On the Sustainability of Integrated Model Systems with Industrial, Ecological, and Macroeconomic Components

H. Cabezas [1, 2], C.W. Pawlowski[1, 3], H.W. Whitmore[4], and A.L. Mayer[1]
[1] U.S. Environmental Protection Agency, Office of Research and Development
26 West Martin Luther King Drive, Cincinnati, Ohio 45268, USA
[4] University of Cincinnati, Department of Economics
2600 Clifton Avenue, Cincinnati, Ohio 45221-0376, USA

At its core, sustainability asks whether the planet will persist into the indefinite future in a regime which is amenable to human existence. The issue of sustainability has naturally arisen from the observation that a growing human population is consuming ever increasing amounts of natural resources and causing a host of environmental impacts. The management of environmental impacts that are the result of human activities requires an understanding of various forces on a global scale. To begin this process of understanding, we have constructed a simple model system which is closed to mass and not limited to energy. It includes a resource pool, three plants species, three herbivore species, two carnivore species, a human population, a generalized industrial sector, and an inaccessible resource pool meant to represent polluted or otherwise biologically inaccessible mass. There is also a price-setting macroeconomic model regulating one of the plant species, one of the herbivores, the industrial sector, and the human population. This is essentially a very aggregated and simplified mini-world. We use this model system to explore the sustainability of some observed trends in the real world such as increasing material consumption by the human population. We also explore and contrast several industrial policy options including the use of bio-based production and non-renewable based production. We further consider industrial policy options that could be used to manage environmental impacts.

1. Introduction

Interest in the concept of sustainability has seen extensive growth in response to the realization that the supporting biological systems of planet Earth can not indefinitely sustain current rates of population growth and resource use (Millennium Ecosystem Assessment Synthesis Report, 2005; Mooney et al., 2005). According to the United States Census Bureau (2005) the human population of the earth increased from approximately 2.5 billion in 1950 to about 6.4 billion in 2005, and the growth has not abated. Consumption expenditures in 1995 U.S. dollar increased from $8.3 to $16.5 trillions in industrialized nations, and from $1.9 to $5.2 trillions in developing nations (United Nations Development Program 1998). At present, humans currently

[2] Corresponding author: cabezas.heriberto@epa.gov, fax 513-487-2511

[3] Postdoctoral Research Fellow, Oak Ridge Institute for Science and Education

appropriate approximately 20% of the world primary production and impact a large fraction of land and sea area, leaving a much reduced resource for the rest of the world's species (Inhoff et al., 2004, Haberl et al., 2004). Net primary production is estimated as the net amount of solar energy converted to plant organic matter through photosynthesis. Although sustainable rates of population growth and natural resource consumption are not known with certainty (and most likely fluctuate over time), monitoring the impacts of human activities on ecosystems provides an indirect way to estimate these rates.

Sustainability, at its core, is an effort to create and maintain a regime in which the human population and its necessary material consumption can be supported indefinitely by the biological system of the Earth. Sustainability, in fact, is not a goal but a path through time. We envision sustainability as a corridor through time in a multidimensional space where the coordinates are measurable ecological, industrial, economic and other variables. A sustainability corridor is one where the path of the system stays within certain prescribed limits. This means, for example, that biodiversity and human population sizes are appropriate, the industrial processes perform efficiently with minimal environmental impacts, and the economy functions sufficiently well to provide employment and meet human needs. Because the system is integrated, deviations in any one dimension have an impact on the other dimensions, e.g., inefficient and wasteful production causes pollution which damages ecosystems. Hence, constructing a sustainability corridor requires at least a basic understanding of the relationship between production processes, ecosystems, and economies. Here we begin to explore these relationships with a simulated model system that has a foodweb with an integrated industrial sector and a simple economy. We envision that such models could eventually be used to steer a course through a sustainability corridor similar to the way that central banks use basic economic theory to promote policies that influence national economies.

2. Model System

2.1 Model System Structure

The model system is a simple foodweb open to energy. The system is closed to mass, and in this sense represents a grossly simplified mini-planet. This is useful for the study of sustainability because the system must function with finite material resources. The food web consists of the following compartments representing trophic levels or classes of species: (1) three plant compartments (P1, P2, and P3) representing primary producers, (2) three herbivore compartments (H1, H2, and H3) representing plant eating species in a very aggregated sense, (3) two carnivore compartments (C1 and C2) representing meat eating species also in a very gross and aggregated sense, (4) one compartment (HH) representing human beings, (5) one compartment (IS) collectively representing industrial production, (6) a resource pool (RP) representing in the aggregate all natural resources (air, water, nutrients, etc.), and (7) an inaccessible resource pool (IRP) collectively representing resources that have been made biologically unavailable due to industrial production. IRP is meant to roughly represent the effect of pollution. The model system structure is shown in Figure 1. Solid circles

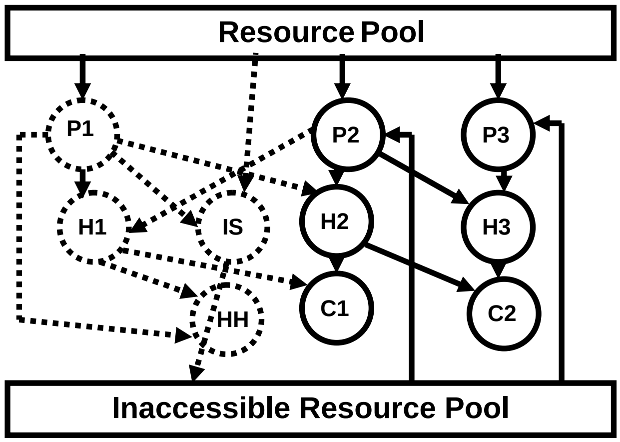

Figure 1. Structure of model system with an integrated ecological foodweb, industrial sector, and economy.

and squares (P2, P3, H2, H3, C1, C2, RP, and IRP) represent compartments which are wild or which have no economic value and are, therefore, not considered to take part in markets. Solid arrows indicate mass flows that are driven by biology. Dotted circles represent compartments (P1, H1, IS, and HH) which are part of the economic system and do take part in markets. Dotted arrows indicate mass flows which depend on human decision making based on either policy or markets. P1 and H1 respectively represent domesticated plants and herbivores. Note only the wild plants P2 and P3 are able to recycle mass out of the inaccessible resource pool and make it available to the rest of the system. Without P2 and P3, human activity would eventually drive all mass into the inaccessible resource pool and the system would cease to function. Lastly, all of the compartments have a resident mass except for the industrial process (IS) compartment which has none. This reflects the fact that biological reproduction requires the presence of a population while industrial production does not require an initial mass of the product.

2.2 Mathematical Model

The ecosystem expressions are based on simple Lotka-Volterra (Cabezas et al., 2005, Fath et al., 2003) type arguments. These are ordinary differential mass balances that are linear in each variable. They represent biological growth through the conversion of mass from one compartment into the mass of another compartment. There are also linear mortality terms moving mass out of the biological compartments and into the resource pool (RP).

The macroeconomic expressions arise from a price-setting model. Firms, which produce P1, H1 and IS, attempt to maximize their profits, and humans their utility. A formal EPA Report is being written containing the details of the macroeconomic model (Whitmore et al., 2005). The production of IS requires a mixture of P1 and RP. The firms set prices for their goods depending on their current stock and projected demands. Consumers purchase given the prices There is no equilibrium at which markets clear. Excess supply increases firms' stock of goods, and deficits are made up with increased production in later time steps.

The model for the industrial process is a steady state abstraction devoid of the details normally found in engineering models for production processes. It is meant to illustrate the appropriate place for engineering models used with ecological and economic models in the study of sustainability. It is the hope of the authors that this will stimulate further research where more appropriately structured process models will be used.

2.3 Simulation Algorithm

Conducting a simulation with the resulting model involves a series of sequential steps. In a given time step the sequence of events is as follows:

1. The industrial sector (IS) sets the wage rate. We assume this sector dominates the labor market.
2. Based on the wage rate, all industries set their prices and their production targets in order to maximize profit based on projected demand of their products.
3. Humans determine their demands for goods (P1, H1, and IS).
4. Industries determine their demands for goods and labor.
5. Checks are done for internal consistencies of flows (to be sure they meet positivity constraints on flows and compartment masses) and to insure that mass is conserved.
6. The next time step is taken (flows are transferred) for both the economic and ecological parts of the model.

3. Simulated Experiments

Our simulations explore, starting from a base case, the implications of a production system (IS) based on: (1) an agricultural resource (P1), and (2) a natural resource (RP). These three scenarios are further considered under high and low human mortality rates, giving a total of six different scenarios. Human mortality was chosen because it empirically appears to be a particularly critical parameter for the system. For the six scenarios, the mass in each compartment and the per capita gross domestic product (PGDP) for the economy are summarized in Table 1, all for the final steady state of the system. Since the system is not meant to represent any real system, nor is it calibrated to mimic the behavior of any real system, the mass and money units are relative and dimensionless.

The six scenarios were created varying the human mortality and the amounts of P1 and RP required for production in the following manner. The human mortality rate was set to 0.1 for low mortality and 0.22 for high mortality, varying by a factor of 2.2. For the base case industrial production, 0.102 mass units of P1 and 0.677 mass units of RP were required to manufacture one unit of the industrial product (IS). Industrial production based on an agricultural resource (P1) was represented by increasing the required amount of P1 to 0.650 mass units and keeping the required quantity of RP at 0.677 mass units. Industrial production based on a natural resource (RP) was simulated by lowering the mass units of P1 required to 0.100 while keeping those of RP at 0.677. As discussed later, these modest variations seem to be a viability limit for this model.

Table 1. Simulated Experiments and Summary Final Results

	P1 Mass	P2 Mass	P3 Mass	H1 Mass	H2 Mass	H3 Mass	C1 Mass	C2 Mass	HH Mass	RP Mass	IRP Mass	PGDP Money
Base Prod.: High HH Mortality	19	0	2.4	4E-3	0	0	2.0	0	10.7	1.7	1.1	3.1E-4
Base Prod.: Low HH Mortality	14.1	0	1.7	0	0	0	0	0	19.2	1.6	8.1	1.4E-4
P1 Prod.: High HH Mortality	19.6	0	2.4	5E-3	0	0	2.0	0	10.7	1.7	1.1	3.1E-4
P1 Prod.: Low HH Mortality	14.3	0	1.7	0	0	0	0	0	19.1	1.6	0.8	1.4E-4
RP Prod.: High HH Mortality	0	0	0	0	0	0	0	0	0	37.5	0	0
RP Prod.: Low HH Mortality	10.8	0	5.1	0	0	0	0	0	14.8	4.5	2.2	2.4E-4

4. Discussion and Summary

While the model used in this study is not calibrated to any specific system, we hope that the results are sufficiently generic to give hints of the possible behavior of real systems. Hence, based on the results for this model, we present the following observations:

1. We were unable to find any model parameter sets that resulted in a simulation without the loss of species (compartment mass zero), while we simultaneously found numerous parameter sets that gave severe loss of species or even non-functioning systems (all biological compartment masses zero). Hence, the region of parameter space consistent with functioning systems is small.
2. Observation 1 is further supported by the six simulated scenarios. Here we see that the modest variations in human mortality and the proportions of P1 and RP required to produce a unit of industrial product (IS), seem to represent the limit for changes in these three parameters while maintaining a viable system. That is, non-functioning systems appear when these parameters are varied beyond the limits studied here.
3. The human mortality rate or at least the size of the human population appears to be singularly critical for this model. For example, for two of the three scenarios

with high mortality rate, the resulting lower human population leads to fewer species lost and improved human welfare as measured by the per capita gross domestic product of the model.

4. For this model, production systems based on a biological resource (P1) and a natural resource (RP) both lead to heavy loss of species. However, both of the biologically based production scenarios were viable, whereas one of the natural resource production scenarios yielded a system having no functioning biological system.
5. In three of the six scenarios, the system had non-zero compartments for P1, P3, HH, RP, and IRP and zeros for all other compartments. This is the absolute minimum number of non-zero compartments necessary to keep the industrial process (IS) operating and the human population fed. The loss of P1 would leave the human population without a food source and the industrial process without feedstock. The loss of P3 would leave the system without the ability to recycle mass out of IRP so all mass would eventually collect in IRP. We hypothesize that this may be the logical consequence of the economic utility functions. These were written to reflect actual economic decision making valuing P1, HI, IS, and HH, but placing no economic value on P2, P3, H2, H3, C1, and C2.

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7. References

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