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An Ecological-Economic Integrated General Equilibrium Model

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Abstract

A thorough analysis of sustainable development requires a better understanding of how economic and ecological systems interact over the long run. This paper provides an integrated model to analyze interactions between economic and ecological systems. The linkages between these two systems are generated by a utility function contains both economic outputs and ecological services in the demand side and by introducing land as the common input in production of economic outputs and ecological services in the supply side. The optimal allocation of land between these two systems thus determines the trade-off between economic outputs and ecological services of an ecosystem.

Keywords: sustainable development, ecosystem, general equilibrium,
the specific-factor model of trade.

I. The Nature of the ‘Environmental Crisis’ and Sustainable Development:

There has been a marked growth of interest in the past thirty years in the quality of the environment, the disruption of the earth’s natural ecosystems and the depletion of resources due to the rising intensity and frequency of environmental related problems all over the world. Some problems, like greenhouse effect and climate change, ozone depletion, species extinction, depletion of fossil fuels and various minerals, are of global magnitude. Others, like acidification, toxic contamination, deforestation, land degradation, fishery and marine destruction, water depletion, and landscape loss, are of national or local magnitude. These environmental problems have resulted ‘in mounting cleanup costs of toxic waste sites; in reduced productivity of croplands, forests, grasslands and fisheries; in rising health care costs for cancer, birth defects, allergies, emphysema, asthma and other respiratory diseases; and in the spread of hunger.’ (Brown et al. 1993). These problems, if not deal with properly in time, may produce irreversible damages to the earth’s capacity to sustain life. More and more evidence have shown that the common cause of recent environmental problems is human activities, especially population growth and increased material aspects of per capita consumption of goods and resources brought about by economic growth (The Blueprint for Survival, *Ecologist*, 1972).[1]

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[1] Two of the world’s most prestigious scientific institutions, National Academy of Science (NAS) and Royal Science (RS) issue a joint statement in 1992 which states that

In the 'Earth Summit' at Rio in 1992, the United Nations Conference on Environment and Development (UNCED) firmly identified the need to integrate the environment into all levels of economic decision-making. For this to be conceivable, a better understanding of how economic and ecological systems interact over the long run is required. In this paper, we setup a general equilibrium model that contains both economic system and ecological system. The supply side setup of the economic system follows that of the specific-factor model of trade. What's new in this paper is that we first introduce the concept of production into ecological system and treat the physical and biological characteristics of ecosystem as inputs of an ecological production function. The economic system and ecological system share a common input, land. And both systems produce outputs that consumed by human society. The linkages between economic and ecological systems are thus generated in the demand side through a society's utility function and in the supply side through the shared input land. Such an integrated model thus provides a platform that allows us to analyze the interactions between economic activities and environmental changes.

In the next section of the paper, we first review the economic literature on

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'Unrestrained resource consumption for energy production and other uses…could lead to catastrophic outcomes for the global environment. Some of the environmental changes may produce irreversible damage to the earth's capacity to sustain life. …. The future of our planet is in the balance.' The IPCC's (Intergovernmental Panel on Climate Change) report in December 1995 also pointed out that the major cause of the increase in temperature is not natural factors but the emission of green house gases, including CO_2 and CFC, due to human activities.

natural resource management to explain the need to take ecosystem into consideration in economic decision-making in the era that sustainable development is an inevitable common goal of every society. It is followed by a step-by-step construction of a general equilibrium model. And, the last section contains the conclusion and discussion of future work.

II. Economic Literature on Natural Resource Management

Economists' attention on issues associated with scarcity of exhaustible natural resource starts in 1930s due to the oil shortage. Most of economic studies focus on the intertemporal allocation efficiency (Hotelling, 1931; Ramsey, 1928), on intergenerational justice (Hartwick , 1977), and on utility maximization over time (Solow, 1976, 1986; and Dixit et al. 1980) of exhaustible natural resource like oil and mineral. The objects of analysis in the above literatures are natural resources with market values so that the optimal extraction rates can be analyzed as a dynamic optimization problem that choosing a consumption path to maximize present value of these resources. However, as Heal (1998) pointed out "while the result derived from Hotelling-Hartwick rule is fascinating and surprising, it is also slightly suspect from an environmental perspective: ***imagine all trees replaced by buildings of equivalent value***." Some may claim that supply and demand would take care of this problem since as we approach such a situation, the price of trees might rise, and that of dwellings fall, to a point where it is impossible to replace trees by dwellings of equal market value. The key difference between economic goods and ecological goods is they are not substitutable in terms of the ***ecological function*** provided by the latter. For exhaustible natural resources like oil and other minerals, which do not play much role in maintaining ecological stability, it may be appropriate to allow for the substitution of natural by produced capital of equal market value. However, some natural resources, like forest, land, air, water, terrestrial and aquatic biomass etc., are critical elements in maintaining the integrity and stability of ecological environment.

Alternatively, Barbier and Markandya (1993) establish the tradeoff between economic growth and environmental degrading by incorporating the interactions of consumption and environmental quality into a model of social welfare optimization. They develop a dynamic optimization model to maximize the net benefits of economic development, subject to maintaining the services and quality of natural resources over time. An important implication derived from their model is that both the initial level of environmental quality as well as the rate of social discount are significant factors in determining the optimal choice between sustainable and unsustainable growth. This implication reasonably explains the current status of environments in the developing countries: an economy with a low initial level of environmental quality tends to choose environmentally unsustainable economic growth because the benefits of increased consumption occur in the present whereas environmental degradation and collapse is a future problem. In other words, a low initial level of environmental quality forces resource users today to discount the future heavily.

One problem still remains. The discounting method traditionally used in dynamic optimization problems is not appropriate approach in problems associated with sustainable development. The reason is that the full ecological effects of human activities, even if tractable, often are not seen for a very long time because of the time it takes for a given action to propagate through components of the whole ecosystem. Moreover, utility-discounting was ethically inappropriate by giving earlier generations systematically greater weight than later ones simply by reason of position in time.

There are two conclusions can be derived from the above literature review. First, in the issues associated with sustainable development, the object of analysis should be broaden to include ecological goods. Second, discounting method traditionally used in dynamic optimization problems is inappropriate in dealing with sustainable development related issues both technically and ethically. Therefore, in this paper, we provide an integrated general equilibrium model that contains both economic and ecological goods. The economic and ecological systems are connected through the social utility function and the production functions of the two systems by a natural resource (land) constraint. The optimal allocation of natural resource that maintains sustainable ecosystem can be derived by setting an appropriate objective functions so that various issues associated with sustainable development can be analyzed without using discounting method.

In the next section, the model is briefly described.

III. An Ecological-Economic Integrated General Equilibrium Model

The basic needs that human beings must have to survive and maintain good health are clean air, clean water, enough food, clothing, and shelter. In today’s society, most of these basic needs, for example, food, clothing, and shelter, are economic goods and services that provide and trade in markets. Even so, most of the raw materials of economic goods and services are outputs of ecosystems. Let alone some other basic needs of human beings, for example, clean air and water, are ecological goods and services that market alone can not provide. Therefore, both economic goods and services and ecological goods and services are essential to human welfare. The utility function of a society thus should contain consumptions of economic goods and services, C, and that of ecological goods and services, N. That is,

$$U = U(C, N).$$

Assume that the economy produces two goods, good 1 and good 2. Then C denotes the consumption index of the economy defined as

$$C = C_1^k C_2^{1-k}.$$

Egor (2002) suggests a flexible ways of expressing the complementarity that combined with some substitutability at the margin between economic outputs and ecological services as following:

$$U = \left[C^{\frac{\sigma-1}{\sigma}} + N^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}.$$

$\sigma \geq 0$ is the elasticity of substitution between C and N.[2]

Market equilibrium implies that

$$C_1 = y_1.$$

$$C_2 = y_2.$$

Therefore, the utility function of a society can be rewritten as

$$U = \left[(y_1^k y_2^{1-k})^{\frac{\sigma-1}{\sigma}} + N^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}. \qquad (1)$$

The Economic System

The economic system is represented by a modified Ricardo-Viner model. There are two sectors, agriculture (Y_1) and manufacturing (Y_2), and three inputs, X_1 is the

[2] The value of σ can be anywhere between 0 and ∞; the larger the σ, the greater the substitutability between C and N. The limiting case of $\sigma = 0$ is where C and N must be consumed in a fixed proportion as complements to each other. The other limiting case, with $\sigma = \infty$, is where C and N are perfect substitutes for each other.

factor specific to the production of good 1, and X_2 specific to good 2. The third factor, land, is the mobile factor that used in the production of goods 1 and 2. Land is also an essential input in the production of ecological goods and service. Let the land employed in sectors 1, 2, and N be denoted as Z_1, Z_2, and Z_N, respectively. The production functions of the economic system can be written as

$$y_1 = f(x_1, Z_1)\,. \qquad (2)$$

$$y_2 = g(x_2, Z_2)\,. \qquad (3)$$

The income produced by the economic system is

$$y = y_1 + py_2\,. \qquad (4)$$

In order to focus on the interaction between economic and ecological systems, assume that demands for both goods in a simplified form that a fixed proportion k of income is spent on good 1 and the rest on good 2.[3]

$$p \cdot y_2 = (1-k)y\,. \qquad (5)$$

The market structures for goods and factor inputs are perfect competitive. Use the price of good 1 as numeraire so that the price of good 2 is *p*. The competitive market equilibrium conditions require that the price of each good equal to its unit production cost. That is,

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[3] Define a consumption index $C = C_1^k C_2^{1-k}$. This demand function is derived from consumer optimization problem. See appendix B.

$$w_1 a_{x1} + r a_{z1} = 1. \qquad (6)$$

$$w_2 a_{x2} + r a_{z2} = p. \qquad (7)$$

The land resource constraint is

$$Z_1 + Z_2 + Z_N = \overline{Z}. \qquad (8)$$

The Ecosystem

An ecosystem is a ***community*** of living (the organic or biotic component like plants, animals including man, and micro-organisms) and nonliving things (the inorganic or abiotic component like soil and rock, water, and air) that depend on one another. All of the earth’s ecosystems together make up the biosphere. Within the biosphere the organic components and the inorganic environmental components are intimately connected through a series of large-scale cyclic mechanisms which involve the transfer of energy, water, chemical elements and sediment throughout the biosphere. The ecosystem services provided by this complex set of systems include climate control, air resources and purification, water resources and purification, soil formation and renewal, waste removal and detoxification (dilution, decomposition, recycling), natural pest and disease control, biodiversity and gene pool (for adaptation to changing conditions), potentially renewable matter resources (forests, grasslands, wildlife, soil, water, food) nonrenewable mineral resources (copper, aluminum, iron, uranium), nonrenewable energy resources (oil, coal, natural gas) renewable energy resources (sun, wind, flowing water, geothermal heat, plant matter, biomass), recycling vital chemicals (carbon, oxygen, nitrogen, water, phosphorus, sulfur). (Miller (2002), p. 99) These ecological services support and sustain all life and all economies on the earth. In terms of economic concept, the ecological services are joint outputs of the organic components and the inorganic environmental components of inter-locking ecosystems. Therefore, we treat the whole mechanism of ecosystem functions as an ecological production function. However, how exactly each of the systems (for example, carbon cycle) works and how these different systems are related to each other are beyond the state of knowledge today, therefore, we simplify the ecological production function by treating the non-living environment as a composite input, A (for abiotic) and the living components as a composite input B (for biotic). The third input in the production of ecological goods and services is land. This is because according to Aldo Leopold’s philosophy of land ethics,

> “*That land is a community is the basic concept of ecology, but that land is to be loved and respected is an extension of ethics.*
>
> *The land ethic simply enlarges the boundaries of the community to include soils, waters, plants, and animals, or collectively the land….*”
>
> —Aldo Leopold (1887-1948) , *A Sand County Almanac*

Ecological goods and service thus is a composite output jointly produced by land and the abiotic (A) and biotic (B) environments upon it. Therefore, the ***Ecological***

production function is specified as following:

$$N = N[E(A,B), Z_N] = ABZ_N\,, \qquad (9)$$

where A is the abiotic characters of the ecosystem that represented by local climatic, hydrologic, edaphic, and geomorphologic (landscape, etc.) factors. B is the biotic feature of an ecosystem which in general can be represented by the measure of biodiversity that contains the number, composition, and distribution of species. The ecological production function specification in equation (9) is definitely oversimplified, but since our purpose at this stage is to study the interactions between economic system and ecosystem. The linear form ecological function serves the purpose.

The utility-maximization conditions of the above model are

$$\frac{\partial L}{\partial Z_1} = U^{\frac{\sigma}{\sigma-1}-1} C^{\frac{\sigma-1}{\sigma}-1} \bullet k \bullet f^{k-1} f'_{z1} g^{1-k} - \lambda_z = 0\,. \qquad (10)$$

$$\frac{\partial L}{\partial Z_2} = U^{\frac{\sigma}{\sigma-1}-1} C^{\frac{\sigma}{\sigma-1}-1} \bullet (1-k) \bullet f^{k} g^{1-k-1} g'_{z2} - \lambda_z = 0\,. \qquad (11)$$

$$\frac{\partial L}{\partial Z_N} = U^{\frac{\sigma}{\sigma-1}-1} N^{\frac{\sigma-1}{\sigma}-1} \bullet AB - \lambda_z = 0\,. \qquad (12)$$

$$\frac{\partial L}{\partial \lambda_N} = \overline{Z} - Z_1 - Z_2 - Z_N = 0\,. \qquad (13)$$

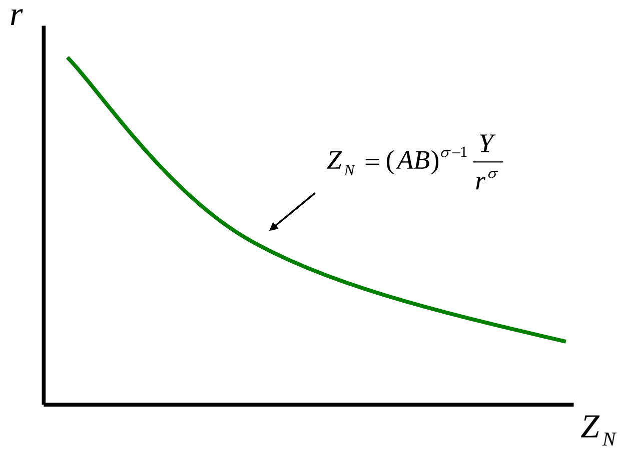
<u>Land demand in ecosystem</u>:

The optimal allocation of land in ecosystem and in economic system derived from equations (10)-(13) are

$$Z_N = (AB)^{\sigma-1} \frac{Y}{r^{\sigma}}. \qquad (14)$$

The above ecosystem land demand function is inversely related with the land rental rate. It is illustrated in the following Figure 1.

Figure 1 Ecosystem Land Demand Function



Land allocation in economic system:

The optimal allocation of land within the economic system is solved according to equations (10) and (11). It is the same as that of allocation of mobile factor in the specific-factor model of trade, which is summarized as following:[4]

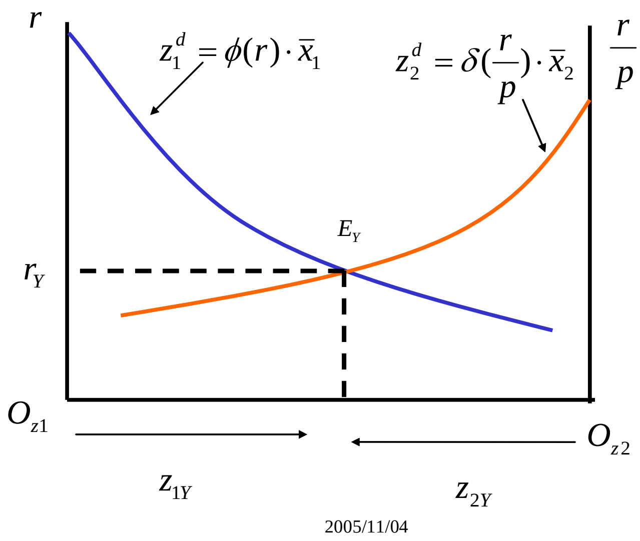
The land demand function in sector 1 of the economic system is

$$Z_1 = \phi(r) \bullet \bar{x}_1. \qquad (15)$$

[4] See Caves and Jones (1984), Chapter 6.

It is illustrated in Figure 2 by the curve Z_1 with the origin O_{Z1}.

Figure 2 Land Market Equilibrium in Economic System



Define the land demand elasticity in sector 1 as $\gamma_{z1} = -\frac{(\hat{Z_1^d / \bar{x}_1})}{\hat{r}}$. Then the land demand function in sector 1 can be written in growth form as

$$\hat{Z}_1 = \hat{\bar{x}}_1 - \gamma_{z1}\hat{r}. \qquad (15a)$$

Similarly, the demand for land in sector 2 is

$$Z_2 = \delta(\frac{r}{p}) \cdot x_2. \qquad (16)$$

It is illustrated in Figure 2 by the curve Z_2 with the origin O_{Z2}.

Define the demand elasticity of mobile factor in sector 2 as

$$\gamma_{z2} = -\frac{\dfrac{d(\frac{z_2}{x_2})}{\frac{z_2}{x_2}}}{\dfrac{d(\frac{r}{p})}{\frac{r}{p}}} = -\frac{(\widehat{\frac{z_2}{x_2}})}{(\widehat{\frac{r}{p}})},$$

The land demand function in sector 1 can also be written in growth form as

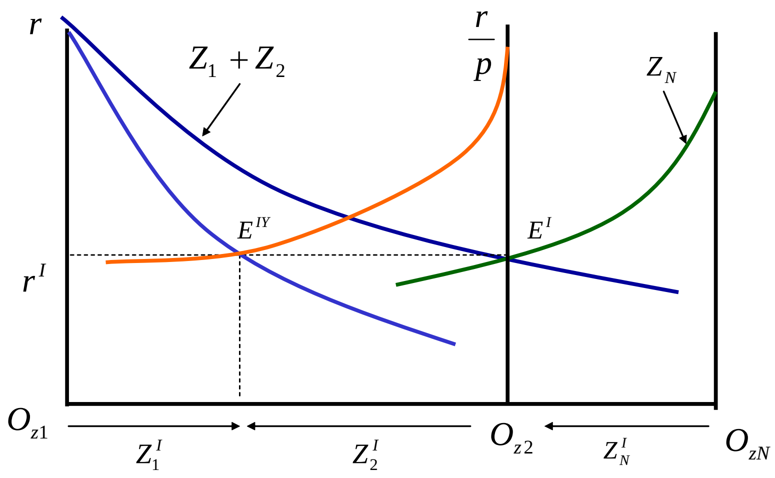
$$\hat{Z}_2 = \hat{x}_2 - \gamma_{z2} \cdot (\hat{r} - \hat{p}). \qquad (16a)$$

For any given size of land allocated to economic system, the intersection of Z_1 and Z_2, point E_Y in Figure 2, determines the equilibrium land rental rate, r_Y. Z_{1Y} of land is allocated to the production of good 1 and Z_{2Y} to that of good 2.

Land allocation equilibrium:

The equilibrium allocation of land among goods 1, 2 and ecosystem services is illustrated in Figure 3. In Figure 3, the land demand functions of goods 1 and 2 are added horizontal to obtain the aggregate land demand function of economic system $Z_1 + Z_2$ and the ecological land demand function in Figure 1 is flipped rightward. The intersection of aggregate land demand curve, $Z_1 + Z_2$, and ecosystem land demand curve, Z_N, determines the integrated equilibrium point E^I, where the superscript I denoted for “integrated equilibrium”. The integrated equilibrium land rental rate is r^I. The land allocated to goods 1, 2, and ecosystem are Z_1^I, Z_2^I, and Z_N^I, respectively.

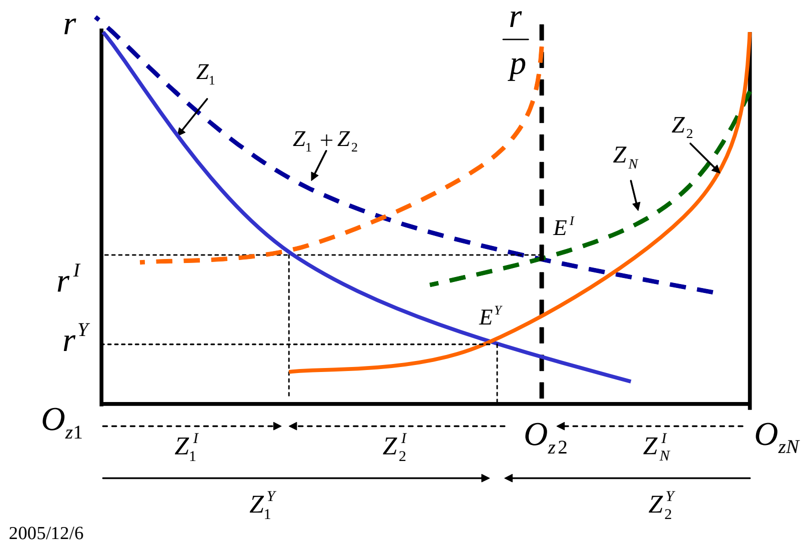
Figure 3 The Integrated Land Allocation Equilibrium



No-ecosystem equilibrium

Due to the confusion of economic goods and services with ecological goods and services, and due to inapplicable of market mechanism to ecosystem goods and services, the role of ecosystem is ignored in traditional economic analysis. The following Figure 4 illustrates the distortion of land allocation when ecosystem is ignored. The no-ecosystem equilibrium is represented by point E^Y with land rental rate r^Y lower than r^I. The land allocated to goods 1, 2, and ecosystem are $Z_1^Y > Z_1^I$, $Z_2^Y > Z_2^I$, and $Z_N^I = 0$, respectively. Compared the no-ecosystem equilibrium with the integrated equilibrium, land is under-priced so that too much of it is allocated to economic production. The no-ecosystem equilibrium in the traditional economic analysis is not the welfare maximization equilibrium.

Figure 4 No ecosystem case



The above analysis shows that the land rental rate in the integrated equilibrium, r^I, is determined jointly by parameters in economic as well as those in ecological systems.

The economic goods and services produced in the integrated equilibrium expressed in the growth form is

$$\hat{y} = -[k\theta_{z1} + (1-k)\theta_{z2}]\gamma_{z1}\hat{r} + k\,\hat{\bar{x}}_1 + (1-k)\,\hat{\bar{x}}_2 + (1-k)(\theta_{z2}\gamma_{z1} + 1)\hat{p}\,, \qquad (4a)$$

where $\theta_{xi} = \dfrac{x_i w_i}{py_i}$ and $\theta_{zi} = \dfrac{Z_i r}{py_i}$ are the share of specific factor and land in good *i*.

The ecological goods and services supplied can be expressed as

$$\hat{N} = \sigma(\hat{A} + \hat{B}) - k\hat{x}_1 - (1-k)\hat{x}_2 - \gamma_{ZN}\hat{r} - (1-k)\theta_{z2}\gamma_{Z2}\hat{p}\,, \qquad (9a)$$

which shows how economic parameters and variables affect the ecological goods and services provided in a society. Therefore, conditions and variations in ecological system, for example, changes in abiotic or biotic conditions affect not only the outputs of ecological goods and services provided, they also affect the outputs of economic system, and vise versa.

IV. Conclusions and Future Works

This paper constructs a general framework to integrate economic and ecological systems into a model of social welfare optimization so that the interactions of economic outputs and ecological goods and services can be analyzed. It allows us to have a better understanding of how economic and ecological systems interact over the long run so that environmental concerns can be integrate into economic decision-making, and vise versa. However, this framework is only a simple illustration of how economic and ecological systems can be integrated. In order to obtain a closed form solution, we assume that the ecological production function is a liner function of abiotic, biotic characteristics, and size of ecosystem land. In the real world, the ecological production function is a much more complicated function of these and other variables. The next step of research should apply the ecological principles of relevance into the ecological production function so that the above framework can be actually applied to economic and environmental management.

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