Title: Integrating Economics and System Dynamics Approaches for Modeling an Ecological-Economic System

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Abstract

This article describes collaboration between system dynamicists and economists to model a multi-sector, ecological-economic model of population and resource dynamics that is firmly based on economic theory and leverages the strengths of both fields. This model illuminates how an SD approach allows model complexity to be extended in order to effectively model interactions between an economic system and an ecological system. Specifically, the simulation exercise demonstrates how SD model analysis can help explain the counterintuitive model behaviors due to increases in the natural resource carrying capacity or regeneration rate. The simulation results also reveal that allowing for out-of-equilibrium states (adaptation) significantly impacts the dynamics of ecological economic systems, a point often neglected in the economics literature. These findings, while familiar to system dynamicists, highlight the potential for SD to contribute to other disciplines, including economics.

Keywords: Ecological Economics; Model-Based Theory Building; Population-Resource Dynamics; Adjustment Time; Adaptation

1. Introduction

Although system dynamics (SD) has been applied to economic systems from its beginnings, synthesis of SD and economics methods has not been the norm. Economics is the social science that studies how to allocate limited resources to best satisfy our needs and wants. Application of SD in the economics domain is facilitated by an understanding of how economists address this fundamental question based on economic theory. This article brings an SD perspective to an analytical framework from the economics literature and shows how the SD approach helps to analyze the dynamic interactions between economic and ecological systems. One author is an economist, another is a system dynamicist, and the third straddles the two fields

The primary contribution of this paper is the application of an SD approach to an ecological-economic model that is simple and firmly based on economic theory, in contrast to the substantial body of work on limits to growth that is well known among system dynamicists (*cf.*, Meadows et al., 2004). While system dynamicists may not rely heavily on economic theory because of the seemingly unrealistic assumptions employed, economists are indifferent to models that seem to disregard economic theory. The analysis of an ecological-economic system presented herein strives to bridge the gap that tends to exist between the two disciplines. The model consists of a set of functions that represent (i) the behavioral assumptions for economic agents based on economic theory; (ii) the biological behaviors of a natural resource stock (a simple ecosystem); and (iii) the inter-dependence between the economic and ecological systems. Economic theory provides a solid foundation for the system equations, and SD provides analytical tools and a way of thinking when studying such a system that often leads to deeper insights into the complex dynamics of the system (Common and Stagl, 2005).

More specifically, in demonstrating a firmly theory-based application, this article extends prior studies that depict interactions between nature and a specific sector of an economy (*e.g.*, Moxnes, 2001 and 2005; Dudley, 2005 and 2008). The multi-sector, general equilibrium model presented herein depicts interactions between nature and an economy as a whole. The analysis of the simple model of two output sectors, one input sector, and two stock variables serves as a thought experiment that can help to motivate the potential expansion and application of this type of modeling approach for other case studies of interest.

Furthermore, building on a group of population-resource dynamics models commonly known as the BT-type models, the ecological-economic system represented by the model accommodates out-of-equilibrium states by using hill-climbing logic that seeks but does not enforce equilibrium.[1] The out-of-equilibrium state is a result of added complexity of the model by incorporating both the natural resource and man-made capital as productive inputs in order to better address the sustainability of the economy. Allowing for different adaptation time periods for markets to reach the equilibrium state necessitates the use of an SD approach.

One main finding from our sensitivity analysis is that increases in what would seem to be nearly equivalent resources parameters, the regeneration rate and the natural resource carrying capacity, result in remarkably different system behaviors. While the

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[1] Nagase and Uehara (2011) provide a comprehensive review of the BT-type models.

former shifts up the dynamic population and resource paths, the latter causes these paths to oscillate.

Another major finding is that while changing the system's adaptation time periods by similar amounts in different sectors has minimal impact on the dynamics of the system, changing the adaptation time periods asymmetrically across different economic sectors significantly alters the dynamics of the system. This finding emphasizes the significance of studying the effects of delays in market adjustment processes and highlights the potential for SD to contribute to economics.

The article is organized as follows. Section 2 introduces the model and explains the economic theory behind it. Section 3 defines the context and reference behavior pattern that the model seeks to explain. Section 4 provides the results of parameter sensitivity analyses. Discussion and conclusions follow in Section 5.

2. The Model

We present our model with three methods: a mathematical description, a causal loop diagram, and a boundary table. While SD articles do not always present mathematical equations, they are integral to communicate with a wider audience including economists and ecologists. These documentation methods are complementary to each other rather than being equivalent.[2]

2.1. A Mathematical Description

The model to be introduced is a static general equilibrium model whose dynamic transitional process from one time period to another is given by a set of first-order differential equations. For simplicity, this model depicts an economy consisting of two sectors (harvest and manufacturing). Input availability in each time period is bounded by the existing sizes of population, renewable natural resource stock, and man-made capital stock. We describe the period-by-period behavior of agents, the dynamic transitional process from one time period to another, and a way to incorporate these mathematical specifications into SD.

2.1.1. Period-by-period behavior of agents

Let us now describe the specifics of the model (time subscripts are suppressed for all variables), in each time period, agents make production and consumption decisions with the given sizes of population (*L*), natural resource stock (*S*), and man-made capital (*K*). As a consumer, a representative agent maximizes utility subject to the budget constraint:

$$\max_{\{h,m\}} \quad u(h,m) = h^{\beta} m^{1-\beta} \qquad s.t. \quad p_H h + p_m m = (1-s)\left(w + \frac{rK}{L}\right)$$

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[2] Full details of the model are provided in the online supporting materials. Nagase and Uehara's (2011) circular flow diagram provides a useful visual representation for those who are not familiar with the BT-type models.

where h and m denote per-capita consumption levels of harvested good (H) and manufactured good (M), respectively. Parameter s denotes the saving rate, and w and r are (endogenously determined) prices of labor and man-made capital, respectively.[3] This optimization problem yields the consumption demand functions for the two goods:

$$H_C \quad = \quad L \cdot h \quad = \quad \frac{(1-s)\beta}{p_H}(wL + rK) \tag{1}$$

$$M_C \quad = \quad L \cdot m \quad = \quad \frac{(1-s)(1-\beta)}{p_M}(wL + rK) \quad . \tag{2}$$

Two sectors' aggregate production functions are defined as

$$H(L) = \alpha S L_H \tag{3}$$

and

$$M(L_M, H_M, K) = \nu L_M{}^{1-\gamma}\left[\pi H_M{}^{\rho} + (1-\pi)K^{\rho}\right]^{\frac{\gamma}{\rho}} \ ; \ \gamma,\ \nu \in (0, 1) \tag{4}$$

where H_M denotes the amount of good H consumed as an input, and L_i the amount of labor employed in sector i ($L_H + L_M = L$). By assumption $\rho < 1$ so that the elasticity of substitution $\sigma = 1/(1-\rho)$ is positive. α, ν, and γ are efficiency parameters.

Departing from many of the existing BT-type models, this model introduces a constant-elasticity-of-substitution (CES) production function for good M. The degree of substitutability between man-made capital and natural resources plays a critical role for the sustainability of an ecological economic system that faces natural resource constraints. Studies on substitutability have been almost exclusively conducted using CES production functions.[4] With $\sigma < 1$, inputs are complements so that the natural resource is essential for production, meaning that production becomes increasingly difficult as the natural resource becomes scarce. While the ubiquitous employment of the Cobb-Douglas (C-D) function in economics is an implicit support for $\sigma = 1$, ecological economists assert $\sigma < 1$ (*e.g.*, Cleveland et al., 1984; Cleveland and Ruth, 1997; Daly, 1991; Daly and Farley, 2010), although the empirical evidence remains inconclusive (*cf.*, Nagase and Uehara, 2011).

The first-order conditions for the two sectors' profit maximization are:

$$p_H \alpha S \quad = \quad w \tag{5}$$

$$p_M \nu (1-\gamma)(L - L_H)^{-\gamma}\left[\pi H_M{}^{\rho} + (1-\pi)K^{\rho}\right]^{\frac{\gamma}{\rho}} \quad = \quad w \tag{6}$$

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[3] For simplicity each agent has one unit of labor to be allocated across the two sectors, and the rental price of capital is evenly distributed back to all agents.

[4] For a more complex case of multiple inputs, a translog production function can yield the elasticity of substitution between any two inputs (Stern, 1994).

$$p_M \nu \left(L - L_H\right)^{1-\gamma} \gamma \left[\pi H_M{}^{\rho} + \left(1-\pi\right) K^{\rho}\right]^{\frac{\gamma}{\rho}-1} \pi H_M{}^{\rho-1} \quad = \quad p_H \tag{7}$$

$$p_M \nu \left(L - L_H\right)^{1-\gamma} \gamma \left[\pi H_M{}^{\rho} + \left(1-\pi\right) K^{\rho}\right]^{\frac{\gamma}{\rho}-1} \left(1-\pi\right) K^{\rho-1} \quad = \quad r \tag{8}$$

Using equations (1) and (2) and the production functions, the static market equilibrium conditions in the *H*- and *M*-markets are given by

$$\frac{\left(1-s\right)\beta}{p_H}\left(wL + rK\right) + H_M \quad = \quad \alpha S L_H \tag{9}$$

and

$$\frac{\left(1-s\right)\left(1-\beta\right)}{p_M}\left(wL + rK\right) \quad = \quad \nu\left(L - L_H\right)^{1-\gamma}\left[\pi H_M{}^{\rho} + \left(1-\pi\right) K^{\rho}\right]^{\frac{\gamma}{\rho}} \ . \tag{10}$$

Equations (5) through (10) yields the static equilibrium solution set {L_H*, H_M*, *w**, *r**, p_H*, p_M*}.[5] The harvest level *H** in this model is determined endogenously rather than exogenously as a result of economic activities, in contrast to some other studies on the dynamics of population and natural resource (*e.g.*, Shukla *et al.*, 2011).

2.1.2. Dynamic transition

Given {L_H*, H_M*, *w**, *r**, p_H*, p_M*}, the following equations provide the transitional dynamics for the three stock variables:

$$\frac{dL}{dt} \ = \ L\left[b\left(h*, m*\right) - d\left(h*, m*\right)\right] \tag{11}$$

where $b \ = \ b_0\left(1 - \frac{1}{e^{b_1 h*}}\right)\frac{1}{e^{b_2 m*}}$ and $d \ = \ d_0 \frac{1}{e^{h*\left(d_1 + d_2 m*\right)}}$;

$$\frac{dS}{dt} = G(S) - H* = \eta S\left(1 - \frac{S}{S_{max}}\right) - H* \tag{12}$$

$$\frac{dK}{dt} \quad = \quad \frac{s\left(w* L + r* K\right)}{p_M *} - \delta K \tag{13}$$

Equations (11) and (12) characterize this model as a Gordon-Schaefer Model, using a variation of the Lotka-Volterra predator-prey model (*cf.* Nagase and Uehara, 2011).

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[5] H_C* is obtained by substituting p_H*, *w** and *r** into the production function for *M*. *H** = H_C* + H_M*. *M** is obtained by substituting L_H* and H_M* into the production function for *M*.

Equation (11) represents a Malthusian population dynamics in the sense that the higher per-capita consumption of the harvested good leads to higher population growth. *b* and *d* denote the birth and death rates, respectively. Meanwhile, this model adopts Anderies' (2003) formulation that incorporates the impact of the per-capita consumption of harvested and manufactured goods, in order to reflect *the demographic transition hypothesis*.[6] More specifically, real income and fertility are negatively correlated, and mortality is negatively correlated with improved nutrition and infrastructure. The term $b_0\left(1-1/e^{b_1h^*}\right)$ depicts that, as consumption of harvested good (nutrition) increases, so does the birth rate, up to a maximum of b_0. The term $1/e^{b_2m^*}$ represents the downward pressure on the birth rate, as consumption of manufactured good increases. The death rate function $d = d_0 / e^{h^*(d_1+d_2m^*)}$ depicts that improved nutrition reduces the death rate via the term h^*d_1, and higher consumption of manufactured good reduces the death rate via the term $h^*d_2m^*$. Parameters b_2 and d_2 make this model non-Malthusian.

Equation (12) defines the resource growth dynamics. $G(S)$ represents a logistic growth function of S; η denotes the intrinsic growth rate, and S_{max} denotes the carrying capacity.

Equation (13) represents a standard economic approach to modeling capital accumulation. Capital accumulation is a basic component in the growth literature. Incorporating capital accumulation into an ecological-economic model allows us to investigate the role of substitutability between man-made capital and natural resources for sustainability, in contrast to numerous studies on the economics of sustainability that focus primarily on nonrenewable resources (*e.g.*, Hartwick, 1977). The first term on the right hand side represents the amount of manufactured good used for capital formation. s is the savings rate, and δ is the capital depreciation rate, both of which are exogenously given (for simplicity). Man-made capital accumulation depends indirectly on natural resource through the production of manufactured good. Therefore in our model natural resource is of the so-called "growth-essential" type (Groth, 2007).

2.1.3. Modeling Approach

Economics has generally taken a strategy of simplification to be able to employ analytic approaches. However, simulation approaches are likely to be unavoidable for models of complex systems used primarily for increasing understanding (Dasgupta, 2000). To the best of our knowledge it is not possible to derive analytically the static equilibrium solution set $\{L_H^*, H_M^*, w^*, r^*, p_H^*, p_M^*\}$ for this model. By employing an SD approach, this model is able to address the complexity of an ecological economic system without requiring simplifications that would be often needed for analytic solutions--the standard modeling approach in economics. In addition, while economics generally focuses on the analysis of a steady state and its comparative statics, and growth theory employs growth accounting, SD approaches focus on the transition paths. Therefore our use of SD

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[6] The hypothesis consists of four basic stages: (I) Population has high birth and death rates that are nearly equal, leading to slow population growth; (II) Death rate falls yet birth rate remains high, leading to rapid population growth; (III) Birth rate falls; (IV) Birth and death rates are both low and nearly equal, stabilizing the population at a higher level than at stage I.

promotes a shift of focus in economics modeling and analysis, by emphasizing the benefits of simply letting the system reveal its dynamics instead of constraining the model specification so that a steady state must emerge.

Our modeling process involves two steps. First, a general equilibrium model drawing from economic theory is built with its transitional dynamic process. Second, the model is expanded to incorporate adaptation (out-of-equilibrium conditions) using the SD approach. To be more specific, the second step employs an approach suggested by Sterman (1980, 2000). For example, the manufacturing sector seeks to find the optimal amounts of inputs, labor (L_M), harvested good (H_M), and man-made capital (K) to satisfy the first order conditions (6), (7), and (8).

2.2. Summary Model Diagram and Boundary Table

To help grasp the whole picture of the model, two model descriptions are provided: a causal loop diagram (CLD) and a model boundary table.

Figure 1 shows the CLD for this model. As with many other BT-type models, this model has two primary stock variables (population and natural resource), two output sectors (harvesting and manufacturing), and one input sector (labor). Key loops among these sectors and variables are labeled “Malthusian Pop Growth,” “Resource Limiting Harvesting,” and “Labor for Harvesting.” Meanwhile, unlike other models, this model incorporates man-made capital as an additional input sector, and the model also allow the harvesting sector and manufacturing sector to be in disequilibrium. These new features are shown in red. The system contains several feedback loops that strive to keep supply, demand, and labor in balance in a non-instantaneous fashion, buffered by inventories.

Manufacturing and the new man-made capital stock are connected in a reinforcing loop labeled “Efficiency Driver,” which is balanced by a Depreciation loop. Manufacturing also depends on harvested good (natural resources), creating a loop labeled “Multiplier Effect.” Population dynamics depend not only on harvested goods but also on manufactured good (such as, perhaps, medical technology), creating a “Technology Loop.”

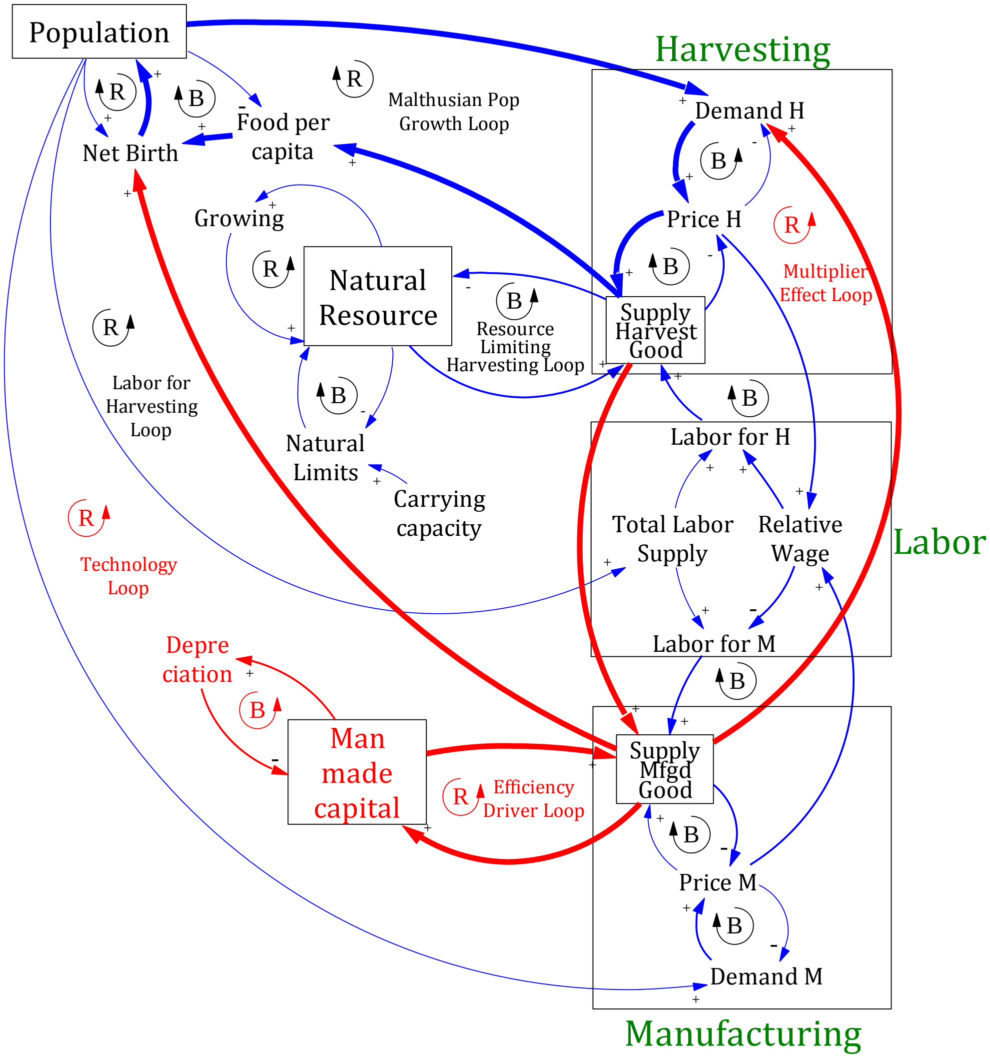

Figure 1. Causal loop diagram of the extended model. Bold lines make key loop easier to see. Several loops are named to improve clarity, while others are not. For example, in both the Population sector and the Natural Resource sector, there is a reinforcing loop and a balancing loop based, respectively, on Food per capita and Carrying capacity. In the Harvest, Labor, and Manufacturing sectors there are many loops that keep supply, demand, and labor in balance.

Table 1 documents the boundary of our model and clarifies endogenous, exogenous, and excluded variables in order to avoid misinterpretation of our simulation results and to underscore the limitations of the model. Exogenous variables for population dynamics follow those of Anderies (2003). The carrying capacity and the regeneration rate of natural resources are exogenous (constants). The other exogenous variables except for adjustment times are standard economics treatment. Adjustment times are exogenous as is often the case for system dynamics models, although adjustment times could also be endogenous (*cf*., Kostyshyna, 2012).

It is obvious that the excluded variables listed in Table 1 are by no means comprehensive. These variables are indicative of the suitable directions for the subsequent expansion of the model. Inclusion of nonrenewable resources would be suitable to depict an economy for which this sector is significant, so that the resulting SD analysis would help, for example, analyzing the transitional process of such an economy as this sector wanes. Pollution problems as negative externalities prevail and, along with the natural resource depletion, are critical issues especially in developing economies (ADB, 2009). Finally, combined with the aforementioned variables, international relationships are likely to be quite relevant factors. When an economy is open, it can import resources and new technologies from abroad, alleviating the risk of a collapse. Or opportunities to export natural resources may expose the weak state of the economy’s resource ownership and management, facilitating the risk of a collapse.

Endogenous	Exogenous	Excluded
Population - Population - Birth Rate - Death Rate	**Popultion** - Impact of H on population - Impact of M on population - Maximum fertility rate - Maximum mortality rate	- Non-renewable resources - Negative externalities (pollution) - International relationships (exports, imports, immigration, emigration)
Natural Resource - Renewable resource - Natural Growth Rate of S - Harvesting Rate of S	**Natural Resource** - Regeneration rate of natural resource - Carrying capacity	
Harvesting - Inventory of H - Supply and demand of H - Price for good H	**Harvesting** - Efficiency parameter - Adjustment time for p_H	
Manufacturing - Inventory of M - Supply and demand of M - Price for good M	**Manufacturing** - Adjustment time for p_M - Efficiency parameter - Substitution parameter - Output elasticity	
Labor - Labor to H industry - Labor to M industry - Wage for H industry - Wage for M industry	**Labor**	
Man-Made Capital - Man-made capital - Return to man-made capital	**Man-Made Capital** - Capital depreciation rate - Adjustment time for the return to man-made capital	
Household - Total earning - Earning - Spending	**Household** - Consumer preference for goods - Savings rate	

Table 1. Model Boundary clarifying which variables are endogenously calculated, which are constants or time-series inserted exogenously, or potentially interesting but excluded

3. Problem Definition and Reference Behavior Patterns

Before presenting the simulation results, it is necessary to define our choice of the reference behavior mode for this thought experiment. In today's world, a problem of sustainable development faces *a new economic reality* in which natural resource constraints are largely defining the future outlook (UNESCAP, 2010). While major economic growth models such as Solow growth model, neoclassical growth model, Ramsey-Cass-Koopmans model, and Overlapping Generations Model do not embrace natural resource constraints as a primary component of their models, the UNESCAP report argues that natural resource constraints such as food, water and energy supplies, as well as climate change will play an increasingly important role in defining the sustainability of economies in the Asia and Pacific region. Natural resource constraints are a genuine problem for sustainable development.[7] For our thought experiment we need graphs and/or other descriptive data showing the reference behavior of the problem that reflects the aforementioned new phenomenon. Therefore, although the model does not intend to seek fitness to any particular historical data, it is worthwhile to draw hints from historical cases that depict the systemic behavioral patterns of our interest.

One possible reference pattern could be a collapse. There are many historical cases of collapse (*e.g.* Diamond, 2005). One of them is the boom and bust in Easter Island. As shown in Figure 2 below, Easter Island faced a severe collapse after depleting natural resources.

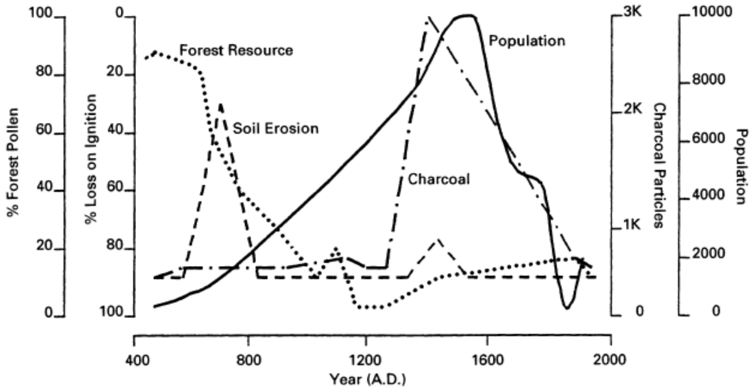

Figure 2. Easter Island dynamics from archaeological study by Bahn and Flenley (1992)

Another possibility could be dynamics in which population increases at the beginning and becomes stabilized later without depleting natural resources, which we would prefer in terms of sustainable development and can be found historically in Japan. Figure 3 shows the population and cultivated land during the *Edo* period (1603-1868) when the Japanese economy was closed in that imports, exports, immigration, and emigration were all negligible. Therefore, Japan’s growth during this period depended solely on its own natural resources. Population growth was S-shaped and then stabilized, until the *Edo* period ended and the new government opened the country. Compared with the peak cultivated land in 1948, there seemed to be enough arable land uncultivated.

The reference behavior pattern for the present research is Figure 2 or Figure 3, or a variation of these behavior patterns, and we choose 300 years as time horizon for our analysis. The choice of time horizon influences the analysis of the dynamics of a system, and must be long enough to reflect how problems emerge and how causes and effects impact the dynamics of the system (Sterman 2000). The *Edo* period lasted 265 years; Easter Island’s boom and bust played out over 1600 years. While a 1600-year time frame would be too long, the *Edo* period would be simpler than the situation faced by the current developing economies--a highly dynamic and rapidly changing situation including environmental, economical, and social aspects (Leach *et al*., 2010). Hence it would be prudent to consider a timeframe somewhat longer than the *Edo* period.

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[7] For a good review of these standard economic growth models, see Romer (2011).

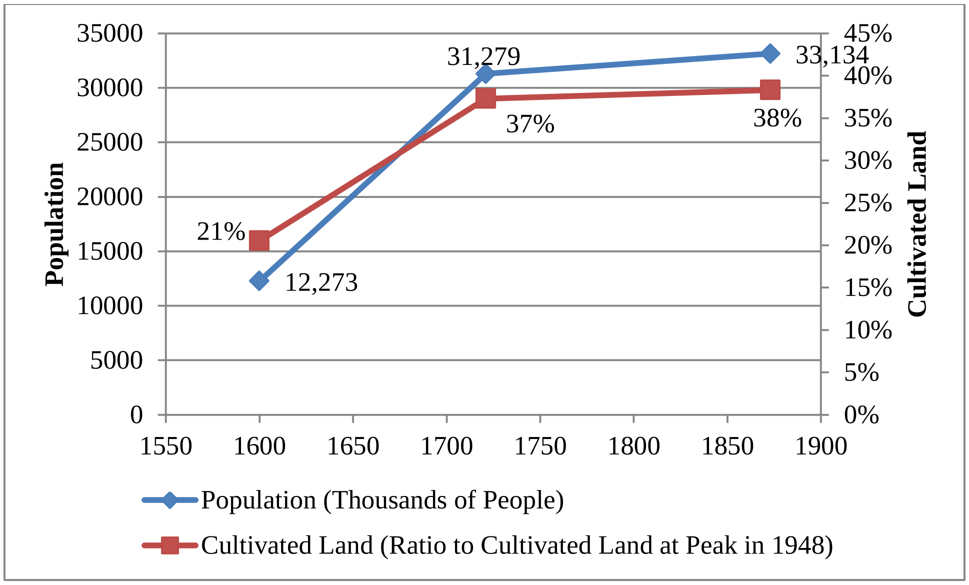

Figure 3. Population and Cultivated Land in Japan during Edo Era (1603-1868). Source: Oishi (1977) and Kito (2007)

4. Results

4.1. Basic Model Tests

Many model tests are presented in SD (Sterman, 2000). What is unique with the present model is that structural assessment was made based on economic theory. In other words, we assume that this model passes the structure assessment tests because the basic structure of the model follows economic theory. We also verified that the integration step-size was adequate, and we initialized the model to maintain an approximate equilibrium.

Typically, a full suite of model tests, including sensitivity tests, extreme condition tests and many other tests would be performed prior to the actual application of the model, to find answers to the questions posed at the outset of a modeling project. However, since the present research aims to show how the use of the system dynamics method can contribute to ecological economics, sensitivity analysis is presented as a primary research result rather than as model testing.

4.2. Baseline Model Run

The baseline model run is shown in Figure 4. Population grows rapidly, then declines and reaches a stable value well above the initial value. The Natural Resource declines to about half the carrying capacity. The behavioral pattern of the base line model is a variation of the behavior shown in Figure 2, with the population and resource stock levels stabilizing without a collapse.

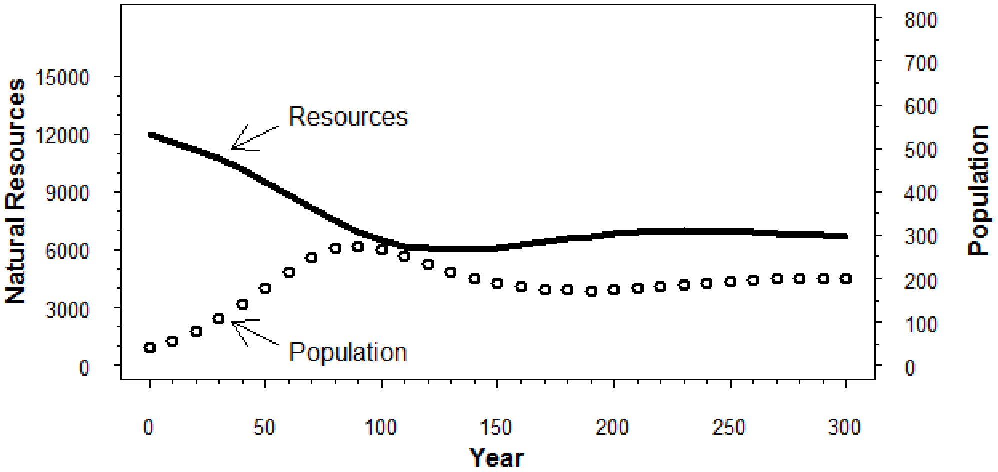

Figure 4. Population and Resource Dynamics: Baseline Model Run

4.3. Sensitivity Analysis Results

For this study, sensitivity analysis provides a primary result as well as serving as an important model validation tool. It is used to investigate possible transitional paths for the modeled system. Given the complexity of the system, it is virtually impossible to identify an optimal solution that takes into account of all of the necessary information, including possible future states. Sensitivity analysis can be a useful tool for studying alternative transition paths and highlighting important ecological-economic issues for our society.

We focus on two ecological economics issues that are critical for determining policies to achieve a sustainable economy: sensitivity to the key resource parameters, and adaptation (out-of-equilibrium conditions).

4.3.1. Sensitivity to Key Resource Parameters

BT-type models can easily incorporate time-dependent exogenous technological changes that increase resource carrying capacity, S_{max}, and/or the natural resource regeneration rate, η. As we demonstrate below, the results are very intriguing. Prior research has indicated that higher resource regeneration rates η can sustain larger population sizes, and that growth of carrying capacity S_{max} tends to lead to oscillations. Our SD model yields similar results, as shown in Figures 5 and 6 and allows for deeper interpretations.[8,9]

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[8] To make the difference explicit between with and without technological progress, only one growth rate is reported for each technological progress. The results of sensitivity analysis applying various growth rates show qualitatively similar patterns.

[9] Initial values of S and L are somewhat arbitrarily chosen in order to illustrate a specific baseline pattern. Therefore the interpretation of sensitivity analysis results focuses on changes from baseline.

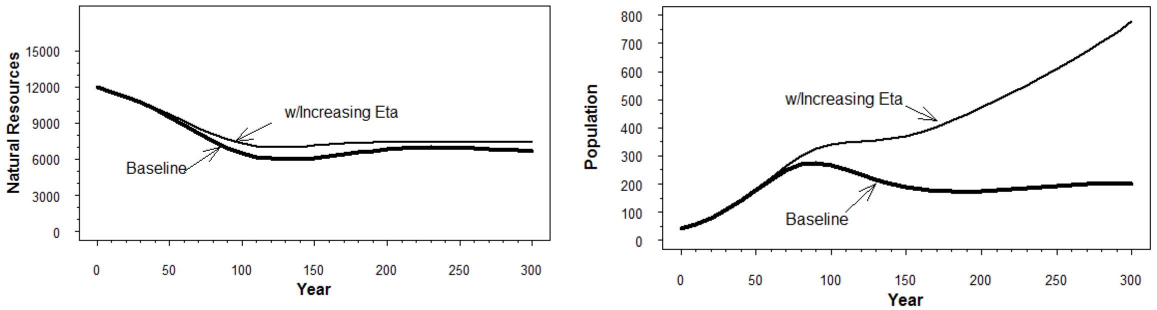

Figure 5. Impacts of exogenous technological change that increases η (η= 0.04$e^{0.005t}$, with carrying capacity fixed)

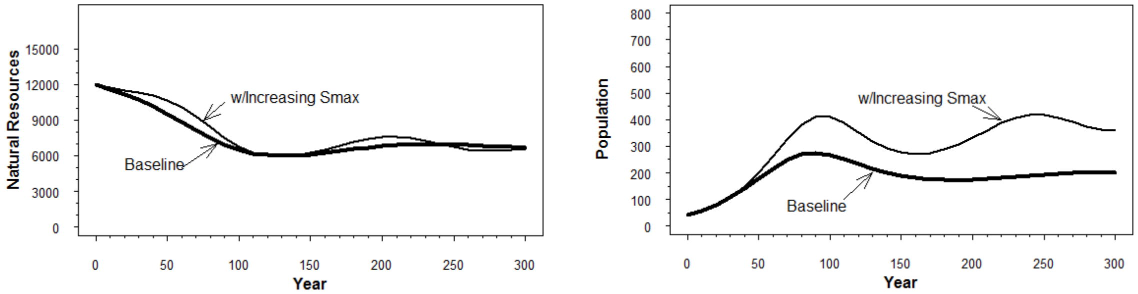

Figure 6. Impacts of exogenous technology change that increases S_{max} (S_{max} = 12000$e^{0.005t}$, with fixed resource regeneration rate)

The results seem counterintuitive. The growth function $G(S)$ is monotonically increasing with respect to both S_{max} and η (*i.e.*, $\partial G(S)/\partial S_{\max} > 0$ and $\partial G(S)/\partial \eta > 0$); however, the differences in the behaviors portrayed in Figures 5 and 6 are clear. While a higher growth rate results in sustained increases in population, a higher natural resource carrying capacity causes population and natural resources to oscillate.

While the observed dynamic behaviors are the result of complex relationships among positive and negative feedback loops, the difference in S_{max} is the key reason for the oscillation. As shown Figures 7a and 7b, while increases in η raise the growth curve for all values of $S < S_{max}$, S_{max} remains fixed. Meanwhile, increases in S_{max} not only raise the growth curve but also expand the curve to the right. The oscillation of a system with a higher carrying capacity has been well investigated in SD. Sterman (2000) specifies two conditions for overshoot and/or oscillation to occur: that negative loops include some significant delays, and/or carrying capacity is not fixed. This model incorporates delays, adaptation logic, and variable carrying capacity. When the carrying capacity changes, the system seeks for a new steady state that is consistent with the new carrying capacity. With significant delays in the negative loops (*e.g.*, a downward pressure of population growth on available food intake in our model), the system tends to oscillate, as shown in Figure 6.

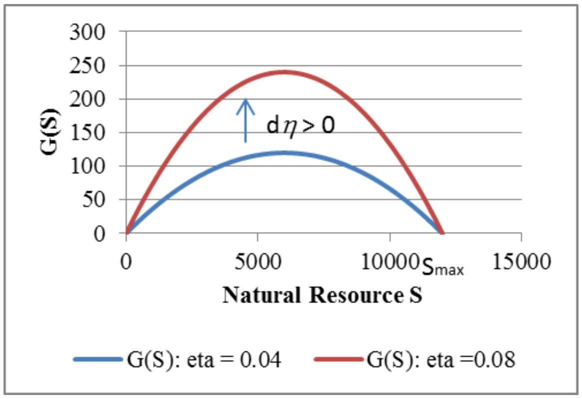

Figure 7a. Impact of η on $G(S)$

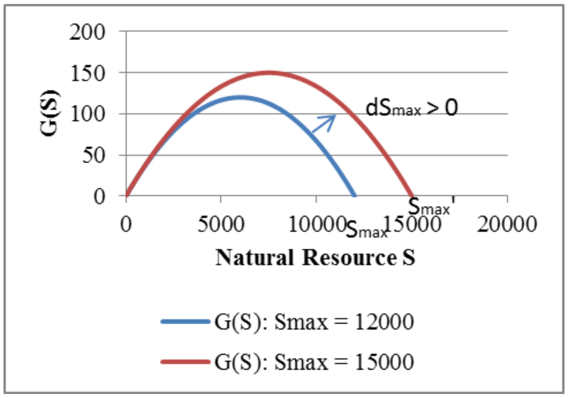

Figure 7b. Impact of S_{max} on $G(S)$

4.3.2. Sensitivity to Adaptation Time Constants for Price Change Mechanisms

Figure 8 shows the effects of varying the adjustment time constants. There are four adjustment time constants: the price of H (p_H), the price of M (p_M), the rent of the man-made capital (r), and the demand for H from the M sector (H_M). Simulation results demonstrate that while changing all the adjustment time constants by the same degree does not significantly change the dynamics of the system, using *different* adjustment time constants makes a non-negligible difference. For example, when the price adjustment processes for H_M, p_H, and r are relatively faster than the adjustment of p_M, population and other variables oscillate dramatically (as shown by the upper curves in Figure 8). The reason behind is that, at the beginning of the simulation period, the delayed response of producers to changing conditions makes good M expensive relative to good H, inducing consumers to spend more on good H than otherwise. This leads to sharp increases in consumption of H and population, as shown by the first set of peaks in Figure 8. Likewise, when the delayed response of producers makes good M relatively cheaper, the result is large decreases in consumption of H and population.

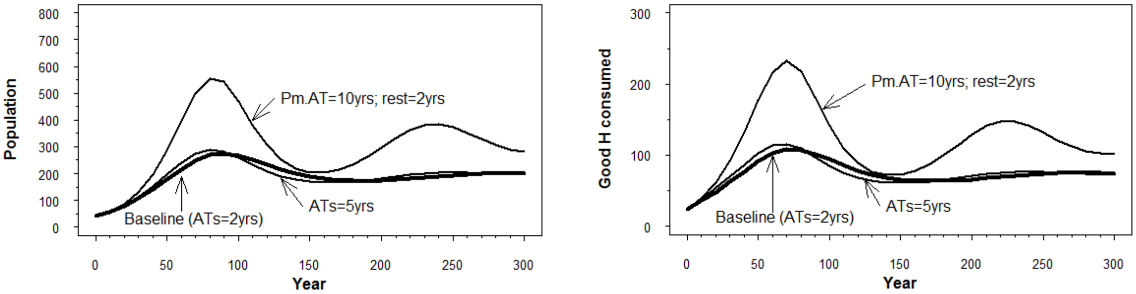

Figure 8. Impacts of Different Adjustment Times on Population and the Consumption of Good *H*. 2, 5, and 10 are used for the adjustment time periods.

Although oscillations resulting from adaptive processes and delays are nothing new to system dynamics, the concept of adaptation (out-of-equilibrium) and its importance have been recognized in ecological economics only recently (*e.g.*, Common and Stagl, 2005; de Vries, 2010; Folke, 2002; Leach *et al*., 2010; Levin *et al*., 1998; Stagl, 2007).

Leach et al. (2010) argue that conventional policy approaches to development and sustainability have ignored the dynamics and complexity of ecological-economic systems in order to be able to use standard equilibrium thinking and its associated policy implications. Ideally, ecological-economic systems are both predictable and controllable. However, both ecological systems and economic systems are changing rapidly. Given the dynamic and complex nature of ecological economic systems, we face risks, uncertainty, ambiguity, and ignorance; that is, we have imperfect knowledge (Leach *et al*., 2010).

Therefore, the use of adaptation is more than a philosophical or preference issue. Based on actual examples, Folke *et al*. (2002) argue that we should adopt a dynamic view that emphasizes far-from-equilibrium conditions. Robert Solow, a Nobel Memorial Prize laureate in Economic Sciences, points out the importance of disequilibrium in his two articles about natural resources and economic growth (Solow 1974a and 1974b). Whereas the first article, with an orthodox formal growth model, employs an equilibrium model, the second article, without a formal model, discusses the importance of disequilibrium and its impact on resource allocation. Studies by Hommes and Rosser (2001) and Forini *et al*. (2003), for example, apply adaptation to fishermen's price expectation formation in their fishery market models in order to study the "learnability" of equilibria−the ability of the system to adjust to changes and find new equilibria. However, adaptation is rarely addressed in ecological-economic models.[10]

5. Discussion and Conclusion

The extended ecological-economic model developed and tested in this study is based on economic theory and prior research by many economists, especially those focused on ecological economics. This study aims to demonstrate the benefits of employing the SD method to complement the analytical methods used in economics. These benefits include: 1) a greater reliance on simulation rather than analytic solutions, which allows the use of more complex formulations of the model; 2) the use of various diagrams to improve the transparency and accessibility of the model logic and assumptions; 3) a focus on the analysis of the feedback structures and the time dynamics; and 4) an emphasis on running a wide variety of experiments to fully exercise the models and increase the understanding of different causes and their effects on the dynamic outcomes of the system. The model developed for this study strives to overcome the three predispositions that often preside in economics: over-simplification of models, the predominance of an equilibrium-oriented paradigm, and a focus on the so-called balanced-growth path in the growth literature characterized by a long-run steady state with constant growth rates. Our sensitivity analysis results provide new and useful insights to those who face complex and dynamic ecological-economic systems.

Some of the specific concerns and questions raised by the results of the present research include: 1) exploration of resource carrying capacity and regeneration rates

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[10] Learning is not absent in economics. Learning plays a key role in modern macroeconomics. Learning in macroeconomics refers to models of expectation formation in which agents revise their forecast rules over time, for example in response to new data (Evans and Honkapohja, 2008).

exhibits both favorable and adverse potential outcomes; specifically, technologies that improve the resource regeneration rate may be preferred to those which improve the carrying capacity, and 2) testing the impact of different speeds of adjustment to out-of-equilibrium conditions among the key variables reveals major differences in the system response, including trajectories that are relatively steady and others where population exhibits large oscillations. The latter finding in particular reinforces the importance of not relying on equilibrium-oriented methods and also highlights the importance of identifying how much delay can be tolerated in adjustment processes before adverse and possibly irreversible results might occur.

These findings must be considered preliminary, however, since the model on which they are based is subject to various limitations, especially the restrictive model boundary documented in Table 1, and the need for further investigation, including the application/calibration of the model to represent, for example, actual developing economies in a realistic fashion.

The simple and extensible model presented in this study can serve as a starting point for investigating the role of such critical factors as input substitutability, resource management regimes, population growth, and adaptation in an economy under natural resource constraints, in order to evaluate the sustainability and resilience of an ecological-economic system. The analysis of the model presented highlights the considerable potential of SD methods to complement economics research, especially ecological economics, which strives to address the complex interactions between the economy, ecological systems, and human behavior.

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