Ecological and Evolutionary Agent-Based Models

Introduction

An **agent-based model** (ABM), also called an **individual-based model** (IBM), is a computational modeling approach that allows scientists to make and test predictions about populations and communities with a bottom-up approach. Many ecological models, like life-table or survival analysis models, take average population parameters like birth or death rate, and use these values to predict changes in the whole population. ABMs instead focus on how **behaviors**, **attributes**, and **state variables** of individuals give rise to population-level phenomena. Using an ABM framework, scientists can test how small changes in these features of a population affect long-term population trends.

Attributes are aspects of an individual that will not change over time. This may depend on the individual, but might include things like the species, the color, and the age of reproduction. **State variables** are aspects of an individual that can change over time including things like location, reproductive state, and feeding status. **Behaviors** are often coded as responses to state-variables and can include habitat selection, growth, reproduction, dispersal, and foraging. For example, we could imagine the agent "Beyonce." Beyonce's attributes include that she is 'female,' 'human,' and 'born in Texas.' Beyonce's state variables could include 'located in EagleBank Arena,' 'Pregnant,' and 'Hungry.' Her behaviors might be 'Singing' in response to her location, or 'looking for food' in response to being hungry.

Within ecology, AMBs were first used to examine succession in forest environment but have since been used to examine a variety of ecological systems including fisheries, brown bears, flocking birds, migration, and infection dynamics. Because ecology is fundamentally concerned with dealing with highly complex systems, a range of modeling approaches are necessary for understanding the functioning and emergence of ecosystem processes and population interactions. However, individual-based models are unique because they directly address the fundamental question of ecology: How does order (ecosystems, evolution, and population dynamics) emerge from the actions of individuals in a species, population, and their interactions?

ABMs are typically constructed and implemented in computer simulation environments, and can then be used to test how changes in individual behaviors will affect the overall behavior. One simulation environment is **NetLogo**: An open source and free multi-agent programmable modeling environment. It was created in 1999, and has been in continuous development ever since. Today we will be using the NetLogo environment to investigate evolution and natural selection using a few of the built-in teaching models.

Peppered Moths

To find this model, open NetLogo, click 'File' then 'Open Models Library' this model is under 'Sample Models', in the 'Biology' folder and in the 'Evolution' sub-folder and is called 'Peppered Moths' When the model opens, click on the 'Info' tab and read through the documentation.

This project models a classic example of natural selection - the peppered moths of Manchester, England. The peppered moths use their coloration as camouflage from the birds that would eat them. (Note that in this model, the birds act invisibly.) Historically, light-colored moths predominated because they blended in well against the white bark of the trees they rested on. However, due to the intense pollution caused by the Industrial Revolution, Manchester's trees became discolored with soot, and the light-colored moths began to stick out, while the dark-colored moths blended in. Consequently, the darker moths began to predominate.
Now, in the past few decades, pollution controls have helped clean up the environment, and the trees are returning to their original color. Hence, the lighter moths are once again thriving at expense of their darker cousins. This model simulates these environmental changes, and how a population of moths, initially of all different colors, changes under the pressures of natural selection.

Procedure:
Part 1:
1. Setup the model, leave the presets, but switch 'cycle pollution' to on. Run the model for ~350 ticks and watch the output.
   a. At ~350 ticks, stop the model, right click the output window and copy the image. Paste it into a new word document, **label it with the model settings you used**, and answer these questions below it.

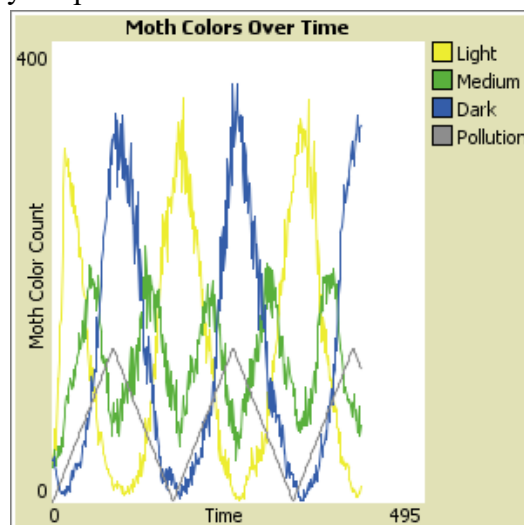Here is an example of what your plot could look like in the document:

Figure 1. Ticks: 411, Speed: **10, Num-moths: 100, Selection: 50, Mutation: 15, Cycle-pollution: on**

Questions:
1. What happens to the proportions of the moths of each type over time? How does it relate to the pollution level?
2. Why would the moth population respond to the pollution levels this way?

Part 2:
The SELECTION slider determines how moths are harvested by the birds that feed on them. SELECTION wraps up nicely many factors that determine the survivability of a species - how many birds there are, how hungry they are, and just how important camouflage is to escaping predation. SELECTION provides a probabilistic window - the lower the level of the slider, the wider this window. At 0, a moth's color ceases to matter. At 100, a moth needs to be perfectly camouflaged to avoid being seen (and thus devoured).

1. Keep Cycle Pollution set to 'on', run the model a few more times, varying the selection level.
   a. Paste a copy of a graph at SELECTION set to 0 and a graph at SELECTION set to 100.

Questions:
1. Explain the differences you see between the two graphs. What does this difference indicate?
2. How does differential survival and reproduction rates of individual moths affect the species?

Part 3:
The MUTATION slider controls the rate of mutation at birth. For the purposes of the simulation, the mutation rate is much higher than it might be in real life. When MUTATION is set to 0, moths are exactly the same as the parent that hatched them. When it is set to 100, there is no correlation between a parent's color and the color of its children. (Best results are seen when MUTATION is set to around 10 or 15, but experiment with the rate and watch what happens.)

1. Bring selection back to 50, but now vary mutation rates.
   a. Paste a copy of the output at MUTATION = 0 and MUTATION = 100

Questions:
1. Changing the mutation rate to 100, in essence makes variation not heritible because parents do not transmit their color to their children. What happened in your model when mutation was at 100? What does this indicate about the importance of mutation in natural selection?
2. What happens when mutation rate is set to 0? What is the importance of variation in a population?

Part 4:

Part 4:

Under normal circumstances, the average population will tend to stay constant, at a level dependent on the speed and selection rates. Watch what happens when a drastic change in the environment occurs. (You can force this with the POLLUTE-WORLD and CLEAN-UP-WORLD buttons.) Can you kill off all of the moths in a matter of a few time-steps?

Paste a graph of the run where all the moths were killed off in the fewest number of ticks.

Questions:
1. Why can you kill the moths off in a few time steps? What does this indicate could happen in an environment to cause a species to go extinct?
2. How could the model be modified so that the proportions of each moth color type would not change through time?

Red Queen

To find this model, open NetLogo, click 'File' then 'Open Models Library' this model is under 'Curricular Models', in the 'BEAGLE Evolution' folder and is called 'Red Queen'. When the model opens, click on the 'Info' tab and read through the documentation.

This model demonstrates the ideas of competitive coevolution. In the model there are two species: frogs and snakes. The snakes are the only predators of the frogs, but the frogs produce a fast acting poison that kills the snakes before they can be eaten. However, the snakes have developed an anti-venom to counter the frog's poison. In this model, we assume that there are no other predators of the frogs, or prey that are consumed by the snakes. As such the two species enter a biological arms race in order to keep up with each other. The name Red Queen comes from Lewis Carroll's "Through the Looking Glass", where the Red Queen says, "…it takes all the running you can do, to keep in the same place." In this model under the right conditions, the two species evolve as fast as they can, but neither is able to gain an advantage over the other.

Procedure:

Like in the Peppered Moths model, change the values using the sliders and observe the results. Answer the questions and include the relevant output graphs in your discussion.

Questions (Include Relevant Output Graphs):
1. With the initial settings of the model, both of the species will usually persist for a long period of time. Both of the species persist, but their population levels change over time, what is the relationship between the populations of the frogs and snakes? What happens to the levels of the poison and resistance during this time?
2. Modify the INITIAL-RESISTANCE-MEAN and INITIAL-POISON-MEAN, do both species continue to persist? What happens to the resistance and poison values?
3. Set the INITIAL-RESISTANCE-MEAN and INITIAL-POISON-MEAN to the same value, but change the INITIAL-NUMBER-FROGS and INITIAL-NUMBER-SNAKES, what happens to the population levels over time? What happens to the poison and resistance values?
4. Evolution is not need or goal-directed, yet we observe that many of the traits that assist a species persist. Why?

GenEvo 3 - Genetic Drift and Natural Selection

To find this model, open NetLogo, click 'File' then 'Open Models Library' this model is under 'Curricular Models', in the 'GenEvo' folder and is called 'GenEvo 3 - Genetic Drift and Natural Selection'. When the model opens, click on the 'Info' tab and read through the documentation.

This model allows for the exploration and comparison of two different mechanisms of evolution: natural selection and genetic drift. It models evolution in a population of asexually reproducing bacteria, E. coli. It starts with different types of E. coli, each with a different types (trait values) represented by different colors. When 'natural selection' is off, the model shows that competing types of E. coli, each reproducing with equal likelihood on each turn, will ultimately converge on one type without any selection pressure forcing this convergence. This is called genetic drift, an idea explained in more detail in Dennett's *Darwin's Dangerous Idea* that explains that genetic drifts can occur without any particular purpose or 'selecting pressure'. When 'natural selection' is on, one of the type of E. coli cells has a selective advantage. It gains more energy from sugar in a given time unit. This results in faster reproduction by that type of cells. An important thing to note is this model includes one mechanism of natural selection called *r-selection*.

Procedure:

Like in the Peppered Moths model, change the values using the sliders and observe the results. Answer the questions and include the relevant output graphs in your discussion.

Questions:
1. Run the model with natural selection set to off. What happens? Why?
2. Notice that the E. coli cells with selective advantage often wins the race when the % selective advantage is high. When the % selective advantage is low, statistical advantage in favor of any of the other colors might result in different outcomes. Is there a tipping point above which % selective advantage always makes the color win?
3. In each simulation, the time required for a single type to become dominant varies. Does an increase or decrease in the carrying capacity have an effect on how fast a color wins? Now check this same phenomenon in the presence and absence of natural selection.
4. Does color have any adaptive advantage when the natural selection is set to off? Does the persistence of a trait always mean it is providing an advantage?

Save your word document with your plots and answers as LastName_ModelingLab and submit it to your instructor.

Agent-Based Modeling Pre-Test

For the following questions, please respond to the best of your knowledge and using only the information in the question and what you know. Please do not refer to any outside sources (textbooks, notes, internet, etc.). Any reasonable attempt to answer the question will be awarded full credit.

1. A species of cactus lacks spines. How would biologists explain how a species of cactus without spines evolved from an ancestral cactus species with spines?

2. A species of cheetah has the ability to run fast. How would biologists explain how a species of cheetah with the ability to run fast evolved from an ancestral cheetah species without the ability to run fast?

Agent-Based Modeling Post-Test

For the following questions, please respond to the best of your knowledge and using only the information in the question and what you know. Please do not refer to any outside sources (textbooks, notes, internet, etc.). Any reasonable attempt to answer the question will be awarded full credit.

1. A species of elm lacks winged-seeds. How would biologists explain how a species of elm without winged-seeds evolved from an ancestral elm species with winged-seeds?

2. A species of mouse has claws. How would biologists explain how a species of mouse with claws evolved from an ancestral mouse species without claws?

3. A species of suricata has pollex. How would biologists explain how a species of suricata with pollex evolved from an ancestral suricata species without pollex?

Modeling Lab Teaching Guide

1. Have students take the pretest, give them about 15 minutes. Collect the papers. Stress that any answer will be awarded credit.

2. Walk students through the powerpoint

   a. The powerpoint includes NetLogo installation instructions

3. Have students perform the lab.

   a. Students will have files with their plots and questions as their final product.

4. Administer the post-test, give them 15 minutes, collect paper at the end.

Please send all final student files to agarrets@gmu.edu, put their pre and post tests into the folder behind the board, and I will pick them up later.