AN ECOLOGICAL-ECONOMIC INTEGRATED GENERAL EQUILIBRIUM MODEL*

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August 3, 2007

Abstract

This paper constructs a general equilibrium model to analyze the ecological-economic interface of sustainable development. We introduce an ecological goods and services into the specific factor model of trade to integrate the economic system with its surrounding ecosystem based on the perspective that the economy is a subsystem of a larger ecosystem. It allows us to put the non-market ecological goods and services on the same platform of welfare analysis with economic goods and services without confronting the problems of comparing oranges and apples and of utility-discounting. The model shows that overlooking the ecosystem results in a misallocation of land and a distortion in the price of economic goods and services. Misallocation of land normally leads to the destruction of habitats and landscape that degenerates ecosystem functions. A distortion in commodity price in the economic system usually sends incorrect signals to industrial and trade policies.

Keywords: ecological-economic integrated model, ecological pyramid, eco-productivity, ecosystem, general equilibrium model, land, specific model of trade, sustainable development.

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* The author is grateful to Eric W. Bond, Dai-Gee Shaw and An-chi Tung for helpful comments in the preliminary draft.

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I. Introduction

There has been a growing concern over degrading natural ecosystems worldwide as well as the widening gap of per capita income among the richest and the poorest across and within countries in recent decades. To tackle these problems, it is proposed that economic development should be socially just and ecologically sustainable [16,17,18]. Many efforts have been made to formulate policies and strategies to implement the concept of *sustainable development* at local, national, and global levels. Conceptually, the fundamental question of sustainable development is how to design a set of coherent policies to maximize social welfare subject to various economic, social, and ecological constraints. For the ecological dimension, Arrow et al. [1] points out that "…there are limits to the carrying capacity of the planet. It is, of course, possible that improvements in the management of resource systems, accompanied by resource-conserving structural changes in the economy, would enable economic and population growth to take place despite the finiteness of the environmental resource base, at least for some period of time. However, for that to be even conceivable, signals effectively reflect increasing scarcities of the resource base need to be generated within the economic system." That is, in order to design a set of coherent policies for *sustainable development*, we need to integrate ecological and economic dimensions of a society into all levels of decision-making.

In this paper, we construct an ecological-economic integrated model by incorporating an ecosystem production function into a conventional general equilibrium model. This model links the economic system with its surrounding ecosystem based on the perspective that the economy is a subsystem of a larger ecosystem. It allows us to put the non-market ecological goods and services on the same platform with marketed economic goods and services without confronting the problem of comparing oranges and apples. We first illustrate how the wellbeing of a society is affected by its economic and ecological attributes. Then we apply the concept of ecological pyramid into the model to analyze the interaction between the economic system and the ecosystem.

Before we present the model, a brief literature review is given. The concern over natural resources in economics can be dated back to classical economics, with emphasis on the role that natural resources play in the functioning of an economic system. For example, both Malthus and Ricardo consider land to be the key to many characteristics of a country's economy. Neoclassical economists, on the other hand, are interested in issues related to optimal allocation of individual exhaustable natural resources, for example, oil and other minerals, over time.[1] The inter-temporal efficiency and/or intergenerational justice issues regarding the allocation of exhaustable natural resources are treated as dynamic optimization

[1] The study of natural resources in neoclassical economics started with Ramsey [12] and Hotelling [10]; and followed by Solow [14], Hartwick [9], and Dixit et al. [7].

problems and analyzed by the utility-discounting approach.

However, Beltratti, Chichilnisky and Heal [2] points out two major limitations of applying the conventional neoclassical approach on issues critical to sustainable development: The first one lies in the utility-discounting approach. "A positive discount rate forces a fundamental asymmetry between present and future generations, … This asymmetry is troubling to many who are concerned with environmental matters such as climate change, species extinction and disposal of nuclear waste, as many of the consequences of these may be felt only in the very long run..." The second limitation is on the object of study. The object of study in neoclassical economics is a single commodity, for example, minerals, forest products, fishes, etc. They are economic goods that can be purchased and sold in the market. The role these natural resources play in the functioning of the ecosystem is not recognized. On the other hand, the object of concern for sustainable development is the integrity and resilience of the ecosystem. There is no "market" to determine the optimal production and consumption of ecological goods and services. It is obvious that the new challenges economists confront in dealing with the ecological aspect of sustainable development is the biophysical constraints of the ecosystem.

The type of biophysical constraints considered in this paper is the ecological pyramid and its *primary productivity*.[2] This is because Daly [6] asserts that a general principle of sustainability is to keep the absolute scale of the economy within the *ecological carrying capacity*. *Ecological carrying capacity* is a complex concept that represents the maxima of a wide variety of services generated by the environmental resource base. As an approximation, we adopt the idea proposed by Miller [11] that "ultimately, the planet's *net primary productivity* limits the number of consumers (including humans) that can survive on the earth. In other words, the Earth's *net primary productivity* is the upper limit determining the planet's *carrying capacity* for all consumer species." The model in this paper is constructed based on these ideas.

We present the framework of the model in Section II, solve the general equilibrium of the model in Section III, analyze the applications of the model in Section IV, and provide concluding remarks in Section V.

II. The Model

The ecosystem contributes to human welfare directly by providing goods and services to human society and indirectly by maintaining the integrity and stability of the Earth's life-support system. Both ecological goods and services (N) and

[2] The *gross primary productivity* is the rate at which an ecosystem's producers (mostly, plants) convert solar energy into chemical energy by the process of *photosynthesis*. The producers use some the biomass they produced for their own respiration to stay alive, grow, and reproduce. Only what is left, called *net primary productivity* (NPP), is available for use as food by other organisms (consumers) in an ecosystem." See Miller [11] p. 86-87.

economic goods and services (y) are essential components of the social welfare function of a region or society [15]. In general, N is a composite goods of fresh air, clean water, wholesome foods, biological diversity, aesthetic functions, micro-climatic conditions, waste disposal capacity and so forth provided by the ecosystem. Later, when we apply the model to analyze its implications on the ecological pyramid, N then specifically refers to the *primary productivity* of an ecosystem.

Suppose the social welfare function is a CES (*constant elasticity of substitution*) function that contains both y and N as suggested by Kraev [8]:

(1) $$U = \left[y^{\frac{\sigma-1}{\sigma}} + N^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}},$$

where σ is the elasticity of substitution between y and N.[3]

We define economic goods and services as a composite output of two commodities y_1 and y_2 produced in the economic system. That is,

(2) $$y = y_1^k y_2^{1-k},$$

where k is the proportion of economic income spent on commodity 1.

1. *The ecosystem and the ecological production function*

It is important to recognize one crucial difference between y and N when we construct a model to analyze the optimal composition of these two components of

3 Kraev [8] shows that y and N are in general complementary to each other, but are substitutable at the margin, in this CES form.

social welfare.　Economic goods and services have a price attached to them as measures of values assigned by producers and consumers in the economic system. Most ecological goods and services, for example, green plants producing oxygen, bacteria cleaning water and fertilizing soil, insects pollinating plants, are of vital value to human society, but they are not a marketed commodity and cannot be priced. However, we do consume and enjoy ecological goods and services produced by the ecosystem.　We thus attempt to apply the concept of production function in economics to formulate the functions of the ecosystem.

An ecosystem is a *community* of living (the organic or biotic component like plants, animals including man, and micro-organisms) and non-living things (the inorganic or abiotic component like soil and rock, water, and air) that depend on one another.　In terms of economic concept, N can be viewed as the joint outputs of many continuous, interlinked biogeochemical cycles (for example, hydrologic, atmospheric, and sedimentary cycles) from the abiotic (non-living) environment (air, water, soil, and rock) to living organisms, and then back to the abiotic environment. The types, quantities, and qualities of goods and services provided by the ecosystem are determined jointly by its abiotic and biotic characteristics.　Thus, the outputs of the ecological production function are the ecological goods and services; the inputs are the abiotic and the biotic characteristics of the ecosystem; and the technology is the biogeochemical cycles governed by Nature. The biogeochemical cycles of the biosphere are very complex systems. How exactly each of the biogeochemical cycles works and how these different cycles are related to each other are beyond our understanding. In order to analyze how the economic system and the ecosystem interact, we need to simplify the complicated functions of the ecosystem into a manageable form.

We treat the non-living environment as a composite input, A (for *abiotic* components like climate, soil, water, air, nutrients, and solar energy) and the living components as another composite input, B (for *biotic* components like plants, animals, and micro-organisms). The third input is the size of the ecosystem represented by the size of eco-land, Z_N.[4] Thus, N is a composite output jointly produced by land and its abiotic and biotic environments. In order to obtain a closed form solution for the model that allows us to derive intuitive interpretations of how the model works, we further assume that the ecological production function has a linear form as follows:

$$(3) \qquad N = N[E(A,B), Z_N] = ABZ_N ,$$

where $E(A,B) = AB$ denotes the average ecosystem productivity. This linear form

[4] The idea here is derived from: "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*

specification makes it possible to interchange A, B, and Z_N in the analysis of the ecological pyramid.

Further suppose that this society is endowed with land of size $\bar{Z}$ and with two specific factors of quantities, $\bar{x}_1, \bar{x}_2$ for economic production. The transformation function of the society thus can be expressed in implicit form as

(4) $$H(y, N; \bar{Z}, \bar{x}_1, \bar{x}_2) = 0 .$$

The above framework is consistent with the perspective of classical economists in the nineteenth century in that a country's land and the productivity of land are important in determining the characteristics of its economy. We adopt this perspective because Richards [13] points out that an important adverse effect the unconstrained expansion of economic activities brought about on natural systems is through dramatic modification on land-cover around the world. Furthermore, according to the concept of ecological pyramid, land is the common base for both the economic system and the ecosystem. Therefore, we use land as the mobile factor that can move between the two systems.

Next, we describe the structure of the economic system and extend it to include the ecosystem to form the integrated model.

2. *The economic system*

The specific-factor model of trade [10] is extended in two aspects to form the economic subsystem. First, land, the mobile factor, is used in the production of economic goods 1 and 2, as well as in the production of ecological goods and services. Second, a demand function of economic goods and services and aggregate economic income are added to the original model to form a complete general equilibrium model.

Two goods, y_1 and y_2 are produced in the economic system using three inputs. x_1 is the factor specific to the production of good 1, and x_2 specific to good 2. The third factor, land, is the mobile factor used in the production of goods 1 and 2, and in N. Let Z_1, Z_2 and Z_N be the land employed in sectors 1, 2, and N, respectively. The production functions of goods 1 and 2 in the economic system can be written as

(5) $$y_1 = f(x_1, Z_1),$$

(6) $$y_2 = g(x_2, Z_2).$$

The supplies of specific factors are fixed at their endowment levels,

(7) $$x_1 = \bar{x}_1,$$

(8) $$x_2 = \bar{x}_2.$$

Let good 1 be the numeraire so that p denotes the relative price of good 2 in terms of good 1. Then the income produced by the economic system is

(9) $$Y = y_1 + py_2.$$

We assume that the demand functions for economic goods and services have a simple form: a fixed proportion k of income is spent on good 1 and the rest on good 2.[5]

(10) $p \cdot y_2 = (1-k)Y$.

Further assume that the market structure of goods and factor inputs are perfectly competitive. The competitive market equilibrium condition is that the price of each good is equal to its unit production cost. That is,

(11) $w_1 a_{x1} + r a_{Z1} = 1$,

(12) $w_2 a_{x2} + r a_{Z2} = p$,

where w_i are returns to specific factor i; r, the land rental rate; a_{xi} and a_{Zi}, the unit factor requirement of goods i, $i = 1,2$.

Finally, the land resource constraint is

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

The goal of the society is to maximize the welfare represented by the CES function in equation (1) subject to the transformation function in equation (4).

III. Welfare Maximization Compositions of Economic and Ecological Goods and Services

The product transformation curve derived from equation (4) is

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5 Define a consumption index $y = y_1^k y_2^{1-k}$. This demand function is derived from consumer optimization problem.

$$ABdy + f_{Z1}dN = 0\,.$$

The opportunity cost of economic output is the *rate of product transformation* (RPT), that is,

(14) $$RPT = -\frac{dN}{dy} = \frac{AB}{f_{Z1}(x_1, Z_1)}\,.$$

The rate of change of RPT is

$$-\frac{d^2N}{dy^2} = -\frac{1}{(f'_{Z1}(x_1, Z_1))^3}ABf''_{Z1} > 0\,.$$

It means that the opportunity cost of economic output is increasing, because as more *y* is produced, an increasing amount of N must be sacrificed for per unit of *y*.

On the demand side, the marginal rate of substitution between *y* and N derived from the welfare function is

(15) $$MRS = -\frac{dN}{dy} = \frac{MU_y}{MU_N} = \frac{y^{\frac{-1}{\sigma}}}{N^{\frac{-1}{\sigma}}}\,.$$

1. <u>The welfare maximization condition</u>

The welfare maximization allocation of land between y and N is derived when MRS=RPT, that is, $\frac{MU_y}{MU_N} = \frac{MP_{ZN}}{MP_{Zy}}$, which implies

(16) $$f'_{Z1}(x_1, Z_1)y^{\frac{-1}{\sigma}} = ABN^{\frac{-1}{\sigma}}\,.$$

Equation (16) is the welfare maximization condition of the general equilibrium model in equations (1)-(13). It determines the optimal composition of *y* and N. It means that the welfare of the society is maximized when the marginal utility of land in the economic system is equal to that in the ecosystem.

The welfare maximization condition is illustrated in Figure I.[6] The various combinations of *y* and N defined by the transformation function in equation (4) is illustrated by the transformation curve $T^N T^y$. The highest welfare level that this region can achieve is represented by the utility curve U* that tangents to $T^N T^y$. At the equilibrium point E*, the marginal utility of land in the economic system, $f'_{Z1}(x_1, Z_1) y^{\frac{-1}{\sigma}}$, is equal to that in the ecosystem, $ABN^{\frac{-1}{\sigma}}$. The optimal composition of *y* and N, *y** and N*, derived from equation (16) is

(17) $$N = [\frac{AB}{r}]^{\sigma} y .$$

Equation (17) shows that the optimal ratio of *y* to N is determined by $\frac{AB}{r}$ and σ. $\frac{AB}{r}$, the slope of the transformation curve, represents the opportunity cost of *y* in terms of N. The higher the ecological productivity of land, AB, the steeper is the slope of the transformation curve, and the higher is the opportunity cost of economic outputs. Higher AB and/or lower *r* implies that less *y* and more N are produced.

How the elasticity of substitution affects $\frac{N}{y}$ depends on the shape of the production possibility frontier (PPF). If PPF extends in the direction of N (*y*), that is, $\frac{AB}{r} > (<) 1$, $\frac{N}{y}$ rises (falls) with σ. It is because when the productivity of eco-land is higher (lower) than that of economic land, a higher σ encourages the

6 See also Tisdell [15], Figure 1.

substitution of N (*y*) for *y* (N) in consumption.

2. The land market equilibrium

From the ecological production function in equation (3) and the welfare-maximization condition in equation (17), we can derive the eco-land demand function as

(18) $$Z_N = \frac{(AB)^{-(1-\sigma)}}{r^{\sigma}} y .$$

It is apparent that the higher the land rental rate, the higher the opportunity cost of N, and less land is demanded by the ecosystem. That is, the eco-land demand is inversely related to the land rental rate as illustrated by the Z_N curve in Figure II.

By total differentiating equation (18) and rearranging terms, the eco-land demand function can be written in growth form as

(18a) $$\hat{Z}_N = -(\hat{A}+\hat{B}) + \sigma[(\hat{A}+\hat{B}) - \hat{r}] + \hat{y} .$$

The first term in equation (18a) represents the production substitution effect resulting from a variation of eco-land productivity. It means that at a higher eco-productivity more N can be produced at any given Z_N. Thus, AB is substituted for Z_N so that less eco-land is demanded. The term $(\hat{A}+\hat{B}) - \hat{r}$ in the second term represents the relative marginal value of land in consumption. $(\hat{A}+\hat{B}) - \hat{r} > 0$ means that the marginal productivity of eco-land is higher than that of economic land, that is, the PPF is curved toward N-axis. In such a case, higher $(\hat{A}+\hat{B}) - \hat{r}$ encourages the substitution of N for y in consumption and more eco-land is demanded. The last term is the income effect of eco-land demand. Since N is a normal goods, the demands for N and Z_N increase with y.

Given the total land endowment, $\overline{Z}$, and the eco-land demand described in equation (18), the rest of the land will be employed in the economic system. The allocation of the size of land $\overline{Z} - Z_N$ between sectors 1 and 2 within the economic system is exactly the same as the allocation of the mobile factor in the specific-factor model of international trade.

Substitute the endowment constraint of specific factor 1 in equation (7) into the production function in equation (5). Solve the cost-minimization condition to obtain the demand for land in sector 1 as

(19) $$Z_1 = \phi(r) \cdot \overline{x}_1 .$$

It is shown by the downward sloping curve Z_1 from left to right in Figure III.

Set $\gamma_{z1} = -\dfrac{(\hat{Z}_1 / \overline{x}_1)}{\hat{r}}$ as the land demand elasticity of sector 1. Then sector 1's land demand function can be expressed in growth form as

(19a) $$\hat{Z}_1 = \hat{\overline{x}}_1 - \gamma_{Z1}\hat{r} .$$

Similarly, the demand for mobile factor in sector 2 is

(20) $$Z_2 = \delta(\frac{r}{p}) \cdot \overline{x}_2 ,$$

which is shown in Figure III by the curve Z_2 from right to left with origin O_{Z2} and vertical scale $\frac{r}{p}$. Define the demand elasticity of mobile factor in sector 2 as $\gamma_{Z2} = -[d(\frac{Z_2}{x_2}) \Big/ \frac{Z_2}{x_2}] \Big/ [d(\frac{r}{p}) \Big/ \frac{r}{p}] = -(\overset{\wedge}{\frac{Z_2}{x_2}}) \Big/ (\overset{\wedge}{\frac{r}{p}})$. Sector 2's land demand function can also be written in growth form as

(20a) $\hat{Z}_2 = \hat{\hat{x}}_2 - \gamma_{Z2}(\hat{r} - \hat{p})$.

Set $\theta_{xi} = \frac{w_i x_i}{p_i}$ and $\theta_{Zi} = \frac{rZ_i}{p_i}$ as the factor share of specific factor i , i = 1, 2 , and of land employed in the two economic sectors, respectively. The production functions of sectors 1 and 2 written in growth form are

(5a) $\hat{y}_1 = \theta_{x1}\hat{\hat{x}}_1 + \theta_{Z1}\hat{Z}_1$,

(6a) $\hat{y}_2 = \theta_{x2}\hat{\hat{x}}_2 + \theta_{Z2}\hat{Z}_2$.

Substitute equation (19a) into equation (5a) and equation (20a) into (6a), respectively. Then substitute the resulting equations (5a) and (6a) into the eco-land demand functions in equation (18a) to obtain

(18b) $\hat{Z}_N = -(1-\sigma)(\hat{A} + \hat{B}) + k\hat{\hat{x}}_1 + (1-k)\hat{\hat{x}}_2 - \gamma_{ZN}\hat{r} + (1-k)\theta_{Z2}\gamma_{Z2}\hat{p}$,

where $\gamma_{ZN} = \sigma + k\theta_{Z1}\gamma_{Z1} + (1-k)\theta_{Z2}\gamma_{Z2}$ can be interpreted as the "shadow" land demand elasticity of the ecosystem.

Furthermore, the land endowment constraint in equation (13) can be expressed in growth form as

(13a) $\lambda_{Z1}\hat{Z}_1 + \lambda_{Z2}\hat{Z}_2 + \lambda_{ZN}\hat{Z}_N = \hat{\bar{Z}}$,

where $\lambda_{Zi} = \dfrac{Z_i}{\bar{Z}}$ is the share of land employed in sector *i*, *i* = 1, 2, N.

The equilibrium land rental rate is obtained by substituting the three land demand functions in equations (18a), (19a) and (20a) into the land endowment constraint in equation (13a). That is,

(21)
$$\begin{aligned}\hat{r} &= -\frac{1}{\gamma_Z}\hat{\bar{Z}} - \frac{1}{\gamma_Z}\lambda_{ZN}(1-\sigma)(\hat{A}+\hat{B}) + \frac{1}{\gamma_Z}(\lambda_{Z1} + k\lambda_{ZN})\hat{x}_1 \\ &\quad + \frac{1}{\gamma_Z}[\lambda_{Z2} + (1-k)\lambda_{ZN}]\hat{x}_2 + \frac{1}{\gamma_Z}[\lambda_{Z2}\gamma_{Z2} + (1-k)\lambda_{ZN}\theta_{Z2}\gamma_{Z2}]\hat{p},\end{aligned}$$

where $\gamma_Z = \lambda_{Z1}\gamma_{Z1} + \lambda_{Z2}\gamma_{Z2} + \lambda_{ZN}\gamma_{ZN}$ is the aggregate land demand elasticity. It is a weighted average of land demand elasticity of goods 1, 2, and of the ecosystem, the weight being their corresponding land share.

Equation (21) is the equilibrium land rental rate derived from the land market equilibrium condition. At any given commodity price, *p*, the allocation of land in the ecosystem and the economic system is illustrated in Figure III. The width of the horizontal axis, $O_{Z1}O_{ZN}$, is equal to the total land endowment $\bar{Z}$. Multiply sector 2's land demand function by its price *p* to rescale Z_2 as $pZ_2 = p\delta(\frac{r}{p}) \cdot \bar{x}_2$. The economic land demand function, $Z_y = Z_1 + pZ_2$, is the horizontal aggregation of Z_1 and pZ_2. It is drawn in Figure III from left to right. On the other hand, the eco-land demand function Z_N in Figure II is flipped around and drawn in Figure III leftwards. The intersection of Z_y and Z_N determines the equilibrium point E^I, where superscript I denotes the “integrated’ equilibrium. The equilibrium land rental rate thus is r^I, and the land allocated to the economic system and the ecosystem are $Z_y^I = O_{Z1}O_{Z2}$ and $Z_N^I = O_{ZN}O_{Z2}$, respectively. Furthermore, the equilibrium point of the economic system is E^{Iy}, the intersection of Z_1 and Z_2. It determines the optimal allocation of Z_y within the economic system. It is clear that $Z_1 = O_{Z1}Z^{Iy}$ and $Z_2 = Z^{Iy}O_{Z2}$.

3. *The commodity market equilibrium*

The equilibrium commodity price is determined in the economic system. Substitute equation (9) into equation (10) to obtain commodity price as

(22) $$p = \frac{(1-k)y_1}{ky_2}.$$

A higher $(1-k)$ means a stronger demand for good 2, which in turn implies a higher price, ceteris paribus. Furthermore, an increase in y_1 leads to a lower price of good 1 and higher *p*. Similarly, an increase in y_2 reduces *p*.

In the above specification of the economic system, the relative commodity price is a pure economic variable determined by demands and supplies of the two commodities. However, since it affects the relative cost of land and the land demand of good 2, the commodity price thus plays a crucial role in determining the level of eco-land and ecological goods and services provided in the integrated equilibrium. In Figure III, the commodity market equilibrium price determines the height of good

2’s land demand function Z_2 and the position of aggregate land demand function of economic system, Z_y.

Total differentiate equation (22) to obtain

(22a) $\hat{p} = \hat{y}_1 - \hat{y}_2$.

Substitute equation (19a) into equation (5a) and equation (20a) into (6a) to get

(5b) $\hat{y}_1 = \hat{\bar{x}}_1 - \theta_{Z1}\gamma_{Z1}\hat{r}$,

(6b) $\hat{y}_2 = \hat{\bar{x}}_2 - \theta_{Z2}\gamma_{Z2}\hat{r} + \theta_{Z2}\gamma_{Z2}\hat{p}$.

Equations (5b) and (6b) imply that the supply of good *i* is positively related to the endowment of specific factor *i* and negatively related to the relative cost of mobile factor. The relative cost of mobile factor is defined as the cost of mobile factor for per dollar value of good produced. Using good 1 as the numeraire, the relative cost of mobile factor of good 1 is *r* and that of good 2 is r/p. An increase in *r* raises the cost of production and results in a reduction in outputs of both goods. On the other hand, an increase in *p* leads to an increase in the output of good 2 because it reduces the relative cost of mobile factor of good 2.

Substitute equations (5b) and (6b) into equation (22a) to get

(22b) $$\hat{p} = \frac{1}{(1+\theta_{Z2}\gamma_{Z2})}\hat{\bar{x}}_1 - \frac{1}{(1+\theta_{Z2}\gamma_{Z2})}\hat{\bar{x}}_2 - \frac{\theta_{Z1}\gamma_{Z1} - \theta_{Z2}\gamma_{Z2}}{(1+\theta_{Z2}\gamma_{Z2})}\hat{r}.$$

Equation (22b) is the commodity price that maintains commodity market equilibrium. It shows that the relative price of economic goods is determined by a society's endowments of specific factors, $\bar{x}_1$ and $\bar{x}_2$, and its cost of mobile factor. An increase in the endowment of specific factor 1 increases the supply of good 1 and raises *p*. Furthermore, the extent of variation in *p* caused by the variations in $\bar{x}_1$, $\bar{x}_2$ and *r* depends on the cost shares of land and the land demand elasticity in the economic system, that is, θ_{Z1}, θ_{Z2}, and γ_{Z1} and γ_{Z2}, respectively.

4. *The integrated equilibrium*

The equilibrium allocation of land is solved by substituting the equilibrium land rental rate in equation (21) into the three land demand equations (18b), (19a), and (20a) to obtain

$$\begin{aligned}\hat{Z}_N &= \frac{\gamma_{ZN}}{\gamma_Z}\hat{\bar{Z}} - (1 - \frac{\lambda_{ZN}\gamma_{ZN}}{\gamma_Z})(1-\sigma)(\hat{A}+\hat{B}) \\ &+ [k - \frac{(\lambda_{Z1}+k\lambda_{ZN})\gamma_{ZN}}{\gamma_Z}]\hat{\bar{x}}_1 + \{(1-k) - \frac{[\lambda_{Z2}+(1-k)\lambda_{ZN}]\gamma_{ZN}}{\gamma_Z}\}\hat{\bar{x}}_2 \\ &+ \{(1-k)\theta_{Z2}\gamma_{Z2} - \frac{[\lambda_{Z2}\gamma_{Z2}+(1-k)\lambda_{ZN}\theta_{Z2}\gamma_{Z2}]\gamma_{ZN}}{\gamma_Z}\}\hat{p},\end{aligned} \tag{18c}$$

$$\begin{aligned}\hat{Z}_1 &= \frac{\gamma_{Z1}}{\gamma_Z}\hat{\bar{Z}} + \frac{\gamma_{Z1}}{\gamma_Z}\lambda_{ZN}(1-\sigma)(\hat{A}+\hat{B}) + \frac{\gamma_Z - \gamma_{Z1}(\lambda_{Z1}+k\lambda_{ZN})}{\gamma_Z}\hat{\bar{x}}_1 \\ &- \frac{\gamma_{Z1}}{\gamma_Z}[\lambda_{Z2}+(1-k)\lambda_{ZN}]\hat{\bar{x}}_2 - \frac{\gamma_{Z1}}{\gamma_Z}[\lambda_{Z2}\gamma_{Z2}+(1-k)\lambda_{ZN}\theta_{Z2}\gamma_{Z2}]\hat{p},\end{aligned} \tag{19b}$$

$$\begin{aligned}\hat{Z}_2 &= \frac{\gamma_{Z2}}{\gamma_Z}\hat{\bar{Z}} + \frac{\gamma_{Z2}}{\gamma_Z}\lambda_{ZN}(1-\sigma)(\hat{A}+\hat{B}) - \frac{\gamma_{Z2}}{\gamma_Z}(\lambda_{Z1}+k\lambda_{ZN})\hat{\bar{x}}_1 \\ &+ \frac{\gamma_Z - \gamma_{Z2}[\lambda_{Z2}+(1-k)\lambda_{ZN}]}{\gamma_Z}\hat{\bar{x}}_2 \\ &+ \frac{\gamma_{Z2}}{\gamma_Z}\{\gamma_Z - [\lambda_{Z2}\gamma_{Z2}+(1-k)\lambda_{ZN}\theta_{Z2}\gamma_{Z2}]\}\hat{p}.\end{aligned} \tag{20b}$$

The growth form of equation (3) is

(3a) $\hat{N} = \hat{A} + \hat{B} + \hat{Z}_N$.

The welfare-maximization level of ecological goods and services produced by the ecosystem is derived by substituting Z_N in equation (18c) into equation (3a) which results in

$$
\begin{aligned}
\hat{N} = {} & \frac{\gamma_{ZN}}{\gamma_Z}\hat{\bar{Z}} + \{\sigma + \frac{(1-\sigma)\lambda_{ZN}\gamma_{ZN}}{\gamma_Z}\}(\hat{A}+\hat{B}) \\
& + [k - \frac{(\lambda_{Z1} + k\lambda_{ZN})\gamma_{ZN}}{\gamma_Z}]\hat{\bar{x}}_1 + \{(1-k) - \frac{[\lambda_{Z2} + (1-k)\lambda_{ZN}]\gamma_{ZN}}{\gamma_Z}\}\hat{\bar{x}}_2 \\
& + \{(1-k)\theta_{Z2}\gamma_{Z2} - \frac{[\gamma_{Z2}\lambda_{Z2} + (1-k)\lambda_{ZN}\theta_{Z2}\gamma_{Z2}]\gamma_{ZN}}{\gamma_Z}\}\hat{p}.
\end{aligned} \tag{3b}
$$

Similarly, the equilibrium outputs produced by the economic systems can be derived by substituting $\hat{Z}_1$ and $\hat{Z}_2$ in equations (19b) and (20b) into $\hat{y}_1$, $\hat{y}_2$ in equations (5a) and (6a). That is,

$$
\begin{aligned}
\hat{y}_1 = {} & \frac{\theta_{Z1}\gamma_{Z1}}{\gamma_Z}\hat{\bar{Z}} + \frac{\theta_{Z1}\gamma_{Z1}}{\gamma_Z}\lambda_{ZN}(1-\sigma)(\hat{A}+\hat{B}) + [\frac{\gamma_Z - (\lambda_{Z1} + k\lambda_{ZN})\theta_{Z1}\gamma_{Z1}}{\gamma_Z}]\hat{\bar{x}}_1 \\
& - \frac{\theta_{Z1}\gamma_{Z1}}{\gamma_Z}[\lambda_{Z2} + (1-k)\lambda_{ZN}]\hat{\bar{x}}_2 - \frac{\theta_{Z1}\gamma_{Z1}}{\gamma_Z}[\lambda_{Z2}\gamma_{Z2} + (1-k)\lambda_{ZN}\theta_{Z2}\gamma_{Z2}]\hat{p},
\end{aligned} \tag{5c}
$$

$$
\begin{aligned}
\hat{y}_2 = {} & \frac{\theta_{Z2}\gamma_{Z2}}{\gamma_Z}\hat{\bar{Z}} + \frac{\theta_{Z2}\gamma_{Z2}}{\gamma_Z}\lambda_{ZN}(1-\sigma)(\hat{A}+\hat{B}) \\
& - \frac{(\lambda_{Z1} + k\lambda_{ZN})\theta_{Z2}\gamma_{Z2}}{\gamma_Z}\hat{\bar{x}}_1 + \frac{\{\gamma_Z - [\lambda_{Z2} + (1-k)\lambda_{ZN}]\}\theta_{Z2}\gamma_{Z2}}{\gamma_Z}\hat{\bar{x}}_1 \\
& + \frac{\{\gamma_Z - [\lambda_{Z2}\gamma_{Z2} + (1-k)\lambda_{ZN}\theta_{Z2}\gamma_{Z2}]\}\theta_{Z2}\gamma_{Z2}}{\gamma_Z}\hat{p}.
\end{aligned} \tag{6c}
$$

The aggregate economic output defined in equation (2) can be written in growth form as

(2a) $\hat{y} = k\hat{y}_1 + (1-k)\hat{y}_2$.

By substituting equations (5c) and (6c) into equation (2a), we obtain the equilibrium level of economic goods and services as

(2b)
$$\begin{aligned}\hat{y} = {} & \frac{[k\theta_{Z1}\gamma_{Z1} + (1-k)\theta_{Z2}\gamma_{Z2}]}{\gamma_Z}\hat{\bar{Z}} + \frac{[k\theta_{Z1}\gamma_{Z1} + (1-k)\theta_{Z2}\gamma_{Z2}]}{\gamma_Z}\lambda_{ZN}(1-\sigma)(\hat{A}+\hat{B}) \\ & + \{k - \frac{[k\theta_{Z1}\gamma_{Z1} + (1-k)\theta_{Z2}\gamma_{Z2}]}{\gamma_Z}(\lambda_{Z1} + k\lambda_{ZN})\}\hat{\bar{x}}_1 \\ & + \{(1-k) - \frac{[k\theta_{Z1}\gamma_{Z1} + (1-k)\theta_{Z2}\gamma_{Z2}][\lambda_{Z2} + (1-k)\lambda_{ZN}]}{\gamma_Z}\}\hat{\bar{x}}_2 \\ & - \{\frac{[k\theta_{Z1}\gamma_{Z1} + (1-k)\theta_{Z2}\gamma_{Z2}][\lambda_{Z2}\gamma_{Z2} + (1-k)\gamma_{ZN}\theta_{Z2}\gamma_{Z2}]}{\gamma_Z} - (1-k)\theta_{Z2}\gamma_{Z2}\}\hat{p}.\end{aligned}$$

Equations (1)-(13) form the framework of the ecological-economic integrated general equilibrium model. And, equations (21), (22b), (18c), (19b), (20b), (3b), (5c), (6c), and (2b) are the solutions to the model. In the next section, we apply this model to analyze related issues.

IV. Applications

1. Overlooking the ecosystem results in misallocation of land and distortion in commodity price

If the ecosystem is overlooked, the model is reduced to the specific-model of trade. That is, the equilibrium land rental rate in the absence of the ecosystem is

(21a) $$\hat{r}^{yo} = \frac{\lambda_{Z1}}{\gamma_Z^{yo}}\hat{\bar{x}}_1 + \frac{\lambda_{Z2}}{\gamma_Z^{yo}}\hat{\bar{x}}_2 + \frac{\lambda_{Z2}\gamma_{Z2}}{\gamma_Z^{yo}}\hat{p},$$

where $\gamma_Z^{yo} = \lambda_{Z1}\gamma_{Z1} + \lambda_{Z2}\gamma_{Z2}$, and superscript *yo* denotes the economic system only.

And the commodity price remains the same as that in equation (22b). In this case, Z_N does not exist anymore in Figure III. The land demand curve of sector 2 is the dotted line drawn from right to left as shown in Figure IV. The land market equilibrium is at the intersection of Z_1 and Z_2, that is, point E^{yo}. The equilibrium land rental rate is r^{yo}, and $Z_1^{yo} = O_{Z1}^{yo}Z^{yo}$, $Z_2^{yo} = O_{Z2}^{yo}Z^{yo}$. r^{yo} is lower than r^I, $Z_1^{yo} > Z_1^I$ and $Z_2^{yo} > Z_2^I$. It implies that the land rental rate is undervalued and results in misallocation of land.[7]

From equation (22b), we can see that a distortion in *r* leads to a distortion in the commodity price. The direction of distortion depends on the relative factor intensity of goods 1 and 2. If good 1 is land-intensive, an undervalued *r* implies that the relative price of good 1 (1/*p*) is undervalued, too. A distortion in commodity price sends incorrect signals to industrial and trade policies.

2. <u>Higher eco-productivity results in higher welfare</u>

Consider two regions: the eco-productivity of region H(igh) is higher than that of region L(ow). That is, $(AB)_H > (AB)_L$. The PPF of region H extends in the direction of N more than that of region L as shown in Figure V. Region H produces more ecological goods and services than region L at any given *y*.

Suppose all other things are the same in the two regions, then the equilibrium

---

[7] Compared with equation (21), the land rental rate in equation (21a) is distorted in two ways. One is $\hat{A}$ and $\hat{B}$ do not appear to be the determinants of equilibrium commodity price and equilibrium land rental rate explicitly. The other is the aggregate elasticity of demand for land omitting the ecosystem, γ_Z^y, is lower than that of the integrated model, γ_Z.

points of regions H and L are e_H and e_L, respectively. At the equilibrium points, $MRT_H > MRT_L$, which implies that the opportunity cost of economic output is higher in region H than that of region L. Region H consumes more of both *y* and N and enjoys a higher level of utility than region L.

Eco-productivity affects the composition of *y* and N and the welfare level by generating a production substitution effect and a consumption substitution effect. Suppose, in Figure V, the slope of the indifference curve U_H at point e_H^s is the same as that of U_L at point e_L. It means that if the opportunity cost of *y* were MRT_L, the consumption composition of region H would be y_H^s and N_H^s. The production substitution effect is shown by the movement from point e_L to point e_H^s, and that of consumption substitution effect by the movement from point e_H^s to point e_H.

In the linear specification of the ecological production function in equation (3), high eco-productivity means that less Z_N is needed to produce any given N. That is, the production substitution effect of a variation of eco-productivity on Z_N is negative in the sense that *less* Z_N is demanded at higher eco-productivity. Moreover, a variation in *AB*, which represents a variation in the relative cost of *y* and N, induces a consumption substitution effect between *y* and N. It is shown in equation (17) that $\frac{AB}{r}$ is the opportunity cost of *y*. Higher *AB* raises the opportunity cost of *y* and encourages consumers to substitute N for *y*. Thus, the consumption substitution effect generates a higher demand for N and Z_N at higher eco-productivity. The consumption substitution effect of eco-productivity on Z_N is positive. The extent of consumption substitution effect depends on σ.

The overall impact of variations in eco-productivity on Z_N thus depends on the relative strength of production substitution effect and consumption substitution effect. When $0 < \sigma < 1$, consumption substitution is relatively difficult between *y* and N. The negative production substitution effect dominates the positive consumption substitution effect so that the net effect of variations in *AB* on Z_N is negative. In other words, higher eco-productivity results in a reduction in demand for eco-land. More land will be allocated to the economic system and results in a lower r.

It can also be seen from equations (19b), (20b), (5c) and (6c) that higher eco-productivity implies that more land can be allocated to produce more economic outputs y_1 and y_2. Higher economic output in this case is not at the cost of ecological goods and services because we can also see from equations (2b) and (3b) that higher *AB* also implies higher *y* and N. High eco-productivity raises the overall productivity of land so that more of *y* and N and a higher welfare level can be attained.

On the other hand, in the case of $\sigma > 1$, substitution in consumption is very easy between *y* and N. The positive consumption substitution effect dominates the negative production substitution effect. From equations (3b)and (2b) we can see that when $\sigma > 1$, more N and less y will be consumed at higher eco-productivity than in the case of $0 < \sigma < 1$. From equations (19b) and (20b), we notice that less land is left for the economic system, which leads to a higher r, lower p, lower y_1 and y_2.[8]

The implication of a variation in eco-productivity on land allocation is illustrated in Figure VI for the case of $0 < \sigma < 1$. Suppose the land market equilibrium described in Figure III is that of region H, which is replicated in Figure VI and relabeled with sub- or super-script H. The land market equilibrium points of region H are E_H^I and E_H^{Iy}, and the equilibrium land rental rate is r_H^I. The land allocated to the economic system and the ecosystem are $Z_y^H = O_{Z1}O_{Z2}^H$ and $Z_N^H = O_{ZN}O_{Z2}^H$, respectively.

From equation (18) we can see that a reduction in eco-productivity results in an increase in eco-land demand at any given r. This means that the eco-land demand curve of region L, Z_N^L, lies above that of region H in Figure VI. Assuming other things are equal in the two regions, the land market equilibrium points of region L are E_L^I and E_L^{Iy}. The land allocated to the ecosystem is $Z_N^L = O_{ZN}O_{Z2}^L$, and that to the economic system is $Z_y^L = O_{Z1}O_{Z2}^L$. The land rental rate in region H is lower than

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[8] The shape of indifference curve is steeper in the case of $\sigma > 1$ than that of $0 \le \sigma \le 1$ and e_H is located at the northeast of e_L in Figure V.

that in region L, $r_H^I < r_L^I$. Region H allocates more land to economic production, $Z_y^H > Z_y^L$, and less to the ecosystem.

The influence of eco-productivity on ecological and economic variables is summarized in Table 1. One important conclusion is that eco-productivity plays an important role in determining the allocation of land between the economic system and the ecosystem and the resulting land rental rate and associated economic variables.

In summary, region H produces more ecological goods and services and attains a higher welfare level than region L regardless of the magnitude of σ. However, a variation in eco-productivity has different impacts on the allocation of land and economic variables. If substitution between *y* and N is easy, less land is allocated to the economic system, and less economic goods and services are produced and consumed at region H than that at region L.

Next, we extend the above analysis to examine how a variation in eco-productivity and/or economic activity affects the ecological pyramid of a region.

3. Implications of the model on land-cover change and the ecological pyramid

Land allocation and the associated land-cover are essential determinants of regional environments since "the size, shape, and spatial relationships of land-cover types influence the dynamics of populations, communities, and ecosystems." [5]. Recent studies indicate that land-cover change increasingly represents a fundamental source of change in global as well as regional environments. Richards [13] points out two important trends evident in land-cover change over the centuries: the total land dedicated to human use (e.g., settlement, agriculture, forestry, and mining) has grown dramatically, and increasing production of goods and services has intensified both the use and the control of land. By altering the physical environment and the biotic community living on it, land-cover change has altered the various functions of the ecosystem. For example, deforestation and/or reforestation alter the amount of sunlight the land absorbs, and the amount of moisture it releases, which can affect rainfall patterns.

Next, we analyze how land allocation in a region affects the size of the ecological pyramid. Given the equilibrium allocation of land, we can derive the ecological pyramid for regions of various eco-productivity as follows. In Figure VII, the triangle $\Delta O_{Z1}TO_{ZN}$ represents the prototype of an ecological pyramid on a region of land size $O_{Z1}O_{ZN}$. Suppose the ecological pyramid of the low eco-productivity region is a similar triangle to the prototype, except that the size of eco-land is $O_{Z2}^{L}O_{ZN}$ instead of $O_{Z1}O_{ZN}$. That is, the ecological pyramid of the low eco-productivity region is $\Delta O_{Z2}^{L}T^{L}O_{ZN}$.

The linear form specification of N in equation (3) allows us to transform eco-productivity into Z_N. That is, define $\frac{(AB)_H}{(AB)_L} = \alpha > 1$. $N_H > N_L$ implies that

$(AB)_H Z_H = \alpha(AB)_L Z_H > (AB)_L Z_L$ so that $\alpha Z_H > Z_L$. This means that we can find a point at the left of O_{Z2}^{L} on the horizontal axis, O_{Z2}^{H*}, such that $\frac{(AB)_H}{(AB)_L} = \frac{O_{ZN}O_{Z2}^{H*}}{O_{ZN}O_{Z2}^{L}}$. The relative eco-productivity of region H of eco-land size $O_{Z2}^{H}O_{ZN}$ is equivalent to that at eco-land size $O_{Z2}^{H*}O_{Z2}^{H}$ in terms of the prototype triangle $\Delta O_{Z2}^{L}T^{L}O_{ZN}$. In this way, the ecological pyramid of region H is represented by $\Delta O_{Z2}^{H*}T^{H*}O_{ZN}$. It is clear that $\Delta O_{Z2}^{H*}T^{H*}O_{ZN} > \Delta O_{Z2}^{L}T^{L}O_{ZN}$. Comparing the welfare-maximization equilibrium of region H and region L, we can see that even though $Z_N^H < Z_N^L$, $y_H > y_L$ and $N_H > N_L$.

Analogously, the impact of economic activity on ecological goods and services provided by an ecosystem can also be analyzed. Suppose there is an increase in the endowments of specific factor 1, that is, $\hat{\bar{x}}_1 > 0$, it is clear from equation (19a) that it shifts up the Z_1 curve to Z_1' in Figure VIII. The new land market equilibrium point is $E^{I'}$ with the new land rental rate at $r^{I'}$, and $r^{I'} > r^{I}$. The higher return to land attracts land towards the economic system. The size of land employed in the economic system increases from $O_{Z1}O_{Z2}$ to $O_{Z1}O_{Z2}'$, and that of the ecosystem falls from $O_{ZN}O_{Z2}$ to $O_{ZN}O_{Z2}'$.

An increase in specific factor 2 has similar results on *r*, Z_y, Z_N, *y* and N as those in the case of specific factor 1. The differences between the two are in the allocation of land within the economic system between Z_1 and Z_2, in the composition of *y*, and *p*. In the case of $\hat{\bar{x}}_1 > 0$, $\hat{y}_1 > 0$ $\hat{y}_2 < 0$, and $\hat{p} > 0$. On the other hand, in the case of $\hat{\bar{x}}_2 > 0$, $\hat{y}_1 < 0$ $\hat{y}_2 > 0$, and $\hat{p} < 0$. The results are exactly the same as those of the specific-factor model of trade. In addition, our model shows that an expansion in the scale of the economic system raises the land rental rate, crowds out ecosystem production, and less ecological goods and services are produced.

Furthermore, as the size of eco-land reduces from $O_{ZN}O_{Z2}$ to $O_{ZN}O'_{Z2}$, the size of the ecological pyramid shrinks from $\Delta O_{Z2}T_I O_{ZN}$ to $\Delta O'_{Z2}T'_I O_{ZN}$ as shown in Figure IX. An expansion in the scale of the economic system thus reduces the size of the ecological pyramid.

V. Concluding Remarks

A coherent set of policies for sustainable development must take into account the interactions between the economic, environmental and social dimensions of a society. Economic analysis can be of value in socio-economic planning for sustainable development by providing a systematic framework to deal with the problems of defining and maximizing social welfare subject to various economic, social, and biophysical constraints. In this paper, we first focus on integrating the ecological and economic dimensions of sustainable development by incorporating an ecological production function into a conventional general equilibrium model of economic analysis. This model allows us to examine the interaction between the economic system and the ecosystem. We find that overlooking the ecosystem results in misallocation of land and a distortion in the commodity price of economic goods and services. Misallocation of land normally results in destruction of habitats and landscape and this degenerates many ecosystem functions. And, the distortion in commodity price normally sends incorrect signals to industrial and trade policies in the economic system.

We then use the model to analyze how eco-productivity affects a region‘s economic output and welfare. In general, the region with high eco-productivity enjoys higher welfare than that with low eco-productivity. Moreover, when the substitution between y and N is difficult in consumption, that is, $0<\sigma<1$, high eco-productivity raises the overall productivity of land. The society attains a higher level of welfare when more y and N are produced and consumed. In this case, higher economic output is not produced at the cost of ecological goods and services

Finally, we analyze the impact of economic activity on the ecological pyramid. An expansion in economic activity, caused by an increase in the endowments of specific factors, raises land return in the economic system and encourages land to move out of the ecosystem; and, in turn, leads to a shrinkage in its ecological pyramid.

We have shown how the economic activity of a region and one of its biophysical constraints interact with each other using a simplified linear form of ecological production function in the above analysis. This ecological-economic integrated model provides a more comprehensive evaluation of economic outputs versus ecological goods and services than that shown in conventional economic models. However, an ecosystem is a complex dynamic interacting system composed of subsystems of hydrosphere, atmosphere, lithosphere, and biosphere. A more realistic specification of the ecological production function requires knowledge of each of the subsystems and of their interactions. One strand of future research is to incorporate the core concepts and principles that govern each subsystem and their interactions into the above model. Another aspect worth exploring is to incorporate topics in resource and environmental economics into the model, e.g. how inputs taken from the ecosystem to the economic system and how waste discharge to the ecosystem affect the functioning of the ecosystem. Of course, a conjunction of the above two in one way or another is worth exploring, too. Finally, we share the remarks of Tisdell [15] that "the more relationships between economics, ecology and the environment are studied, the more acutely one becomes aware of the fact that our knowledge is imperfect, that many gaps remain to be filled and that we need to convince more people to join in exploration and discovery in this area because of the magnitude and importance of the task." We hope that the integrated economic-ecological model in this paper will stimulate and encourage further research toward the goal of sustainability.

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	Production substitution effect (1)	Consumption substitution effect (2)	Overall substitution effect	Z_N	*r*	N	*y*	*welfare*
$0<\sigma<1$	—	+	(1) > (2)	—	—	+	+	+
$\sigma>1$	—	+	(1) < (2)	+	+	+	—	+

Table I The influence of high eco-productivity on ecological and economic variables

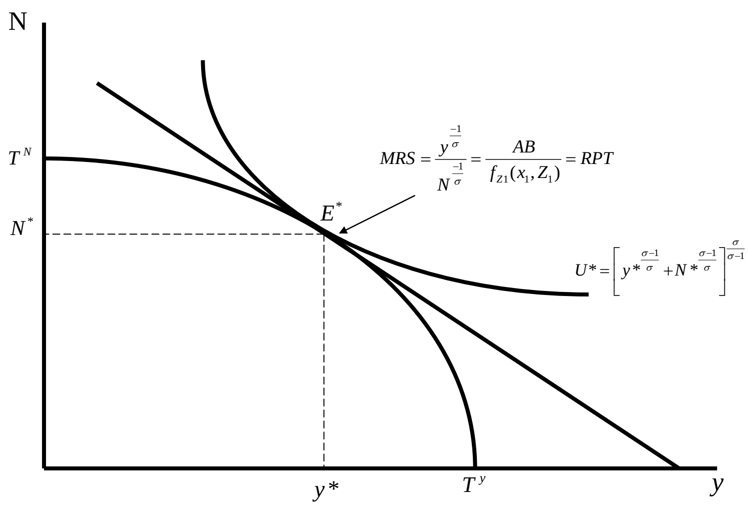

Figure I The welfare maximization composition of economic and ecological goods and services

The optimal composition of *y* and N at the equilibrium point E* are *y** and N*. Any other composition of *y* and N will not generate a utility level higher than U*. At the right hand side of E*, the marginal cost of economic output is greater than the marginal rate of substitution,. The society can increase her utility by reducing *y* and increasing N. That is, the society's utility level can be increased by moving towards E*.

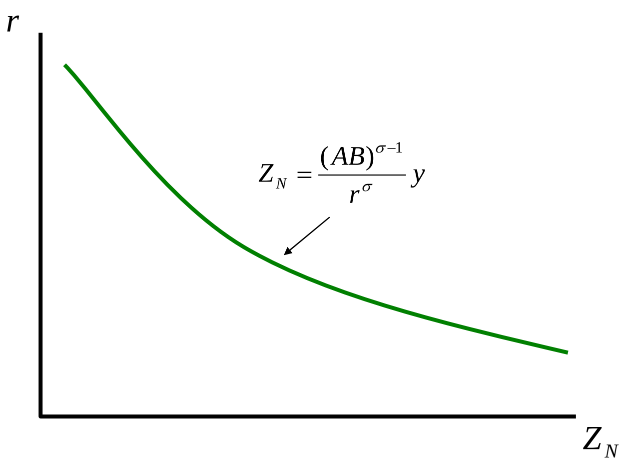

Figure II The eco-land demand function

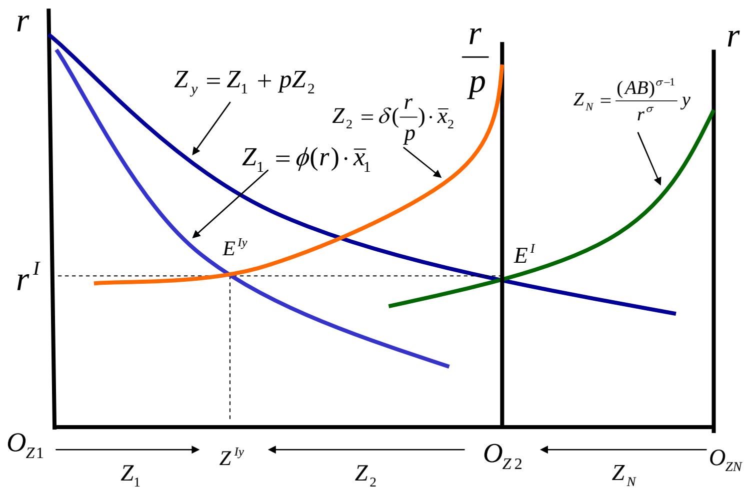

Figure III The allocation of land in the integrated equilibrium

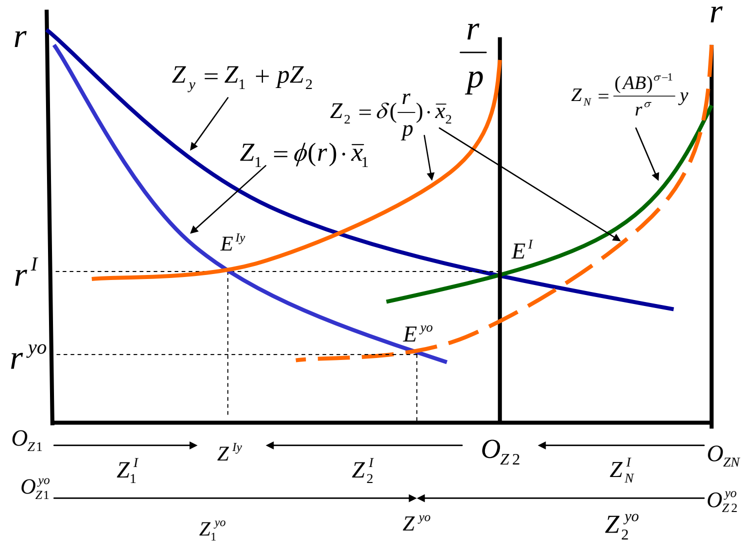

Figure IV Overlooking the ecosystem results in misallocation of land

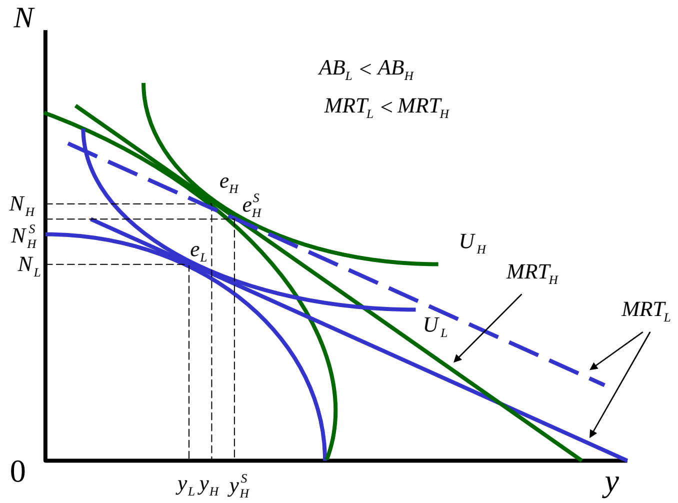

Figure V High eco-productivity results in high level of welfare

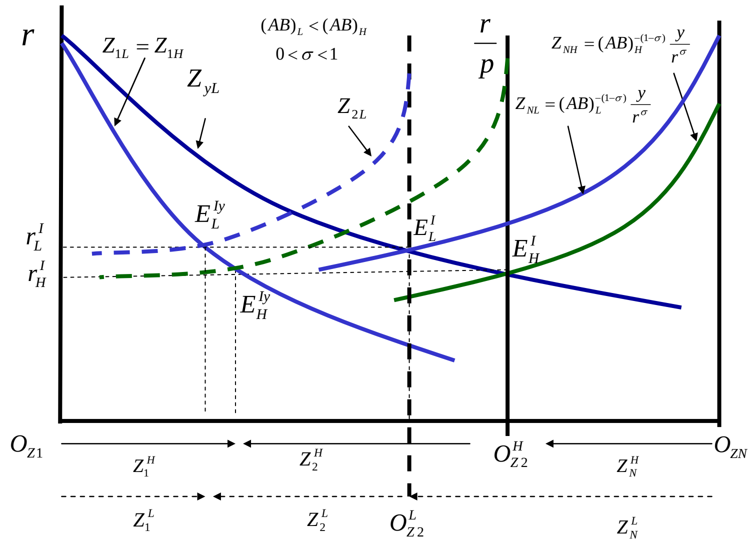

Figure VI Land allocation at different eco-productivity

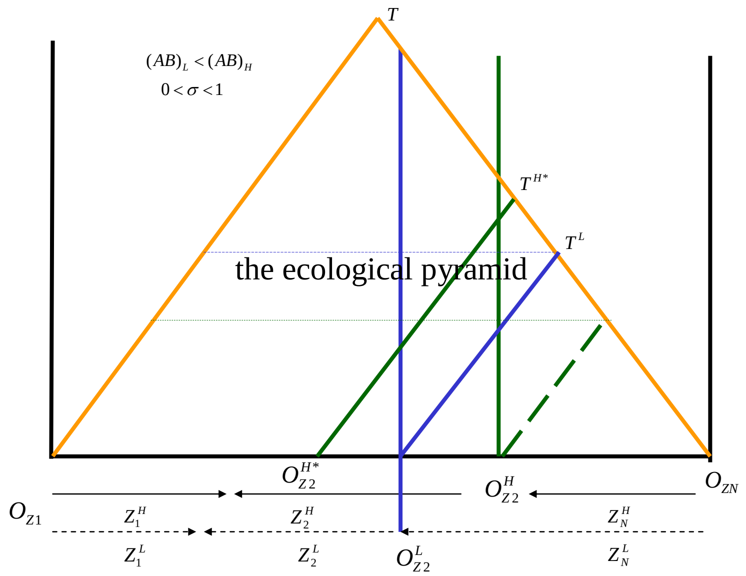

Figure VII The equilibrium land allocation and the ecological pyramid correspond with various eco-productivity

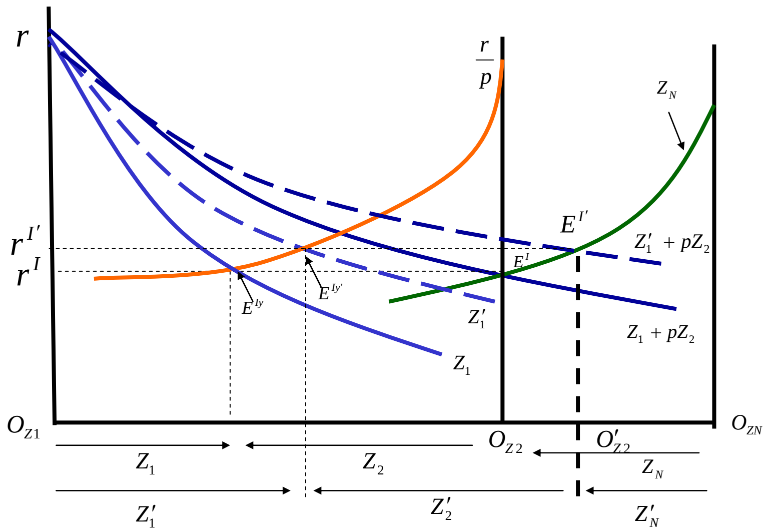

Figure VIII The impact of a variation in the endowment of specific factor 1 on land allocation

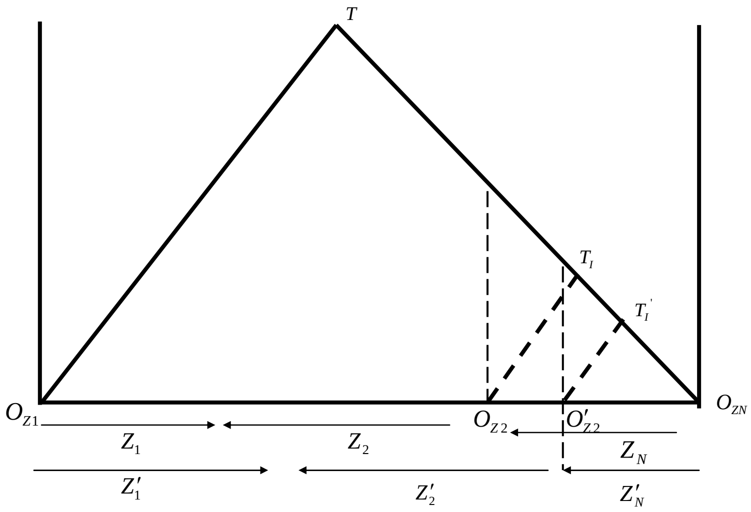

Figure IX An increase in the endowment of specific factor 1 reduces the size of the ecological pyramid