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The role of input–output analysis of energy and ecologic systems

In the early development of ecological economics—a personal perspective

Bruce Hannon

Jubilee Professor of the Liberal Arts and Sciences, University of Illinois, Urbana, Illinois, USA

Address for correspondence: Bruce Hannon, Jubilee Professor of the Liberal Arts and Sciences, University of Illinois, Rm. 220, 607 S. Mathews, Urbana, IL 61801. bhannon@uiuc.edu

A summary is provided of the early history of research on the flow of nonrenewable energy resources through the economy and of the flow of renewable energy resources through a natural ecosystem. The techniques are similar, and many specific applications are provided. A combined economic and ecological technique is also defined. The early history and people of the International Society Ecological Economic are cited.

Keywords: modeling; economy; ecosystem; energy

Introduction

The idea of combining economics and ecology into a single discipline has it roots in the ideas of Robert Costanza in the mid-1970s when he was completing his PhD thesis with the Energy Research Group (ERG[a]) at the University of Illinois in Urbana (1960–1985). Clark Bullard, Robert Herendeen, and Bruce Hannon had developed the energy input–output (I–O) matrices for the U.S. economy and were using them to calculate the energy conservation potential for shifts in decisions by consumers, commercial and industrial firms, and government. Herendeen and Hannon had developed analogous theory and applications for the ecosystem, beginning in 1973. Over the next decade, Costanza, Herendeen, and Hannon continued this ecosystem work while Drs. Costanza and Herman Daly were founding the International Society of Ecological Economics. The increasingly active society now has a very large membership and a prestigious journal. This paper lays out the theory of (I–O) first as it applies to economics, then as it was modified to include physical energy flows, next as it was applied to ecosystems, and finally to a combined ecological-economic system.

The ERG used a combined energy-dollar flow (I–O) theory to more accurately track the total (direct and indirect) energy flow from the ground to produce each item of final consumption. This allowed them to account for all the energy consumed in a given year to all of the items of final consumption, without multiple counting. With this information, ERG evaluated hundreds of consumption alternative items and processes for their energy-conserving potential. They developed the energy I–O matrix for 4 years—1963, 1967, 1972 and 1977—as these were the only databases created by the U.S. Census Bureau at the time. With this same theory and the data on employment, they were also able to calculate the direct and indirect labor cost of each unit of final consumption. This gave them a way to address the energy-labor substitutions that were happening in the economy and to estimate the increase in labor demand as energy became increasingly expensive.

The main problem in developing a similar theory for the ecosystem is defining the net output of an ecosystem, the analog of Final Demand for the economic system. The ERG was in the position of

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[a] Greek for Energy.

creating a new accounting definition for the ecosystem, something that had been done long before for the economic system. They ultimately decided that the ecosystem net output (export − import) was the combination of the new biomass formed in the period plus any net exports of biomass. Ecosystem respiration, the emission of low temperature heat, was contained in the net input to the system and was included in the total output but not in the net output. This imbalance of energy flows allowed them to calculate an overall efficiency for the ecosystem and for the combined ecological economic system.

It is appropriate to say what this paper does not intend to accomplish. I am not trying to write the entire up-to-date history of the use of I-O from the beginning of *Ecological Economics*. ERG supplied what was then part of a good foundation. However, very few if any, improvements have been made to date in producing the accurate energy intensities needed to evaluate the consequences of consumption decisions. Also, I am not trying to summarize all of the history of I-O modeling in ecology since those early days. There are several recent papers, some coauthored by me, in the use of I-O in ecology that are excluded in this paper.

What follows then is a recounting of the early development of ecological economics from a personal point of view, from the place where I stood, deep in the Midwest, at a big university in a small Illinois town. Great strides in this field were being made elsewhere, and those accomplishments are still being made by the many who have joined the field since those early days.

History of the energy input–output theory

In the 1930s, Wassily Leontief was putting the finishing touches on his development of the (I–O) matrices of the U.S. economy, just in time for its strategic use in converting our industry to a war footing. His process allowed the direct and indirect demands of industry to be estimated for a given Gross National Product (GNP). The government stated its concepts of the needs for the items of war in terms of the numbers of airplanes, tanks, guns, explosives, and so forth for each of the 4 or 5 years they expected the war to last. Leontief was able to determine for this final bill of goods the flows of steel, aluminum, energy, and such needed from each industry, directly and indirectly.[1] Then these flows were compared to the capital stocks needed in these industries to meet the wartime demands. What they found was that the output of war material and energy plus those of personal consumption was not possible given then-current capacities in any of the major sectors. Two major endeavors were soon undertaken: massive new construction programs in steel production and shipbuilding, including conversion of many industries to the production of military items—for example, the auto companies converting to the production of military vehicles—and the substantial reduction of personal consumption of cars, gasoline, tires, and certain kinds of food. How did he do it?

Imagine a matrix of exchanges between each entity involved in the production economy. The industries may be very materials-oriented, such as the steel or the auto industries, or service-oriented, such as the finance or transportation industries. The industries are listed down the rows of the matrix and in the same order, across the columns of the matrix. At each intersection in the matrix, the annual exchange between the row industry and the column industry was found from industry records and posted in dollars. The net outputs of each of these industries—their contribution to final demand—were also estimated for the year. The total of all of these net outputs was the GNP as it came to be called then.[2] This GNP, more recently named the Gross Domestic Product (GDP), consisted of vectors of personal consumption items, government consumption items, new capital formation, net exports, and changes in inventories. Both Simon Kuznets, who designed this accounting framework, and Leontief would later get Nobel prizes in economics for this work.

The list or vector of net inputs to the economy was also estimated and arranged across the bottom of the exchange matrix. The net inputs were composed of separate vectors of the labor inputs to each industry, their profits, depreciation, and taxes paid. The dollar value of the total input of each industry (the column sum) was equal to the total output of each industry (the row sum). With this special set of data, Leontief showed how a total requirements matrix could be calculated. Each element in this derived matrix was the total direct and indirect requirements from the row industry by the column industry per dollar of that industry's total output. The total required output of each of the industries was the product of a special form of the inverted exchange matrix times the GNP. By comparing these total outputs with the expanding demands (scenario versions of the GNP), a feasible transition to a wartime economy could be estimated. Private entrepreneurs, such as Henry J. Kaiser, were essentially given blank checks to build steel and ship construction enterprises at the estimated rates. At the same time, rationing of consumer goods and price controls were put into place. The overall success of this effort is legendary.

After the war, these capacities for production remained, driving the ensuing economy in a variety of new and unique ways. No formal transition plan of reduction was forthcoming, even though the policy-generating process to quickly return to a peacetime economy was at hand. For example, the production of explosives required the production of nitrogen. After the war, these munitions companies desperately sought new uses for their nitrogen. One was found: the production of ammonia as a fertilizer of annual crops, particularly corn. This flood of cheap ammonia contributed to a glut in corn production, leading to the current billions in federal revenues spent annually on price support programs.

The classic input–output theory

The mathematics behind the Leontief idea is rather simple. Let this exchange matrix be x and the total output of each industry be vector X. Divide the columns in matrix x by their respective total outputs to form matrix A, the (normalized) direct requirements matrix, so

$$x * \dot{\mathbf{X}}^{-1} = A \tag{1}$$

where $\dot{\mathbf{X}}^{-1}$ is the inverted matrix of the diagonalized vector X.

$$\text{Then } A * X + Y = X \tag{2}$$

where vector Y is the vector of net outputs (its sum is the GDP).

$$\text{Then } Y = [I - A] * X \tag{3}$$

where I is the unity matrix.

Or, to find the vector of required industry outputs for a desired net output Y

$$X = [I - A]^{-1} * Y \tag{4}$$

requiring the inversion of matrix $[I - A]$.

The x matrix and Y vector are routinely assembled by the Bureau of Economic Analysis (BEA) in the U.S. Department of Commerce and published about every 5 years.

Input–output energy analysis

In 1969, a group of Hannon's students analyzed the direct and indirect energy use in making and delivering soft drinks and beer in refillable and throwaway containers. The interest was to see if the system of refillable containers was more or less energy intensive than the system of throwaway containers. By that time the glass refillable containers were being rapidly displaced from the market by glass and aluminum throwaway containers. The production of the glass container, for example, had to be traced all the way back to the sand from which it was made. It was very tedious and time consuming to find as many inputs to this process chain as possible. Even the chain of processing of the major inputs to the bottle-making chain, such as the plastic and paper packaging, was involved in the final calculation. Along the way, the enormous difficulty of the infinite regress involved was realized. There were several basic forms of energy, and the process had to be tracked for each of them. Nevertheless, the research was completed at the University's Center for Advanced Computation (CAC).[3] The little pamphlet became extremely popular and the basis for many state legislative attempts to ban or tax these containers and many court challenges to the idea of requiring monetary deposits on them. It was found that the total throwaway energy cost was about four times that of the 18-trip (typical) refillable container per unit of beverage. The direct and indirect labor cost of throwaways and refillables were calculated by Hugh Folk, an economics professor at the University of Illinois at Urbana-Champaign. It was found that the provisioning of refillable containers required more and different jobs than that of throwaways.[4]

Several very interesting new issues arose. First was the idea that energy conservation could be achieved by changing one's product choices—the idea of embodied energy in consumer products. Although the ERG were only observers of the complex political process the study had started, they noted the extreme reactions to the idea of a return to refillables from the industries that made the containers—those that made the material for the containers, the paper and plastic packaging of the containers, and the coalition of labor unions. All of them pushed for the throwaway containers. The labor union coalition reaction was especially interesting. There was then even a refillable bottle-washers union in the coalition. Folk had found that since the total payments to labor under either system—refillable or throwaway—were roughly the same, the average wage within these systems would decline with a return to a refillable system. This was due to the increase in relatively low-waged jobs at the retail and wholesale levels and a decline in the relatively high-waged jobs in the glass, aluminum, and container industries. Thus, while the overall labor coalition effect would be an overall increase in jobs, the high union fees paid by the high-waged jobs caused the coalition to lobby for throwaways.

It was also found that while the beer industry had introduced throwaway containers in the 1930s, particularly for the outdoorsman, the major thrust came in World War II when beer was shipped to the troops at the front. Due to the scarce shipping capacity, return of the refillables was not appropriate. After the war, to continue the movement toward throwaways, the container makers along with the metals industries, primarily Reynolds, Alcoa, and Inland Steel, would form special contracts with bottlers, such as Coke and Busch. The 5-year contracts yielded free throwaway containers in the first year with increasingly small discounts as the years progressed. This incentive allowed the bottlers enough income to convert their bottling lines to throwaways and use one-way delivery trucks to wholesalers and retailers. The advent of the Interstate Highway system allowed overnight trucking from the new bottling plants, minimizing bottler inventory costs. Bottlers were then able to successfully invade the territories of smaller bottlers who used refillable containers exclusively. The big bottlers' throwaways were of no use to the local bottlers, who soon went out of business. The prodigious use of the throwaway led to significant waste and littering issues. A strong public reaction to this waste was countered by an advertising campaign that spoke of wasteful consumer littering, turning the issue on its head, and of the ecology of the recycled aluminum container. The last holdout, the individual grocery shopper buying soft drinks in refillable bottles, succumbed to throwaways wherever local aluminum recycling was instituted by waste-conscious communities.

The last effort in this area showed that the modern recycled aluminum soft drink or beer container required about twice the total direct and indirect system energy as its comparable refillable glass container. Today in the U.S., the refillable container is a museum item.

The difficulty of finding the complete energy and labor embodied in these products and the fact that ERG found a significant energy–labor tradeoff in the study initiated a more elaborate effort.

In 1970, Hannon joined the University of Illinois' CAC and attracted two other newly minted PhDs, Clark Bullard (Engineering) and Robert Herendeen (Physics) to the study of embodied energy. They each had the underlying concern over the growing dependence of the economy on finite energy resources. The ERG wanted to see if knowledge of the energy embodied in various products and services would change purchasing decisions. They needed a way to uniquely assign all of the energy of the various forms that moved from the finite resource base to all of the consumer products and services. The (I–O) process seemed to hold promise, and fortunately, there were appropriate economists at the CAC. They formed the ERG using a significant National Science Foundation grant to formally start them off in 1972.

Examination of the U.S. Census Bureau data revealed a particularly extreme variation (more than a factor of 10) in the apparent prices paid for energy across the economic sectors. It was abundantly clear that ERG would have to use physical units in the transactions matrix (x) rather that the given dollar values of the exchanges. This proved to be an enormous task but well worth it in the end. The current process used by those at Carnegie-Mellon to produce up-to-date energy intensities is significantly flawed because they do not use the physical units in the transactions matrix.

They use the given dollar values of energy, but ERG found that the price paid for energy varied by a factor of 10 over the full range of commerce and industry. The final work published by the ERG in 1977 is most definitive.[5] In this article, they compared the change in the energy intensities between 1972 and 1977, a period in which energy prices increased suddenly and the economy made significant adjustments.

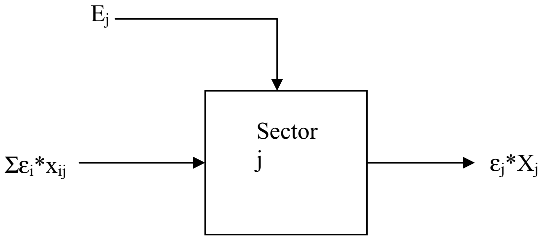

Figure 1. The energy balance for a specific type of energy for the *j*th sector of the economy for a given year. The energy intensities are the ε_i. E_j is the direct energy used in Sector j. The x_{ij} are the elements of the economic transactions matrix except that the energy rows are in physical units (BTUs).

In the early 1970s, Bullard and Herendeen[6] published the details of how these calculations were made. The result was a set of energy intensities, similar to economic prices. These intensities were the direct and indirect energy amounts (by type) that moved from the finite resource base per unit of output of each of 400 sectors of the economy during a given year. During this time period, the ERG had to take over the entire university computation facilities, usually around 3 a.m., to allow inversion of the appropriate matrix!

The intensities were derived from the energy balance in the following figure, for each energy type. In Figure 1, the vector E is the list of the physical amount of energy of a specific type (coal, crude oil, refined petroleum, natural gas, electricity) used by each sector of the industry and commerce, and ε_i is the i^{th} element in the vector of energy intensities of this type (physical units, e.g., BTUs, per dollar) embodied in each of the (nonenergy) inputs x_{ij} to Sector j, summed for the total direct and indirect embodied energy input to this sector. To calculate a total annual physical measure of the energy moving from the natural resource base ERG combined the coal intensity, the crude petroleum intensity and a portion of the electricity intensity representing the contribution of nuclear and hydropower. To calculate the energy embodied in imports (e.g., Japanese autos), ERG assumed they had the same energy inputs as their domestic counterpart.

From Figure 1, we get, in vector and matrix form,

$$\varepsilon * x + E = \varepsilon * \dot{\mathbf{X}} \tag{5}$$

solving for E gives, with equation 1,

$$E = \varepsilon * \hat{X} - \varepsilon * A * \hat{X} \tag{6}$$

leading to the vector of energy intensities

$$\varepsilon = E * \dot{\mathbf{X}}^{-1} * (I - A)^{-1}$$

or

$$\varepsilon = e * (I - A)^{-1} \tag{7}$$

where $e = E * \dot{\mathbf{X}}^{-1}$, the vector of the physical energy of a specific type used by each sector per unit of total output of that sector.

These intensities were calculated with equation 7 using the A modified to contain the physical units of energy in the energy sectors for the years in which BEA had constructed the original x matrices that were usable for the years with U.S. Census Bureau Data for that ERG research existed (1963, 1972, and 1977). The major effort became the modification of the A matrix to substitute the physical units of energy for the dollar value and maintain the proper overall energy balance. This took at least two full time–equivalent (FTE) years of effort for each data year. This substitution was needed as a simple calculation showed extreme variation in the apparent energy prices being paid on average by each sector of the economy. The total energy intensities varied greatly across the 400 sectors of the economy.

The bulk of work done during the life of ERG (1969–1985) was the various applications of these intensities to answer questions about the energy conservation potential of the individual sectors of the economy and of individual consumers. The federal support for ERG energy conservation work essentially disappeared in the early 1980s. In the 15 years of energy research by the ERG, a slightly lagged correlation between availability of federal funding of energy conservation research and energy price rises was noted.

The ERG published over 200 papers during its short lifetime, most of which found their way into appropriate professional journals. Over the 1970s, ERG group published 15 articles in *Science* alone. ERG also managed to establish a kind of policy record—perhaps a permanent one—as the only research group to initiate and supply supporting documentation for *two* (unsuccessful) congressional attempts to establish an energy tax. The ERG found that such a tax, placed on the physical energy as it moves from the natural resource base, would produce widespread, effective, and equitable energy conservation. These results are discussed below.

Economist Hugh Folk and Hannon produced a paper on the tradeoff between energy and labor for the 400 sectors of the U.S. economy.[7] They produced the labor intensities in a manner similar to the calculation of the energy intensities. Folk's student, Roger Bezdek, and Hannon published a paper in *Science* in 1974 on the energy and labor differences between a unit of government spending on interstate highway construction and the alternatives of health care, criminal justice, and sewage treatment plant construction.[8] All these alternatives required less energy and created more jobs than highway construction. Analysis of a particular county in southern Illinois, where interstate I-57 was being constructed while a large Corps of Engineers reservoir was also being constructed, revealed no correlation with unemployment there.[9] The major workforce for such construction comes from large cities at great distances just for the weekday work in the county. This result contrasted with the political justification for the highway and reservoir as a cure for high county unemployment.

One of ERG's most successful efforts was the comparison of the energy (combined types) intensities with the labor (total FTE jobs) intensities for a given year. Similar to the container study, they were able to show conclusively that energy and labor tradeoff, or are substitutes, just as had been shown in the container study. They showed that historically when the price of electricity, for example, rose relative to the average (nonsalaried) wage, energy use decreased and employment increased, per dollar of GDP. This would mean that labor productivity would decline and eventually so would real wages, all else staying the same.[5]

ERG showed how direct and indirect energy use varied with household incomes.[10,11] From this and further studies, they concluded that a tax on all energy as it moves from the resource base was the only equitable way to tax energy.[12] Their results showed that direct household energy use—primarily gasoline and heating fuels—saturated with rising income while the total direct and indirect energy use was linear with income and rose proportionately with income. These household energy studies also showed that even though those living in New York City apartments, foreswearing car use and claiming relatively low direct energy use, actually, due to their high relative incomes, used more than the average amounts of energy when the direct and indirect assignments were made to their consumption. For example, gasoline is a direct household energy use while airplane fuel is an indirect use.

In a 1975 *Science* paper, Hannon laid out three dilemmas for the typical person wishing to unilaterally change his total energy footprint.[13] First, energy conservation can only be achieved by driving up the price of energy, especially electricity relative to wages, and this results in more employment. The increase in employment comes typically at the low-waged end of the spectrum while decreases in employment would occur at the high-waged end (as in the drink container example cited earlier). The dilemma comes from the resistance of the high-waged, highly organized employees who can afford to pay high union dues. At the same time, no support for the change comes from the relatively disorganized low-waged employees. In addition, the jobs lost are those that exist in the electricity-intensive sectors while the jobs that would be gained do not yet exist. The second dilemma comes from the linear relationship of total direct and indirect energy use and household income noted above: the only way to actually save energy is to reduce income. Even saving money results in energy use in the investment market. The third dilemma of the person determined to save energy comes from the fact that any voluntary energy-saving effort, such as riding a bus to work rather than driving a car, also saves money. This money savings is then spent on other goods or services, and those require energy (and jobs) to provide. Sometimes, the energy demands of this alternative spending can completely offset the original savings, as when, for example, the dollar savings from a shift from meat to vegetable consumption is spent on gasoline.

The results of this *Science* paper only underscored the need for a rebated tax on all energy forms to steer consumers in the energy conservation direction. This was the main ERG contribution. Today, due to concerns over global warming, the emphasis is on a carbon rather than an energy tax. But such a tax does not tax all energy while the energy tax covers most of the carbon releases to the atmosphere.

While doing his doctoral thesis with ERG, Robert Costanza, now Gund Professor at the University of Vermont and founder of the International Institute of Ecological Economics, showed strong linear

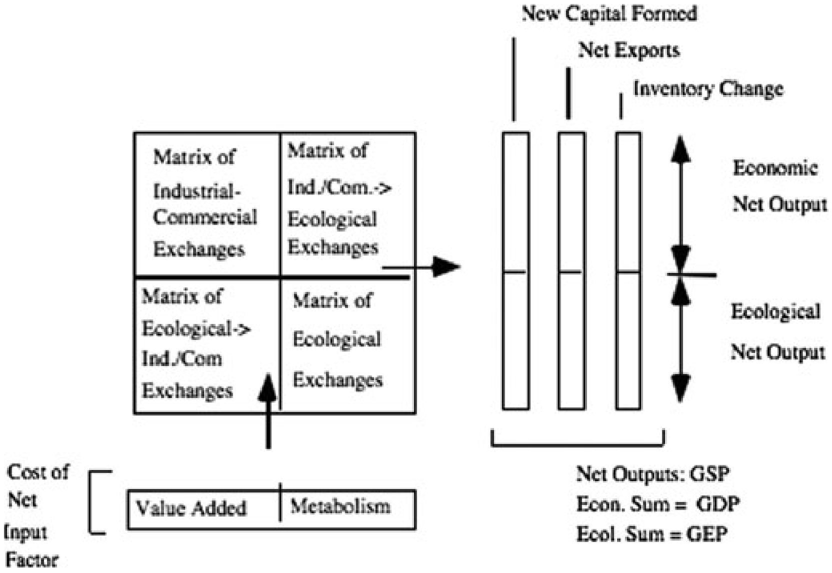

Figure 2. The combined economic–ecological accounting framework.

correlation between the embodied energy and the dollar value of each consumer good.[14]

Cutler Cleveland completed his PhD with Hannon in 1988 on the total energy cost of petroleum energy.[15] He is now professor of Geography at Boston University.

Matthias Ruth completed his PhD with Hannon in 1992, combining economics, ecology and thermodynamics into a single model of a generalized society.[16] He is now Weston Chair in Natural Economics at the School of Public Policy, University of Maryland, where he is the Director of the Environmental Policy Program and Co-Director of the Engineering and Public Policy Program.

Though the papers of the ERG are dated and the working papers are difficult to find, they are available through the Engineering Grainger Engineering Library, University of Illinois at Urbana-Champaign. (The search page is: http://susanowo.grainger.uiuc.edu/engdoc/new/default.asp.)

Extension of the theory to ecosystems

While the study of energy and the economy was fun for everyone in the group, a companion system, in many ways similar to the economy, caught the attention of Herendeen and Hannon. In 1973, Hannon published "The Structure of Ecosystems," a title clearly claiming more than appropriate.[17] He developed an (I–O) framework for the ecosystem where the net output (the GDP of the ecosystem) was its net exports, inventory change, respiration, and new biocapital formation. Respiration was analogous with household and government consumption of the economic definition. The idea was applied to a specific ecosystem to show the direct and indirect energy dependence of the top carnivore on the solar input to the system (see Fig. 2). Robert Ulanowicz of the University of Maryland, and Costanza and Hannon showed how such a matrix approach to ecosystem studies provided an excellent framework to collect the data from many different ecological research projects.[18] Such a framework could be used to show the direct and indirect connections of the various biological elements of the system. For example, if fishing were done on a system, the framework could show where and how much was needed to compensate and stabilize the system. Hannon and Joiris showed that the energy intensities played the role of prices when one took such a view of the ecosystem.[19] Extending the economic analogy further into ecology, Hannon showed how an ecological discount rate could be calculated; in a way, this was nature's time preference rate.[20] Under the proper conditions, the natural discount rate of an individual or a species can be approximated by its rate of respiration energy, the rate of heat release, per

Table 1. **The input–output accounting relationship for the combined economy and ecosystem**

							Net Output, r				Total
		Prod.	**Serv.**	**Min.**	**Anim.**	**Veget.**	Net Export	New Capital	Total, r	Capital Lost[10]	Output[11], P (Row Sum)
Economic	**P**roduction[1]	15000	900	700	500	500	1000	1000	2000	0	19600
Sectors	**S**ervices[2]	8000	2000	100	200	500	50	0	50	100	10950
	Minerals[3]	5000	0	0	0	1000	−1000	0	−1000	200	5200
Ecological	**A**nimal[4]	500	0	100	1000	0	−100	200	100	0	1700
Sectors	**V**egetative[5]	1600	600	0	2000	0	50	1200	1250	0	5450
	Net Input[6]	1000	300	400	18000	20000					
	Biocapital[7]				1800	2000					
	Panel values[8]				3.0	1.0	GSP: $\varepsilon * r = \$2371$				
	Biocapital, $				540	200		97% Efficiency			
	Net Input, $	1000	300	400	540	200	$2440 = Total Net Input				
	Price[9], ε	1.083	0.156	0.267	2.159	0.199					

The net input row is a source of prices that allow the net output, naturally accounted for in different units of measure, to be made commensurate resulting in a Gross System Product (GSP), analogous to the GNP for the economy alone. Since some irreplaceable and irrecoverable flows occurred (open physical system), the GSP (2371) is less than the evaluated net input (2440).

1. Measured in $.
2. Measured in person-hours.
3. Measured in megatons.
4. Measured in ktons.
5. Measured in ktons.
6. Measured as $ for the economy, QuadJoules for the ecosystem.
7. Quadcals of biocapital stock.
8. Cents/Quad Joule of Biocapital. Determined by consensus panel.
9. $/row measure.
10. Capital stock not replaced (e.g., soil erosion).
11. Row sum of all exchange flow + Net Output + Capital Lost.

unit of biomass energy. From metabolism data, it was found that the smaller individuals have a higher discount rate than larger ones and males a higher one than females of the same size. The discount rate should drop as the individual ages and as the species evolves. This natural discount rates captures both the idea of the inevitable entropy creation of living organisms and the duration of captured energy in their biomass. In this sense, it is a measure of the value a specific unit of biomass has to its ecosystem.

Herendeen produced a set of system-wide indicators for the dynamic ecosystem.[21]

Bentsman and Hannon[22] showed how the linear dynamic (I–O) model could be stabilized if certain exchanges cycled within specific frequency and amplitude ranges. More recent work in the (I–O) analysis arena shows how the appropriate definition of the exchanges, the net inputs and outputs, for a combined economic and ecological (I–O) matrix allows the calculation of a system efficiency.[23] The layout is given in Figure 2 with a set of demonstration data given in Table 1.

The key requirement of such a scheme is to determine the economic value of the respiration quantities for each species in the ecosystem. These values would come from a specially arranged panel. These values allow the net input vector to the combined system to be expressed entirely in monetary terms. The system prices can then be calculated by equation 7. These prices can be multiplied by the net output vector to find value of the Gross System Product (GSP value = $2371 in Table 1). Since the net output sum does not contain the lost capital values of each economic and ecological sector, the GSP value is less than the value of the net inputs ($2440 in Table 1). With these two values, the efficiency of the overall system can be calculated (97% in Table 1).

A more general concept of combined system efficiency was suggested in Hannon 1998. The question was whether the addition of human activity to an ecosystem made the whole more or less efficient. Surely, if the result is a decline in overall combined system efficiency, our present position in the ecosystem as currently practiced is not a lasting one.

The work of the ERG at the University Illinois, Urbana, provided one of the foundation stones of the now-flourishing International Institute of Ecological Economics. The modification of the (I–O) economic theory allowed it to be fruitfully used in the analysis of natural resource flow in both economic and ecological systems. The analysis has not only provided a common framework but has brought a consistent physical basis to both systems. It has clarified and identified the definitions of the net output and net inputs so that both systems can be combined into a single analytic framework, such that no flows in either system are omitted or double counted. Though the specific numeric results of this work are dated, the process by which the analyses were done creates a standard for future analysis in this arena.

Conflicts of interest

The author declares no conflicts of interest.

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