RESILIENCE AND SUSTAINABILITY OF AN ECOLOGICAL ECONOMIC SYSTEM WITH ADAPTATION

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Abstract

This paper investigates ecological threshold and ecological economic threshold by developing an ecological economic model: an extension of a population–resource dynamics model developed by Brander and Taylor (1998). The model reflects three important issues concerning an ecological economic system: system boundary, non-convexity, and adaptation. The main findings are: ecological and ecological economic threshold may not be identical; ecological economic threshold may be highly context dependent and dynamic, which suggests the precautionary principle; market response to an external shock may be insufficient to maintain resiliency; we could restore the system even after passing ecological economic threshold by intervention; various transitional paths could be possible to restore the system; and adaptation may affect resilience in a non-negligible way, which suggests the importance of better information and education. Because of the complexity of the model, the system dynamics approach was used to develop and analyze the model.

Keywords: Ecological Economic Threshold; Ecological Threshold; Ecological Economic System; System Boundary; Non-convexity; Adaptation; Resilience

1. Introduction

This paper develops a model of an ecological economic system[1] in order to enhance understanding of thresholds and resilience.

Since ecological economic systems are ‘undeniably’ complex (Limburg et al., 2002) because of intertwined relationships between ecological and economic systems, whose characteristics are described with terms such as non-convexity, non-linearity, feedback loops, adaptation, out-of-equilibrium, and thresholds, it is hard to predict how these systems behave and to implement optimal management (Folke et al., 2002). This paper focuses on thresholds, which are a key concept for the resilience of the systems. Currently, despite their critical importance, there is limited understanding of resilience and thresholds related to ecological economic systems (Carpenter et al., 2005).

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[1] In resilience literature (e.g., Folke et al., 2002; Carpenter et al., 2005), a social-ecological system (SES) may be more common but I will use an ecological economic system for my narrower focus on economic systems rather than broader social systems.

This paper defines two types of threshold; the *ecological threshold* (hereafter *ET*), a threshold for an ecological system independent of economic systems, which is also called the *minimum viable population* or *critical depensation* (Daly and Farley, 2010); the *ecological economic threshold* (hereafter *EET*), a threshold for an ecological economic system. While it is well known that *ET* is not a threshold for an ecological economic system but a threshold in the absence of human activities, *EET* has not been well investigated.[2] In this paper, I will provide a dynamic model to obtain a better understanding of *EET*, how *EET* depends on the context, the relationship between *ET* and *EET*, how markets respond to disturbances to ecological systems, and what measures could be used to maintain or increase the resilience of an ecological economic system.[3]

The model developed in this paper reflects three key issues that are essential for studying ecological economic systems in general. They are 1) appropriate system boundary, 2) non-convexity of ecosystems, and 3) adaptation. They are particularly important for developing economies, as I discuss in the following section.

The model is an extension of a population-resource dynamics model developed by Brander and Taylor and published in American Economic Review in 1998 (henceforth the BT model). The BT model is characterized as a general equilibrium version of the Gordon-Schaefer model, using a variation of the Lotka-Volterra predator-prey model. To reflect the three key factors, adaptive mechanisms for price expectations and a variant of the logistic function proposed by Taylor (2009) for the dynamics of a natural resource that reflects a threshold are incorporated into the BT model.

Because of the complexity of the model, I will adopt a system dynamics approach, which uses computer simulations to analyze complex systems (e.g., Sterman, 2000). While the target of the model is developing economies, the model fitness to a certain economy is not the main focus because developing economies are facing unprecedented phenomena. For example, Lech et al. (2011) describe the current phenomenon as “complex and dynamic” in which environmental conditions, developments in science and technology, social systems and economic systems are changing more rapidly. A UN report (UNESCAP, 2010) called the unprecedented phenomenon “a new economy” in which natural resource constraints are largely defining the future outlook, and a new economic paradigm is needed.

2. Background

2.1. The Three Key Issues

Economic models have been developed in order to study the sustainability of an economic system, and most of them are extensions of either a neoclassical growth model (e.g., Dasgupta

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[2] Kahn and O’Neil (1999) and Muneepeerakul and Qubbaj (2012) point out the similar point developing a model but their models do not model economic systems and adaptation.

[3] In addition to the use of a model, Carpenter et al. (2005) suggest three other approaches to investigate resilience. They are stakeholder assessments, historical profiling, and case study comparison.

and Heal, 1974; Solow, 1974a; Stiglitz, 1974) or endogenous growth theory (e.g., Bretschger, 2005; Bretschger and Smulders, 2006; Pittel, 2002). Whichever growth theory is adopted, these economic models share a preference for simplification. Such simplifications are sensible provided that, as Robert Solow (1956) puts it, "the final results are not very sensitive" (p.65) to such simplifications. Since an ecological economic system is complex, the model of the system should contain an appropriate level of complexity with appropriate simplifications. Here I will discuss the importance of the aforementioned three issues that represent complexity which is necessary for an ecological economic model to be able to provide useful policy insights for developing economies.

1. System Boundary. Since an ecological economic system is undeniably complex (Limburg et al, 2002), it is critical to set an appropriate boundary of the system. Specifically, population, economic growth, and natural resources should all be treated as endogenous variables within the boundary of the system (Dasgupta, 2008). When a variable is treated as exogenous, the feedback loops amongst the variables are lost. Consideration of these feedback loops has not been the primary focus of modern growth economists. New growth theory depicts economic growth and natural resources endogenously, but with a fixed (or zero) population growth on the one hand. On the other hand, unified growth theory treats economic growth and population as endogenous, but natural resources are not incorporated into the models. These assumptions may be sensible for studying an economic system where natural resource constraints and population dynamics do not play significant roles. However, when it comes to developing economies, these are among the most critical issues. Treating ecological systems and economic systems separately is "a poor choice of boundary" (Costanza et al., 1993). The lack of their strong interactions in a model results in severe misperceptions and even policy failures (Costanza, 1987). Folke et al. (2002) call the two assumptions adopted in policy making practices the fundamental errors underpinning past policies for natural resource issues: an assumption that ecosystem responses to human use are linear, predictable and controllable; an assumption that human and natural systems can be treated independently. Dasgupta and Maler (2003) assert that to drop natural resources from a model is not sensible when studying development possibilities today. This is supported empirically as well. For example, a report by the United Nations (UNESCAP, 2010) shows that natural resource constraints actually have an impact on the growth of developing economies. In sum, to set an appropriate system boundary, it is necessary to incorporate endogenously population, natural resources, and economic growth.

2. Non-convexity of ecosystems. Concerning natural resources, in contrast to the abundance of studies on the dynamics of non-renewable resources and economic growth, much room remains for studies on the modeling of renewable resources in conjunction with economic growth. A key is to reflect "ecosystem non-convexity" (Dasgupta and Maler, 2003) or a "non-marginal system" (Limburg et al., 2002) which enables us to address more fully the complexity of the dynamics of renewable resources. Non-convexity of ecosystems often indicates the existence of multiple equilibria, thresholds, and positive feedback loops (Dasgupta and Maler, 2003). One example of such non-convexity is that a renewable resource has a threshold (or

critical depensation level or minimum viable population (Daly and Farley, 2010)). To incorporate non-convex ecosystems into an economic model is particularly important for two reasons (Dasgupta and Maler, 2003). First, developing economies, especially poor economies, often have to operate very close to the threshold. Once an ecological economic system passes the threshold for overusing natural resources, positive feedback drives the system to a different state of equilibrium (often to a bad state). Second, poor economies often depend heavily on natural resources and do not have the substitutes available to rich countries. There are also empirical supports that some thresholds have already been passed (e.g., Rockstrom et al., 2009). In sum, although the locations of these thresholds generally unknown (Daly and Farley, 2010), this does not mean they are negligible for their impacts so that we should strive to understand their roles for eliciting policy implications.

3. Adaptation (learning). Most economic models employ the presumption of instantaneously achieved equilibrium states, neglecting adaptation or learning processes that allow a system to be in an out-of-equilibrium state. When the state of the system is expected to change gradually, ignoring adaptation may not make any notable differences. However, this may not be the case where the state of a system changes rapidly or a sudden external shock occurs. In such situations, agents may have imperfect information and cannot make the rational decisions assumed in instantaneous equilibrium models. Under such circumstances, incorporating adaptation processes into a model could contribute to a better depiction of the dynamics of the system. An economy dependent significantly on non-convex ecosystems may have such an attribute. As Leach et al. (2010) maintain, today's world is highly complex and dynamic in the sense that system state is changing dynamically at a rapid pace. In the context of sustainability and resilience, while the importance of adaptation and out-of-equilibrium has been often pointed out (e.g., Folke et al., 2002; Leach et al., 2010; Levin et al., 1998; Solow, 1974b), modeling out-of-equilibrium has not been developed well. Modeling adaptation or learning is a prevailing subject in modern macroeconomics (e.g., Arifovic and Maschek, 2006; Evans and Honkapohja, 2011), but such modeling approaches to adaptation have not been applied to natural resource issues with a few exceptions (e.g., Hommes and Rosser, 2001 and Forini et al., 2003).[4] Adaptation may be a non-negligible theme in developing economies where the available information is often more limited. In sum, because of the important roles it plays for sustainability and resilience, adaptation that allows for out-of-equilibrium states should be modeled in order to provide further insights that instantaneous equilibrium models could not provide.

2.2. Resilience and Sustainability

Resilience and sustainability are two major criteria to evaluate an ecological economic system. In economics, sustainability or intergenerational equity has been a major focus. The first major contributions are made by Dasgupta and Heal (1974), Solow (1974a), and Stiglitz (1974). Solow

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[4] Adaptation here is a narrower concept and is different from "adaptive management" recently often used in sustainability issues in the sense that the former focuses on how to form an expectation of some variables in the future such as prices. This use of the term is similar to the one used in adaptation or learning in macroeconomics.

(1974a) suggests an operational notion of sustainability which has been often used by later economists. Adopting the notion of John Rawls, Solow forms the problem of sustainability as the maximization of constant consumption per capita which satisfies the max-min principle. There have been various definitions of sustainability proposed since then. The Hartwick rule (Hartwick, 1977) is a practical rule which satisfies the constant per capita consumption criteria. Instead of consumption, Pezzey (1989) proposes non-declining utility. Later, Pezzey with Toman propose an opportunity-based judgment instead of utility-based judgment, that is, non-declining wealth or aggregate capital (Pezzey and Toman, 2005).

Those concepts could be appropriate when an ecological economic system behaves *well*. However, when ecological and economic systems are highly interdependent, as Dasgupta and Maler (2003) argue, the system may have positive feedback processes, thresholds, and multiple equilibria. In this case, the system could cross a threshold and result in a sudden change in the behavior of the system, which could lead to a collapse. Most concepts of sustainability may not reflect this possibility. In reality, however, the possibility of thresholds followed by sudden changes in system behavior, are a realistic issue, especially in developing economies. To take into account such a possibility, the concept of resilience is introduced.[5]

Resilience is a concept rooted in ecology (e.g., Holling, 1986; Pimm, 1984) but it has been also recently been applied to ecological economic systems.[6] For ecological economic systems, Holling and Walker (2003) provide the following explanation of resilience:

"Resilience," as applied to ecosystems or to integrated systems of people and natural resources, has three defining characteristics:
- The amount of change the system can undergo and still retain the same controls on function and structure (still be in the same state, within the same domain of attraction)
- The degree to which the system is capable of self-organization
- The ability to build and increase the capacity for learning and adaptation

The main attribute of the resilience is the first statement. The second and the third definition complement the first. In this paper, I will follow an operational definition of resilience proposed by Derissen et al. (2011) which provides an operational definition of resilience as:

The ecological-economic system in state $(x(t_\Delta), w(t_\Delta))$ *is called resilient to disturbance by an actual shock* Δ *at time* t_Δ *if and only if the disturbed system is in the same domain of attraction in which the system has been at the time of disturbance:*

$$(x(t_\Delta), w(t_\Delta)) \in A_i \Rightarrow (x(t_\Delta+dt), w(t_\Delta+dt)) \in A_i$$

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[5] It should be noted that while sustainability is a normative concept, resilience is a descriptive concept.

[6] For example, Environment and Development Economics (1998, (3), 221-262) published a policy forum on the resilience of ecological economic systems.

where A_i is ith domain of attraction.

Because my model incorporates the non-convexity of natural resource, I will focus on the resilience of the system rather than its sustainability.[7]

3. Model

3.1. The Baseline Model

The BT model explains a pattern of population growth, resource degradation, and subsequent economic decline. The BT model is applied to the economy of Easter Island to depict its historical boom and bust. The BT model is characterized as a general equilibrium version of the Gordon-Schaefer Model, using a variation of the Lotka-Volterra predator-prey model. Resource (S) dynamics and Population (L) dynamics are given by (dropping the time argument for convenience)

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

where $G(S)$, r, S_{max}, and H are a logistic growth function of S (or sustainable-yield), the intrinsic growth rate, the carrying capacity, and the harvest of S, respectively, and

$$\frac{dL}{dt} = L\left(b - d + \phi \frac{H}{L}\right) \tag{2}$$

where $b\!-\!d$ and ϕ are respectively the base rate of population increase and a positive constant. The population dynamics is Malthusian in the sense that higher per-capita-consumption of the resource good leads to higher population growth. There are two sectors, the harvested good (H) and the manufactured good (M).

At any point in time, the production functions for goods H and M are given by

$$H^P = \alpha S L_H \tag{3}$$
$$M^P = L_M \tag{4}$$

where α, L_H and L_M are respectively a productivity coefficient, labor allocated to producing H and labor allocated to producing M.

A representative consumer who is endowed with one unit of labor maximizes utility:

$$u = h^{\beta} m^{1-\beta} \qquad s.t.\ P_H h + P_M m = w \tag{5}$$

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[7] Resilience is often seen as a necessary condition for sustainability (e.g., Maler, 2008; Arrow et al., 1995). However, Derissen et al. (2011) show that their relationship (i.e., necessary and/or sufficient) depends on the situation.

where h, m, β, P_H, and P_M are respectively individual consumption of H and M, preference for consumption of H, and price for H and M.

Solving the representative consumer's and producers' maximizing problems, we can get the reduced forms of the laws of motion:

$$\frac{dS}{dt} = rS\left(1 - \frac{S}{S_{\max}}\right) - \alpha\beta LS \tag{6}$$

$$\frac{dL}{dt} = L(b - d + \phi\alpha\beta S) \tag{7}$$

Three characteristics of the model are worth highlighting. First, the harvest H is determined endogenously as the result of an economic activity explained by a general equilibrium model. Second, agents in this model face a period-by-period optimization problem, without taking into account any consequences of the future resource availability and population size. It would be a reasonable assumption for a situation where the resource stock is in open access and the agents are atomistic (Taylor, 2009). Third, at each moment of time, the economy reaches a *temporary* general equilibrium *instantaneously* given fixed amounts of natural resource stock and population at that point in time. Since the natural resource stock and population will change over time, so do the equilibrium prices and quantities.

3.2. Methods: Main Extensions

The model will expand the BT model so as to reflect the three key issues: appropriate system boundary, non-convexity of natural resources, and adaptation. Since the BT model reflects an appropriate system boundary, non-convexity of natural resources and adaptation are additionally incorporated. To build the model, a system dynamics approach is adopted. Because the extended model includes many components and some of them are technical, I will focus here on explaining how non-convexity and adaptation are incorporated in the model. For the purpose of replication, a full list of equations for the model in Vensim format will be provided upon request.

3.2.1. The Non-Convexity of Natural Resources

While the natural growth function in the BT model does not include a threshold, I include a threshold to reflect the non-convexity of a natural resource. The formulation follows Taylor (2009) which uses the form to incorporate crisis into the BT model.

$$G(S) = r(S - T)\left(1 - \frac{S}{S_{\max}}\right) \tag{8}$$

T represents a threshold and this is what I call *ET*. Once the S is lower than T, even zero harvesting cannot recover S. The interpretation of T depends on the situation. For example, if S

is a forest, crossing T could mean soil erosion due to lower S intensifies a decline in S. It should be noted that the rate of growth at $S = 0$ is strictly negative. "Since a negative stock is not possible, these dynamics will imply a sudden stop to stock depletion as the $S = 0$ barrier is crossed. This has the flavor of a car hitting a brick wall at $S = 0$ and decelerating to zero instantaneously." (Taylor, 2009, p.1250).

3.2.2. Adaptation

Adaptation or learning is applied to producers' learning prices for good H and M to make production decisions.

There are many variations of learning that can be used to model bounded rationality. For example, there is a growing literature in macroeconomics (e.g., Arifovic and Maschek, 2006; Evans and Honkapohja, 2011). Learning in macroeconomics refers to models of expectation formation in which agents revise their forecast rules over time as new data becomes available (Evans and Honkapohja, 2008). To be consistent with the *cognitive consistency principle*, agents are assumed to be about as smart as (good) economists (Evans and Honkapohja, 2011).[8]

Instead of assuming agents to be econometricians, I will adopt simple adaptive expectations (Nerlove, 1958; Sterman, 2000) for two reasons. First, the imperfect knowledge of agents is from the complexity of an ecological economic system in which we even do not know the probability of, for example, passing the threshold of the global climate. Hence learning without assuming the knowledge of probability could be more appropriate for the present model .[9,10] Second, because of its simple learning structure, it is relatively easy to interpret outcome. Agents' knowledge and skills are assumed to be more bounded and they gradually update their beliefs using a simple rule instead of a sophisticated econometric learning as they find the gap between their beliefs and the actual value of the variable.

Adaptive expectations are applied to producers' price expectations in the H and M industry as;

$$p_{i,t}^{e} = p_{i,t-1}^{e} + \frac{1}{AT_i}\left(p_{i,t-1} - p_{i,t-1}^{e}\right) \quad AT_i \geq 1, i = H, M \quad , \tag{9}$$

where $p_{i,t}^{e}$ is the producers' expected price of i for t at t-1, $p_{i,t-1}$ is the market price of i at t-1 and AT_i is the adjustment time or the speed of adjustment for i.

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[8] The most commonly used estimation method may be the *recursive least squares* (RLS) (Evans and Honkapohja, 2008). Another approach is the *sample autocorrelation* (SAC) learning which is applied to the learning of prices for a fishery market (Hommes and Rosser, 2001).

[9] This formation is in line with the Post Keynesian uncertainty which asserts that probability distributions are not the basis for comprehending real world behavior under uncertainty (Davidson, 1991).

[10] There are four sources of imperfect knowledge; risk, ambiguity, uncertainty, and ignorance (Common and Stagl, 2005), which are sorted based on the availability of the information about probabilities and outcomes.

In addition, market prices can be a non-market clearing price to make the adaptive characteristics of an ecological economic system more realistic. The dynamics of market price follows the simplest *tatonnement* process or “market groping” (Day, 1994) as

$$p_{i,t} = p_{i,t-1} + g_i\left[e_i\left(p_{i,t-1}\right)\right] = p_{i,t-1} + \frac{1}{AT}\left[\frac{D_i\left(p_{i,t-1}\right)}{S_i\left(p_{i,t-1}\right)}\right], i = H, M \qquad (10)$$

where $D_i(p_{i,t-1})$, $S_i(p_{i,t-1})$, and AT are quantity demanded at *t-1*, quantity supplied at *t-1* for *i*, and a fixed adjustment time for both *H* and *M*.

Although the pricing mechanism *technically* employs the *tatonnement* process, my model allows market transactions while the market is seeking a market-clearing price, whereas transactions are generally not allowed in the *tatonnement* process until the market-clearing price is found (Takayama, 1974). Due to this difference, non-perishable goods are assumed for *H* and *M* in the present model.

Once price expectations are formed, expected wages for *H* and *M* are formed as well. Since total revenues are paid exclusively to labor in both *H* and *M* industry, assuming zero rent, expected wages are computed as:

$$w_{i,t}^{e} = \frac{p_{i,t}^{e} \times Q_{i,t-1}}{L_{i,t-1}}, i = H, M \qquad (11)$$

where $w_{i,t}^{e}$, $Q_{i,t-1}$, $L_{i,t-1}$ are respectively expected wage for industry *i* for *t*, quantity sold in industry i, and labor in industry *i* at *t – 1*. While adaptive expectations are applied to the price expectation, the quantity sold and labor applied are at the current state. This is a simplification, and can be interpreted as a naïve expectation (i.e., expected value = current value). Since wages should be equal in equilibrium, labor allocation between *H* and *M* industry continues until wages are equalized.

In sum, the model has a self-referential feature (Branch, 2004; Davidson, 1991): the [next] system state depends on expectations, which depend in tern on the [current] system state.

3.3. Model Testing

3.3.1. Learnability of equilibrium

Since the model adopts a general equilibrium structure as a base, the markets should be moving towards equilibrium. When the natural resource *S* and population *L* are changing, the system is always seeking market clearing prices under new *S* and *L* and is therefore often out of equilibrium. To examine the validity of the model, the dynamics of the model are tested with S and L kept constant (i.e., $dS/dt = dL/dt = 0$) to see whether the model can find an equilibrium.[11]

The dynamics were tested by raising the market price for H, P_H, by 10 at $t = 10$ as a shock. To see the effect of different adjustment times (AT) for price expectations of H and M, four combinations of them were tested: 1) both adjustments were relatively quick ($\text{AT}_\text{H} = \text{AT}_\text{M} = 2$); 2) both adjustments were relatively slow ($\text{AT}_\text{H} = \text{AT}_\text{M} = 4$); 3) adjustment for P_H was relatively slow ($\text{AT}_\text{H} = 4$ and $\text{AT}_\text{M} = 2$); 4) adjustment for price M was relatively slow ($\text{AT}_\text{H} = 2$ and $\text{AT}_\text{M} = 4$).

Because of a general equilibrium setting, a shock on the H market affects the M market as well. When P_H changes, the change affects $w^e_{H,t}$ which leads the relative wage, $w^e_{H,t} \big/ w^e_{M,t}$ to differ, causing labor reallocation between the H industry and the M industry. Different labor allocation to the M industry affects the production of M as well.

Figure 3.1.a through 3.1.d show the results. In all four cases, fluctuations of the price *expectations* for both commodities are moderated compared with their actual market prices. This is because suppliers do not reflect the price change totally (i.e., naïve expectations); instead, they update their expectations only partially. Although there are some differences in behavior for different combinations of ATs but they are not so obvious given $dS/dt = dL/dt = 0$. But this differences may make non-negligible different when S and L are endogenous as shown in the next section.

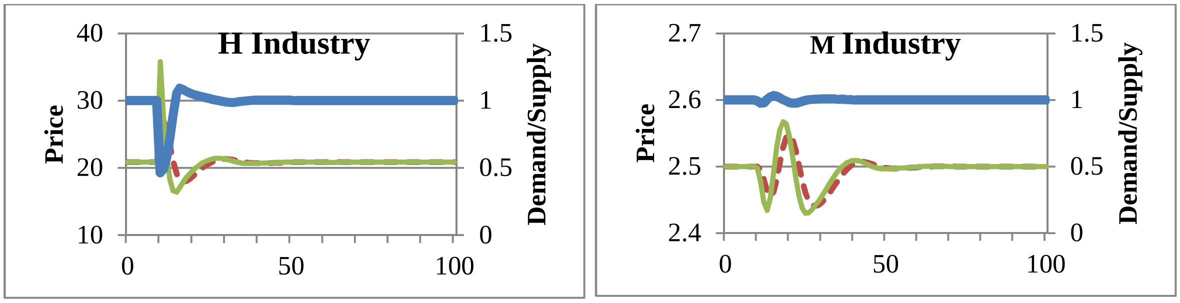
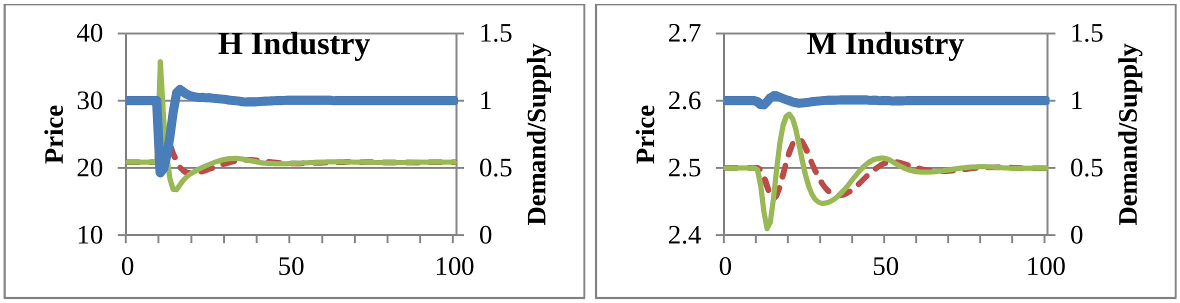


Fig. 3.1.a. $\text{AT}_\text{H} = \text{AT}_\text{M} = 2$



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[11] Learnability here simply means that expected prices converge to actual market prices. Learnability in macroeconomics provides more sophisticated discussions and definitions. For example, there are several concepts of learnability or convergence to equilibrium such as *Rational Expectations Equilibrium* (REE), *Restricted Perceptions Equilibrium* (RPE), and *Consistent Expectations Equilibrium* (CEE). A good summary on these equilibria is made by Branch (2004).

Fig. 3.1.b. $AT_H = AT_M = 4$

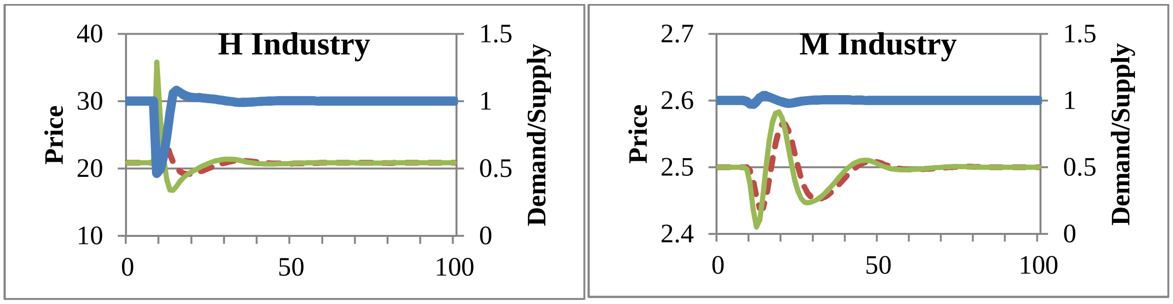

Fig. 3.1.c. $AT_H = 4$, $AT_M = 2$

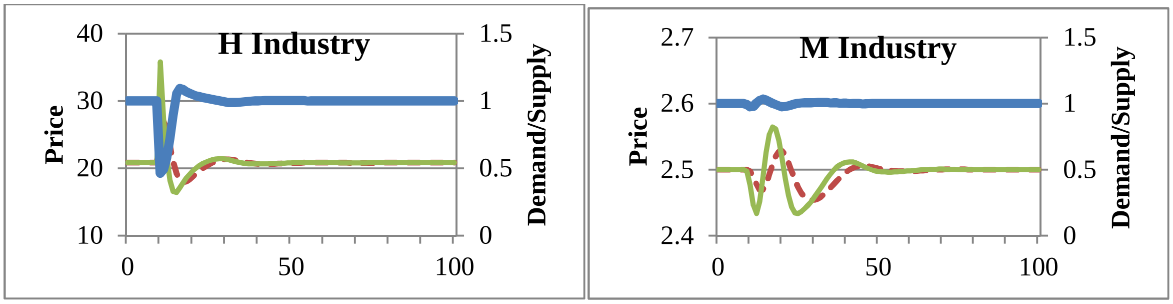

Fig. 3.1.d. $AT_H = 2$, $AT_M = 4$

Dashed Red Line: Expected Price; Thin Green Line: Market Price; Bold Blue Line: Demand/Supply
Horizontal axes are time

3.3.2. Comparison of the Original BT with the Extended Model

To see the impact of different ATs on population and a natural resource, five simulations are reported and compared. These five variations are: without adaptation (i.e., zero adjustment time), and the four different combinations of ATs. Since we do not know actual ATs in developing economies, it is important to do sensitivity analysis using different combinations of ATs to see the variability of results for different ATs.

There are three points worth highlighting. First, with the same ATs, the trough of the natural resource and the peak of population arrive slower than observed in the model without adaptation. This is because the model for the adaptation process involves delays. Second, the results do not change very much when the both ATs are changed by the same degree. This is because in the baseline simulations which has no external shock, variables change gradually, and when ATs are similar, expectations remain close to actual prices. Third, when different ATs are applied to each industry, the dynamics of the natural resource and the population change significantly. A longer AT indicates that agents will respond to a change slowly. When agents in both industries update their expected prices at the same speed, the relative expected wage, $w^e_{H,t} \big/ w^e_{M,t}$, won't change very much as shown in Fig. 3.2.c (i.e., cases for $AT_H = AT_M = 2$ and $AT_H = AT_M = 4$). However, when their adjustment speeds are different, their expected prices and the resultant expected wages will change at different rates, which has a more significant impact on the natural resource and on Population.

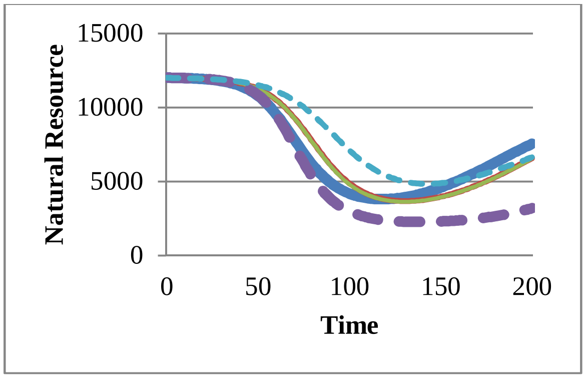

Figure 3.2.a. Natural Resource

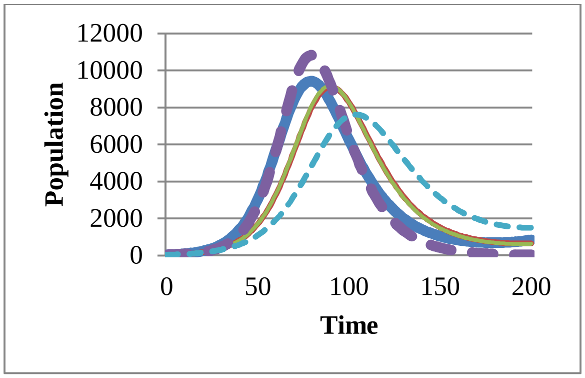

Figure 3.2.b. Population

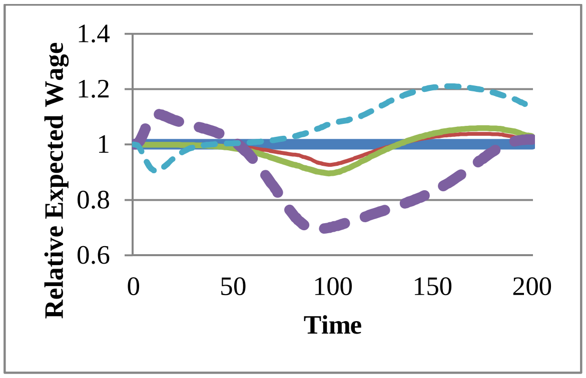

Figure 3.2.c. Relative Expected Wage

Bold Line: No Adaptation;
Thin Line: $AT_H = 2$, $AT_M = 2$;
Normal Line: $AT_H = 4$, $AT_M = 4$;
Bold Dash Line: $AT_H = 4$, $AT_M = 2$;
Normal Dash Line: $AT_H = 2$, $AT_M = 4$

In the simulation results of the model, both P_H and P_M decline at the beginning. When the market prices are going down, the *H* industry with a longer AT will stick more to previous higher prices and will not lower the expected price and expected wage relative to the expected price and expected wage by the *M* industry with a shorter AT, resulted in a higher relative wage. With the higher relative wage, more labor is allocated to the *H* industry and more natural resources are exploited as shown in Figure 3.2.a. Since the consumption of *H* influences population growth rate, population reaches a higher peak, as shown in Figure 3.2.b. Even though adaptation processes take time, model behavior when adaptation is included does not necessarily mean that the overall system response is “slower” when compared to the instantaneous equilibrium model without adaptation. This is possible because of the nonlinear impact of reinforcing feedback loops.

This result reinforces the importance of setting an appropriate system boundary—a boundary that allows researchers to study more fully the interdependencies between population and natural resources.

4. Results

In this section, I show how the models with and without adaptation respond to an external shock. Here the external shock is a hypothetical shock that reduces the stock of the natural resource *S* suddenly. This could be due to a natural disaster such as an earthquake and tsunami.

4.1. The Impact of an External Shock: The Model without Adaptation

Figure 4.1.a. through 4.1.f. show the results obtained from the model without adaptation under three different cases: no external shock (Case 1), a smaller external shock (Case 2), and a larger external shock (Case 3). Figures on the left side show the dynamics of *S*. Figures on the right side show a phase plot for the sustainable-yield, *G*(*S*), (red line) and the harvest *H* (blue line). Ecological threshold, *ET*, is set as *S* = 2,000. To show the eventual convergence of *S*, figure 4.1.b. and 4.1.d. show the results with longer simulation periods (*t* = 1000). Case 1 shows that *H* converges to the sustainable yield in the long run (Fig.4.1.b). In Case 2, although *S* declines suddenly (Fig.4.1.c), it restores to the level where *H* equals to *G*(*S*) (Fig.4.1.d). Hence the system is resilient against this smaller external shock at *t* = 100. Case 3 shows an interesting result. Because of a larger external shock, the system crosses *ET* and *S* goes zero in the end. However, what should be noted here is that the external shock alone does NOT reduce *S* below the *ET instantaneously* but the system crosses *ET* later and *S* goes extinct in the end. This indicates, without economic activities, *S* should recover after the shock, which is shown in the blue dashed line in Fig.4.1.e. After the external shock, *S* = 2,337 > 2,000. *S* ends up crossing *ET* because of the interaction between the ecological and economic systems. As shown in Fig.4.1.f., since *H* is larger than *G*(*S*), *S* keeps declining after the shock. This tells us that to maintain system resilience, we should pay more attention to the ecological economic threshold, *EET*., rather than the ecological threshold, *ET*. Even if the external shock alone does not reduce *S* below *ET*, *S* becomes zero if the external shock reduces *S* below *EET*.

Case 1: No External Shock

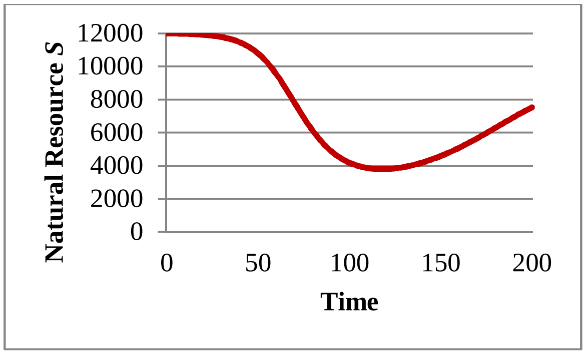

Figure 4.1.a Natural Resource *S*

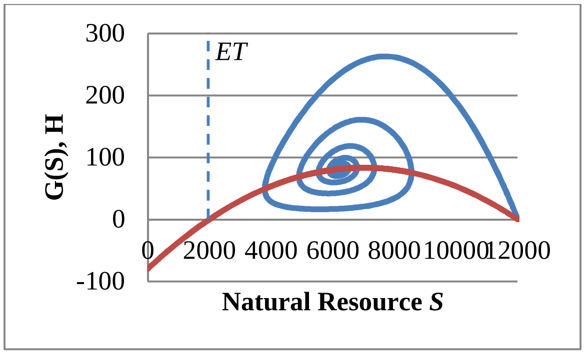

Figure 4.1.b Phase Plot for *S*, *H*, and *G*(*S*)

Case 2: A Smaller External Shock (*S* declines by 1,000 at time t = 100)

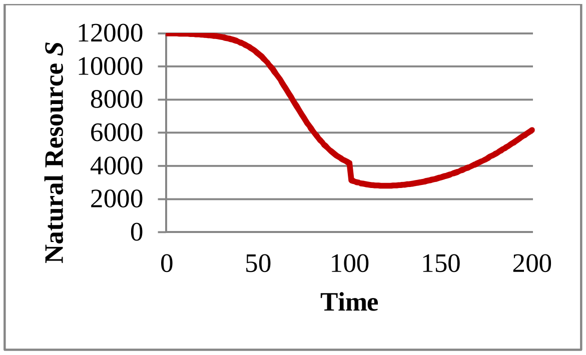

Figure 4.1.c Natural Resource S

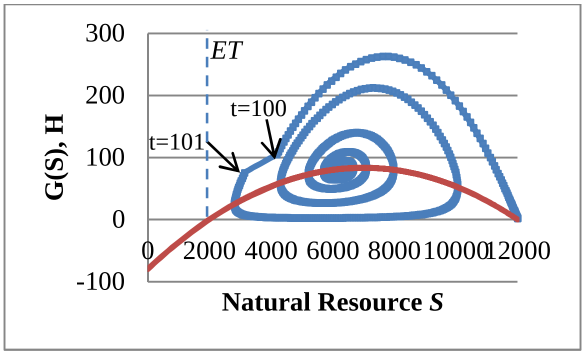

Figure 4.1.d Phase Plot for S, H, and G(S)

Case 3: A Larger External Shock (S declines by 1,800 at time t = 100)

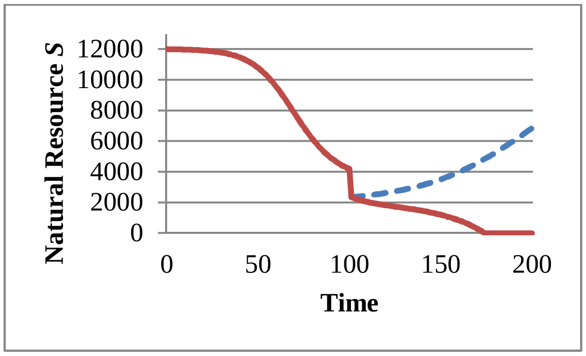

Figure 4.1.e Natural Resource S

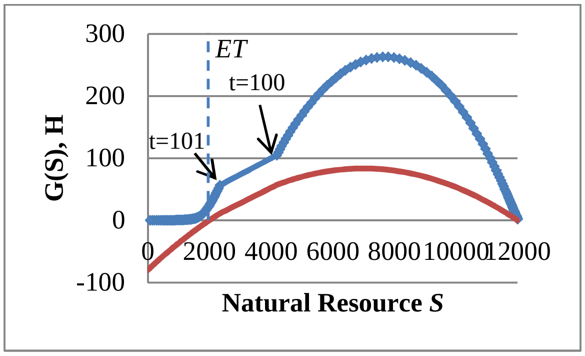

Figure 4.1.f Phase Plot for S, H, and $G(S)$

Since the model adopts a general equilibrium structure as a base, it would be worth investigating how the economic systems respond to an external shock. We could obtain some interpretations from the reduced form obtained from the original BT model; the temporary equilibrium P_H is $1/\alpha S$; the temporary equilibrium quantity is $\alpha\beta LS$. Therefore, with an external shock which reduces S, P_H will go up and the harvest will go down. However, the response via price signals may not be enough to avoid a collapse, or passing *ET* as shown in Fig.4.1.e and 4.1.f. To avoid passing *ET*, the following condition has to be satisfied before passing *ET*:

$$\frac{dS}{dt} = r\left(S-T\right)\left(1-\frac{S}{S_{\max}}\right)-\alpha S L_H \geq 0 \,. \qquad (12)$$

Then we can obtain the relationship between S and L_H as

$$\frac{b-\sqrt{b^2+4TS_{\max}}}{2} \leq S \leq \frac{b+\sqrt{b^2+4TS_{\max}}}{2} \qquad \text{where} \quad b = S_{\max}+T-\frac{\alpha L_H S_{\max}}{r} \qquad (13)$$

Given fixed S_{max}, T, α, β, and r, we can derive a threshold number of L_H. However, as shown in Fig. 4.1.f, $G(S) - H > 0$ after the shock, which indicates that the price signals may not lower L_H

enough to satisfy the above inequality.[12] In sum, although price signals may help increase resilience in an ecological economic system by reducing the harvest, they may be insufficient. One of the reasons for this inadequacy of the price signals is that they do not reflect information about resilience or the *ET* (Levin, et al, 1998).[13]

4.2. Context Dependency of EET

Since *EET* is the result of interaction between ecological and economic systems, *EET* changes as the state of the system changes. Whether the system passes *EET* with an external shock depends on the context.

Figure 4.2a compares *ET* with *EET*. While *ET* is fixed, *EET* is changing (*EET* is the result of complex interactions between ecological and economic systems).[14] By considering both Figures 4.2a and 4.2b, a high correlation between *EET* and population can be observed: when population increases, *EET* rises as well, which means that the system becomes less resilient.

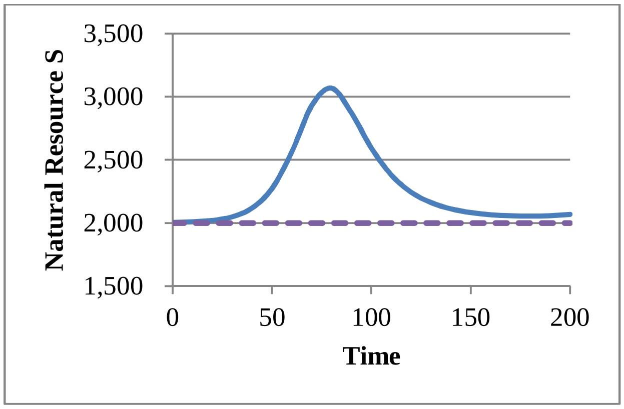

Figure 4.2a. *ET* and *EET*
Solid Line: *EET*
Dashed Line: *ET*

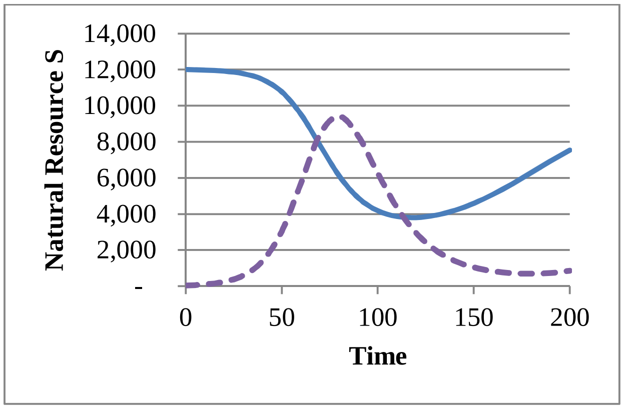

Figure 4.2b. Population and Natural Resource
Solid Line: Natural Resource S
Dashed Line: Population

The context dependency of *EET* can be observed by comparing models with different adaptations as well. Fig 4.3 shows the dynamics of natural resource *S* for models without adaptation and with various adaptations. The external shock reduces *S* by 1,543 units at $t = 100$ which is just above the *EET* for the model without adaptation. With the same shock at $t = 100$, the model with $AT_H = 4$ and $AT_M = 2$ (Bold Dash Line) crosses the *EET* and *S* does not stop until it becomes zero.

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[12] The amount of *S* in which the RHS equals the LHS is actually *EET* IF everything including L_H but *S* is constant, which is not the case for the dynamic model here though.

[13] While it is well recognized the difficulty of observing *ET* (Carpenter et al., 2005), Maler (2008) proposes one approach to price resilience. The basic idea is to evaluate the distance between the current state of the system and the threshold (Maler, 2008). This valuation, however, does not reflect the *EET*.

[14] Since the *EET* cannot be derived analytically, it is derived by simulation.

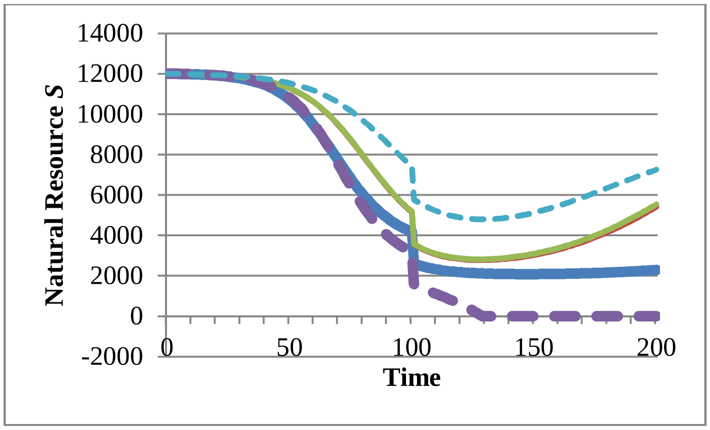


Figure 4.3 Change in Natural Resource *S* after an external shock at *t* = 100
Bold Line: Without Adaptation; Thin Line: AT_H =2, AT_M =2; Normal Line: AT_H =4, AT_M =4; Bold Dash Line: AT_H =4, AT_M =2; Normal Dash Line: AT_H =2, AT_M =4

Table 4.1 shows how much external shock at *t* = 100 each system can tolerate. When an external shock larger than the tolerable maximum external shock is given at *t* = 100 (i.e., *S* crosses *EET*), the system crosses the *ET* later and *S* goes extinct.

Model	EET	Tolerable Maximum External Shock	*S* when the shock Occurs	ET
No Adaptation	2,639	1,543	4,182	2,000
$AT_H = AT_M = 2$	3,051	2,112	5,163	2,000
$AT_H = AT_M = 4$	3,036	2,157	5,193	2,000
$AT_H = 4$, $AT_M = 2$	2,884	290	3,174	2,000
$AT_H = 2$, $AT_M = 4$	3,252	4,146	7,398	2,000

Table 4.1 *EET* at *t* = 100 for different models

There are two things to worth highlighting. First, *EET* differs among the models. Second, interestingly, we can see exaggerated differences in tolerable maximum external shock, ranging from 290 to 4,146. This difference reflects the context of each model at *t* = 100; the size of population, the natural resource level, harvest rate, and regeneration of *S*. These results show that the computation of *EET* is difficult,, if not impossible, in practice, as Carpenter et al. (2005) maintain.

5. Discussion

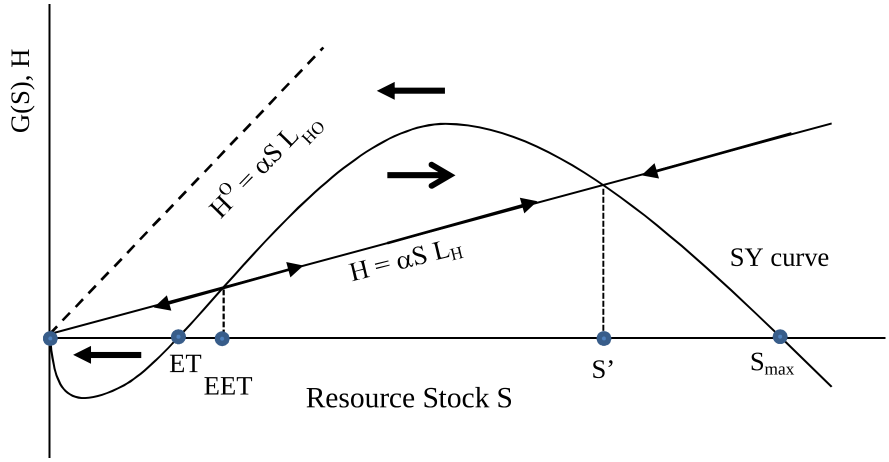
5.1. Ecological Economic Threshold

Simulation results show that even when an external shock which reduces the natural resource stock, *S*, is not large enough for the ecological economic system to pass *ET*, *S* could continue declining until it goes extinct by crossing *ET* due to interactions between ecological and economic systems. This indicates the presence of another threshold: *EET*.

The presence of *EET* has not been a focus in standard textbooks for resource economics and ecological economics, while a critical depensation type sustainable-yield curve (hereafter SY) is often adopted to study the optimal management of renewable resources (e.g., Conrad (2010); Daly and Farley (2010); Tietenberg and Lewis (2011)).[15] While I showed *ET* and *EET* by dynamic simulation, some implications about them could be explained by using the critical depensation type SY curve with a *static* catch-per-unit-effort (CPUE) curve in which the catching effort is fixed, as used by Daly and Farley (2010).[16]

In Figure 5.1, the straight line, H, is called a CPUE curve that shows a linear relationship between effort, L_H, natural resource, S, harvestability coefficient, α, and harvest, H. S_{max} is the carrying capacity. S' is a stable equilibrium point, and *EET* is an unstable equilibrium point. Daly and Farley (2010) dismiss *EET*, saying "[*EET*] is an unstable equilibrium of no practical interest in a dynamic world and hereafter ignored" (p.214). However, this should be the truly important threshold for the resilience of an ecological economic system in which ecological and economic systems affect each other. When an external shock reduces S down to below *EET* but above *ET*, H is greater than the regeneration of S, leading to a collapse. When the CPUE curve is steep enough not to cross the SY curve except at $S = 0$ (H^o in Fig.5.1), which is the only steady state, there is no *EET* and S goes extinct anyway.

With a *dynamic* CPUE curve, as my model shows, L_H is changing over time. This means that the slope of the CPUE curve is changing so that *EET* is context dependent and dynamic. For example, as indicated in Fig.4.1.b and d, S may not go extinct even if the CPUE curve does not cross the SY curve temporarily. Because of the dynamic nature of the system, it is not easy, if not impossible, to find the *EET* analytically.



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[15] Among these textbooks, Conrad (2010) derives conditions for overshoot to occur but does not analyze how economic systems respond to external shocks, which is the focus of this paper.

[16] In textbooks (Conrad, 2010; Daly and Farley, 2010; Goodstein, 2007; Tietenberg and Lewis, 2011), a curve for total revenues is derived by multiplying the sustainable yield curve by the price of the harvest to find the profit maximizing catching effort level. However, in my model, it is assumed that agents do not know the SY curve so that such total revenue curve is not adopted.

Figure 5.1 SY curve and CPUE curves

Since population and labor may change relatively dynamically in developing economies, the dynamic version could be more appropriate for developing economies. In developed economies where population and labor dynamics are relatively stable, the static version could be more appropriate.

There would be two policy implications: EET is more accessible point than ET for government to keep the system resilient; the additional complexity due to EET suggests the further importance of the Precautionary Principle.

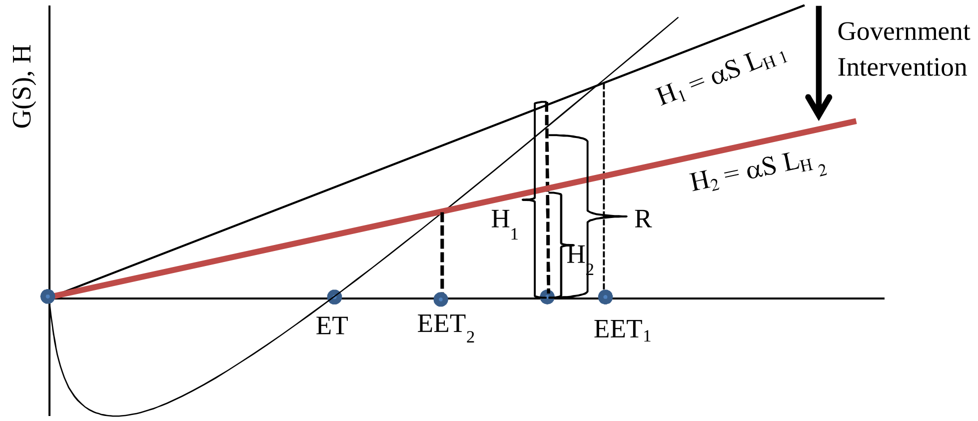

Figure 5.2 SY curve and CPUE curves with Government Intervention

In contrast to ET, EET could be more accessible point for government to intervene to prevent the extinction of S. Even once the system passes EET because of an external shock, EET_1 in Fig.5.2, an enlarged version of Fig.5.1, the system could avoid the extinction of S by lowering the catching effort to L_{H2} by policies such as tax and quota. Achieving a lower L_H, the CPUE curve could be enough flatter that it intersects the SY curve (EET is now EET_2). Since the harvest H_2 is less than the regeneration R so that S will eventually move back to the stable equilibrium where $S > 0$.

L_H should not necessarily be reduced instantaneously to make a CPUE lower enough to make $S > EET$. As long as S is above ET, we can avoid passing the ET by satisfying the inequality (12) at some time before the S passes the ET. This indicates that there are various transitional paths to keep the resilience of the system from drastic reduction to gradual reduction in L_H.

Because of the context dependency and dynamic nature of EET, our knowledge about an ecological economic system is further limited than when we deal with ET only. Hence, when a situation is uncertain as the model shows, and the environmental consequence is non-negligible, the Precautionary Principle should be supported.[17] The principle maintains that instead of a

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[17] While there is no consensus definition of the Precautionary Principle, one often-cited description says 'When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically' (Common and Stagl, 2005, p.389).

"wait and see" attitude, proactive policy is necessary and environmental quality goals should be more stringent than traditionally conceived (Kahn and O'Neil, 1999).[18]

5.2. Adaptation

The impacts of adaptation on the dynamics of an ecological economic system have not been well investigated. However, as simulation results show, how to model adaptation (i.e., the degree and difference in the speed of adjustment) may make a non-negligible difference. There would be three policy implications: further understanding of the role of adaptation, information, and education.

While it is very difficult, if not impossible, to understand and predict how adaptation works, it does not mean that we can ignore the impact of adaptation onmaintaining the resilience of the system. The model developed here shows just one possible outcome. To get a better understanding of the role of adaptation, much more modeling and analysis of ecological economic systems with adaptation should be conducted.

Governments could provide information and education to make an ecological economic system more resilient. Adaptation is justified for the situation in which people are limited in obtaining information. Better availability of information could help people make better decisions. Therefore, governments could help make systems more resilient by providing information. In my model, production decisions are based on price expectations that take market prices into account. Consumers simply use market prices to make decisions. Therefore, the scarcity of the natural resource is not reflected on their decision. The knowledge of the scarcity could induce consumers to consume less. In addition to further information, education could also contribute to resilience. With better education, agents could use more sophisticated learning mechanisms. Without proper education, however, people may not process provided information very well.[19]

6. Conclusion

This paper shows the context dependency and dynamic nature of *EET*. The presence of *EET* adds more uncertainty to the understanding of an ecological economic system, which supports the precautionary principle. Adaptation which reflects an important aspect of an actual ecological economic systems, will affect *EET* in a non-negligible way, a situation that could be improved by providing better information and education. A general equilibrium structure shows that market response to an external shock may be insufficient to maintain resiliency. However, compared with *ET*, *EET* is more accessible in the sense that government could intervene to avoid restore the system even after crossing *EET*, and it is likely that various transitional paths may

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[18] In the same line with the Precautionary Principle, Safe Minimum Standards (SMS) which set the minimum levels of natural capital stocks so that the remaining stocks are above safe minimum levels (Markandya et al., 2002). While the SMS could be applied to ET, it could be difficult to apply to EET because EET could change more dynamically, not constant.

[19] Recent theoretical and empirical studies on the confluence of resilience, learning, and education can be found in Krasny et al. (2011).

exist. Because of the importance of *EET*, we should investigate further to gain a better understanding of *EET*.

For further research, Nagase and Uehara (2011) suggest six points through a comprehensive study of the BT model and its descendants: population dynamics, capital accumulation, substitutability, innovation, institutional designs, and modeling approach. While the present model is already complex, specific components, such as the population dynamics sector are not necessarily all that complex in isolation. Some factors, such as substitutability and institutional designs, are not incorporated into the present model, and to elicit better policy implications for developing economies, these factors may need to be incorporated.

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