To Main Proceedings Document

SYSTEM DYNAMICS AS A FOUNDATION FOR A COURSE ON "SUSTAINABLE DEVELOPMENT"

John F. Heinbokel and P. Jeffrey Potash
Waters Center for System Dynamics
Trinity College of VT
208 Colchester Ave.
Burlington, VT 05401

Abstract

"Sustainable Development" is currently a topic of great social relevance and one that requires the integration of a challenging array of themes from a variety of disciplines spanning the physical and natural sciences, economics and other social sciences, and the humanities. In addition, the focus of 'development' points out the inescapable need to consider these themes through their evolution over time. Both the interdisciplinary breadth and the temporal dynamics of this topic argue that system dynamics should be a valuable tool in helping to guide students in its exploration.

Over the past two years we have explored the use of system dynamics as the central tool in building and presenting a course on Sustainable Development to both standard undergraduate classes and a class composed of middle school and high school teachers, high school students, corporate executives, and leaders in non-profit organizations in our community. These experiments have led us to a course design with several distinctive features, including the use of system dynamics as a central organizing focus.

We have come to see the power in using a limited number of case-studies as vehicles allowing us to focus on specific aspects of depletion and sustainability through a critical lens of human innovation and ingenuity. Included in that mix of cases were intellectual explorations of Easter Island, societal affluence as represented by the !Kung and other hunter-gatherer societies, the development of western agriculture and its projection into the future to meet the needs of a growing human population, commercial fishing and the micro- and macro-economic consequences of stock depletion, energy development and utilization and the impact of substitution and enhanced efficiency, and the integration of these themes within specific individual countries including the simulated scenario represented by STRATAGEM.

Within that organizational framework we consistently strived to support our students in identifying, expressing, comparing and contrasting, and strengthening their mental models of the relevant systems; in developing the ability and inclination to continuously test and extend their understanding through the asking of progressively "better questions;" and in reflecting on the possible futures based on a variety of historical experiences. To those ends the various tools of system dynamics (behavior over time graphs, causal loop diagrams, stock/flow concept maps, and computer simulations) were used consistently to aid the students in developing and refining their understanding. We also consciously explored the repeated utilization of simple transferable structures and relationships. The most obvious such repeated structure was the three-strand depiction of resource utilization (strands of human population, the resource, and per capita usage or demand for the resource) which provided a powerful template for the discussions of many of the case-studies.

I. Introduction

A. Sustainable Development as a theme for an interdisciplinary course

One of the ongoing projects at the Waters Center for System Dynamics has been the development of innovative and interdisciplinary undergraduate courses that move students beyond traditional insights enclosed within specific disciplinary boundaries. We have spoken at previous meetings of the System Dynamics Society about a number of these experiments. The one that has engaged us most recently and that we wish to present here is a course focused on "Sustainable Development." The umbrella of "sustainability" can be used to cover a wide variety of distinctive, albeit related, themes. The communities in which we live face challenges to sustaining their quality of life; Forrester's *Urban Dynamics* (1969) was an early exploration of that theme. The organizations in which we work, learn, or recreate face challenges to sustaining their growth and vitality. Forrester again revealed a pathway here with *Industrial Dynamics* (1961). The context of our particular pedagogic foray into sustainability, however, is along the lines of environmental sustainability, that is, how can the human population and its society continue to utilize the earth's resources in a manner that will permit, or ideally foster, the use of those resources continuously into the future? The definition of the Brundtland Commission of the United Nations is germane here:

> *Sustainable Development:* "*... to meet the needs of the present without compromising the ability of future generations to meet their own needs.*"
> The World Commission on Environment and Development (The Brundtland Commission), Our Common Future (Oxford: Oxford University Press, 1987), p. 43.

The theme of Sustainable Development appealed to us for a variety of reasons. It has a current relevance that should attract many of our students; getting the students' initial attention is still one of the necessary prerequisites to supporting their learning in any field. While our focus is explicitly on the environmental aspects of sustainability, the structures explored and the insights gained should be transferable by the students into a wider domain of sustainability issues. The field of study is inherently interdisciplinary; adequate exploration requires insights from the physical and biological sciences; from economics, sociology, and political science; from history; and from ethics. This is truly a "real world" subject for which any one of our traditionally defined academic disciplines would be insufficient. Finally, as we developed the specific sustainability cases which are at the core of this course, we anticipated that there would be sufficient commonality in the structures and dynamics of the various scenarios that learning would be progressively accelerated as we looked to customize and adjust our prior insights rather than having to define totally new dynamics with each new situation.

B. System Dynamics as an integrating vehicle

If environmental "sustainability" is, indeed, a critically important issue with which society must grapple, it cannot be surprising that individuals and organizations with differing perspectives and motivations have entered the conversations with tightly focused and often self-serving arguments. A caricature of the debate would have an environmental radical, arguing for the cessation of all resource exploitation and a return to simpler, more primitive (but fulfilling!) life styles, in debate with a three-piece-suited captain of industry, bemoaning the threat that such action would pose to next quarter's balance sheet. Caricatures are dangerous, if taken too seriously, but this one points out one of the major dangers in most real world problems. People from different disciplines or with different paradigms of how the world does, or should, work have great difficulty seeing beyond their own perspectives and hence tend to be unable to achieve a balanced, shared, and critical evaluation of the situation. In short, too often the mental models of the players, and of the students of the play, are too parochial to allow for productive analysis and implementation of policy.

Given the intrinsic interest, and controversy, in Sustainable Development, the tools and mindset of system dynamics seems a natural and powerful means to help the class (both instructors and students) to accomplish two vital tasks: 1) support the participants in recognizing, structuring, and refining their mental models of the systems being considered, and 2) provide a clear means for the participants to communicate, to compare and contrast, their mental models with those of others in the class and with those of some of the seminal thinkers in the field of sustainability. This focus on system dynamics as a pedagogic tool is derived from our belief that ultimately our task as educators is to find ways to help our students improve their mental models of how the various systems that surround them function. These mental models are ultimately the lenses through which we view and interpret those systems. Any device that helps students (including us as instructors) to articulate those mental models, to critically examine the links and loops that we believe control the way in which that particular system functions, and to allow ourselves to improve the quality of those mental models, is a device that singularly aids us in our educational mission. The tools of system dynamics that allow us to unambiguously depict the structure and behavior of the system, e.g. Behavior Over Time Graphs (BOTGs, otherwise known as the Reference Mode), Causal Loop Diagrams, and Stock/Flow Concept Maps, and that allow us more rigorously to test those insights against the observed reality and to project into the future the impact of certain policies (e.g. computer simulations), are powerful and broadly applicable tools for that critical task of mental model exploration and refinement.

II. Overview of the course

A. Context and students

Trinity College of Vermont is a small, primarily undergraduate women's college founded by and affiliated with the Roman Catholic order of the Sisters of Mercy. As such its central mission is to provide educational support to women who have been underserved by traditional educational opportunities. Admissions are non-selective and the academic background and intellectual track record of many of our entering students is modest; traditionally a majority of entering students are the first members of their immediate families to attend college. The Waters Center for System Dynamics was initiated at Trinity in part to provide a test of system dynamics as a pedagogic tool for such an audience that did not constitute the "best and brightest" and thus were already reasonably assured of academic success regardless of what was done to or for them.

"Sustainable Development" is a course that has been offered without prerequisites in two successive years to Trinity undergraduates as part of a General Education program that constitutes about one-third of our students' academic program. As such, it has attracted the full range of Trinity students from first year students to seniors, both traditional (18-21 years old) and non-traditional (older than 22) students, and students from a wide range of academic majors. In addition, in the Spring 1999 semester we offered a section of the course in the setting of a local secondary school. Here we formed a hybrid class composed of high school and middle school teachers seeking graduate Education credits, a pair of academically accelerated high school students seeking undergraduate credits, and several adults from both for-profit and non-profit organizations. The basic case studies explored and the materials used were similar with the two types of class, although the direction that each class went with the materials was often quite different.

B. Focus on case studies

Our experiences with the various classes leads us to focus on a limited number of case studies. An explicit historical context, in which many of the cases are developed, allows us to more clearly see the interplay of cause and effect. Such historical explorations clearly indicate that no one system behavior or outcome is inevitable. Societies under similar pressures may succeed or fail. Further, the large scale continued growth of the human population and culture is accomplished through a mosaic of sub-groups, some of which adopt successful strategies and flourish, and some of which fail and disappear.

In addition, by focusing on this limited suite of illustrations we are able to explore each with the full set of system dynamics tools and to configure and reconfigure the manner and sequence with which those tools are applied to best fit each case. Before long, some common templates or generic structures emerge. We are able to carry them from case to case to provide continuity and to accelerate the exploration of each succeeding case.

C. Focus on system tools as a means of communication

The tools of system dynamics, Behavior Over Time Graphs, Causal Loops, Stock/Flow Maps, and Computer Simulations, provide the means for individuals to be explicit and clear on expressing their mental models of the system in question. How have the parameters of this system changed over time? What are the specific interactions that control those changes? How can we quantitatively describe those interactions and their changes in magnitude or dominance as the system evolves? What is likely to be the impact of any change in policy we might be inclined to suggest? For example, students may begin the course with a relatively vague recognition that the "price" of a particular resource will influence the rate at which it is consumed. Once we examine how that "price" has changed over time and once we place "price" explicitly onto the concept map or into the computer simulation describing the system, we are obliged to look very carefully and critically at how that "price" is determined and subsequently how that "price" influences other elements of the system. Inevitably in any group of students, one individual's mental model will lead her to begin developing the connections between "price" and the exploitation of previously marginal elements of the resource, while another student's mental model will focus on the impact of "price" on the equitability of resource distribution among different social/economic strata of the society. Each of these is a valid element of the story; exposing and exploring both is facilitated by the use of these systems tools.

D. Focus on simple transferable 'templates' to provide continuity between case studies

One of the powerful benefits of using a system dynamics foundation is that many of the fundamental aspects of particular systems are repeated both in related systems as well as in systems that do not immediately or obviously seem related. Self-reinforcing growth is perhaps the simplest and most commonly cited of these generic structure/behavior templates. Within the context of sustainable development a variety of such self-reinforcing behaviors are relevant: biological populations, especially that of humans; compound interest acting on savings or investments; the growth of industrial capital; and, perhaps least concrete but critically important, the growth of "expected benefits." Once the connection between structure and behavior is established for any one of these systems, those insights can be quickly and with much less effort transferred to the other systems that share the compounding dynamic. Biology, economics, and human aspiration all share that common foundation.

More complex templates also prove extremely useful. Perhaps the most common basic structure we have used in this course is a conceptually simple three strand template (Figure 1).

1. *Human population* is the first dynamic sub-system; it has a Flow structure that varies from case to case depending on the particular scenario being modeled. A single Biflow or explicit inflows of births and immigration and outflows of deaths and emigration may be used, depending on which depiction helps to tell the desired story.

2. *Resource* comprises the second common strand, although considerable fine tuning of the Stock and Flow depiction of this strand is needed as we move between "renewable," "non-renewable," and "perpetual" resources in the different case-studies. Depending on the resource, it may affect the population strand. Resources such as food or clean water might well require that feedback; copper would be less likely to require that connection.

3. *Per capita demand* is the third and perhaps least obvious Stock that we monitor. As various parameters change in the system, per capita demand would also be expected to change and to exert a critical influence on the other elements of the system. Here we find we have to be especially careful in how we define "demand." Perhaps the clearest illustration of that issue

arises during our discussion of energy. For instance, should we think of "demand" for gasoline in terms of "so many gallons per person per month" or in terms of "so many miles of transportation per person per month"? The latter definition could open rich avenues to explore in such areas as automotive efficiency, use of public transportation, and spatial patterns of residential and commercial development.

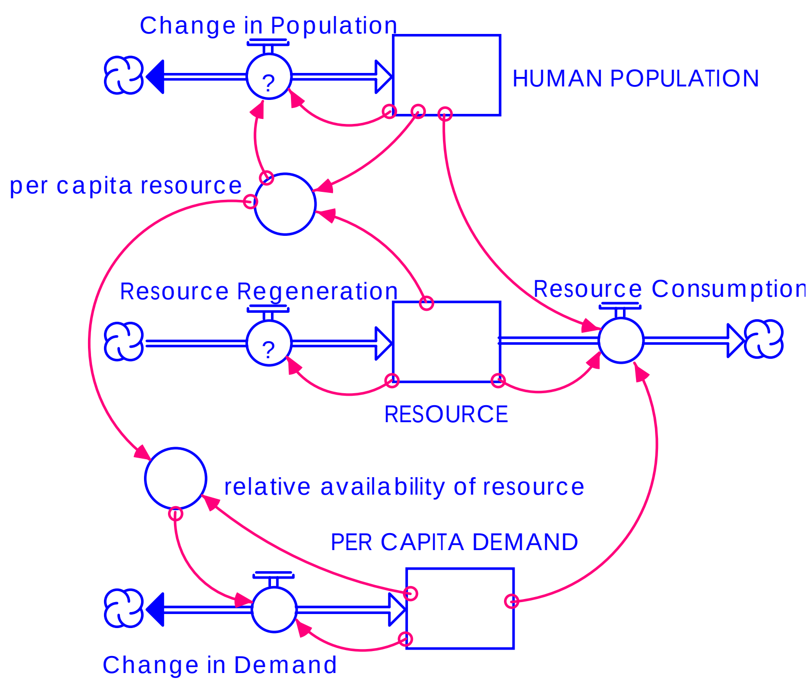

Figure 1: *The very basic three common strands of a sustainable development model. In this illustration the dynamics of the HUMAN POPULATION are kept extremely simplified; the question mark in the population's biflow indicates that the availability of the resource in question may or may not affect the dynamics of the HUMAN POPULATION. The Resource Regeneration Flow also contains a question mark since, in some case studies, that Flow may not exist and in others it cannot be defined as a compounding Flow as depicted here. Resource Consumption depends on a balance between how much there is and how much is desired; the actual definition of that Flow is likely to vary from scenario to scenario and resource to resource. Finally, the relative availability of resource will act, typically through a mechanism of pricing, to affect the Flow that defines any changes in PER CAPITA DEMAND.*

III. Specific illustrations

A. Easter Island (the classic warning story)

The “spaceship earth” vision of sustainable development is not a central or explicit focus of our course, although this initial case study appears very similar. The historical story of human settlement on Easter Island is a rich and illustrative one, but is ideal as a first study for being relatively simple. Several accounts (e.g. Diamond, 1995; Ponting, 1991) paint similar pictures of that history. In the 5th Century A.D. a small number of Polynesian settlers arrived on this island so far removed from other population centers that communication and trade would always be severely limited. With them the settlers brought a set of cultural and religious beliefs, certain artisan skills, and a limited number of foods that could adapt to the conditions on Easter Island and supplement the native palm, nesting seabirds, and porpoises. By the 1500’s the population had apparently grown beyond the resources of the island, rival clans were competing for the favor of the gods by building ever more and larger monuments (the Moi statues). Eventually warfare and cannibalism resulted in the inhabitants’ cultural and physical strengths being so depleted that they could neither resist the encroachment of European cultures nor even remember how the abundant statues had come to be placed around the island far removed from the quarry from whose rock they were carved.

<u>Purpose</u>: Introduce the idea that populations, cultures, and resources are all elements that change over time and that, given the structure of those interactions, the behavior of a system may be very difficult either to predict or to affect.

<u>System Tools and Concepts Developed</u>: Several tools are used in this unit. Behavior Over Time Graphs are introduced and used to help the students understand that major elements of Easter Island changed in systematic and concurrent ways. The human population began very small, apparently rose to 7-10,000, and then fell precipitously; the island began with significant forests, but by the time of European discovery had none; there were no Moi on the island when the first

Polynesians arrived, but eventually there were many, most of which had been toppled; at one point the island produced enough food to support at least 7000 humans, but by European discovery the agricultural fields were significantly degraded (see Figure 2). Given the historian's usual starting and ending points, what can we infer about the path of change experienced by each of these factors? Where the BOTGs suggest correlation of those changes, what can we infer about the causative relationships?

Those second order questions bring us to the introduction of feedback or causal loops. The early phases of human population growth provide the classic vehicle for introducing self-reinforcing or exponential growth. Balancing feedback (death) exists throughout the time course but begins to dominate toward the end as high populations destroy so many trees that erosion degrades the cropland to the point where sufficient food can no longer be produced.

Finally, a complete simulation model is introduced to the class for use in exploring hypothetical policy decisions. *What if* the Easter Islanders had been more efficient in their agriculture such that less land was needed to support each individual? *What if* they had resisted the apparent need to cut ever more trees to support a competitive moving and erecting of Moi? *What if* the birth rate of the Easter Islanders could have been reduced? We cannot pretend that these represent policy options truly available to the natives, but what change in the existing system might have made the outcome more benign? Exploration of the simulation provides the students with their first taste of testing the sensitivity of a modeled system to such policy options. Only a significant reduction in the birth rate results in significant improvement; other options delay the population crash and allow that population to reach a higher level from which to crash - a classic "better before worse" scenario.

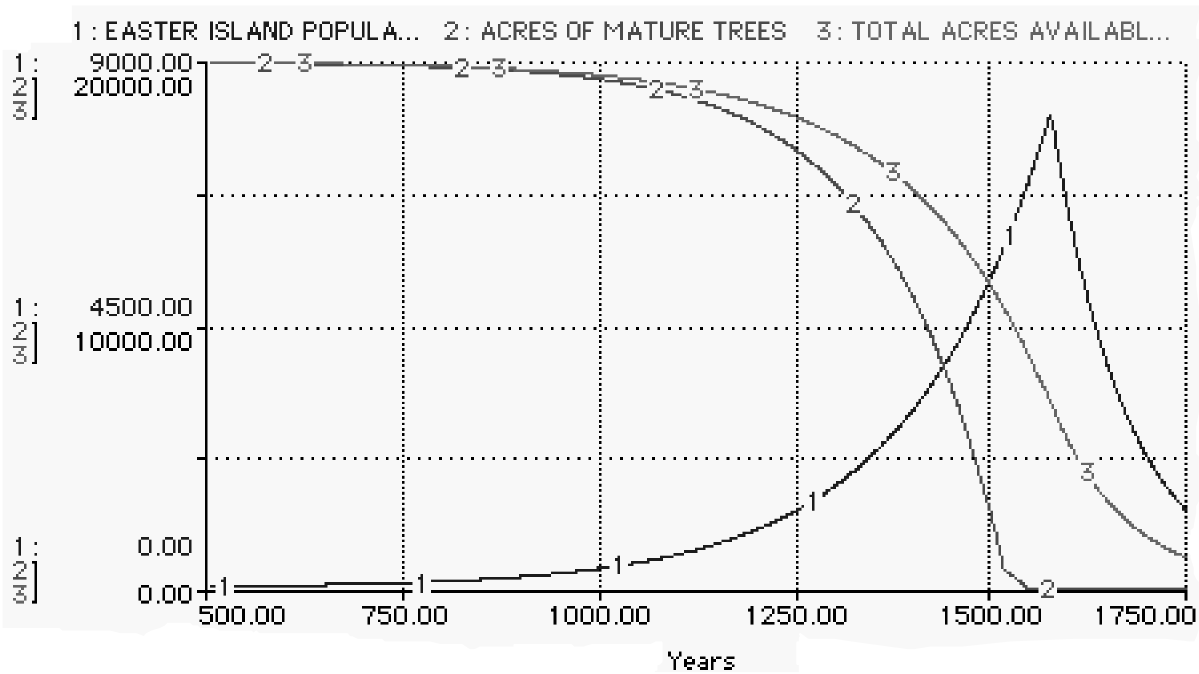

Figure 2: *Behavior Over Time Graphs of three related parameters of the Easter Island story: 1. EASTER ISLAND POPULATION: This Stock grows from a very small seed population in about 500 AD to a peak population of about 7000 at about 1600 before falling precipitously. 2. ACRES OF MATURE TREES: The island starts with a healthy Stock of trees that are utilized by the humans for many purposes. By 1000 AD consumption is beginning to exceed regeneration. 3. TOTAL ACRES AVAILABLE FOR AGRICULTURE: The island begins with a certain acreage of clear land suitable for farming. Tree clearing opens more land, but degradation of the soils and loss of fertility removes productive land at an even faster rate.*

B. !Kung (defining "affluence")

Easter Island provides a powerful scenario with which to introduce the ideas that environmental systems are dynamic over time and that their behavior is controlled by endogenous interactions. It also leaves an unfortunate sense of inevitable and gloomy catastrophe which is not the theme we intend to develop throughout the course. The story of subsistence societies, as recently developed by anthropologists studying the few surviving such cultures, provides a balance in terms of outcomes, the means to introduce a new tool, and a powerful lead-in to the next major case study that follows. The !Kung (small bands of "bushmen" in Southwest Africa) are among the best studied of these groups, and data from and interpretations of a number of those studies provide the database for our analyses (e.g. Lee, 1968; Ponting, 1991; Woodburn, 1982). Basically, the !Kung are organized into small bands of 30-50 individuals (membership in a given band is very fluid, as individuals can join and depart freely), bands move periodically within a relatively small territory as dictated by food and water availability, and the labor of food gathering is divided between the women who gather plant foods and the men who hunt. The diet is diverse, generally adequate and balanced, and easily obtained, requiring an average of less than fifteen hours per week by each of a band's adults; possessions are minimal, but consistent with minimal needs and desires; and the individuals have abundant free time for visiting and other socializing. The lives of these egalitarian subsistence hunter-gatherers, once described as "nasty, brutish, and short" (Hobbes, cited in Gowdy, 1998), indeed, on closer inspection seem to provide a reasonable illustration of "affluence" (Sahlins, 1972).

<u>Purpose</u>: Introduce the idea that stability can also be a characteristic of dynamic systems and that human populations can coexist in a sustained fashion with limited resources. Stocks and Flows are introduced as a final tool with which to map the students' mental models of the systems under consideration.

<u>System Tools and Concepts Developed</u>: Behavior Over Time Graphs are used to introduce and summarize the facts of this scenario as revealed by recent research; essentially, human populations as well as plant and animal food resources remain stable over long periods of time. The human population is further explored with a newly introduced tool, the Stock/Flow Concept Map. When the population inflow exceeds the outflow, the population declines; when inflow dominates, the population increases. The stable !Kung population logically requires the inflow and outflow to be equivalent. These are fundamental system dynamics concepts but not

necessarily intuitive to our students, yet. There is no indication that the !Kung require periodic catastrophes to bring a growing population back into balance with its resources; what dynamic feature of this system then fosters such a balance in the Flows? In fact, it seems that the culture has developed several characteristics that foster such stability. There is an active de-emphasis on the importance of territorial or material possessions, so that there is no need to have a bigger, stronger band with which to assert dominance over others. Marriage (which is tightly linked to child-bearing) is delayed, and infants are nursed for a period of several years, extending the interval between pregnancies. Each of these factors are developed, first conceptually through the Stock/Flow mapping process and then quantitatively through computer simulation (Figure 3).

The food resources available to the !Kung represent two distinct dynamics that this course revisits repeatedly. Animal foods, the responsibility of the men, represent a resource with self-reinforcing growth, that is, the amount harvested in any year affects the ability of the animals to replace the harvested biomass in the following year. This is a classic "renewable" resource. The vegetation, especially the primary food stock of mongongo nuts, is replenished in a fundamentally different manner. As long as the trees themselves are not harvested, the available stock of mongongo nuts will be replenished each year regardless of the previous year's harvest, essentially representing a "perpetual" resource. If the !Kung's population begins to increase, or if the !Kung were to alter their traditional dietary balance, the bands would have two fundamental options for continuing to gather sufficient food. They could focus more energy on the gathering of nuts and other plants (which currently represent about 2/3 of the diet's protein), or devote more time to hunting of animals. The impact of these two strategies are fundamentally different as revealed by exploration of relatively simple simulation models and, in both cases, the increased food acquisition is accompanied by a loss of apparently treasured leisure time.

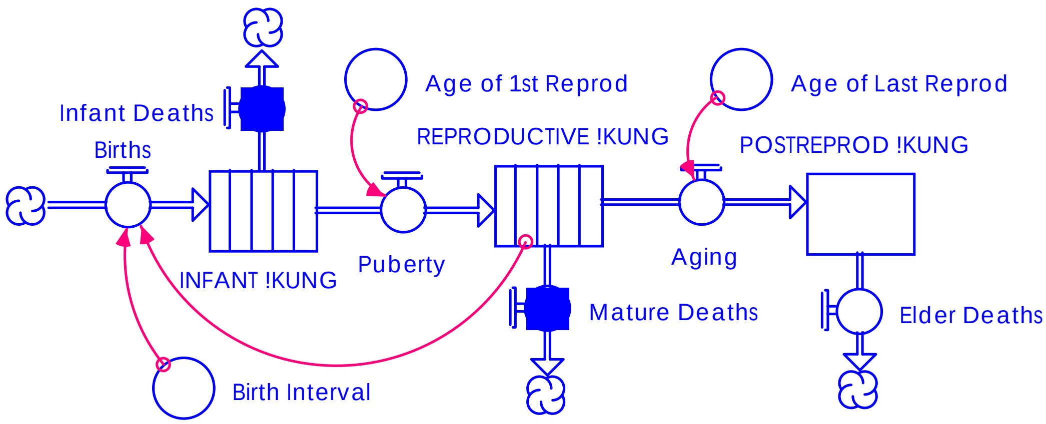

Figure 3a: *Simplified Stock/Flow Map of the !Kung population, emphasizing the controls exerted by the "Age of 1st reproduction" and the "Birth Interval" separating pregnancies in the reproductively active women.*

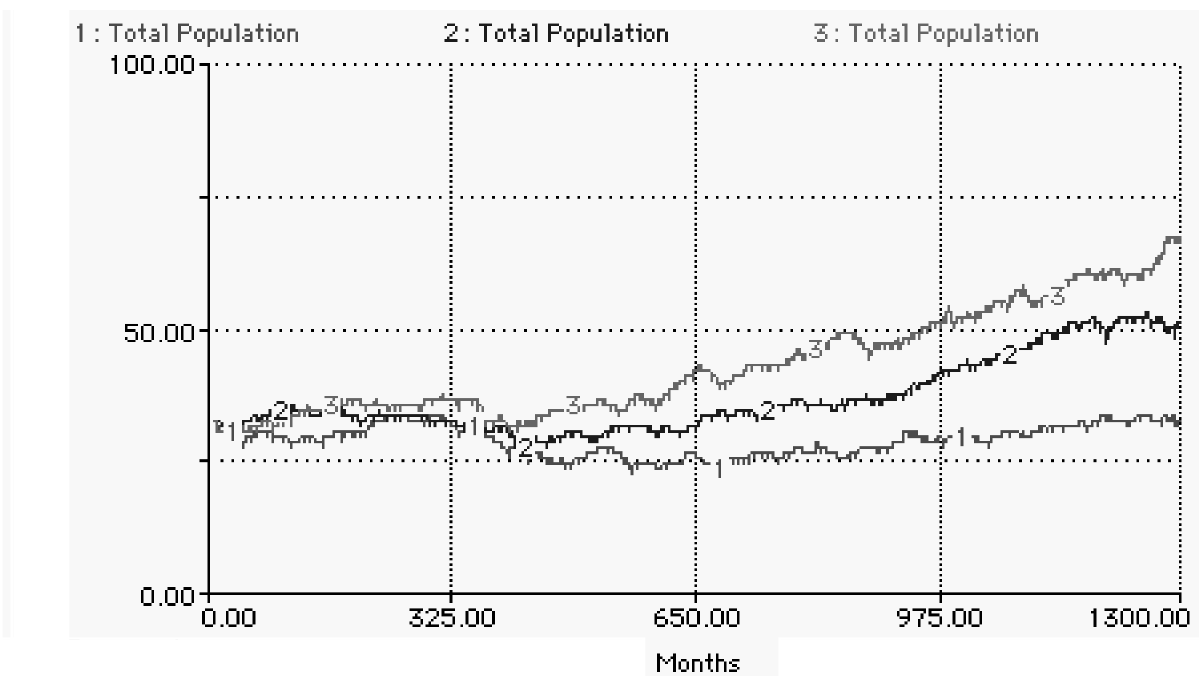

Figure 3b: *Model runs of a slightly more complex simulation of the !Kung population (this model included a "random" factor influencing each of the mortality Flows, accounting for the "jiggles" in the output.*

Run 1 *Birth Interval = 4.5 years*
Run 2 *Birth Interval = 4.0 years*
Run 3 *Birth Interval = 3.5 years*

C. *Western Agriculture (Malthus revisited)*

As benign, or even idyllic, as modern anthropology had made the subsistence hunter/gatherer life-style seem, the historical reality is that it has been replaced almost universally by settled agricultural cultures. The previous model of the !Kung can powerfully illustrate how fragile is the balance that permits their sustainability. Relatively minor changes in birth dynamics quickly result in population shifts (Figure 3b) that put significant strain on the supporting food resources. If population is to grow, then the structure of the food system that underlies that population must change; simply doing more hunting and gathering is not a viable policy. Agriculture, and the growth of communities based on agriculture, meets that structural need. Intense cultivation or husbandry at settled sites permits the production of sufficient food to support growing human population, even in the face of heavier work loads, decreased variety and quality of diet, and enhanced disease transmission through more concentrated human populations.

Even here, however, limits to growth could be expected. Malthus (1798) expressed that concern, observing/predicting that while population grows exponentially, food production could, at best, only be expected to grow linearly, and that such a situation could not be sustained. Given Malthus' assumptions, a simple simulation shows that his conclusions were quite reasonable. And yet civilization's overall experience (not discounting local painful or tragic exceptions to this "rule") is that food production has kept up with or even surpassed the demands placed on it by a growing population. Use of a set of system dynamics tools helps reveal what has been happening and provides a foundation for looking into the future.

<u>Purpose</u>: To explore the mechanisms by which efficiencies and innovations have affected the agricultural production of the United States since the colonial era. Formally develop the idea of "gaps" as forces driving the evolution of resource systems.

System Tools and Concepts Developed: Stock/Flow Mapping provides a powerful frame on which to hang classroom discussion of the history of U.S. agriculture. Ignoring, at least for the time being, the "Per Capita Demand" strand introduced in Figure 1, and ignoring the difference between plant and animal production and contribution to the diet, the structure presented in Figure 4 provides a solid basis for developing the history of over three hundred years of agricultural dynamics and for looking into the future. Population dynamics are relatively straightforward; the novelty here is in distinguishing subsets of agricultural workers and urban/industrial workers. The Stock of FOOD is drained by consumption, largely defined by the size of the population; production of FOOD depends on the interaction of "Acres in Production" and "Production per Acre," which in turn depend on "Agric(ultural) Workers," "Acres per Worker," and "Innovation."

Early in the history of the United States, as population growth required additional food, more acreage was put into production, the additional acreage being tended by new farmers drawn from the growing population ("**1**" in Figure 4), as the center of production moved progressively west. With time two mutually reinforcing trends developed, as mechanization of the farming industry released agricultural workers from the land and the growing need for factory workers in the urban centers absorbed those workers and used them to, among other things, produce more efficient farm implements and machinery, thus further increasing the food production per worker ("**2**" in Figure 4). Most recently, but still driven by profit-motivated innovation, substantial improvements have been made through development of irrigation, more efficient fertilization and pest control, and development of hybrid varieties to massively increase the possible yield of crops from a typical acre of land ("**3**" in Figure 4). Through all these mechanisms -- expansion of land in cultivation, per worker productivity increases, and per acre productivity increases --

the system has been sufficiently altered to at least postpone Malthus' dire prediction. At this point, different futurists (e.g. Hardin, 1993; Simon, 1996) project very different scenarios for global food security. The basic concept map developed here gives our students an effective lens through which to view and interpret these often widely differing projections and to recognize that even these very different world-views are supported by very similar mental models that may differ in only a single element.

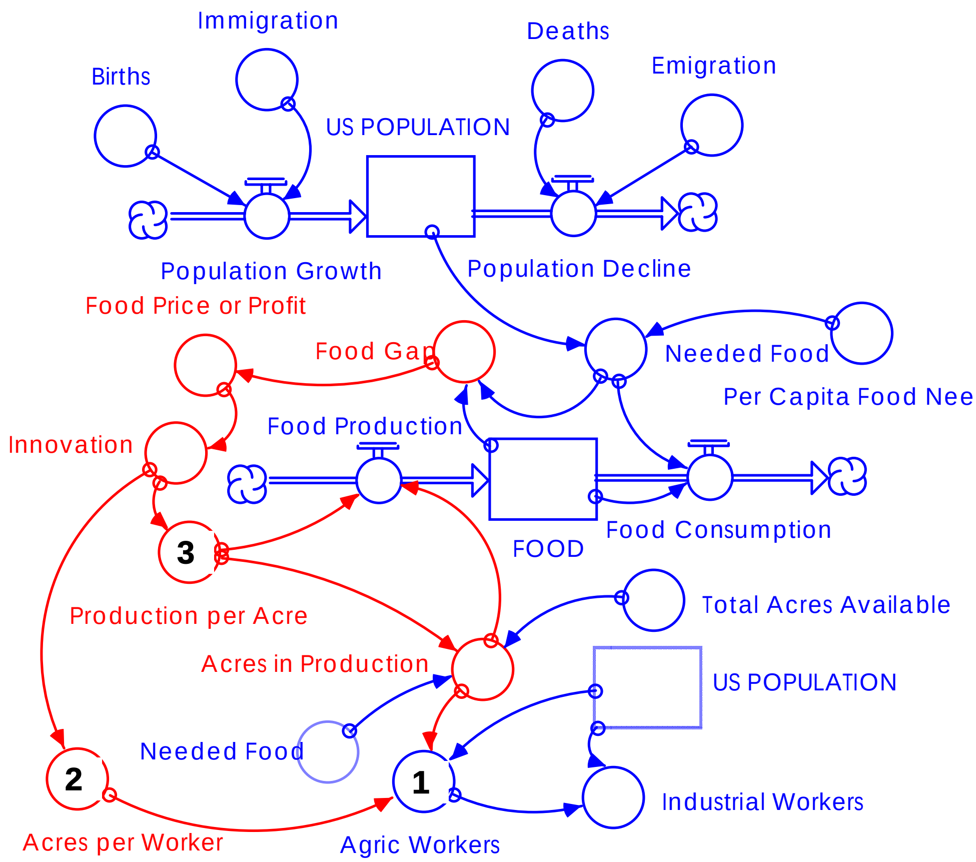

Figure 4: *Simplified Stock/Flow Concept Map of the development of U.S. agriculture. Our mental model identifies three major stages through which this system evolved. The numerals in the lower left portion of the map identify these stages which are discussed in the text. "Innovation" driven by a growing gap between supply and demand supported two of those stages; the portion of the system directly controlled by that Gap -- Innovation relationship is drawn in red.*

D. Commercial Fisheries (micro- and macro-economic dynamics)

Commercial fisheries present a modern story of resource exploitation that has initial similarities to the story already developed for Easter Island's trees and the !Kung's exploitation of animal stocks. The latter is not surprising, since traditional fisheries essentially represent a hunting scenario. The rates and efficiency of exploitation may have increased due to modern technology, but the basic systemic structure is unchanged. We begin this unit by exploring a computer simulation of a simplified fishing situation. We have several variations on this theme available for use depending on the class size and our needs at the moment, but all are conceptually similar to the commercial FISHBANKS, Ltd., in that fleets competing for growing profits lead almost inevitably to a collapse of the fish stock. These simulations are useful in introducing the basic "Tragedy of the Commons" archetype (the first and one of the only times we delve into archetypes) and in providing a frame for developing some of the biological and economic principles that underlie exploitation of wild stocks, such as stock/recruitment relationships, maximum sustainable yield, and maximum economic yield. Perhaps even more valuable, they provide a foundation for exploring the general implications of a changing supply/demand situation which results in rising prices.

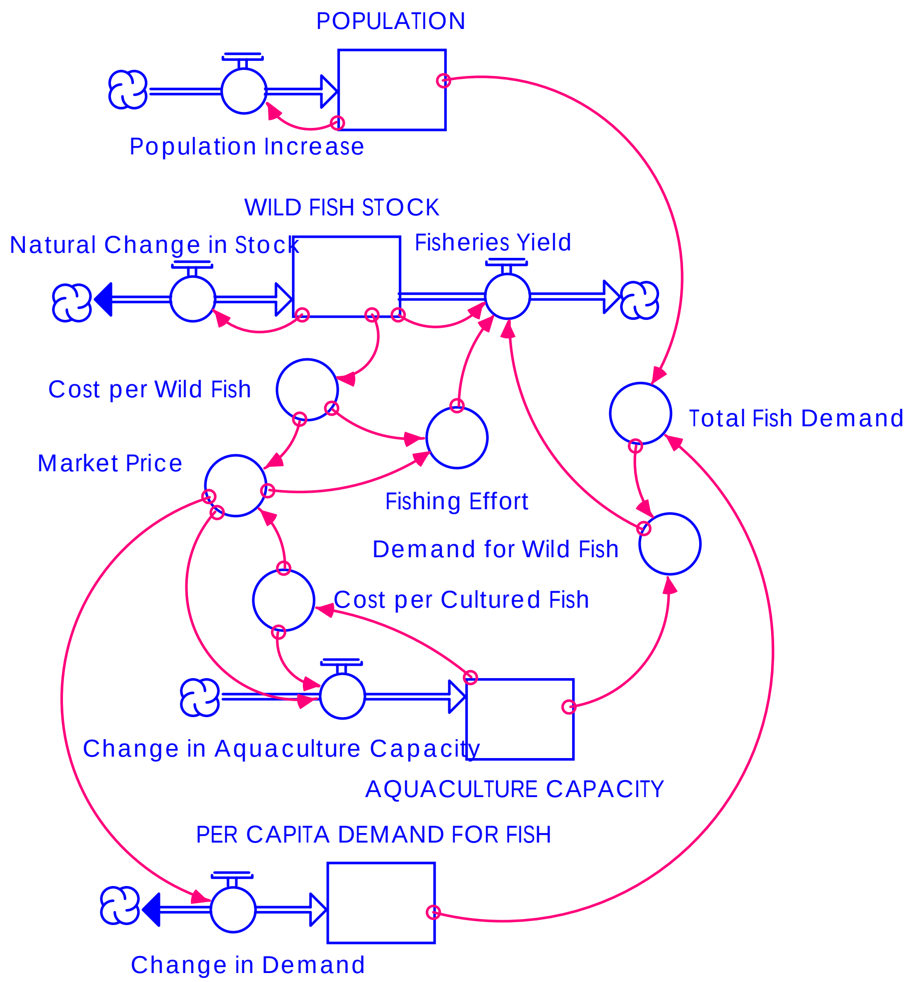

Figure 5: *Concept map of a commercial fishing scenario. Initially there is relatively little AQUACULTURE CAPACITY and a reasonably healthy WILD FISH STOCK; costs of fishing are low and a profit can be made, even with a low Market Price which stimulates growth in PER CAPITA DEMAND FOR FISH. As the WILD FISH STOCK is depleted, costs go up, but so do prices maintaining profitability and the incentive to continue fishing. Finally prices rise to the point where Aquaculture is economically competitive; growth of AQUACULTURE CAPACITY is stimulated and progressively more of the Total Fish Demand is met by cultured sources, which, as economies of scale begin to phase in, become ever less expensive, bringing market price for at least easily cultured species down again and further squeezing the market share of traditional fisheries.*

Purpose: To develop the "Tragedy of the Commons" archetype both for its own sake and as a springboard to examine the microeconomic impacts of rising prices for scarce resources on influencing exploitation patterns and to examine broader scale restructuring of the entire industry as the economics of scarce resources leads to development of substitutes.

System Tools and Concepts Developed: Relative shortage of fish (or, most likely, of any resource) will, in a free market, lead to increased price. Increased price presents the opportunity for increased profits along at least two avenues that we explore in this case study: development of more efficient means to exploit the dwindling resource, and substitution of other resources which are now more attractive from the cost/benefit perspective (see Figure 5, a Stock/Flow Concept Map developed through class discussions to illustrate these points).

Over the past several decades this story has played out in the world's oceans. Increasing per capita demand, increasing population, and decreasing costs, as technological innovations were introduced, stimulated the growth of traditional fisheries to the point of well documented depletions of the supporting fish stocks. As scarcity was felt prices rose and profitability and exploitation continued, depleting the stocks still further. Eventually prices rose to the point where, for a growing number of species, aquaculture became economically viable. Fisheries statistics tabulated by the United Nation's Food and Agricultural Organization (FAO), clearly show a continued rise in availability of sea food as wild-caught contributions have stabilized and even begun to fall. Aquaculture is progressively filling the need that can no longer be met by traditional sources. The powerful lesson growing out of this case study reinforces the insight derived from exploring the previous Malthusian predictions: any simple analysis of a natural resource system that is focused only on the system as it currently exists and which fails to account for ingenuity and innovation is built on a dangerously weak foundation.

E. Energy (a history of substitution; a future of ...?)

Energy is one of the classic sustainability stories of our time and one which is most likely to be immediately engaging to our students. It is likely that some aspect of this energy story will have been newsworthy within the past year. As timely as energy is as a topic, it also has a rich and well documented history. It seems, indeed, that an energy shortage of crisis proportions has been looming for as long as there have been journalists and historians to write about it. As in the case of the Malthusian shortage of food, however, something in the system always seems to intervene just in time to avert the catastrophe. That repeated pattern of looming crisis from which we are saved at the last minute suggests that something systematic may well be operating.

Purpose: To reinforce and further develop the centrality of "price" in controlling the dynamics of initially limited resources.

System Tools and Concepts Developed: This is a powerful application of the basic three-strand paradigm (population, resource, per capita demand) introduced earlier. An historical illustration, involving Britain's use of trees as its primary energy source, as developed by Ponting (1961), provides a first exercise for the class to translate into an explicit stock and flow concept map (see Figure 6).

We ask our students to contemplate the following scenario: As the population and the per capita demand for wood both grow, Great Britain has two options for meeting its increasing need for wood, i.e. domestic or foeign sources. Which source is tapped depends on theie relative prices. Presumably the initial price of British wood is less and it is the preferred stock for exploitation. As that stock is depleted, however, shortage drives up its price until foreign wood is equal or less in price, at which point the consumption switches to foreign sources. In addition, as the price of wood increases in Great Britain, other changes in the system might be expected to occur: wood would be used with greater efficiency (both as fuel and as a construction material), equity of wood availability would lessen as only the financially more well-to-do could afford it, and perhaps most importantly in the long run, consumers will begin to look for economical substitutes, such as coal, to meet their needs.

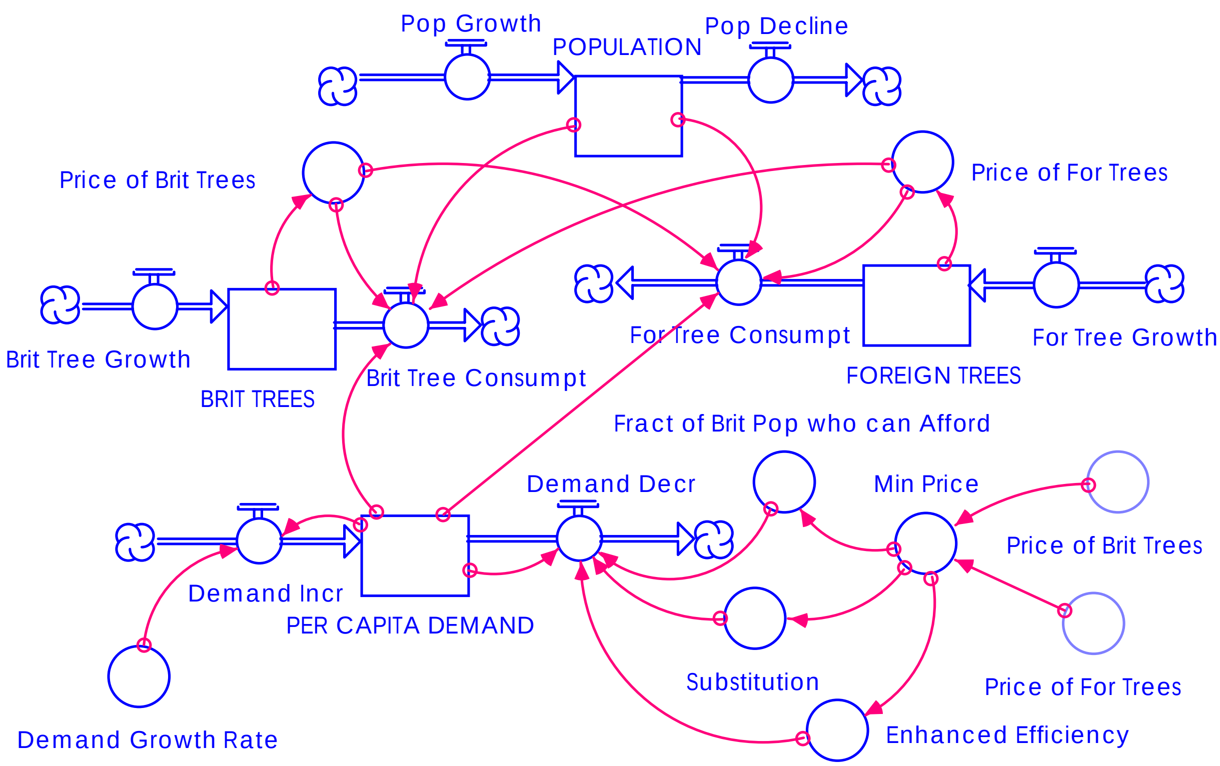

Figure 6: *An illustrative Stock-Flow Concept Map of the system of wood consumption in Great Britain. Wood is used as a construction material as well as for energy in this period, so this example is not a "pure" energy story. The story line developed in this map is described in the accompanying text.*

All of these aspects seem inherent to a wide variety of energy stories: utilization of a wide diversity of sources, often with foreign affairs or global economic consequences; innovation in ways of using that particular source; issues of social equitability, both within a single consuming society and between societies on a global scale; and ultimately, the stimulus to discover or to begin utilizing alternate forms of energy. The historical sequence of wood-coal, coal-oil, and apparently oil-natural gas transitions all share to some degree these common elements which are clearly related in a systemic way.

F. STRATAGEM (applying the fundamental concepts and insights)

Having carefully walked our students through a series of sustainability issues, starting with a generic understanding of the dynamics of population and per capita demand and then developing a series of systemic resource strands influenced by price, innovation, and substitution, we are now ready to move into the most challenging scenario, that is, engaging our students in collaboratively managing the development of an entire simulated country through the commercially available game, STRATAGEM. At the outset, the simulated country begins with very limited economic and human resources. The standard of living is low, the population is doubling on a thirty year pace, food is barely adequate, social services (health care and education) are weak, agricultural and industrial productivity is inefficient, and both environmental protection and energy efficiency are lacking. Any simple, "ideal" strategy is impossible. Needs are great, means are limited, and compromise and careful and thoughtful planning are necessary to maintain and sustain growth of the country's standard of living.

STRATAGEM® is a computer driven game which simulates 50 years of economic development of an initially poor country. Students collaborate by managing five Ministerial Portfolios (Population, Agriculture and Environment, Good and Services, Energy, and Trade and Finance) in an effort to sustainably raise the standard of living of the citizens of this country. Each student analyzes the dynamics of the Ministry for which she is responsible, briefs the other Ministers, and then serves as both an advocate for and a source of information about her ministry as the play develops. In many ways the group dynamics are as interesting and as informative as the actual results of the game, but struggling with the daunting complexity of even this simplification of a real country provides both a test of the level of systems understanding the students have achieved and a final challenging exercise to reinforce and operationalize those lessons that might have, up to this point, still remained more abstract than we desired.

IV. Conclusions

The superficial purpose of this course is to explore and develop our students' appreciation for the factors that influence the sustainability (or lack thereof) of our utilization of a variety of natural resources. Our decision to use system dynamics as the foundation for this study consciously reflects our desires -- as scientist and humanist, respectively -- to find a common language with which to engage our students in open, meaningful conversation around their collective futures. There certainly are a number of ways to accomplish that illumination of the issues of sustainable development, just as there are a number of social or political agendas that address aspects of this subject. Advocates on all sides of the sustainability debate are capable, consciously or unconsciously, of pushing biased, self-serving, or simply incomplete models of how a given policy will affect the world. Our decision to construct a limited number of carefully crafted case studies is designed to provide balance and to avoid extremism on any side of the various arguments. By starting the course with a basic core structure (the "three-strander" of Figure 1) and then adding small but significant modification to illustrate the different courses of behavior that can arise, our students begin to grasp the range of both sustainable and unsustainable possibilities that characterize past, present, and, with extrapolation, future behaviors.

At the core of this course, and indeed all of our curricular experiments, is our more fundamental desire to provide students with a means to develop their systems thinking skills to a point where new habits of mind allow (oblige) them to more effectively visualize the behavior of these systems and to pose better questions about how they do, or might, work. Our students do not exit these courses with definitive answers to life's great questions. We measure our success as educators, however, if our students:

- Can explicitly describe their mental models, employing a common set of systems symbols and structures to facilitate that communication,
- Can use these models to demonstrate their understanding of the basic relationships that control the behavior of that system,
- Are able unambiguously to compare and contrast their mental models with those of others,
- Are able to develop and use a number of simple generic structures to aid in their understanding of and communication about these systems, and
- Can build on their understanding of a system through the asking of progressively better questions that force themselves to extend and deepen their understanding.

If we succeed in these goals, our students will exit our tutelage not just with a solid appreciation of "sustainability" (the system on which we focus in this course) but with a set of tools and habits of mind that will allow them to be much more effective in understanding and ultimately affecting the way the world around them works.

V. References

Diamond, J. 1995. Easter's End. Discover *16*(8): 62-69.

Forrester, J. W. 1961. Industrial Dynamics. Productivity Press. Portland, OR. 464 pp.

----- 1969. Urban Dynamics. Productivity Press. Portland, OR. 285 pp.

Gowdy, J. 1998. Limited Wants, Unlimited Means: A Reader on Hunter-Gatherer Economics and the Environment. Island Press. Washington, DC. 342 pp.

Hardin, G. 1993. Living Within Limits: Ecology, Economics, and Population Taboos. Oxford University Press. New York. 339 pp.

Lee, R. B. 1968. What Hunters Do for a Living, or, How to Make Out on Scarce Resources. (extract reprinted in Gowdy, 1998, pp. 43-63).

Malthus, T. R. 1798. Essay on the Principle of Population. (available on line at http://www.trmalthus.com/essay.htm)

Ponting, C. 1991. A Green History of the World. Penguin. New York. 430 pp.

Sahlins, M. 1972. Stone Age Economics. Aldine de Gruyter. New York. (extract reprinted in Gowdy, 1998, pp. 5-41).

Simon, J. L. 1996. The Ultimate Resource 2. Princeton University Press. Princeton, NJ. 734 pp.

Woodburn, J. 1982. Egalitarian Societies. Man *17*: 431-451 (reprinted in Gowdy, 1998, pp. 87-110).