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System Dynamics Implementation of a Model of Population and Resource Dynamics with Adaptation

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Abstract

We build and analyze a dynamic ecological economic model that incorporates endogenous innovation on input substitutability. The use of the system dynamics method allows us to depart from conventional equilibrium thinking and conduct an out-of-equilibrium (adaptation) analysis. Simulation results show that while improvement in input substitutability will expand an economy, this change alone may not improve sustainability measured by indicators such as utility-per-capita and natural resource stock. It could, however, be possible that in combination with other technological progress, improvement in input substitutability will contribute to sustainable development. Sensitivity analysis also indicates a possible complication with the use of exogenous consumer preference, which is often assumed in standard economics.

Keywords: Endogenous innovation on input substitutability; Out-of-equilibrium (adaptation); Population-resource dynamics; Sustainability; System dynamics.

1. Introduction

Real problems in complex systems do not respect academic boundaries.

Herman Daly and Joshua Farley (2010, xvii)

Sustainable development in developing economies faces *a new economic reality* in which natural resource constraints such as food, water and energy supplies, and climate change are largely defining the future outlook (UNESCAP, 2010, vii). Meanwhile, major economic growth models such as Solow growth model, neoclassical growth model, Ramsey-Cass-Koopmans, and Overlapping Generations Model do not embrace natural resource constraints as a primary component of their models.[1] Ecological economics is an interdisciplinary approach to the study of the interactions between economic systems and ecological systems. Given the essential dynamic complexity of an ecological economic system (henceforth EES), we need a methodological approach that goes beyond the simplified, analytic approaches in conventional economics. We build and analyze a dynamic ecological economic model that incorporates endogenous innovation on input substitutability. Our simulation results indicate that over time improvement in input substitutability *alone* may not make a significant contribution to sustainable development. We also demonstrate the usefulness of the system dynamics approach to ecological economics.

Although EESs are “undeniably complex” (Limburg et al., 2002), standard economics has generally taken a strategy of simplification to be able to employ analytic approaches; however, simplification has many drawbacks. There are many examples of this. First, simpler functions such as the Cobb-Douglas type function, while easy-to-handle analytically, limit the analysis of substitutability between man-made capital and natural resources that is essential for sustainable development under natural resource constraints. Second, natural resources are often treated as exogenous, resulting in missing feedbacks between ecology and economy that are critical in the study of the sustainability of and economy. Third, our focus on the state of equilibrium often results in neglecting the transitional dynamics.[2] However, an approach that specifies behavioral rules and feedback loops allows the system to be in a state of disequilibrium is critical for the study of EESs.

This paper integrates system dynamics (henceforth SD) into economic modeling and analyses to provide deeper insights into the dynamics of EESs. System dynamicists often dismiss economic theories because of its unrealistic (in their view) tendencies. Meanwhile, SD models that are inconsistent with economic theories are not of interest of economists. We contribute to the two disciplines through 1) the development of an ecological economic model that is firmly based on economic theories, and 2) the construction and validation of the model using the SD approach, as explained below.

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[1] Romer (2011) provides a comprehensive review of these standard economic growth models.

[2] There has been a development in equilibrium-seeking adaptive systems in the form of the learning (expectation) theory in macroeconomics (*e.g.*, Evans and Honkapohja, 2009; Evans and Honkapohja, 2011; Bullard, 2006).

Our ecological economic model is an extension of the so-called BT model (Brander and Taylor, 1998) that can depict a pattern of economic and population growth, resource degradation, and subsequent economic decline and is suitable for the study of sustainability and resilience of an economic system.[3] Since its initial appearance, due to its simplicity and extendability the BT model has generated many descendants (Anderies, 2003; Basener and Ross, 2005; Basener et al., 2008; D'Alessandro, 2007; Dalton and Coats, 2000; Dalton et al., 2005; de la Croix and Dottori, 2008; Erickson and Gowdy, 2000; Good and Reuveny, 2006; Maxwell and Reuveny, 2000; Nagase and Mirza, 2006; Pezzey and Anderies, 2003; Prskawetz et al., 2003; Reuveny and Decker, 2000; Taylor, 2009). Our model is motivated by Nagase and Uehara's (2011) synthesis of the existing models of this type, and it is also an extension of the model developed by Uehara et al. (2010).

SD provides useful tools and approaches to analyze complex systems. In addition to technical characteristics of SD as a computer-aided approach to solve a system of coupled, nonlinear, first-order differential equations, what characterizes SD is its emphasis on 1) feedback thinking, 2) loop dominance and nonlinearity, and 3) taking an endogenous point of view. The endogenous point of view is the *sine qua non* of systems approaches (Richardson, 2011). SD also uses several unique techniques for mapping a model, including causal loop diagrams, system boundary diagrams, and stock and flow diagrams, in order to visualize a complex system. To validate a complex model, SD adopts various testing methods such as boundary adequacy test, structure assessment, and sensitivity analysis (*cf*. Sterman, 2000).

There are three main findings from our simulation results. First, over time improvement in input substitutability *alone* may not make a significant contribution to sustainable development. While the production of goods will increase as input substitutability improves over time, utility-per-capita may barely change and natural resource stock declines. Second, however, in combination with resource saving technological progress, over time improvement in input substitutability could increase utility-per-capita and save natural resource stock. Third, sensitivity analysis shows that an exogenous consumer preference, which is often assumed in economics, could be problematic.

Our model is most applicable to developing economies where their sustainability critically depends on natural resources and population dynamics. Consequently, we intend our model to evolve further to provide case studies that can yield policy implications for such economies. A caveat is that current developing economies are going through experiences that are different from those of the developed economies due to, for example, the access to rapidly-evolving technologies and the increased scarcity of natural resources (UNESCAP, 2010). Therefore, we do not seek fitness of our model to any particular *historical* data to validate the model. Instead, we validate our model using the "reference mode" (described in the next section) chosen for the model, so that we assess the

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[3] The unified growth theory incorporates population dynamics endogenously into economic growth models. This theory is a variant of the endogenous growth theory focusing on the transition to a steadily growing economy (*e.g*., Strulik, 1997; Galor and Weil, 2000; Hansen and Prescott, 2002; Galor, 2005; Voigtlander and Voth, 2006; Strulik, and Weisdorf, 2008; Madsen et al. 2010). However, natural resources stocks and flows are fixed or ignored in their models.

performance of our model based on how well it can depict the intended behavioral pattern of the ecological-economic system.

Section 2 presents the model and preliminary model testing, Section 3 provides the primary results from conducting a variety model experiments focused on parameter sensitivity. Section 4 provides a discussion of our results and concluding remarks.

2. Model

2.1 Reference mode

To develop and validate a SD model, we typically need graphs and other descriptive data that represent *a pattern of behavior* of the system to be modeled. In SD, this is called a “reference mode.” A reference mode identifies key concepts and variables for the model and sets the appropriate time horizon of the model during which the modeled system is expected to reveal, through the effects of complex feedback loops, how problems emerge and how they affect the dynamics of the system. Through these choices, the reference mode defines the pattern of behavior of the system. The identified behavioral pattern will become the point of reference, in the process of developing the model and for its validation (cf. Sterman, 2000).

One possible behavioral pattern for our reference mode could be a collapse of an economy. There are many historical cases of collapse (Diamond, 2005). One of them is the boom and bust in Easter Island that faced a severe collapse after depleting natural resources (Figure 1).

Another possible reference pattern could be a dynamics in which population increases at the beginning and becomes stabilized later, without depleting natural resources. Japan presents such an example in its history. Figure 2 shows the population and cultivated land during the *Edo* era (1603-1868). During the *Edo* era, the Japanese economy was closed in that imports, exports, immigration, and emigration were all negligible. Therefore, in terms of natural resources Japan’s growth during this period depended solely on its own. Population growth was S-shaped and then stabilized until the *Edo* era ended, at which point the new, modern government opened the country. Compared with the peak of the size of cultivated land area in 1948, there seemed to be enough arable land uncultivated.

In consideration of the fast-changing modern economy and environment (that favors a shorter time horizon) on the one side and the higher complexity of the modern economic system (that favors a longer time horizon) on the other side, we choose 300 years as the time horizon for our reference mode. Sustainability being the primary theme of our research, we choose the behavioral pattern for our reference mode to be characterized by increasing population followed by the decline in the natural resource stock, leaving possibilities for both a collapse and stabilization of the system. For this purpose, the use of the BT model as the basis of our model development allows us to include the relevant variables and behavioral assumptions for the system.

2.2 Model

Our model can be classified as 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--except that, as revealed shortly, our SD approach does not require an analytic equilibrium solution for each time period.

The model depicts an economy consisting of two (harvest and manufacturing) sectors. Input availability in each time period is bounded by the existing sizes of population, renewable natural resource stock, and man-made capital. In contrast to standard approach in natural resource economics (*e.g.*, Conrad, 2010), agents are rational but myopic; they maximize utility and profit yet only within each time period. It is a reasonable approach for the situation where the resource stock is held in common and agents are atomistic (Taylor, 2009). The renewable resource in our model is a common-property resource (CPR), and the lack of long-term perspectives among agents could result in severe resource depletion that can threaten the sustainability of the economy. The production and consumption activities in each period determine the growth rates of population, resource stock, and man-made capital.

One aspects of our model specification is particularly novel: we allow the model to address the issue of substitutability between natural resource and man-made capital endogenously. For this purpose we introduce a constant-elasticity-of-substitution (CES) production function for the manufacturing sector. Input substitutability in this sector evolves over time due to the endogenous technological change (ETC) driven by the relative input scarcity. Endogeneity of natural versus man-made input substitutability is a critical issue for sustainability, and to the best of our knowledge our model is the first attempt to integrate ETC and substitutability.

2.2.1 Period-by-period behavior of agents

Let us now describe the specifics of the model (time subscripts are suppressed for all variables).[4] 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:

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

h and m denote per-capita consumption levels of harvest good (H) and manufactured good (M), respectively. s denotes the saving rate, w and r are prices of labor and man-made capital, respectively.[5] This optimization problem yields the consumption demand functions for the two goods:

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[4] Nagase and Uehara's (2011) circular flow diagram provides a useful visual representation for those who are not familiar with the BT-type models.

[5] 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.

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

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

where h and m denote per-capita consumption levels of H and M, respectively.

Two sectors' constant-returns-to-scale aggregate production functions are defined as $H(L) = \alpha S L_H$ and $M(L_M, H_M, K) = \nu L_M^{1-\gamma}[\pi H_M^{\rho} + (1-\pi)K^{\rho}]^{\gamma/\rho}$, respectively, where H_M denotes the amount of good H consumed as an input, $L_M = L - L_H$, and γ and $\lambda \in (0, 1)$. $\rho < 1$ so that the elasticity of substitution $\sigma = 1/(1-\rho)$ is positive. α and γ are efficiency parameters.

The degree of substitutability between man-made capital and natural resources plays a critical role in determining the sustainability of EESs in which the economy faces natural resource constraints. Studies on substitutability have been almost exclusively conducted using CES production functions.[6] With $\sigma < 1$, inputs are complements so that the natural resource is essential for production, meaning that production becomes more difficult without the natural resource.[7]

In relation to sustainability, the key discussion of the substitutability is the trade-off between natural resources and the accumulated man-made capital. Whereas mainstream economics has implicitly supported $\sigma = 1$ through the ubiquitous employment of the C-D function, ecological economists assert $\sigma < 1$ for various reasons (*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:

$$p_H \alpha S = w \tag{3}$$

$$p_M \nu (1-\gamma)(L-L_H)^{-\gamma}\left[\pi H_M{}^{\rho} + (1-\pi)K^{\rho}\right]^{\frac{\gamma}{\rho}} = w \tag{4}$$

$$p_M \nu (1-\gamma)(L-L_H)^{1-\gamma}\gamma\left[\pi H_M{}^{\rho} + (1-\pi)K^{\rho}\right]^{\frac{\gamma}{\rho}-1}\pi H_M{}^{\rho-1} = p_H \tag{5}$$

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

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

$$\frac{(1-s)\beta}{p_H}(wL + rK) + H_M = \alpha S L_H \tag{7}$$

and

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[6] Stern (1994) proposes the translog production function because it can effectively model minimum input requirements, any elasticity of substitution, and uneconomic regions, for any number of inputs and outputs.

[7] For a comprehensive discussion about the relationship between substitutability and sustainability, see Hamilton (1995).

$$\frac{(1-s)(1-\beta)}{p_M}(wL+rK)L \quad = \quad v(L-L_H)^{1-\gamma}\left[\pi H_M{}^{\rho}+(1-\pi)K^{\rho}\right]^{\frac{\gamma}{\rho}} \, . \tag{8}$$

Equations (3) through (8) yields the static equilibrium solution set {L_H*, H_M*, w*, r*, p_H*, and p_M*}.[8] The harvest level H in our model is determined endogenously as a result of an economic activity, in contrast to some other similar studies on the dynamics of population and natural resource (*e.g.*, Shukla et al., 2011).

2.2.2 Dynamic transition

Given {L_H*, H_M*, w*, r*, p_H*, and p_M*}, the transitional dynamics for the three stock variables are given by the following equations.

$$\frac{dL}{dt} \;=\; L\left[b(h^*,m^*)-d(h^*,m^*)\right]; \;\; b \;=\; b_0\left(1-\frac{1}{e^{b_1h^*}}\right)\frac{1}{e^{b_2m^*}} \;\text{ and }\; d \;=\; d_0\frac{1}{e^{h^*(d_1+d_2m^*)}} \tag{9}$$

$$\frac{dS}{dt}=G(S)-H^*=\eta S\left(1-\frac{S}{S_{max}}\right)-H^* \tag{10}$$

$$\frac{dK}{dt} \;=\; \frac{s(w^*L+r^*K)}{p_M{}^*}-\delta K \tag{11}$$

Equations (9) and (10) characterize our model as a Gordon-Schaefer Model, using a variation of the Lotka-Volterra predator-prey model (*cf.* Nagase and Uehara, 2011).

Equation (9) represents a Malthusian population dynamics in the sense that the higher per capita consumption of the resource good leads to higher population growth. b and d denotes the birth and death rates. We adopt Anderies' (2003) formulation which incorporates the impact of the manufactured good per capita m as well as h in order to reflect *the demographic transition hypothesis*.[9] More specifically, real income and fertility are negatively correlated, and mortality is negatively correlated with improved nutrition and infrastructure. The term $b_0\left(1-\frac{1}{e^{b_1h^*}}\right)$ depicts that as consumption of harvested good (nutrition) increases the birth rate increases, up to a maximum of b_0. The term $\frac{1}{e^{b_2m^*}}$ represents the downward pressure on birth rate as consumption of manufactured good

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[8] 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.

[9] 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.

increases. The death rate function depicts that improved nutrition reduces death rates via the term hd_1, while improved infrastructure reduces death rates via the term hd_2m.

$G(S)$ represents a logistic growth function of S. η denotes the intrinsic growth rate, and S_{max} denote the carrying capacity.

Equation (11) represents a standard economic approach to model capital accumulation. Capital accumulation is a basic component in growth literature. In ecological-economic modeling, incorporating capital accumulation allows us to investigate the role of substitutability between man-made capital and natural resources for sustainability. The first term on the right hand side represents the amount of manufactured good used for capital formation. s is an exogenously given (for simplicity) savings rate, and δ is the capital depreciation rate. Man-made capital accumulation depends indirectly on natural resource through the production of manufactured good. Therefore, in our model, natural resources are a so-called "growth-essential" (Groth, 2007).

Finally, the transitional dynamics for the input substitutability is given by:

$$\rho(t) = \frac{1}{1+e^{-x(t)}} - 1 \; ; \; \frac{dx}{dt} = \zeta \left| \frac{p_H}{r} - 1 \right| , \; \zeta > 0. \tag{12}$$

Variable x is a measure of knowledge or experience that contributes to the innovation process. Equation (12) yields an S-shaped curve for innovation as knowledge/experience accumulates, as typically observed (Rogers, 1995). The equation also embodies the premise that economic agents respond to price changes that reflect relative resource scarcity (Löschel, 2002). For simplicity, we do not depict explicitly in our model how innovation takes place; meanwhile, one can interpret that we implicitly assume that innovation occurs as a side effect of capital accumulation (Allow, 1962; Romers, 1996; Castelnuovo et al., 2005). By incorporating scarcity-driven ETC, our model endogenizes the motivation for the depicted economy to better-utilize the relatively scarce input. Hence the production function for manufactured good, the capital accumulation rule, and the ETC rule together form a close relationship.

2.3 System Dynamics

While the analyses of economic models tend to depend on terminal conditions of the system and focus on the steady state, a SD approach highlights the transition paths, that is, how the dynamics of a system changes over time. Thanks to the lack of requirement for analytic solutions, a SD approach facilitates the analysis of a complex EES without making undue simplifications.

A SD approach takes two steps. First, we construct an SD model of an EES whose specifications of the feedback loops are based on economic theory and scientific causal relations. Second, we let the model reveal the transitional paths of the variables, by way of an adaptation (out-of-equilibrium) mechanism. For our model, we employ a simple hill-climbing method, an iterative algorithm (Sterman, 1980 and 2000). For example, the manufacturing sector seeks to find the optimal combination of inputs L_M, H_M, and K to maximize profit, *i.e.*, to satisfy conditions (4), (5), and (6). In a standard equilibrium approach in economics, reduced-form analytic solutions represent the optimal values. In using a hill-climbing method, the system begins with an arbitrary set of solutions. The system then repeatedly adopts incremental changes to the solutions to find a better set of solutions. This process ends when no further improvement can be made to the solution set.

Two model descriptions can be helpful to gain a wholesome picture of our model: a causal loop diagram (CLD) and a description of the model boundary. Figure 3 shows CLDs for our extended model. The six boxes represent three stock variables (population, natural resource, and man-made capital) and three markets (harvested good, manufactured good, and labor). Thick arrows indicate critical interaction between man-made capital and natural resource, through the M-market. An arrow tells the direction of causality. For instance an increase in "population" (L) results in a decrease in "food per capita" (h) as the "–" sign indicates. An increase in "food" (H) results in an increase in h ("+" sign attached to the arrow). "R" means that the loop is a positive (reinforcing) feedback loop, while "B" means that the loop is a negative (balancing) feedback loop.

Table 1 documents the boundary of our model and clarifies endogenous variables, exogenously-given parameters, and excluded variables.[10] The choice to highlight specific excluded variables is somewhat subjective. They are chosen for their importance in view of EESs for developing economies. Nonrenewable resources are also important, as most studies on the economics of sustainability focus on nonrenewable resources (*e.g.*, Hartwick, 1977). Societies tend to use less expensive nonrenewable resources first, such as oil, and then switch to more expensive renewable resources such as wind and solar when the marginal cost of the nonrenewable resource begins to exceed that of the renewable resources (Tietenberg, 2011). Negative externalities such as pollution may not be negligible. For example, a study by Asian Development Bank showed that the costs associated with climate change could be equivalent to a loss of 6.7% of their combined gross domestic product (GDP) by 2100 (ADB, 2009). International relationships may be most important factors excluded from our model. When international relationships exist, as is the case for most developing economies, they can use resources and new technologies from abroad and perhaps avoid collapse. Unemployment is also a crucial issue in developing economies, but following the standard treatment in growth literature, for simplicity factors that prevent our SD model from reaching full employment are outside the scope of our model and are excluded. For the purpose of replication, the full model will be provided upon request. Table 2 reports the numerical values adopted for our base model. Exogenous variables for the baseline model are calibrated to generate a behavior such that the population and the natural resource are somewhat stabilized over time as observed in the *Edo* era in Japan (Figure 2). Some values are adopted from Brander and Taylor (1998) or Anderies (2003).

2.4 Model Testing

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[10] Some of the exogenous parameters in our model could be modeled as endogenous. For example, the carrying capacity and the regeneration rate of natural resources could be endogenous via innovation. Adjustment times are often exogenously given in SD models, but these could be endogenous as well. For example, Kostyshyna (forthcoming) suggests an adaptive step-size algorithm to allow a time-varying learning speed (or a time-varying gain parameter) that change endogenously in response to changes in the environment.

In many cases, a full suite of model tests, including sensitivity tests, extreme condition tests and many others would be performed prior to actually applying the model to find answers to the questions posed at the outset of a modeling project.[11] We tested to verify that the integration step-size was adequate. The integration error test is a necessary procedure to avoid producing dynamics resulted from inadequate numerical approximation.

The baseline model run is shown in Figure 4. Population grows rapidly, then declines and reaches a steady state value well above the initial value. The natural resource declines to nearly half of the carrying capacity. The model's behavior in Figure 4 is qualitatively similar to the behavior of the *Edo* era in Figure 2, one of reference modes.

3. Results

3.1 Sensitivity Analyses

For this paper we consider the sensitivity analyses to be a primary result in addition to serving as an important model validation tool. Sensitivity analysis can be used to investigate possible transitional paths for EESs. Given the complexity of such systems, it is almost impossible for an SD model to take account of a complete set of information on all possible future states. Nevertheless, policy makers can learn from SD modeling and analyses various transition paths that highlight possible ecological/economic changes for society (Leach et al., 2010).[12] Given past experiences, Folke et al. (2002) suggest "structured scenarios" as a tool to envision multiple alternative futures and the pathways for making policies.

In this study we analyze the system behavior in response to changes in exogenous variables and the impact of endogenous substitutability on sustainability. The first section describes the system's sensitivity to savings, carrying capacity, regeneration rate, population parameters. The system's responses to these parameters gives us a grasp of how the system behaves. The second section sheds light on a possible problem of a well-accepted modeling approach in economics, that is, an exogenous consumer preference. Third section shows the impact of endogenous substitutability in terms of sustainability.

3.2 Sensitivity to Savings, Carrying Capacity, Regeneration Rate, Population Parameters

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[11] What is particularly unique about our SD model is that structural assessment was made based on economic theory, *i.e.*, we assume that our model passes the structure assessment tests because the basic structure of the model follows standard economic theory.

[12] Leach et al. (2010) points out that dynamics and complexity have been ignored in conventional policy approaches for development and sustainability. They relate this tendency to prevailing equilibrium thinking as we describe in this study.

First, we vary savings rate s by increments from .2 down to .01, which caused population L to increase more rapidly, overshoot more deeply, and then to settle at a somewhat higher steady state value. Natural resources S declines further as s was reduced, but not drastically. Returns to capital r increases significantly and was more volatile (see Figure 5, left plot). Capital accumulation K decreases significantly, as expected. Supply of M decrease as well, but p_M is not affected.

Next we vary resource carrying capacity S_{max} reduced from 12,000 to 6000. Population collapses, even though S stabilizes at the new value of S_{max}. This surprising result requires a close look at its causes.

We then change the resource regeneration rate η from .04 to 0.2. As a result, L increases more sharply and stabilize. This is driven by higher harvest levels. Consequently, natural resources dynamics is relatively unaffected.

In another experiment, we double the sensitivity of births to resource good intake and halves the sensitivity of births to manufactured good intake (see Figure 5, right plot, red trace). Population grows faster, overshoots more, and stabilizes at a higher level. The natural resource stock drops faster and further, ending up at a lower value. When these changes are reversed, population increases slowly and stabilizes at a lower level (see Figure 5, right plot, blue trace). The natural resource stock declines more modestly and stabilizes. Production of manufactured good increases and stabilizes. Returns to capital declines steadily (but not as much as the baseline) and stabilizes.

We also test the impact of higher sensitivities of the death rate to intake of harvest good (doubled) and manufactured good (halved). The results are similar to the birth rate experiment, meanwhile the timing of the peak in L and the drop in S remains unaffected. When the changes were reversed, population dynamics becomes flat, along with all the other variables. This is another counter-intuitive result and requires further investigation of its causes.

3.3 Sensitivity to Consumer Preference

In our model, following standard economics, a preference for harvested good, β**,** is exogenously given.

Although any value between 0 and 1 is consistent with economic theory, a low value for β yields an unexpected system outcome, as shown in Figure 6. When β is 0.15 (*i.e.*, a lower preference for H good), population becomes extinct at time 100. Given that the natural resource S remains abundant, this is a drastic, counter-intuitive result and needs further investigation on its driving factors.

A constant preference for goods is a standard approach in economics, and the effect of varying preferences on an EES has not been investigated. Stern (1997) points out that neoclassical economists are very reticent to discuss the origin of preferences and that preferences are normally assumed to be unchanging over time. Our sensitivity analysis, however, highlights the potential significance of studying the effect of varying consumer preferences.[13] The importance of endogenous preferences for sustainability issues has been argued in ecological economics (Common and Stagl, 2005; Georgescu-Roegen, 1950; Stern, 1997), evolutionary economics (Gowdy, 2007), and institutional economics (Hahnel and Albert, 1990; Hahnel, 2001). Gowdy (2007) argues that neoclassical economics assumes that consumer choices are based not only on price signals but also on other incentives such as individual's personal history, their interaction with others, and the social context of the individual choice. The author calls the former the *self-regarding preference* and the latter *the other-regarding preference*. If these factors change over time, then preferences should reflect these changes. Gowdy (2007) asserts further that modeling the other-regarding behavior would be more realistic for sustainability research. Common and Stagl (2005) argue that to change preference is a normative requirement from a sustainability perspective, including the idea that there could be an ethical basis for changing preferences. While there have been several discussions on endogenous preference, there is no standard way of modeling endogenous preference in economics literature.[14]

3.4 Impact of Endogenous Substitutability Factor, ρ

As described in Section 2.2, the dynamic equation for substitutability factor ρ generates an s-shaped curve for the value of ρ over knowledge accumulation (KA) index x, varying from modest substitutability ($\rho = -1$, $\sigma = 0.5$) to high substitutability ($\rho \approx 0$, $\sigma \approx 1$) which would be the maximum substitutability ecological economists would think. The point at which ρ begins to shift rapidly upwards depends on endogenous technological change (ETC) which is driven by relative resource scarcity.

Figure 7 shows the results of an experiment to verify that ρ is in fact being endogenously influenced by the evolving state of the system over time. The resource regeneration rate, η, a parameter that strongly impacts S, L, and the production rates for H good and M good, is first doubled and then halved. With a higher η, natural resource is more plentiful, p_H remains relatively low for a long time, and there is less pressure to learn (Figure 7, left plot, trace 1). Consequently ρ remained low longer (Figure 7, right plot, trace 1) before resource depletion eventually stimulates p_H, which increases KA index x and ρ.

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[13] It is not impossible to solve this problem using an exogenous preference. For example, a Stone-Geary type utility function (Anderies, 2003) incorporates the minimum amount of the quantity demanded for H into the utility function as $U(h,m) = (h - h_{\min})^{\beta} m^{1-\beta}$. Then we can derive the demand function $h = (1-\beta) h_{\min} + \frac{w\beta}{p_h}$. Hence, the first part does not depend on the price. It means that people put their effort to harvest at least the minimum level, h_{min}, irrespective of the price.

[14] One example of modeling endogenous preference is proposed by Stern (1997). Using the symmetric characteristics of production and consumption, he proposes the factor augmentation model using an analogy to endogenously augmenting technology in production.

Once the endogeneity of ρ in our SD model is verified, we can compare the model results with a fixed ρ and those with an endogenous ρ. Simulation outcomes of six key variables, utility-per-capita, population *L*, natural resource stock *S*, *H* production, *M* production, and substitutability factor ρ are shown in Figure 8, with $\rho = -1$, and endogenous ρ. As Figure 8 indicates, while model behavior with endogenous ρ contributes to larger *L*, *H*, *M*, and more use of *S*, utility-per-capita shows barely discernable. Barely changing utility-per-capita is somewhat counterintuitive since our population dynamic is not Malthusian but following the demographic transition hypothesis. Hence to check how the population dynamics affect the system, sensitivity analysis to population parameters are conducted next.

Next, we investigate how an endogenous ρ affects the dynamics of the model through the six population parameters: maximum birthrate b_0; sensitivity of birth rate to resource good intake b_1; sensitivity of birth rate to manufactured good intake b_2; maximum death rate d_0; sensitivity of death rate to resource good intake d_1; and sensitivity of death rate to manufactured good intake d_2. A few illustrative samples are shown in Figure 9, and the rest of the results are summarized in the following paragraphs. In each box, there are three plots representing the outcomes with the parameter at its initial value (green, 3), doubled (red, 2), and halved (blue, 1).

The sample plots shown in Figure 11 as well as many other plots not shown reveal that the effects of endogenous ρ are modest. When maximum birthrate b_0 is reduced by half (trace with 1's), population grows much more slowly, and the steady state population is much smaller (not shown). In this scenario, when ρ is endogenous the steady state population, harvested good, manufactured good (shown in Figure 9) are all noticeably higher; and natural resource stock somewhat less. At baseline b_0 (trace with 3's), the impact of endogenous vs. fixed ρ is not noticeable. When b_0 is doubled (trace with 2's), model variables are all significantly impacted, but the impact of endogenous vs. fixed ρ is not noticeable.

Results when varying sensitivity of birth rate to resource good intake b_1 are similar, except that the impact of endogenous ρ is noticeable for all three values of b_1. As with b_0, the impact of endogenous ρ is most apparent when b_1 is halved and population growth is much slower (as shown in Figure 9). When sensitivity of birth rate to manufactured good intake b_2 is varied, the results (not shown) are similar to when b_1 is varied.

When maximum death rate d_0 is varied, *L*, *H*, *M*, and *S* are all impacted considerably, as would be expected. The impact of endogenous ρ on *H* production is most apparent; when d_0 is increased population declines (as shown in Figure 9). For *M*, *L*, and *S*, the impact of endogenous ρ is apparent for all three values of d_0, though less for *S*.

When the sensitivity of death rate to resource good intake d_1 is varied results are very similar to the results for changing d_0. For sensitivity of death rate to manufactured good intake d_2 the effects on model behavior are much less than with the other five parameters. Endogenous ρ has a small impact on *L*, *H*, *M*, and *S* for all values of d_2.

Overall, the impact of the current formulation for endogenous substitutability, ρ, is modest. In particular, the impact on utility-per-capita is barely discernible. We provide possible interpretations in Section 3.5.

3.5 Impact of Technological Progress on Utility-per-Capita

As mentioned above, endogenously improving substitutability affects *M, H, L* and *S*, but not utility-per-capita. We next investigated the impact of combining endogenously improving substitutability with other aspects of technological progress. Since the purpose of this investigation is to study the impact of different *combinations* of knowledge accumulation and technological progress rather than studying endogenous drivers for technological progress, we employ exogenous formulation for technological progress.

Since our motivation is to understand what influences utility-per-capita *u*, we first consider how *u* is calculated as a function of H_C, M_C, and L:

$$u(h,m) = u\left(\frac{H_C}{L},\frac{M_C}{L}\right) = \left(\frac{H_C}{L}\right)^{\beta}\left(\frac{M_C}{L}\right)^{1-\beta} \tag{13}$$

Since dH_C, dM_C, and dL can be positive, zero, or negative, there are many combinations that could lead to $du > 0$.

We experiment with the two primary types of technological progress discussed in the literature on economic growth (*e.g.*, Groth, 2007): 1) total factor productivity for *M*, and 2) resource-saving or H_M-augmenting technological progress. For simplicity, in the following tests, a simple form of exogenous technological progress is used to simulate each type technological progress.

$$E_k = E_{k,t=0}e^{\lambda_k t} = e^{\lambda_k t} \tag{15}$$

where *k* is either TFP or H_M-augmenting, and $E_{k,t=0}$ and λ_k are, respectively, an initial productivity, which is assumed to be 1, and growth rate of productivity for *k*.

Figure 10 shows selected results. There are several points worth highlighting. First, for both types of technological growth using simple models, consistent with the literature (Stiglitz, 1974; Groth, 2007), utility-per-capita could increase when the technological progress is large enough, even with limited and constant substitutability, $\rho < 0$.

Second, utility-per-capita is larger when substitutability changes (improves) endogenously, for both types of technological progress: TFP and H_M-augmenting. However, the mechanism for the two types is quite different. With TFP, *Hc*, *Mc*, and *L* are higher and *S* is lower with endogenous substitutability compared to constant substitutability. This means that in the endogenous substitutability case, the increases in *Hc* and *Mc* are large enough to overcome the increase in *L*, which is not true for constant substitutability. With H_M-augmenting technological progress, however, *Hc, Mc*, and L are lower, and S is higher with improving substitutability compared to constant substitutability. This means that the decreases in L are large enough to overcome a decrease in Hc and Mc, compared with the results of constant substitutability.

In sum, regarding technological progress and substitutability, while further experimentation is warranted given the complexity of the model, preliminary experimentation indicates that endogenous substitutability coupled with H_M-augmenting technological progress could be a useful strategy that could improve utility per capita without over-consuming S.

4. Discussion and Conclusion

The extended ecological economics model developed and tested in this paper draws heavily on economic theory and prior research by many economists, especially those focused on ecological economics. Our aim is to demonstrate the benefits of employing the system dynamics method to complement the methods used in the economics field. These benefits include: a) a greater reliance on simulation rather than analytical solutions, which allows the use of more complex formulations; b) the use of various diagrams to improve the transparency and accessibility of the model logic and assumptions; c) a focus on the analysis of the feedback structures and the time dynamics as well as equilibrium conditions; and d) an emphasis on running a wide variety of experiments to fully exercise the models and increase understanding.

In addition to striving to remain faithful to economic theory, we subject the model to a variety of sensitivity tests. These tests yield new insights. Some of the specific findings include: 1) the common practice of assuming fixed consumer preferences rather than endogenously determining the relative preferences for different goods depending on current conditions, 2) the assumption that all important results can be found by finding equilibrium solutions rather than taking into account how complex systems learn and adapt based on disruptions and other changes that drive them out of equilibrium perhaps for long periods of time, 3) the model’s response to very small savings rates indicates a higher degree of volatility and vulnerability, 4) exploration of resource carrying capacity and regeneration rates exhibit both favorable and adverse outcomes and constraints, 5) experiments with the sensitivity parameters in the population model indicate the potential for both population collapse and for trajectories that are more steady and do not lead to collapse, and 6) experiments with input substitutability factor, ρ, including making ρ endogenous, suggest that influence of this parameter may not be strong.

Experiments that combined exogenous technological progress with endogenous substitutability suggest that it may be possible to maintain or improve utility per capita while maintaining relatively high levels of population and not over-consuming the natural resource. While this result is based purely on experimentation with a theoretical model, it is nonetheless intriguing.

All of the findings in this research must be considered highly preliminary, however, since the model on which they are based is subject to many limitations, especially the restrictive model boundary documented in Table 1, and the need for much more testing, including the application/calibration of the model to represent actual developing economies in a realistic fashion.

We hope nevertheless that we demonstrate convincingly that the system dynamics method has considerable potential to complement economic research, especially ecological economics, which strives to address the complex interactions between the economy, ecological systems, and human behavior. We specifically highlight several constructive directions for the further development of ecological economic models that can help improve our understanding of the dynamic interactions between population growth, resource depletion, manufacturing, capital formation, savings rates, substitutability of manmade capital, innovation, etc.

Appendices

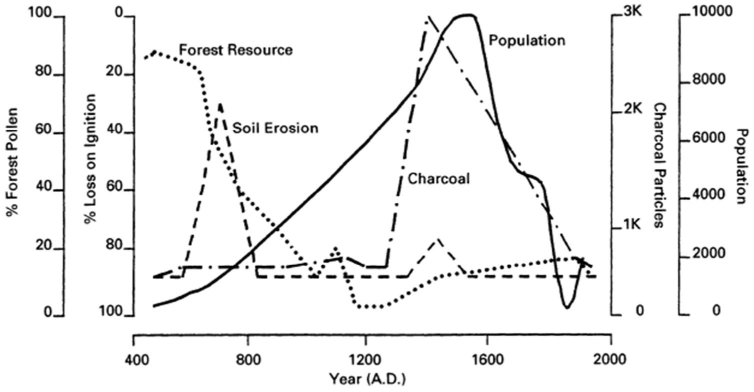


Figure 1. Easter Island dynamics from archaeological study by Bahn and Flenley (1992)

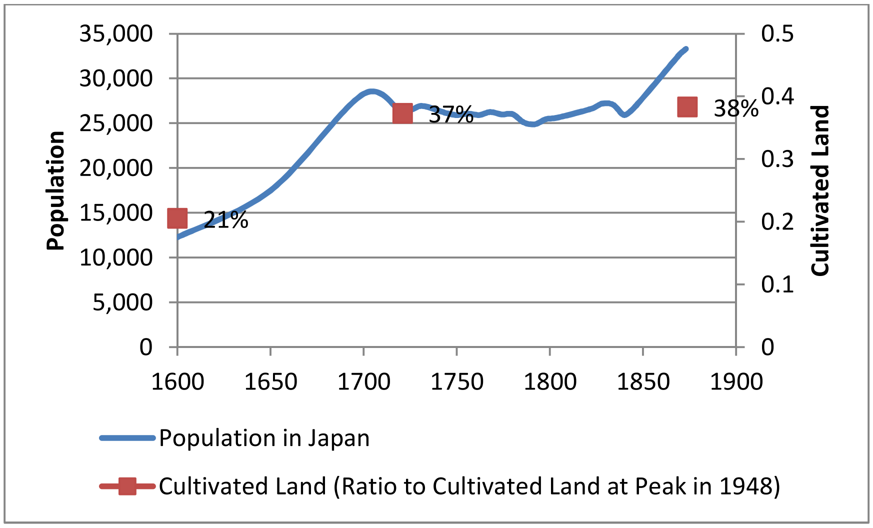


Figure 2. Population and Cultivated Land in Japan during Edo Era (1603-1868). Source: Wikipedia and Kito (1996)

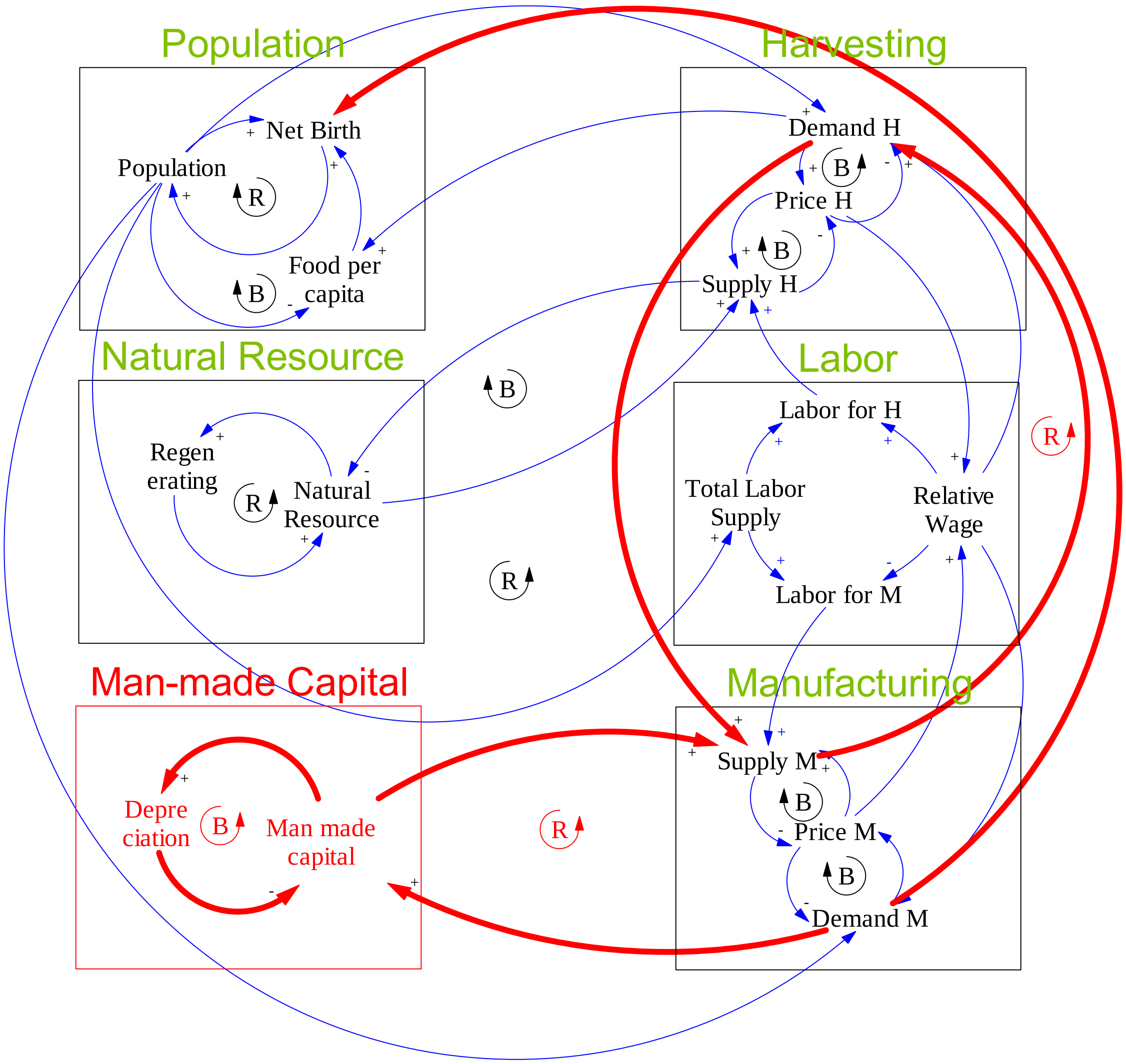


Figure 3. Causal Loop Diagrams for the Extended Model. Red texts and thick arrows indicate newly added items.

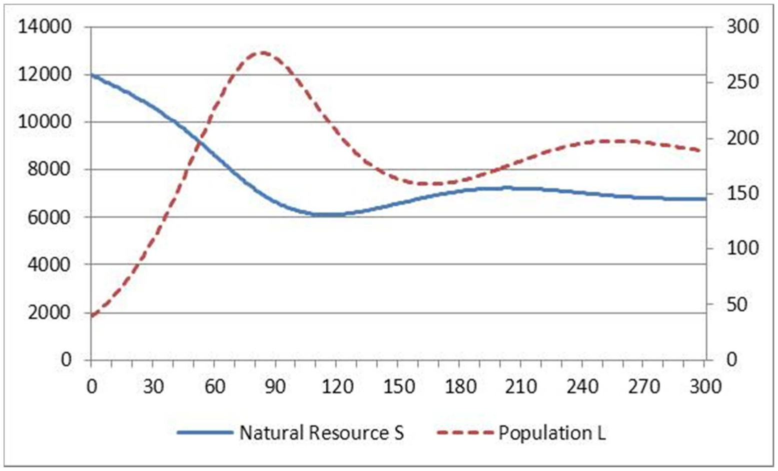


Figure 4. Extended Model Population and Resources

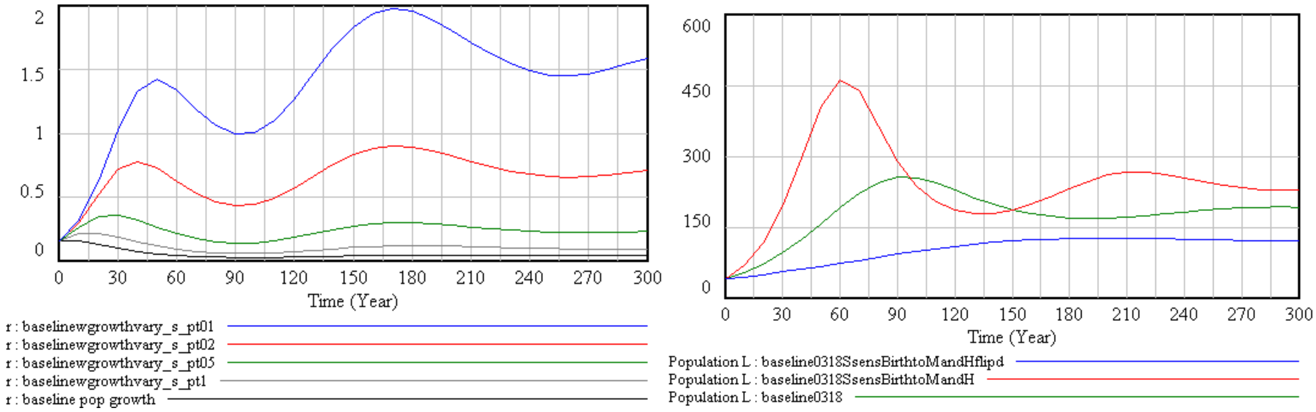


Figure 5. Sample sensitivity plots. Left plot is returns to capital over time as a function of decreasing savings rate. Right plot is Population for baseline (green), with sensitivity of births to intake of harvest good and manufactured good exaggerated in one direction (red) and the opposite direction (blue)

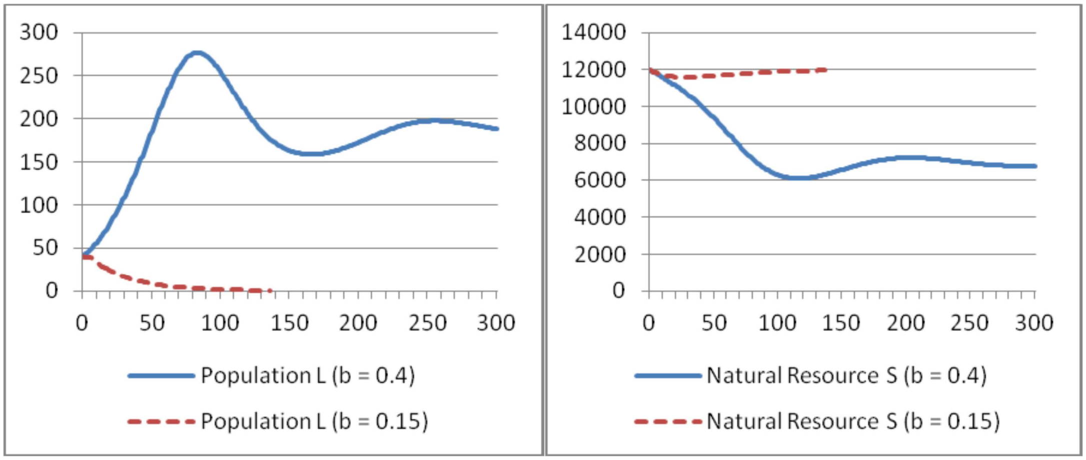


Figure 6. Dynamics of Population and Natural Resources with Different Values for Fixed Consumer Preference, β

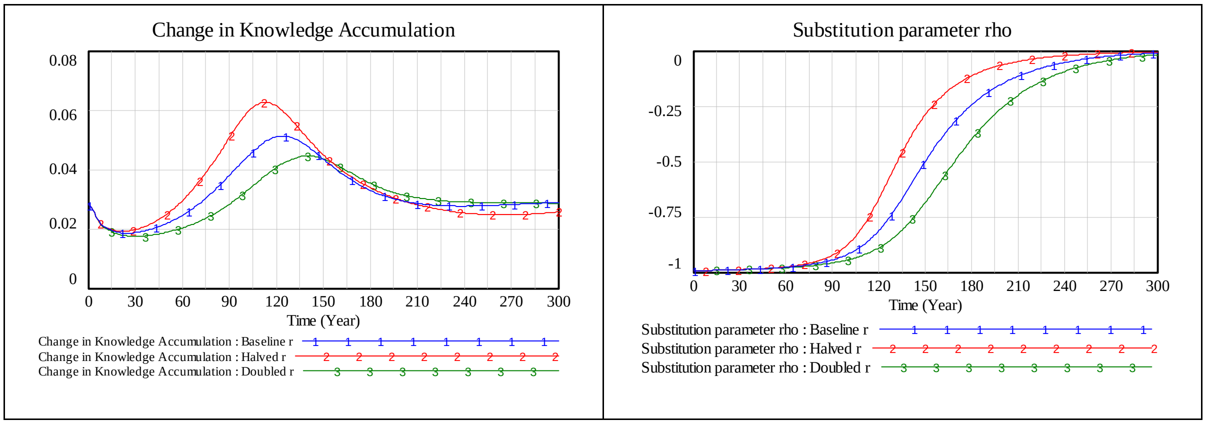


Figure 7: Test results to verify the logic that calculates ρ endogenously. Change in Knowledge Accumulation over time is shown on the left, and rho is shown on the right. The traces in each sub-plot reflect three values for the resource regeneration rate: baseline (3) in the middle, doubled (1) lower and to the right, and halved (2), higher and to the left

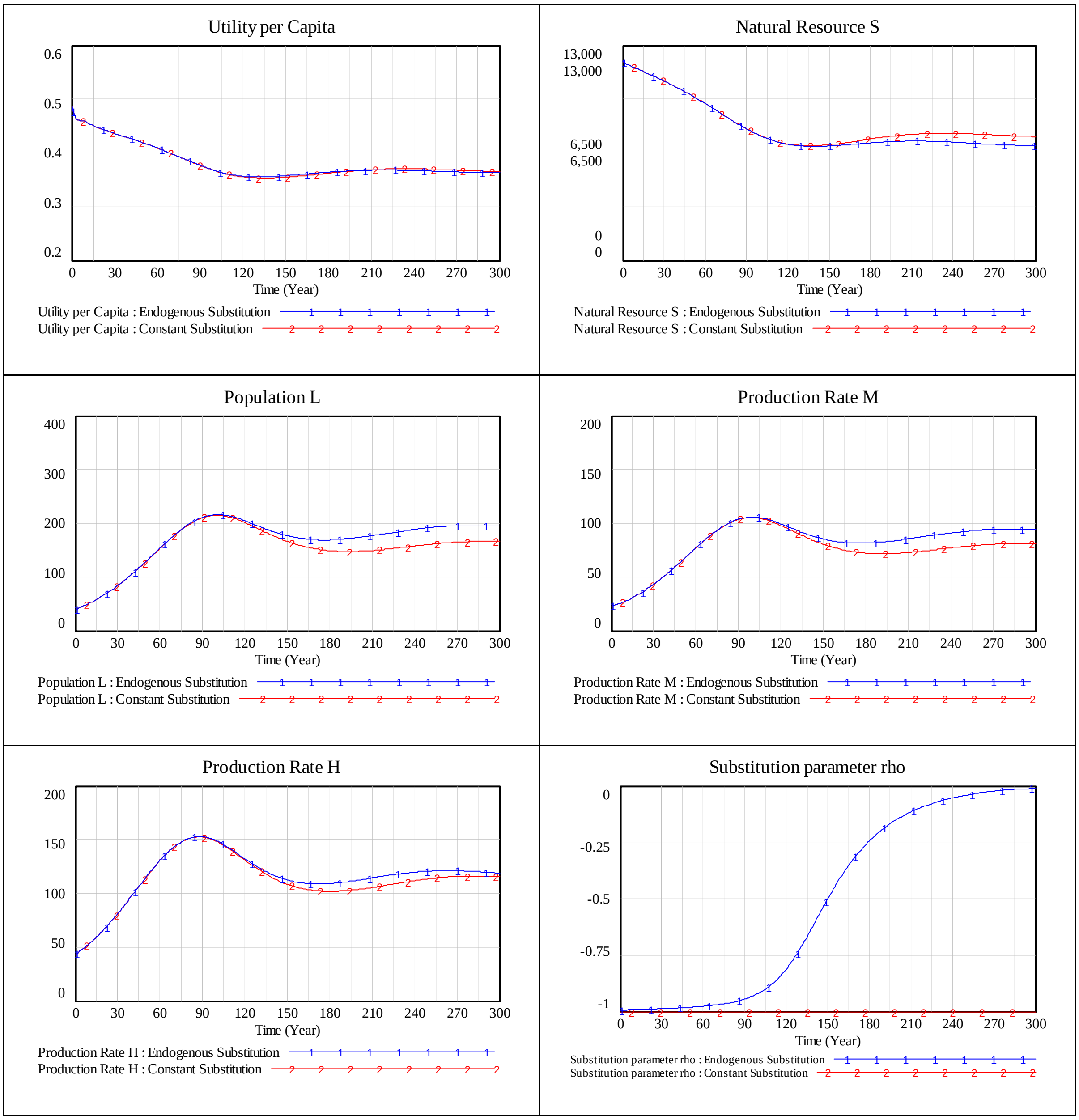


Figure 8. Impact of endogenous ρ compared to fixed ρ for six key model outcomes. Traces show ρ = endogenous (1), and –1 (2).

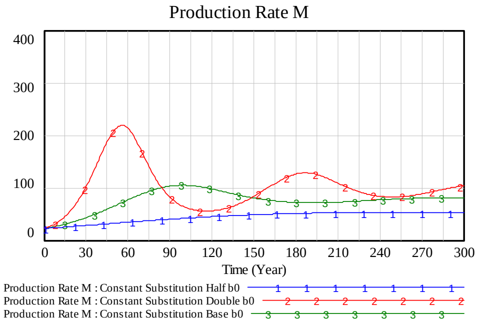
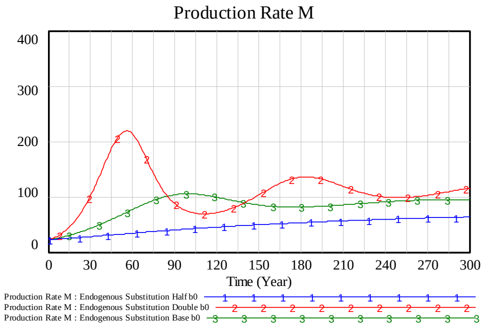
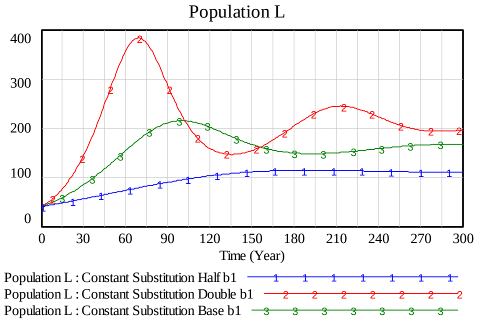
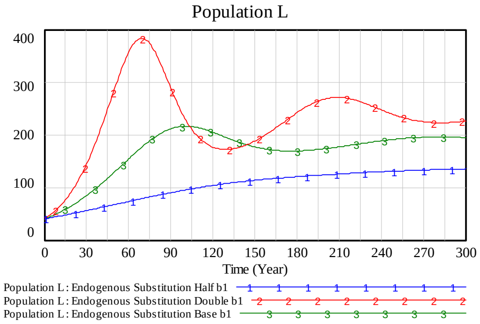
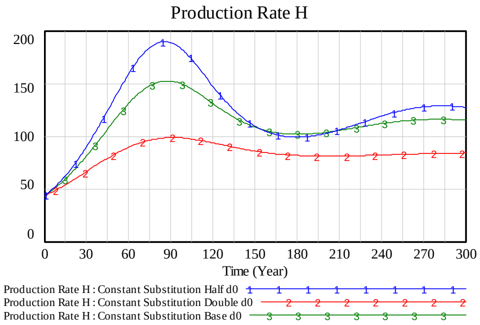
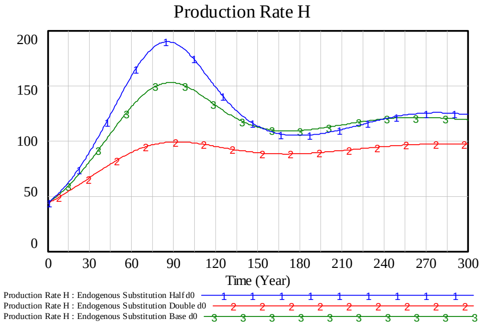
	$\rho = -1$	ρ Endogenous
b_0, maximum birthrate		
b_1, sensitivity of birthrate to resource good intake		
d_0, maximum death rate		

Figure 9. Example plots contrasting fixed ρ with endogenous ρ when varying parameters associated with population dynamics.

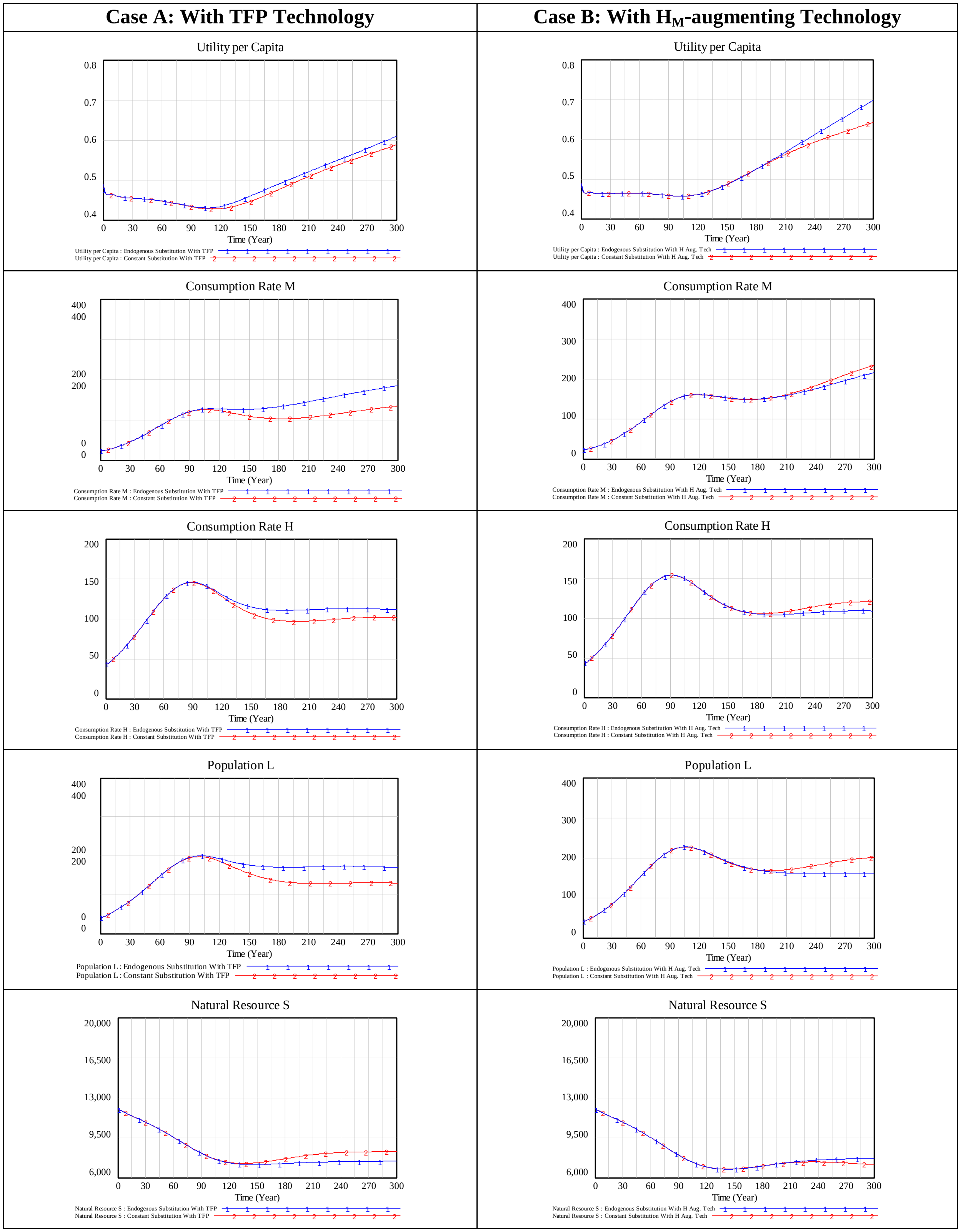


Figure 10. Comparison two types of technological progress with fixed (trace 2) versus endogenous substitutability (trace 1)

Endogenous	Exogenous	Excluded
Population - Population (L) - Birth Rate (b) - Death Rate (d) **Natural Resource** - Resource stock (S) - Growth of S (G) - Harvesting of S (H_S) **Harvesting** - Inventory of H - Supply of H (H_S) - Demand for H ($H_C + H_M$) - Price of good H (p_H) **Manufacturing** - Inventory of M - Supply of M (M_S) - Demand for M (M_C) - Price of good M (p_M) **Labor** - Labor for H sector (L_H) - Labor for M sector (L_M) - Wage (w) **Man-Made Capital** - Man-made capital (K) - Rental price (r) **Household** - Total earning ($w + r$) - Spending ($p_H h + p_M m$)	**Population** - Initial population (L_0) - Impact of H and M on population (b_1, b_2, d_1, d_2) - Maximum fertility rate (b_0) - Maximum mortality rate (d_0) **Natural Resource** - Initial natural Resource (S_0) - Regeneration rate of natural resource (η) - Carrying capacity (S_{max}) **Harvesting** - Efficiency parameter (α) - Adjustment time for p_H **Manufacturing** - Adjustment time for p_M - Efficiency parameter (ν) - Substitution parameter (ρ) - Weight parameter for H-K composite (γ) - Distribution parameter(π) **Man-Made Capital** - Capital depreciation rate (δ) **Household** - Consumer preference for good H (β) - Savings rate (s)	- Non-renewable resources - Negative externalities of production (pollution) - International relationships (exports, imports, immigration, emigration) - Unemployment

Table 1. Model Boundary

Parameter	Value	Reference
Population		
- Initial population (L_0)	40	Brander and Taylor
- Maximum fertility rate (b_0)	0.1	Anderies
- Maximum mortality rate (d_0)	0.2	Anderies
- Sensitivity of birth rate to resource good intake (b_1)	1	Anderies
- Sensitivity of birth rate to manufactured good intake (b_2)	1	Varies as in Anderies
- Sensitivity of death rate to resource good intake (d_1)	5	Anderies
- Sensitivity of death rate to manufactured good intake (d_2)	1	Varies as in Anderies
Natural Resource		
- Initial natural Resource (S_0)	12,000	Brander and Taylor
- Regeneration rate of natural resource (η)	0.04	Brander and Taylor
- Carrying capacity (S_{max})	12,000	Brander and Taylor
Harvesting		
- Efficiency parameter (α)	0.00015	-
- Adjustment time for p_H	2	-
Manufacturing		
- Adjustment time for p_M	2	-
- Efficiency parameter (ν)	1	-
- Substitution parameter (ρ)	-1	-
- Weight parameter for H-K composite (γ)	0.5	-
- Distribution parameter(π)	0.5	-
Man-Made Capital		
- Capital depreciation rate (δ)	0.1	-
Household		
- Consumer preference for good H (β)	0.4	Brander and Taylor
- Savings rate (s)	0.2	-

Table 2 Parameter Values used in the baseline model

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