Can Agent-based Modeling Contribute to Theory in Ecology?

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What is “Theory” in Ecology?

- Population Ecology:
  - How does the number of organisms in a population change over time?

- Behavioral Ecology:
  - How do individual organisms “behave” (decide what to do)?
What is “Theory” in Population Ecology?

- Source:
  J. Roughgarden 1998


- Example: Logistic model of density-dependent population growth

\[ \frac{dN}{dt} = r \left( 1 - \frac{N}{K} \right) N \]

N = number of organisms
r = intrinsic rate of population increase
K = “carrying capacity”
What is “Theory” in Population Ecology?

- Example: Predator-Prey Population Model

\[ \frac{dN_1}{dt} = rN_1 -aN_1N_2 \]
\[ \frac{dN_2}{dt} = baN_1N_2 -dN_2 \]

- Characteristics of “Theory” in Population Ecology

  - Basis for theoretical models: Intuition
    - (Because the actual processes are complex, unknown)
Characteristics of “Theory” in Population Ecology

- Basis for theoretical models: Intuition
  – (Because the actual processes are complex, unknown)

- Assumptions are few but sweeping, very wrong
  – (To make the math tractable)

- Models are rarely tested or compared
  – (Because data are rarely available from systems as simple as the models)

- What is the value of conventional ecological theory for addressing real-world environmental issues?

- Answer: *None!*

- Ecological theory is too abstract and over-simplified to be of practical use
Status of Theory in Population Ecology

  - What is the value of conventional ecosystem theory for addressing real-world environmental issues?
  - Answer: None!
  - Ecologists suffer from “physics envy”: “To be a real scientist, you have to have theory”

What is “Theory” in Behavioral Ecology?

- Models of how individual organisms make such decisions as:
  - What habitat to use
  - What to eat
  - Who to mate with
What is “Theory” in Behavioral Ecology?

- Example: “Optimal foraging” by fish
  - Hypothesis:
    Fish forage in habitat that provides a good tradeoff between food intake and mortality risk
  
  - Test: Laboratory experiment of fish choice between sites differing in food, risk

Characteristics of “Theory” in Behavioral Ecology

- Basis for theoretical models:
  - Fitness optimization
    (because evolution demands fitness)
  
  - Cognitive science
    (to understand real decision mechanisms)
## Characteristics of “Theory” in Behavioral Ecology

- **Basis for theoretical models:**
  - Fitness optimization (because evolution demands fitness)
  - Cognitive science (to understand real decision mechanisms)

- **Models are sometimes tested vs. observations**
  - (But alternative good models are rarely compared in rigorous tests)

- Few theories link individual behavior to population consequences
Can Agent-based Modeling Contribute to Ecological Theory??


### New Computer Models Unify Ecological Theory

Computer simulations show that many ecological patterns can be explained by interactions among individual organisms.

Michael Huston, Donald DeAngelis, and Wilfred Post

Most mathematical models on population growth are based on the idea that individuals are distributed according to a certain spatial pattern. This is usually achieved through a process called "spatial model". However, these models often fail to capture the complexity of ecological interactions that occur in real ecosystems. In contrast, agent-based models (ABMs) allow for a more detailed representation of individual organisms and their interactions.

Agent-based models (ABMs) are a type of computer simulation that uses a bottom-up approach to model complex systems. In an ABM, each individual is represented as an agent that follows a set of rules based on its environment and interactions with other agents. The behavior of each agent is determined by its own characteristics and the rules of the model, which can be parameterized to reflect different ecological scenarios.

Agent-based models are particularly useful for studying ecological systems because they can capture the emergent properties that arise from the interactions between individual organisms. ABMs are also flexible and can be used to test different scenarios and hypotheses about how ecological systems work.

### How Agent-based Modeling Can Contribute to Ecological Theory (1)

- An ABM can provide a “virtual ecosystem” in which to test conventional models.

  - Doug Donalson:

    Spatial relations that are ignored in conventional models have important effects

How Agent-based Modeling Can Contribute to Ecological Theory (1)

- An ABM can provide a “virtual ecosystem” in which to test conventional models.
  - Railsback & Harvey:
    
    One of the most common assumptions of behavioral ecology—that animals make decisions by maximizing food intake rate—cannot explain simple, common behaviors


How Agent-based Modeling Can Contribute to Ecological Theory (2)

- “Proof of concept” models showing that an alternative explanation for some phenomenon is feasible.
  - Boids: Maybe bird flocking and fish schooling emerges from simple individual behaviors instead of being a centrally organized group behavior.
How Agent-based Modeling Can Contribute to Ecological Theory (3)

- Linking behavioral ecology to population ecology: Understanding how population dynamics emerge from individual behaviors
  - Thulke et al: What individual behaviors must be included in a model to reproduce the wave-like spread of rabies in fox populations?

What is “Theory” in Individual-based Ecology?

- *Fundamental Axiom*: Population phenomena emerge from actions of individuals

- *Theories*: Models of how individual organisms interact with:
  - Each other
  - Their environment
What is “Theory” in Individual-based Ecology?

- **Theories**: Models of how individual organisms interact with:
  - Each other
  - Their environment

- **Proofs**: Evidence from simulation experiments testing ability to reproduce observed patterns
  - Strength of evidence depends on refinement of the experiment
  - (Strong inference)

Characteristics of “Theory” in Individual-based Ecology

- Basis for theoretical models:
  - *Autecology*
    - (The often vast literature on traits of individual organisms)
  - Behavioral ecology
Characteristics of “Theory” in Individual-based Ecology

- Basis for theoretical models: Autecology, behavioral ecology

- Assumptions are many-but small, testable, and readily replaced
  - Assumptions are made to describe real mechanisms, not for mathematical convenience

Characteristics of “Theory” in Individual-based Ecology

- Basis for theoretical models: Autecology
- Assumptions are many but small, testable
- Models are easily tested and compared
- Individual- and population levels are linked
  - Populations are collections of individuals, instead of having inherent characteristics
Characteristics of “Theory” in Individual-based Ecology

- Basis for theoretical models: Autecology
- Assumptions are many but small, testable
- Models are easily tested and compared
- Individual- and population levels are linked
- An accepted ‘mathematics’ or common language is lacking

Potential Contributions of Agent-based Simulation to Ecological Theory

- Integrating theory and models across scales and levels:
  - Linking behavioral and population ecology
- Making theory and models more mechanistic, reality-based
- Expediting model testing and use of strong inference