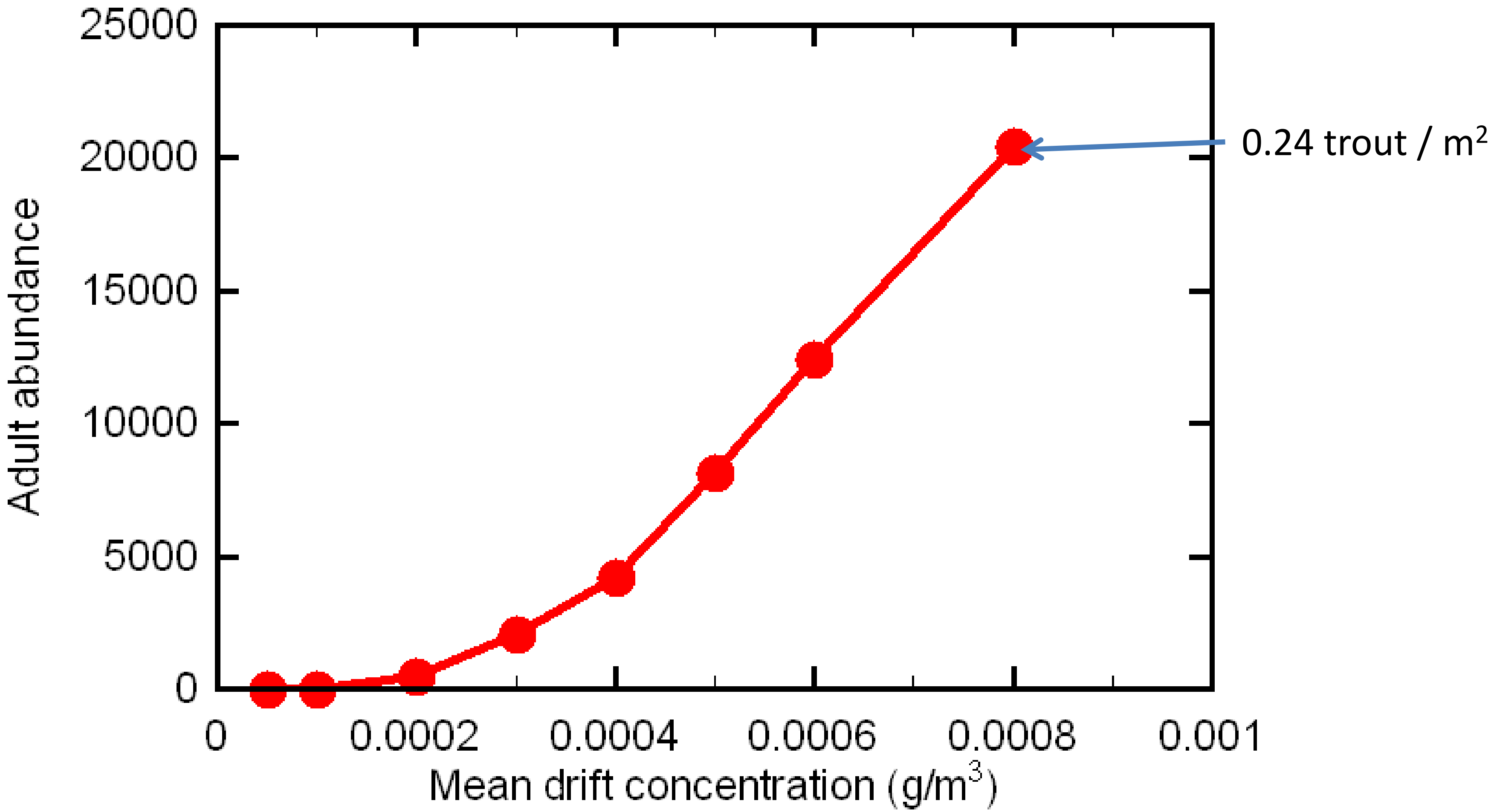
Example of general understanding: Is the “limiting factors” paradigm useful?



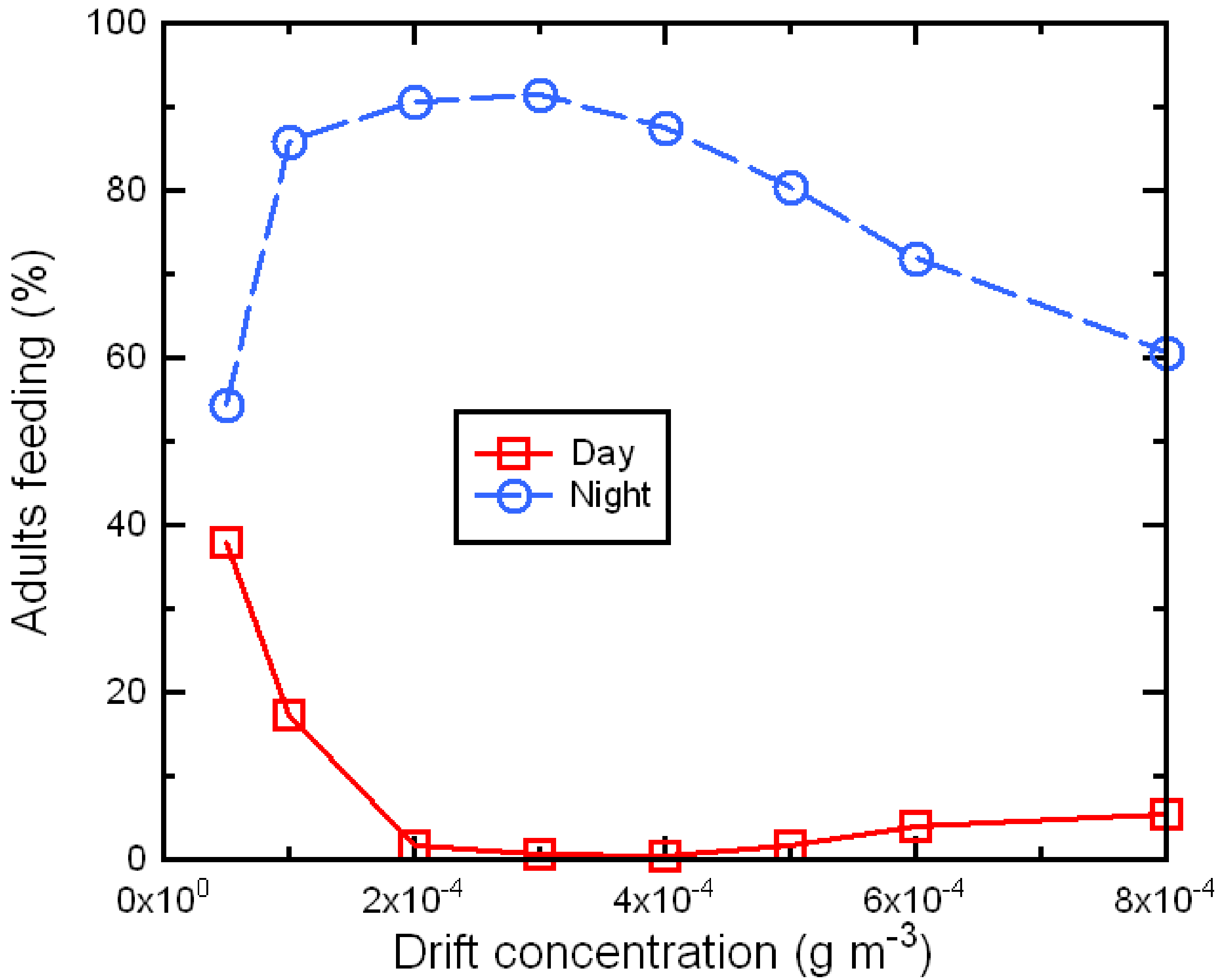
The simulation experiment

- Simulate 8 levels of increasing food availability
- Multi-year simulations of trout

Model results: Food always “limits”!



Activity selection (deciding when to feed vs. hide) is how model trout convert food to survival



Is this conceptual model of 'limitation' useful?

- No! (in our model)
- Instead:
  - Because of tradeoff behaviors, *any factor* that affects growth or survival likely has *some* effect on abundance

- (One of several common fish management beliefs shown by the model to be illogical)

General understanding: Will stream restoration promote or discourage anadromy?

- In Atlantic salmon, brown trout, steelhead:

  some juveniles migrate to the ocean and some stay in streams...

General understanding: Will stream restoration promote or discourage anadromy?

- We assume anadromy is an adaptation that depends on survival and growth...

Evolutionary Applications www.evolutionaryapplications.org

Evolutionary Applications ISSN 1752-4571

ORIGINAL ARTICLE

State-dependent life history models in a changing (and regulated) environment: steelhead in the California Central Valley

William. H. Satterthwaite,[1,2] Michael P. Beakes,[1,3] Erin M. Collins,[4] David R. Swank,[1,3] Joseph E. Merz,[5,6] Robert G. Titus,[4] Susan M. Sogard[3] and Marc Mangel[1]

Center for Stock Assessment Research, Department of Applied Mathematics and Statistics, University of California Santa Cruz, Santa Cruz, CA,

inSALMO represents anadromy as an individual adaptive behavior

- Individuals become anadromous *if* expected reproductive output of going to the ocean exceeds that of remaining resident

- considering: growth, predation risk

If we improve stream habitat, will we reduce the number of fish that go to the ocean??

- Habitat improvement increases stream survival, which—according to life history theory—should cause more individuals to remain resident

- But we are trying to conserve the ocean-going life history more...

inSALMO results

Railsback, Harvey, and White. 2014.
Canadian Journal of Fisheries and Aquatic Sciences **71:1270-1278.**

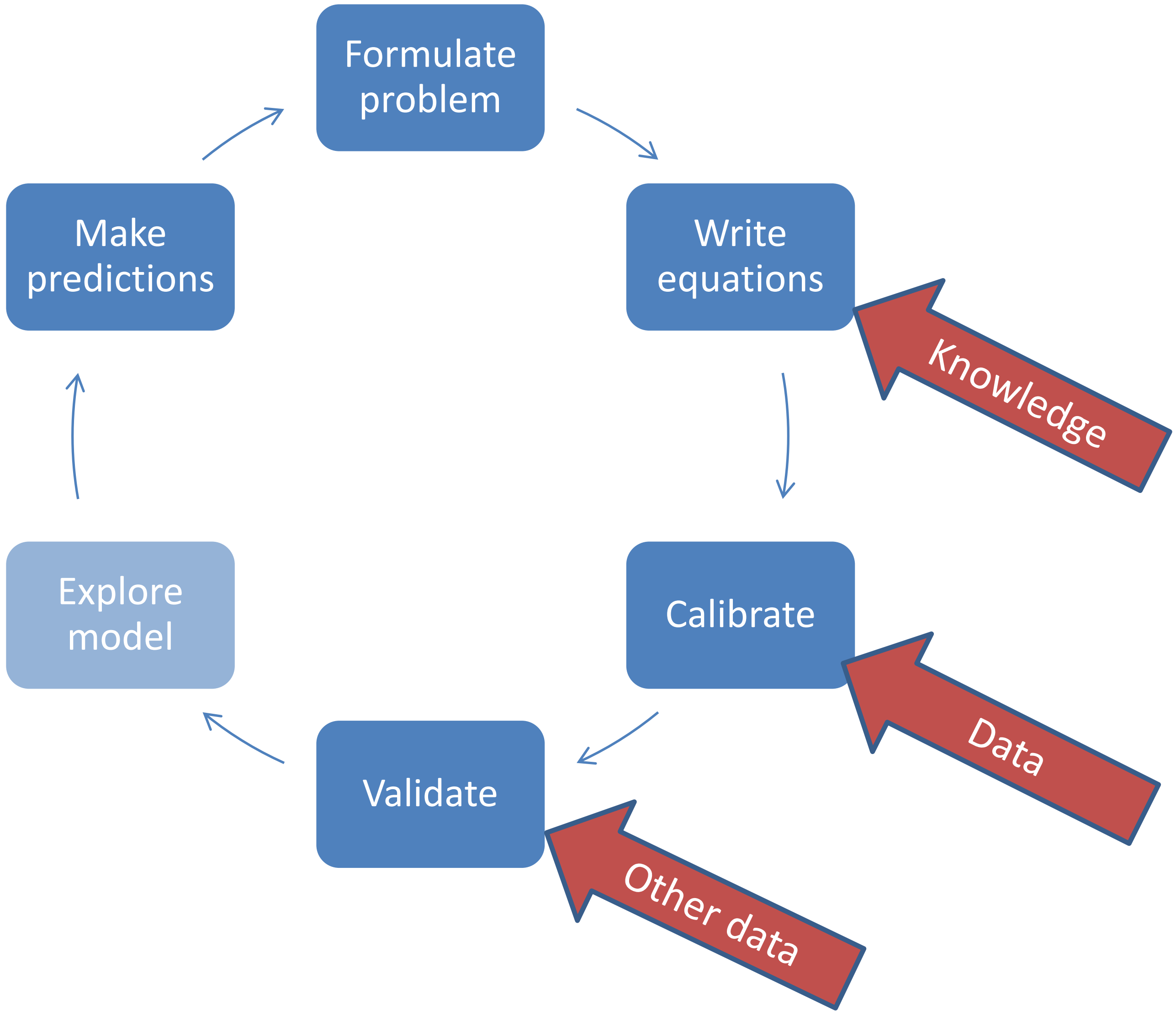
- Low stream survival does *not* produce more anadromous individuals:
  - More juveniles *choose* to go to the ocean
  - but they die before they can

- High-quality stream habitat produces more residents *and* more anadromous fish
  - Stream restoration can be good for both anadromous *and* resident life histories

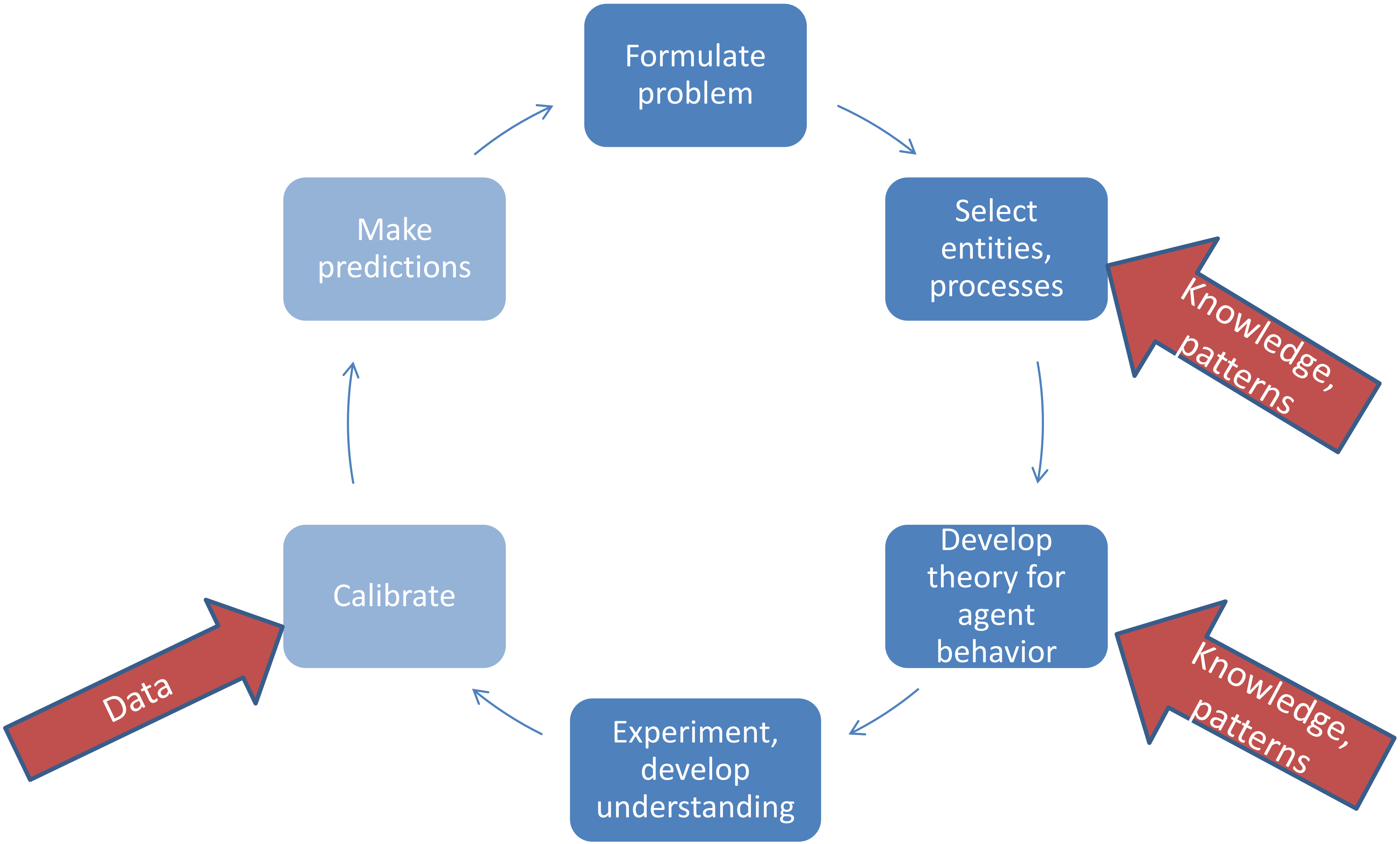
Conclusions

- Successful models require a specific problem (or class of problems) about a specific real system
- Pattern-oriented modeling is a strategy to design models, develop theory for agent behavior, and link models to empirical science
  - Multiple qualitative patterns can be more powerful than large data sets
  - Validate from the bottom up, not by fitting or attempting to reproduce top-level data
- A well-designed model that captures the essential mechanisms can apply to many situations and problems.
  - Specific applications
  - General understanding

A traditional modeling cycle



A multi-scale modeling cycle



- Books, publications, links: www.humboldt.edu/ecomodel