System Dynamics Modeling of Community Sustainability in NetLogo

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Abstract

The goal of this project is to apply system dynamics modeling to a basic instance of the contemporary issue of sustainability. System dynamics modeling is especially well-suited to the topic of sustainability; the flows and stocks involved with this sort of modeling are the keys needed to express the relationships between quantities and to observe their interactions. My project would model an arbitrary system, which would be a basic model representative of more realistic systems. The results of the model will be displayed to the user graphically. The goal of this project is to create a system that functions harmoniously over a sustained period of time rather than one that spirals wildly out of control. Sustainability is of course a large, well-researched field and more complex research has certainly been conducted prior to this. However, I think that my project would nonetheless increase student understanding of the issue and system interactions, and that system dynamics provides a particularly insightful prospective for this topic.

Keywords: Multiagent, dynamic simulation, group navigation, herds, swarms

1 Introduction

The numbers on which the system is based, instead of being simply arbitrary, are based loosely on data for Kenya from the CIA World Factbook (https://www.cia.gov/library/publications/the-world-factbook/geos/ke.html). The basis for the system is the relationship between food and population. For example, if there is insufficient food, people starve, which means that there are fewer workers to grow the food, etc. System dynamics are essential for predicting the long-term results of these continual interactions. The key facets of the model are regular spoiling, consuming, and growing of food and births and deaths amongst the population. There are various levels of complexity in these facets: the birth rate is constant; the food is only grown by a fraction of the population selected to represent a normal percentage of people able to work; and the death rate is variable, based on food available (i.e. if people cannot eat, they starve). Also, my project will involve regular periodic perturbations in the form of famines, the intensity of which may be defined by the user. For example, population density is used to create a ceiling above which the population cannot sustainably exist, and AIDS is used to add the complexity of an epidemic, the ultimate result of which is extinction. Drastic weather events, too, lead to extinction, because they eliminate a random percentage of food and population at random intervals. Over the long time scales used for this model, this randomness means that eventually weather events will result in the demise of the population, especially when coupled with other difficulties. The philosophy behind weather events is that their random aspect will, by providing different outcomes, provide critical insight into the model and how the population seeks to rebound from disaster. It is important to bear in mind that the goal of the project is not to create a sustainable system but a model that strives for sustainability and, even in its failures, offers insights into the nature of a sustainable environment. The model is designed as a study of sustainability rather than a simulation thereof.

2 Background

The field of system dynamics was established by Jay Forrester in the 1950s, and it has been a useful modeling tool ever since. The keys to system dynamics are stocks, flows, and the ways in which they interact, all of which can be shown in the model diagram. In order to prepare myself for the implementation of system dynamics modeling in NetLogo, I read the System Dynamics Guide and other sections from the NetLogo 4.0.3 User Manual, consulted the NetLogo dictionary, and read through a guide to Individual (Agent) ? Based Modeling with NetLogo: A Predator-Prey Example which, though it does not relate to system dynamics per se was still useful in increasing my familiarity with and knowledge of NetLogo. I read "System Dynamics Modelling in Supply Chain Management," "?Evaluating Strategies to Improve Railroad Performance– A System Dynamics Approach,? and "System Dynamics and Agent-Based Simulations for Workforce Climate" from the ACM Digital Library. I have also consulted an article called The Tragedy of the Sahel, which uses system dynamics to show the instability of the Sahel desert system. I used this for a paradigm of a basic ecosystem to model, and it eventually inspired me to choose system sustainability as a topic. For reference and factual information, some of which I included in the parameters of my model, I consulted the CIA World Factbook's page on Kenya.

3 Development

3.1 Requirements

I expect a reasonably sustainable simulation of the system over a considerable length of time; it may prove impossible to create unconditionally infinite sustainability in NetLogo, given various mathematical inaccuracies. The sustainabilty is dependent on the parameters, some of which are intended to be user defined; thus there are a variety of potential outcomes, but it is the ability of the program to simulate a reasonable degree of sustainability which will be regarded as a success. It should be noted that, with AIDS coded into the model, the intent of this epidemic is to cause a forcing of such magnitude that the population becomes extinct. Clearly, this is not sustainable; the purpose of AIDS is to allow for the study of the system and its efforts to sustain itself as the population nevertheless plummets. Thus, AIDS is an intentional exception to the rule that the general sustainability of a feature is indicative of its relative success. Like AIDS, weather events are an intentional exception, as the randomness these intermittent catastrophes provide is key to the ultimate goal of the model: understanding. This model must operate within the range of system dynamics insofar as is possible, and any non-system dynamics code segments must serve the purpose of the model without corrupting its nature.The relationships between components may not be defined outside of the system dynamics portion of the model, i.e. all interaction must be accomplished with system dynamics tools. The main specification is that as little code as possible is situated in the Procedures tab of the main NetLogo interface and as much as possible in the system dynamics interface, which compiles code directly from the model diagram. This applies in particular to the famine functionality, the algorithm for which requires calculations that the system dynamics interface cannot facilitate.

3.2 Overview

Various data were obtained from the CIA World Factbook entry for Kenya, which were then used to create a basic model of a population with a set birth rate and a set death rate based on these values. From there, other factors were added, and as functionality increased, so did complexity.

3.3 Limitations

The system dynamics interface inherently limits certain aspects of the model; e.g. there is only a limited capacity for if-else loops. This interface has been bypassed in creating the famine aspect of this program, but in most cases, as stated above, to bypass the system dynamics component would be to compromise the nature of the program. As discussed above, the AIDS and weather events features limit the sustainability of the model, though in doing so they do not violate the spirit of this project. Another limitation is the inability of the system to deal with very large numbers; the project must be run with starting values of 1,000 for food and population rather than, say, 100,000.

3.4 Iterative Evaluation Plan

The program performance must be tested after each new major addition to ensure that the system continues to function in a reasonable manner. The model was run and informally evaluated for its reasonability. Depending on these results, corrective measures may have been taken to prevent the populations from overshooting or dying off too quickly.

3.5 Research Theory and Design Criteria

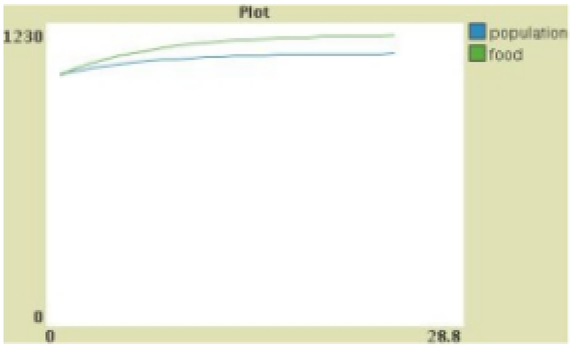
This project rests on system dynamics theory, in which all mathematical relationships are implicit in the model design. The processes involved in the creation of the model involved adding components and altering the relationships between existing components, after which the model was run and the results observed. The graph displayed was informally analyzed for mathematical relationships. Eventually, when the user-controlled functionality for periodic famines was added, the code was tested repeatedly with various levels and intervals of famine in order to ascertain that the algorithm behind the periodicity was functioning correctly and that the model was oscillating as expected. In order that the project be sustainable, population density was included and it was found that his created a smooth maximum the population could not exceed.

3.6 Testing and Analysis

The program performance must be tested after each new major addition to ensure that the system continues to function in a reasonable manner, as described above. It is critical to recall that the goal is not unconditional sustainability; the outcome of extinction is, when reasonable, an acceptable result. Methods of testing include checking program data against real data from the CIA World Factbook, examining data for unanticipated aberrations, and checking the data trend against trends from similar models. For example, upon adding the famine functionality, I checked the trend against data from generic models with periodic perturbations and found that these generic trends supported the famine trend; therefore it was reasonable. As previously stated, I can perform specific structural and functional testing to examine the effects of new additions; sometimes, this may require other components to be disabled for simplification's sake. A large part of this functional testing would be dynamic testing, in which many different combinations of widely varying values for different parameters would be used to test functionality. Process modeling would be useless for trend comparison, but the use of mathematical relationships would probably not extend beyond graph comparisons. At first, I found that there were two outcomes for the model as it currently exists: extinction or overshoot. The reason for there not being a middle path of sustainability may have something to do with mathematical inaccuracies in NetLogo over extremely long timescales; the program occasionally behaves strangely with large values. However, all this is now moot, since population density provides a ceiling; the two outcomes are now sustainability or perdition. For the basic parameters population:1000, food:1000, land:15, this population density ceiling occurs around population 1120; however, the ceiling occurs at similar values when the initial population is considerably higher or lower. Thus, since the ceiling is clearly a function of land available and not arbitrarily based on population, it can be regarded as a very successful addition. The focus of all of the testing, barring that concerning AIDS, was to keep the model within reasonable bounds of conduct.

3.7 Visual Representations of Developmental Procedures and Results

Clockwise from top right: final System Dynamics Model Diagram; results with famines, AIDS, and weather events; results with famines and AIDS; results with AIDS; results with famines; basic results. Blue indicates uninfected population, green is food stocks, and orange is infected population.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population
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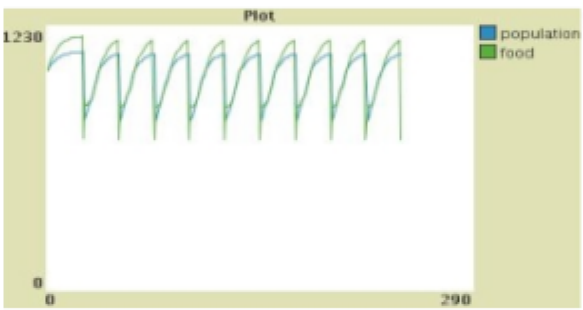
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population
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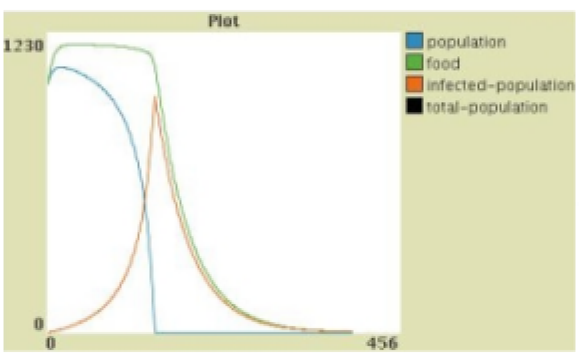
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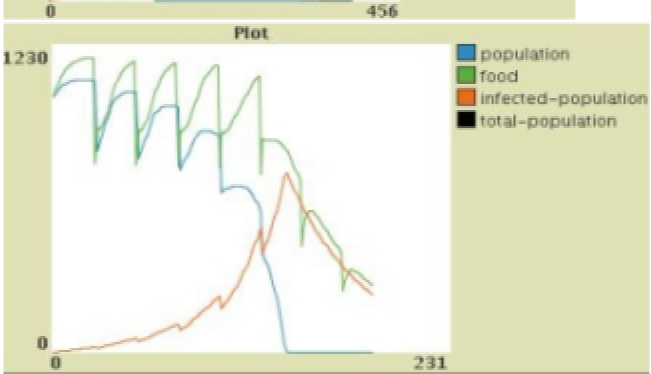
food
infected-population
total-population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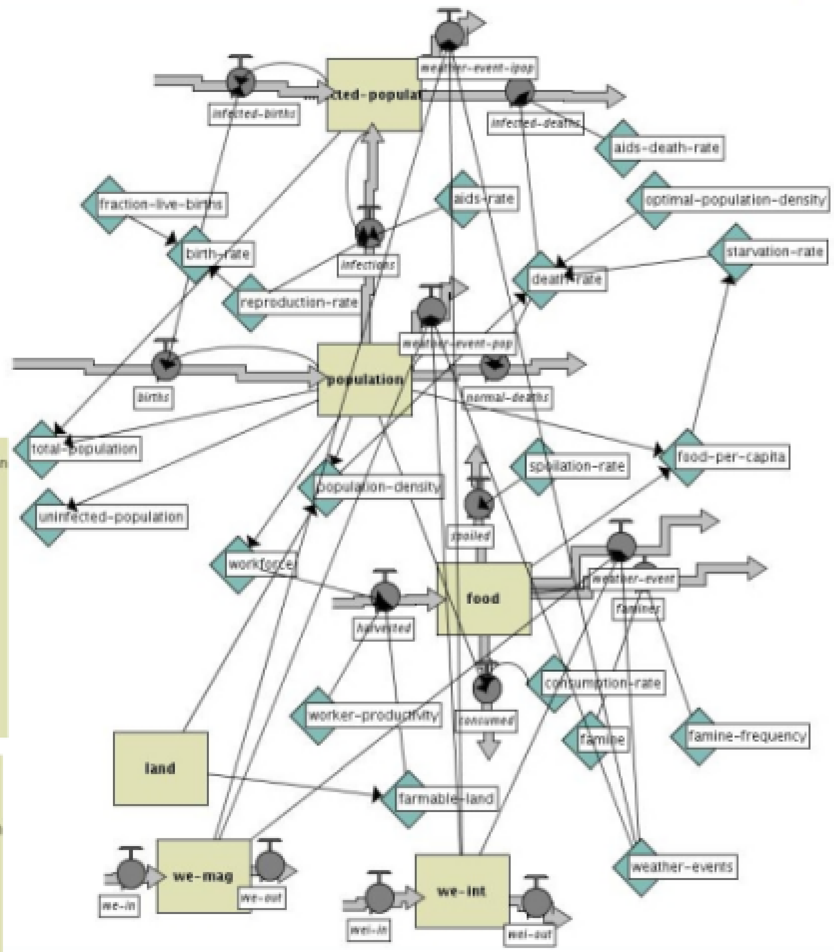
total-population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food
land
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we-int
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fraction-live-births
aids-rate
optimal-population-density
birth-rate
starvation-rate
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reproduction-rate
total-population
food-per-capita
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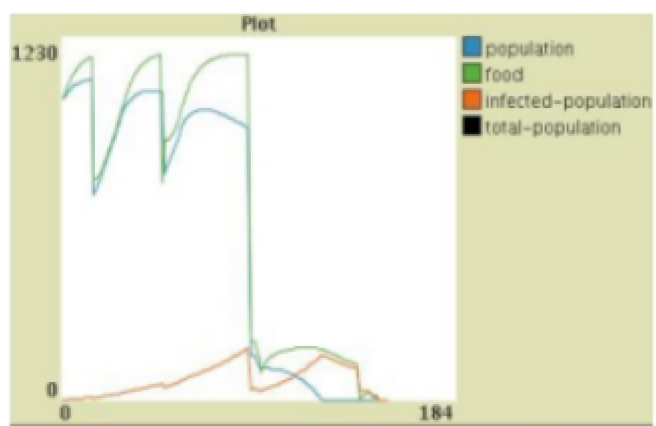
farmable-land
weather-events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population
food
infected-population
total-population

4 Quality Assessment

The specific aspect of this program which requires the most testing and offers the most accurate assessment of the project quality as a whole is the periodic famine functionality. The goal of this is to implement periodic pulses in the form of famines in a meaningful and functional way. Periodic pulses depend not on the stocks and flows of the system dynamics model but represent outside influences based on dt, which the model itself cannot simulate and must therefore be coded in the main NetLogo procedures tab. Both the magnitude and the frequency of the famines are alterable by sliders in the user interface, thus making the model much more interactive but also harder to test. Different scenarios with these variables must be tested in order to ascertain that the pulses do indeed function as intended. The addition of population density, as above mentioned, greatly increased the sustainability of the model and simultaneously made it more realistic, since there must clearly be a limited amount of space on which the population can live and grow food.

5 Results

Without AIDS, sustainability is a very real and achievable outcome; with AIDS, it it is an outcome which could hardly be expected and indeed cannot occur, since this is a very confined population devoid of immunities. It is similar with weather events, since their randomness and destructive potential necessitate the population's eventual and ultimate demise. One must also examine the time period required for such an outcome to become apparent. The model, with the right parameters, can not only be sustainable but can achieve this sustainability within a reasonable time period.

As of now, the model is generally sustainable. It is difficult for famines to destroy the population entirely, and population density prevents overshoot. Only AIDS and weather events, which in the context of this model are inherently unsustainable, cause extinction. After 1000 steps, or years, the model with neither famines nor weather events will reach a sustainable maximum of 1184.78 for population and 1109.35 for food, the starting values being 1000 for each. However, for famines of interval 50 steps and magnitude 50 (out of 100), the values range from 592-1184 for food and 714-1109 for population. Thus, though there is a fluctuation of over 40, the model still maintains its maximum value and is, barring weather events, as sustainable as before.

5.1 Discussion and Conclusion

The population-food model fulfills the intention of the project in that it is well-suited to system dynamics and is an effective study of sustainability. The basic stocks and flows, if not the more complex variables, allow for an easy understanding of the interactions on the most basic level, and the testing methods lend themselves to good analysis of the model's sustainability. The addition of weather events has facilitated true randomness, both in interval and magnitude. By introducing this random factor in the form of intermittent weather events and catastrophes, an important step towards making the model realistic has been taken, providing at the same time for insights into the abilities of the model to bounce back from disaster. The interactive elements of the program, particularly with regard to famines and weather events, allow for user immersion and a better understanding of both system dynamics and sustainability.

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