A simple example of a socio-environmental system: coupled rabbit and farm dynamics

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Summary

Quantitative models are excellent tools for understanding the dynamics of complex socio-environmental systems (SES), and for explicating those dynamics in a meaningful way to students. Here we utilize both a dynamical and an agent-based model to examine a suite of human-environment interactions in a hypothetical SES. Specifically, the hypothetical SES involves the management of rabbit populations while maximizing nearby farm productivity and profitability. The purpose of this exercise is to demonstrate how manipulating different components of these two alternative models can help students visualize and analyze key features of the SES, such as feedbacks and adaptation. The models also allow students to assess how different decisions, like implementing certain policies, influence tradeoffs and synergies in the SES.

Introduction

Rabbits are well known for being a friendly species, charismatic and nice with children. But rabbits can also be an important problem for farmers. These animals can be very destructive to gardens and farms. A partial list of crops that rabbits damage are:
  o Vegetables: beans, beet, broccoli, carrot, lettuce, and peas
  o Trees: almonds, apple, blackberry, cherry, citrus
  o Herbs: cilantro and parsley

Rabbits can also damage irrigation systems by gnawing and cutting pipes, especially in small tubes. In addition rabbits can be a source of diseases, including some that are harmful to human and to livestock.

Learning Goals:
  o Ability to describe a socio-environmental system, including the environmental and social components and their interactions
  o Ability to identify disciplines and approaches relevant to the problem.
  o Ability to consider the importance of scale and context in addressing socio-environmental problems.
      • Understand that ecological and social processes often vary across differing contexts, including space, time, and conditions (e.g. economic or political).
      • Understand that ecological and social processes interact across different scales.

Scenario:

In a community near your place of work, a few individuals of a rabbit population have been observed grazing near the farms. Farmers living in this community are increasingly concerned about the potential damage a rabbit population would do to their properties. They fear that if the rabbit population starts to grow, it will negatively impact their crops, income, and eventually their savings.

In the light of this situation, a group of farmers decides to contact government officials to demand actions. As a result, the government agency agrees to send an expert in socio-environmental systems to analyze the situation and the potential scenarios the farmers will encounter in the future. For that they ask you to develop models that adequately take into account the biological aspects of the rabbit population coupled with the productive and economic system of the farmers. Your goal in using these models is to gain a quantitative understanding of the potential consequences that the rabbit population may have on the farmers' financial situation under different scenarios of control management and ecological dynamics. The results from the models will guide farmers in deciding which methods of rabbit control to use by helping them to understand the long term financial results.

The Conceptual Model
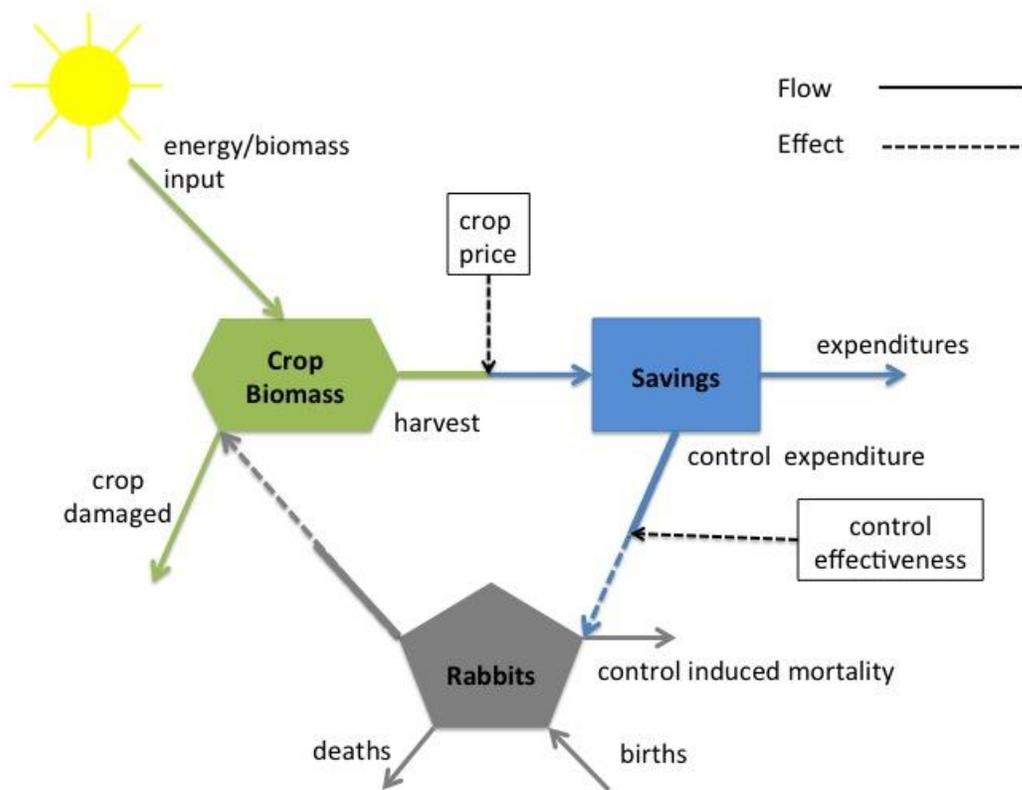
The Mathematical Model

A system of ordinary differential equations (ODE) can describe the changes over time of the main crop produced by the farmers and the financial situation of the farmers over a period of time relevant for management.

Crop biomass accumulation:
First let's define the dynamics of the crop production, by the differential equation dC/dt (the relative change in crop biomass per unit of time).

$$\frac{dC}{dt} = B_t - hC_t \quad eq. 1$$

B_t is the biomass accumulated per unit of time t [Kg of biomass / month], and h is the harvesting rate [Kg of biomass harvested / (Kg of accumulated biomass*months)].

Financial system of farmers:
The group of farmers generates income I by harvesting the crop, C, and sell it a price p. A portion of this income, s, is accumulated in a savings account S and then expended (e.g., on farm equipment) at rate e. The savings account dynamics (dS/dt the relative change of saving over time) is then defined as

$$\frac{dS}{dt} = phC_t - eS_t \quad eq. 2$$

with

$$I = phC_t.$$

In words, the input of the saving account is the income I (phC_t) and the output from the saving are the expenditures (eS_t)

Rabbit population dynamics:
Previous research have shown that the dynamics of the rabbit population, once introduced in a new habitat, can be described by a simple exponential growth model, such that

$$\frac{dR}{dt} = rR_t \quad eq. 3,$$

with

$$r = b - d$$

where r is the intrinsic growth rate of the population (birth minus death). You decide to adopt this model as a starting point, but later you will try other growth models as well.

Effect of rabbits on crop growth:
After several weeks of interviews, data collection, and literature review you conclude that each rabbit generates a per-capita loss of crop biomass per unit of time. You decide to include this effect into the model. Thus, you define d as the degradation rate that each rabbit

individual has on crop production per unit of time. The units of parameter d are [crop biomass lost / rabbit*time]. You modify eq. 1 to incorporate the per-capital effect of rabbits such that

$$\frac{dC}{dt} = B_t - hC_t - dR_t \quad eq.\,1b$$

Thus, the relative change in crop biomass (dC/dt) now depends not only on the input of biomass per unit of time (B_t) and the total crop biomass harvested (hC_t), but also on the loss of biomass due to the presence of the rabbits (dR_t).

Implementing the Mathematical Model in the Computer

Make sure to have already installed the programs R and RStudio to your computer, as well as the two packages in RStudio called "manipulate" and "deSolve". Once that is completed, open RStudio, find the "file" tab at the top of your screen. Go to "open file", navigate to the folder where the file "Agro_Saving_Rabbits.R" is located, then double-click that file to open it. To run the model, click on the button "source" at the top-right of the code panel located in the top-left of your screen. After running the model you should the model results plotted over time for the three state variables at the far right of the screen. Click on the small cog wheel icon located at the top-left of the plot panel (far right panel). Now you should see a new panel come up in the middle of the screen that shows the different parameters that you can manipulate manually.

Model 1: Constant investment in rabbit control.

To start out, find the slider that controls parameter r (the intrinsic growth rate of the rabbit population) and systematically change the value of r through the entire range of values.

1. What changes are observed in the rabbit population?
2. Can you describe the growth pattern?
3. What is the effect of r on farmers' savings? Why don't you see any change?

Press the source button again to set the parameters to their default values. Systematically change the value of the d parameter (the one at the top of the manipulator panel) and observe the changes that occur to the plots.

4. How do changes in d influence the farmers?
5. At what value of d does crop biomass become "0"?

Now, explore different combinations of parameters d and r.

6. What can you say about the influence of rabbit population growth on farmer savings in the long term?
7. How important (sensitive) is parameter r compared to d in determining the outcome of the farms (Crops biomass and savings)? Specifically, how fast do farms collapse

($C = 0$)? Describe in real-world terms why farms are more sensitive to one parameter than the other.

8. What happens if you change both the price and expenditure parameters? How do changing these parameters change the outcome of the state variables?

Control Interventions:
Now let's consider different alternatives on how the farmers may attempt to control the rabbits. Each of these alternatives will have different characteristics in terms of efficiency and costs.

Let's investigate an action management in which farmer's invest a proportion (q) of their savings to control rabbits. Let's define the effectiveness of the method by v representing the number of rabbits killed per dollar spent on control. Equations 2 and 3 become

$$\frac{dS}{dt} = phC_t - eS_t - qS_t \; eq.2$$

$$\frac{dR}{dt} = rR_t - vqS_t \quad eq.3$$

Savings are now depleted by how much money the farmers decide to designate to control the rabbits (qS_t) and rabbits are killed by the control action on top of their natural mortality. How many rabbits are killed by the control action depends on how much money you spend on control (qS_t) and how effective the control method is (v).

Let's come back to R software, push source again and set parameter d to the maximal value. Now start systematically changing the control expenditure parameter, q.

9. What happen to the rabbit population?
10. Why do changes in the control expenditure (q), have no effect on the rabbit population? (hint: check the value of the other parameters)

Now go ahead and systematically manipulate v.

11. How do external factors (e.g., prices and expenditures) influence the socio-environmental system? Compare you answer to the one in question 8.

Time to deliver:
After you collected all the available data, had time to develop the models, and reviewed the results, farmers are eager to know about your findings and recommendations. The government agency designated to help the farmers is asking you to recommend, approximately, how much of their savings should be spent (if any) to maximize savings over a period of 10 years (120 months). But the farmers want to know how to maintain their productive system over a period of 30 years (360 months).

12. Would you make the same recommendations to the farmers as you would for the government?

Model 2: The effect of space and resource limitation

Before we assumed that rabbit population growth was a constant parameter. However, new information suggests that over long time scales rabbit population growth is limited by resource availability across the landscape. In this case the resource limitation is how much grass is available for them to eat. Grasses grow in patches distributed across the landscape between farms. Because grass is important to rabbit population growth, and rabbits affect farm crops, we need to consider this factor into our analysis. We will use an agent-based modeling approach to consider the spatial distribution of grass. The program, which runs the model, is called NetLogo.

Instructions for opening up and initializing NetLogo:
Double click "SESYNC_RabbitsCrop_ABM.nlogo" to open the NetLogo file. To begin we will click "setup". You notice the large box in the middle of the program in mostly green with small "rabbit ears" and "household" icons. The box provides a nice way to visualize how our model "entities", including rabbits and farms, are spatially distributed across a landscape (i.e., the green background area). Click "setup" to initialize the model. Here the rabbits and farms are distributed randomly across the landscape, but with data collected in the field, you could distribute the rabbits and farms in a more realistic manner. For example, maybe rabbit density is twice as high in the north as in the south part of the landscape. When the model is run you will see the rabbits rapidly moving around the landscape. You should try slowing the model down some to see how the rabbits move (move the speed slider at the top from "normal" to "slower". The rabbits and farms are programmed with certain behaviors that dictate how they move and interact with each other and their local environment. So, as we move through this exercise we are essentially testing out how different behaviors or farms and rabbits influences the system over time.

Make sure the switches "grass?", "crop-land-on?", "food-search?", "rabbit-adapt?", and "farm-adapt?" are all OFF. Also, make sure all the parameters are set to the following: grass-regrowth-time = 25, rabbit-gain-from-grass = 5, rabbit-reproduce = 5%, rabbit-gain-from-crops = 0, control-measures = 0.0. We will discuss these parameters in more detail soon. This model will run for 360 months as in the previous models. Focusing your attention on the three state variables on the right, press "go" with the two curved arrows. Notice that the three state variables follow the same patterns as those from "Model 1" above. That is, the rabbit population grows exponentially causing the farms to collapse (crops and savings = 0). Even though we can see rabbits running around, the model is still based on the previous equations where rabbits and farms affect each other equally with no individual variation in behavior or environmental change.

To evaluate how resource limitation affects the system, switch on "grass?". Make sure the other switches are OFF and the parameters are set as in the paragraph above. "Setup" the model. Notice that we have green and brown patches now. The green patches are areas

with grass and brown patches are bare (i.e. no food for rabbits). Rabbits acquire energy from grass patches as they walk over them. Rabbits die when they run out of energy. In other words, we no longer are using the *r* parameter from earlier to define the growth rate of the rabbit population. Instead rabbit population growth is constrained by resource limitations. "Grass-regrowth-time" indicates how fast grass grows back in a patch after it has been eaten, "rabbits-gain-from-grass" indicates how much energy rabbits gain from patches of grass, and "rabbit-reproduce" indicates the reproductive rate of rabbits. Press "go" with the two circle arrows again to run the model for the full 30 years. You can also press the plain "go" button to run the model just one time step. That way you can see what happens to patches as rabbits move over them one step at a time.

13. What is the effect of considering resource limitation on rabbit population growth? and on crops and savings?
14. Does resource limitation on rabbit population growth bode well for farmers?

Change the value of the "grass-regrowth-time" from 25 to 50 and rabbit growth rate from 5 to 10%. Make sure the other parameters are set as before. Click "Setup" and then "Go" (with double arrows).

15. How does increasing these two parameters influence crop dynamics and what are the implications for the savings over time?
16. Are these new patterns favorable or negative to farmers?
17. Given the dynamics in the rabbit population, why do you think it is important to collect field data on the rabbit population for as long a period of time as possible?

Now let's look at another spatial feature. In the previous models farms where defined as a conglomerate where the damage of rabbits was distributed equally to all farms. However, in reality, farms are unevenly distributed in space and therefore the effect of rabbit damage on farms will vary in space as well. In addition, rabbits behave such that they can search for the most profitable food source in terms of energy gain. In other words, rabbits don't move randomly in space (as they were in the previous exercise), they direct their movements to food. This means that if the crops are highly palatable and energy rich for rabbits then it is likely they will be attracted to the farms and cause extensive damage. The consequences of these spatial features should be included into our analysis.

To analyze this situation turn on the switches "crop-land-on?" and "food-search?" (make sure the "grass?" switch is also on). Make sure all the parameters are set to the following: grass-regrowth-time = 25, rabbit-gain-from-grass = 5, rabbit-reproduce = 5%, rabbit-gain-from-crops = 0, control-measures = 0. Then setup the model. The yellow area now represents the actual area of each farm (with the barns randomly located on the farm land). A rabbit only damages a farm's crops when it passes over the land. When that happens, the crop yellow will change to a lighter yellow to indicate that it has been damaged. With the "food-search?" switched on rabbits move toward areas with more food energy, which can include crops. The amount of energy gain from crops can be manipulated by the slider "rabbit-gain-from-crops". Let's assume that crops with low "rabbit-gain-from-crops" energy are also less profitable crops for farmers, while crops with high energy (i.e., 10

energy units) are most profitable for farmers. There is an incentive to plant the most profitable crops. Systematically manipulate the "rabbit-gain-from-crops" slider through the full range of values to see how it influences the SES. Tip: make a simple chart in which you can record model results at different parameter values.

18. What happens to crops and savings after 30 years as you increase the "rabbit-gain-from-crop" value?
19. Does it make sense then for farmers to plant the most profitable crop? Why?
20. How might mowing down the grasslands surrounding the farms (i.e., no grass for rabbits) impact farmers' crops and savings?

The farmers like to plant their most profitable crops if possible. They tell you that if the rabbits became a big problem they would just invest in more effective control measures (e.g., poison) of rabbits rather than planting different crops. With this in mind, you build the model to include "control-measures". The control-measures determines how many of the rabbits on a farm are killed by the farmer per time step. The control-measures is proportional to how much of a farmer's savings he/she spends on rabbit control. In other words, it costs the farmer more to implement more effective control measures. Thus, the control-measures is essentially a combination of parameters v and q in Model 1 above.

Let's try it out. First, make sure the switches 'grass?", "crop-land-on?", and "food-search?" are all ON. Make sure the parameters are set to the following: grass-regrowth-time = 25, rabbit-gain-from-grass = 5, and rabbit-reproduce = 5%. Setup the model. Try systematically changing both the "rabbit-gain-from-food" and "control-measures" sliders to different values and running the model for 30 years for each combination of the two parameters. Remember that this model has an element of randomness, so you may want to run the model multiple times at each combination of parameters to determine the overall effect.

21. Is it possible for the farmers to plant their most profitable (but also most delicious for rabbits) crops and still have savings after 30 years? How is it possible?

Model 3: Evolution and adaptation: the role of heterogeneity

The previous model exercise showed you that farmers can plant cash crops that attract rabbits as long as they spend approximately 30 – 50% of all their savings on control measures. However, after reviewing more literature and talking to rabbit biologists, you learn that rabbits often adapt to the controls by becoming more tolerant (i.e., not dying) to them. At first you are worried that there is no way to incorporate adaptation into the model. But you remember that an agent-based model simulates the behaviors of individual rabbits (rather than the population as a whole), and because natural selection acts on individuals, you realize you can build the model to include rabbit adaptation to control measures over time.

To start, make sure the switches "grass?", "crop-land-on?" and "food-search?" are all on. In addition, make sure all the parameters are set to the following: grass-regrowth-time =

25, rabbit-gain-from-grass = 5, rabbit-reproduce = 5%, rabbit-gain-from-crops = 10, and control-measures = 0.5. Now switch on "rabbit-adapt?", then setup and run the model for 30 years. To help visualize how rabbit "tolerance" to control measures changes while the model is running, pay attention to the "Histogram Tolerance" and "Average Rabbit Tolerance" boxes at the right of the screen. The histogram shows how many rabbits have a certain level of tolerance to controls for each month. The average value is the mean tolerance of all rabbits for each month.

22. In general what happens to the tolerance values over the course of the 30 years?
23. What happens to farm crops and savings after 30 years?
24. What are the implications for how control programs are implemented?
25. Should farms use the same control measures across space and over time?

After talking to other farms where rabbits are a big problem, you learn that farmers don't all use the same control measures at the same time. They tell you that they watch their neighbor farmers, and if their neighbors make more income than them, they use the same control measures as them the next time around. The assumption is that farms with more income/savings than me are doing something right, so I should copy them!

You realize that this means the farms will probably try and adapt to rabbits as well! Farms with no rabbit damage will likely have more savings if they don't spend it on control measures. Alternatively, farms with lots of rabbit damage need to spend more money on control or the rabbits will eat all their crops (thus savings = 0).

Let's look at what happens when we include farm adaptation to rabbits. First, make sure the switches "grass?", "crop-land-on?", "food-search?", and "rabbit-adapt?" are all on. In addition, make sure all the parameters are set to the following: grass-regrowth-time = 25, rabbit-gain-from-grass = 5, rabbit-reproduce = 5%, rabbit-gain-from-crops = 10, control-measures = 0.5. Now switch on "farm-adapt?", then setup and run the model. To help visualize how farms adapt their control measures while the model is running, pay attention to the "Histogram control" and "Average Farm Control Effect." boxes at the right of the screen.

26. In general what happens to the "control measures" values of farms over the course of the 30 years?
27. How do adaptive strategies of farms affect the rabbit population over time compared to the models without the adaptive strategies?
28. Step out of the model. Can you think of other realistic ways that farms may adapt to rabbits rather than just copying their neighbor's strategy?