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In Search of a Harmonious Ecological Economy

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The classical growth model describes the relationship between the ecosystem and the economy it supports as input-output and unilateral. The neoclassical model amends this relationship as bilateral. However, much focus has been on micro analysis—such as assessing optimal returns of commercial harvesting and alike. This research intends to address the issue of sustainability of an ecological economy, not a particular species/industry, by incorporating this bilateral relationship. On modeling this problem, a standard economic welfare function is augmented to include utilities derived from both tangible consumption and intrinsic value of biodiversity. This objective functional is controlled by the dynamic of biodiversity, which is subject to natural variation and habitat destruction. To search for the existence of a dynamic equilibrium and its paths, we make use of the optimal control theory, dynamic optimization conditions, and phase diagram analysis. This study concludes that: i) economic sustainability is contingent upon the dynamics of biodiversity, and ii) destabilizing biodiversity loss is not an inevitable course of economic development. The two determinants of sustainability identified in the study are the utilization rate of carrying capacity of the ecosystem and policy on land use.

INTRODUCTION

The term ‘biodiversity’ only became a household name after the news of the unprecedented loss of species has reached the general public. Today the implication of biodiversity on economic systems has redefined the concept of sustainable growth. From here, economics branches out one of its newest interdisciplinary fields -- ecological economics, or “bioeconomics”, in which the state of economic system is recognized as an integrated part and important variable of the ecosystem. Despite our technological prowess, we are still a species among species, living in a constrained ecosystem.

Biodiversity is defined at three dimensions: the full range of species on Earth, the genetic variation within each species, and the functional diversity among ecosystems. At the species level, biodiversity has its direct implication to economic production. Hunting, harvesting, and fishing are notable examples. At the ecosystem level, diverse systems offer specialized ecological functions that enhance the economic productivity of the local societies. At the genetic level, biodiversity ensures the long-term survival of a species. Thus, regardless the scale of measurement, biodiversity supports and sustains the economic productivity. For model construction, this paper would rely on the species definition of biodiversity.

Economic activities could be harmful to biodiversity — from over harvesting, crop monoculture, to habitat destruction. In other words, ecological production (i.e., biodiversity) should be considered as part of the opportunity cost for economic production. This inherent tradeoff relationship suggests that equilibrium in an ecological economic system will be non-static, and, most likely, conditional. The implied saddle-point dynamic equilibrium condition will be explored in this study.

The outline of the paper is as follows. The literature review section provides the background for understanding the nature and contribution of this optimization technique. The subsequent section models an economic framework in which the dynamics of biodiversity are the key constraint. The third section develops the theoretical methodology for conducting equilibrium analysis, which includes phase diagrams to illustrate the motion of possible trajectories. After condition for sustainable equilibrium state is identified, parameters for policy reference are then derived. The last section concludes this research by discussing the implications of its findings and general application.

LITERATURE REVIEW

In neoclassical growth models (Lucas, 1988; Romer, 1990), productivity growth is controlled by exogenous forces such as technology, capital formation, and human capital. Other factors such as fluctuation in biological resource stock and ecological services were presumably to have no effect on growth. The two systems — economy and its ecosystem — were perceived as separate, and linked together by a unilateral input-output relationship, in which the ecosystem serves as a source of input. This method of modeling, however, contradicts with observations. Numerous evidences suggest that the development of an economic society relies on the continuous supply of ecological resource, but the consumption of biological stock affects the rest of ecosystems, which in turn may disrupt economic growth. This study intends to address this bilateral relationship.

Another highlight of the research is its macro-scale focus of analysis, instead of the conventional micro approach in modeling dynamic optimization problems. Much work in natural resource modeling (Clark, 1990) has been done on studying the tradeoff between a specific species population (such as fish) and commercial returns from its harvesting. This research, instead, explores a general model that accentuates the interactions between all species and productivity of an economic society.

To search for the dynamic equilibrium in this model, optimal control techniques are deployed. The optimal control theory involves solving a nonlinear/dynamic problem using the optimization techniques provided by the calculus of variations. The techniques of this theory such as Pontryagin’s maximum principle (Pontryagin, 1962) are extensions of the classical variation techniques by Euler, Lagrange, Legendre, Weuerstrass, Hamilton, and Jacobi. These techniques along with the dynamic optimization theory (Clark, 1990; Kamien and Schwartz, 1991) are the key instruments for modeling. Once the objective functional is defined, the maximum principle establishes a necessary condition for optimality, and Euler equation provides additional constraints that an optimal control must be subject to.

RESEARCH MODEL

The objective functional of an economy is structured to maximize the discounted utility /economic welfare streams derived from both consumption and biodiversity. That is, the economic agents are presumably aware of the intrinsic value of biodiversity. The utility, therefore, is assumed to be derived from both the consumption of tangible output and ownership of the biodiversity "asset," as viability of biodiversity is recognized as an important asset, in which sustainability relies upon.

The economic welfare (W) is constructed accordingly to be a function of consumption (C) and biodiversity (S). Standard utility assumption and diminishing marginal utility condition would then apply. $W_C > 0, W_S > 0, W_{CC} < 0, W_{SS} < 0.$

Dynamics of Biodiversity

A nonlinear optimization problem is established next:

$$\overset{\circ}{S} = f(S) + g(u) \tag{1}$$

with u (land use) as the portion of natural habitat converted to economic production and S as the number of species or stock of biodiversity.

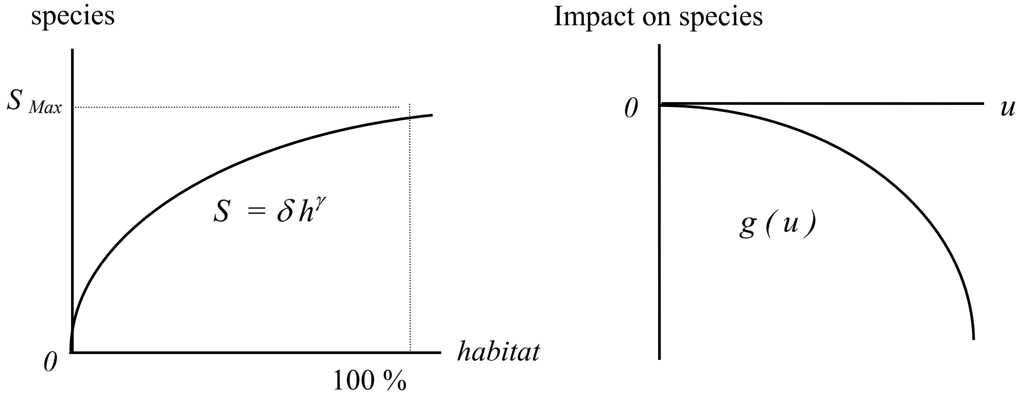
$\overset{\circ}{S} = \frac{dS}{dt}$ is the dynamics of biodiversity, defined as the sum of natural variation in biodiversity, $f(S)$, and the effect from land use, $g(u)$. Biodiversity is a product of natural evolution, which is subject to factors such as genetic mutation, diseases, climatic shifts, and environmental changes. Extinction does occur as part of the process of evolution, but is relatively stable over a large time scale. However, destruction of natural habitat, which is the nursery of biodiversity, has led to subsequent species loss at an unprecedented rate. The overwhelming threats to biodiversity are habitat destruction, land-use change, and introduction of exotic species (Wilson, 1997).

The change in natural variation function is believed to be positive, $f'(S) > 0$, since the growth rate of biodiversity seems to surpass the normal rate of extinction based on the fossil evidence. Furthermore, the current biodiversity level is much greater and more complex than it once was. On its rate of increase, or $f''(S)$, two scenarios are mathematically possible. The conventional wisdom has it that that the current species development has gradually approached Earth's carrying capacity; that is, biodiversity would grow at a diminishing rate, or a negative value for $f''(S)$. Another possibility, though unlikely, is that the carrying capacity has not been sufficiently exploited. Under this assumption biodiversity could grow exponentially, or a positive value for $f''(S)$.

The parameter *"u"* denotes land use in the land use function $g(u)$. Land conversion leads to depletion of natural habitat and habitat fragmentation, both contribute to biodiversity loss. Being the species nursery, natural habitat determines the viability of species. Furthermore, the effectiveness of a habitat in supporting species is hinged on how complete it is. As a habitat becomes fragmented, it loses it capacity to support species at an accelerating rate. This is due to the edge effect, in which the peripheral part of a habitat functions not as species nursery, but as a buffer zone to fence out intruders. Therefore, the effective area of a fragmented habitat is significantly less than that of a non-fragmented one similar in size.

FIGURE 1 illustrates the relationship between habitat loss (or land use) and species viability. Wilson's island biogeography model defines the species-habitat function as $S = \delta(1-u)^{\gamma}$. The values of δ and γ depend on the type of ecosystem and species. Notice that initial habitat size is normalized to unity, so land use could be expressed as $u = 1 - h$. An increase in habitat size will contribute to species growth or higher biodiversity level, or $S_h > 0$. Based on multiple observations, Wilson concluded that marginal life-supporting capacity of habitat diminishes as it increases in size, $S_{hh} < 0$.

FIGURE 1
HABITAT, LAND USE, AND SPECIES



The land-use function has a negative effect on biodiversity. As habitat is converted for economic use (u↑), less biodiversity will be available (S↓). The species-habitat function suggests that the negative impact of land use on species accelerates as more land is taken. That gives $g(u)$ function the following property: $g(u)' < 0$ and $g(u)'' < 0$. The implication is that land use has a non-linear or disproportional impact on biodiversity, and as the habitat loss continues, loss in biodiversity intensifies.

Dynamic of biodiversity, the gap between natural variation and habitat effect, serves as the constraint of this non-linear optimization problem.

The Objective Functional

The objective of the system is to maximize the discounted utility streams derived from consumption and biodiversity, subject to the growth constraint of biodiversity.

$$\text{Maximize Welfare} = \int_0^{\infty} W(C, S)\, e^{-\rho t}\, dt$$

$$s.t. \quad \overset{\circ}{S} = f(S) + g(u) \text{ , whereas } S(t_0) = S_0,\ u(t_0) = u_0 .$$

Consumption is derived from economic production, in which land is an input. Biodiversity is affected by the use of land as well. The utility function could be reduced to a function of land, $W(u)$. Hamiltonian is: $H = e^{-\rho t}\, W(u) + \theta\,[\, f(S) + g(u)\,]$. To avoid including time factor in the Euler equation ($\overset{\circ}{\theta} = -H_S$), which complicates stability analysis, the current-value Hamiltonian is used instead. $H = e^{\rho t} H$. Hence,

$$H = W(u) + \lambda\,[\,f(S) + g(u)\,] . \tag{2}$$

The current-value shadow price $\lambda\,(t) \;=\; e^{\rho t}\,\theta\,(t)$ is the marginal value of species (S) at time t. For example, if the species stock is reduced by one unit, its value at time t will be reduced by $\lambda\,(t)$. Hamiltonian $H\,(\,S,\,u,\,\lambda\,,\,t\,)$ is the sum of two value flows: $W(\,u,\,t\,)$ as the accumulated utility flow and $\lambda\;V(\,S,\,u,\,t\,)$ as the value of species or biodiversity flow. In other words, H represents the total rate of increase in economic welfare. The maximum principle asserts that an optimal control, or $u(t)$ in this problem, must maximize this rate of increase on welfare. To identify the optimal choice of $u(t)$, one needs to first determine the shadow price $\lambda\,(t)$. This price is calculated by solving for the first-order conditions, Euler equation, and the transversality condition.

First-Order Condition: $H_u = 0 = W\,' + \lambda g'. \Rightarrow \lambda = \,-\,W\,'/g\,'$. (3)

The shadow price λ of biodiversity is determined by marginal utility of land use and marginal effect of land use on species dynamics. It is of greater value (or cost) if marginal utility of land use increases. In addition, a decrease in the effect of land conversions on species would also contribute to a higher λ .

Second-Order Condition requires a negative value for maximization, which is confirmed as follows. $H_{uu} \;= W\,'' + \lambda g\,'' < 0$.

THE DYNAMIC OPTIMIZATION EQUILIBRIUM

After finding the shadow price, equilibrium or optimal choice of u and S can be solved from Euler equation and transversality condition. The phase diagrams will assess the stability of the equilibrium using isoclines derived from the optimization principles.

Euler equation: $\mathring{\lambda} \;= \rho\lambda - H_S \;\Rightarrow\; \mathring{\lambda} \;= \lambda(\,\rho - f\,'\,)$ (4)

Transversality condition, which is needed to provide a boundary condition, is replaced by the assumption that the optimal solution approaches a steady state. That is, the optimal solution would tend to settle down in the long run as the environment is stationary by hypothesis (Kamien and Schwartz, 1991). Equation (5) is obtained from differentiating equation (3) with time, and equation (4) and (5) merge into equation (6). With equations (1) and (6), isoclines $\dot{u} = 0$ and $\dot{S} = 0$ can be derived. The two isoclines establish the framework for phase diagram, and equilibrium stability analysis can be conducted.

$$\mathring{\lambda} \;=\; -\frac{g'W''\dot{u} - W'g''\dot{u}}{g'^{2}} = -\frac{g'W'' - W'g''}{g'^{2}}\cdot\dot{u} \tag{5}$$

$$\dot{u} = \frac{W'g'(\rho - f')}{g'W'' - W'g''} \tag{6}$$

Phase Diagram Analysis

Isocline $\dot{u} = 0$ is obtained by setting $\dot{u}$ or equation (6) to zero. The u-isocline is solved as: $f\,' = \tilde{\rho}$. The slope of this function is infinity. Isocline $\dot{S} \;= 0$ is obtained by setting $\dot{S}$ to zero. The S-isocline is a curve with a positive slope, and the optimal species stock level, which is determined as S^* from u-isocline, gives rise to the condition: $f\,(S^*) \;=\; g\,(u^*)$. The species & land-use pair

(S^*, u^*) is the meeting point of these two isoclines, and represents a possible equilibrium of the system. To assess the stability of (S^*, u^*), the next step is to develop the Jacobian matrix.

Expressions (1) and (6) are two differential equations in the dynamic system, and Jacobian matrix is derived from them. The signs in the matrix control the motion directions of trajectories in the system, which is the basis of stability analysis.

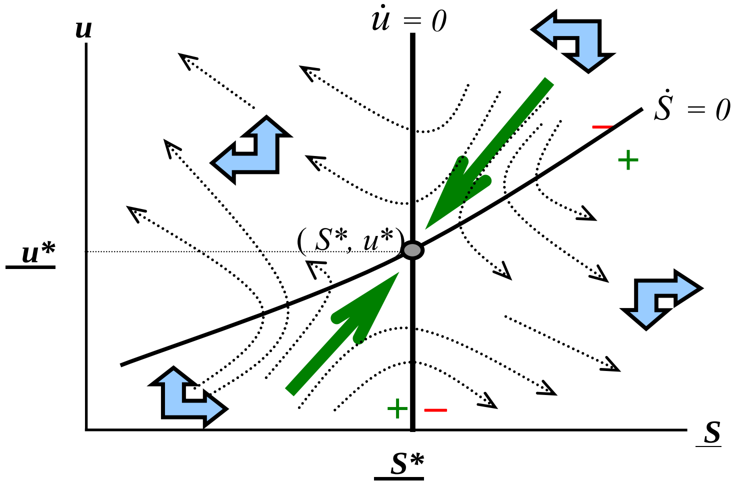
$$\boldsymbol{J} = \begin{bmatrix} \partial \dot{S} / \partial S & \partial \dot{S} / \partial u \\ \partial \dot{u} / \partial S & \partial \dot{u} / \partial u \end{bmatrix} = \begin{bmatrix} f' & g' \\ -\dfrac{W' g' f''}{g' W'' - W' g''} & \partial \dot{u} / \partial u \end{bmatrix}$$

The geometric analysis of trajectories in the phase diagrams is facilitated by considering the two isoclines $\dot{u} = 0$ and $\dot{S} = 0$, which divide the trajectory space into four quadrants. Direction of the motion in each quadrant is controlled by $\partial \dot{u} / \partial S$ and $\partial \dot{S} / \partial u$. The value of f'' (positive or negative) determines $\partial \dot{u} / \partial S$. These two cases are discussed next.

The Case of Limited Carrying Capacity

If living organisms in an ecological economy has sufficiently exploited its carrying capacity, biodiversity or species growth is expected to converge at some point. This is the case when the evolutionary process has approached a maturing stage, and the variation in species has, therefore, slowed down. In this case, f'' takes on a negative value. Conclusions on signs and trace of the Jacobian matrix can then be reached. The product of the two characteristic roots, which is the determinant of Jacobian, is negative. This provides a necessary and sufficient condition for a saddle point.

FIGURE 2
PHASE DIAGRAM



The existence of a saddle point implies that stable motion of a trajectory is only obtained when initiating from a specific path. In other words, a saddle point is a conditional equilibrium.

Most trajectories would diverge away from the equilibrium, except the ones that fall along the path. In the framework of an ecological economy, this condition suggests that a harmonious, symbiotic relationship between the two systems does not occur naturally. The so-called dynamic equilibrium exists under two circumstances: the economic society accidentally initiates from a certain stock of biodiversity and pattern of land use, or the economy aligns its policy on production and land use with the specific condition required to get on the equilibrium path.

The dynamic equilibrium path is attainable under conscientious institutional planning and monitoring. Policy variables are ascertained by examining the attributes of this specific growth path, which originate from two scales of tradeoffs. At the macro scale is the tradeoff between biodiversity maintenance and the conversion of natural habitat into economic land. At the micro scale is the tradeoff between economic value of species extraction and the benefit of biodiversity conservation, which arises from the assumption of a diminishing growth rate in biodiversity.

The Case of Unlimited Carrying Capacity

In this scenario, the rate of biodiversity expansion (f'') takes on a positive value. The trace of the Jacobian matrix, which is the sum of two characteristic roots, is positive. The sum of the two characteristic roots, which is the determinant of the Jacobian, is also positive. This indicates that the two characteristic roots are both positive, and the solution is unstable.

The system with biodiversity explosion would be a chaotic one, with temporary equilibrium being established only to be replaced by another whenever there is an influx of new species. Since each of these equilibria is not sustainable, the system consequently collapses. If this were the contemporary ecosystem, humans and other species would not co-exist. The policy analysis as follows is made, instead, based on the convergence case.

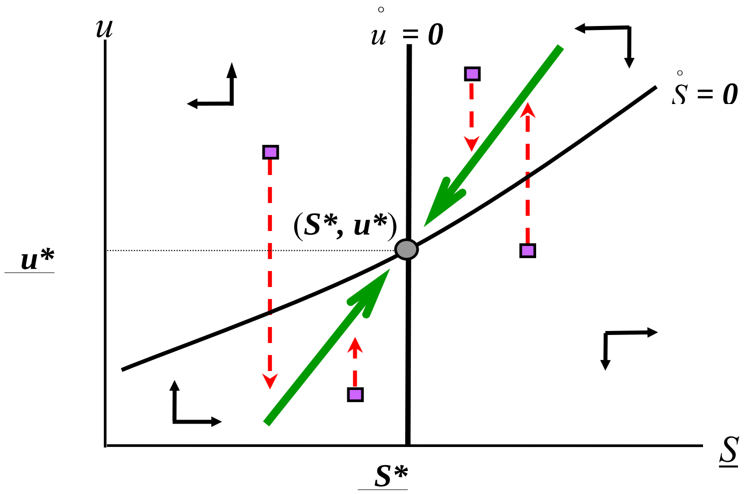
Policy Planning

Policy instruments considered for reaching the dynamic equilibrium are biodiversity conservation and land use control, which are derived from the two tradeoffs identified previously. At issue is how to align the development policy to the one proposed along the path of sustainable growth.

The optimal policy for achieving sustainable growth is illustrated in FIGURE 3. Two cases are shown: $S_0 < S^*$ and $S_0 > S^*$. When initial biodiversity level is below what suggested in the dynamic equilibrium state ($S_0 < S^*$), the optimal policy involves a gradual reduction of land use (u) to restore species back to the stock level indicated along the optimal path for each state of habitat depletion. Such policy requires restoring land back to its natural state, and keeping the habitat intact as much as possible. If initial biodiversity level exceeds what is suggested in the dynamic equilibrium state ($S_0 > S^*$), additional land use could improve the economic welfare without jeopardizing the viability of biodiversity.

The institutional involvement is necessary, as externality is associated with biodiversity. This spillover effect leads to excessive land conversion and biodiversity exploitation under market applications. Each of the examples shown in FIGURE 3 requires having an institution to impose land control and preservation policy. However, a successful policy requires effective implementation, monitoring, and allowing for market mechanism to take over when appropriate. The implementation of policy should also be gradual, since any adjustment on current resource use will have to deal with the market reactions first.

FIGURE 3
OPTIMAL POLICY



CONCLUSIONS

The objective of this research is to determine the validity of several conjectures: i) the collapse of an ecological economy is not an inevitable outcome of development, ii) the existence of a saddle-point equilibrium, which is achievable with corresponding policy. To validate these hypotheses, a model for the ecological economy was developed. It incorporates dynamic interactions of biodiversity with economic production, and includes the variation of biodiversity as the growth constraint of the economic society.

Findings from the phase diagram lend sufficient evidence for these conjectures. In addition, two “equilibrium paths” to sustainable growth have been identified. To arrive at either of these paths, the economy would need to coordinate its production, land development, and habitat conservation.

Other factors that may play a role in sustainability include globalization, introduction of exotic species, and demographic change. International trade, for one, poses new challenges to biodiversity. With trade the economic cost of species depletion and habitat deterioration are often dislocated, making it difficult to address the issue of accountability. This is one of many potential factors that await further inquiry.

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