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METHODS

Ecological pricing and economic efficiency

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Abstract

There is a need to accurately account for the contributions of environmental assets to the overall economy. Such accounting would permit policies that allow protection of important natural resources and aid the analytic process to determine an accurate basis for a sustainable economy. The aim is to develop an accounting framework for ecology that is sufficiently consistent with the economic framework that the two can be fruitfully combined. With appropriate definitions of the flows, the two systems can be connected into a common framework. No single measure of the system productivity and efficiency can be given for the combined system, however, until the ecosystem metabolism can be converted into economic terms. This could be done with a series of economic valuation techniques. Ecological prices could then be estimated and a single measure of ecological economic output could be given. With the net combined system input and output now in common terms, a technical system efficiency measure can logically be proposed. Because human activity inevitably involves dissipation, such emissions would now have a monetary price. Because such emissions are irrecoverable, the total output of the combined system is greater than it is under the current definition, giving rise to a technical system-wide efficiency measure.

Keywords: Ecosystem; Economy; Prices; Input–output

1. Introduction

To achieve a sustainable economy, we must learn to value the economic contributions of all natural resources to the economy. This means that we must ultimately be specific about the value we place on every aspect of the environment external to the economy (Nordhaus, 2000). Matthews and Lave (2000) argue that to analyze the effectiveness of environmental programs and regulation and to improve environmental policy analysis requires the complex and controversial practice of evaluating the value of exchanges between nature and the economy. Bockstael et al. (2000) make the point that explicit valuation is a particularly human activity and, therefore, to measure the contributions of the environment

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around the economy, we must evaluate the unit exchanges of between them. These authors point the direction and lay out the goals for this paper. The input–output framework is chosen as the simplest, data-rich analytic process available for the early development of such an analysis.

Specialists in both economics and ecology extended the general analogous link between ecology and economics using input–output analysis through a series of papers. Hannon (1973) introduced input–output theory into ecology and applied it (Hannon and Joiris, 1987) to the North Sea ecosystem. The theoretical similarities of time value in the two systems also have been described (Hannon, 1990). More recently, a generalized ecological accounting framework was proposed (Hannon et al., 1991). But these efforts were dedicated mainly to demonstrating how ecological systems could be thought of in a parallel way with economic systems. Little attempt was made to combine the two systems into a single framework. The idea of the pricing of ecological flows in economic terms seemed insurmountable. The efforts of Costanza et al. (1997) to price the services rendered to the economy by the ecosystem have proven controversial and stirred up useful discussions (Arrow et al., 2000). The need for ecological pricing is the main focus of this paper. In addition, I have introduced the definition of a technical system efficiency measure.

The economist Winter (1964) described in great detail how a process like natural selection could be interpreted in understanding the behavior of the firm. Economists (Hirshleifer, 1978) also described the analogs of competitive behavior in biology and economic systems. Ecologists (Rapport and Turner, 1977) elaborated on consumer behavior and production analogies in natural communities. These authors stressed the nature of the analogues between the two fields.

The purpose is to combine the natural and economic processes in a common framework to make possible the formal rejoining of man and nature — of human activity and its environmental repercussions. This amalgam will allow the calculation of a set of economic prices for ecological goods and services.

The simplest method for combining these systems is the input–output accounting framework. In this framework, the analogy between the use of such a tool in both economics and ecology can be realized technically. The systems can be combined into a single matrix representation. Input–output systems provide a great deal of information for relatively small amounts of data collection and they force a balancing of inputs and outputs, thus eliminating under and multiple counting. With some additional data, I argue that the combined system can provide a means to calculate economic prices for ecological goods and services, and a measure for technical efficiency. However, the system is static, linear and requires a system equilibrium assumption. These requirements limit its usefulness. For my purposes here though, it supplies a reasonable tool to demonstrate how to calculate the economic value of ecosystem services. It is a useful point of beginning.

Ultimately, this analytic process cannot be completed without the conversion to monetary units of physical inputs to the economy from its external environment. This means that people must determine the unit values of such inputs and this requires evaluation techniques such as contingent valuation. While the process has considerable difficulties, particularly with the issue of aggregation of value, the field contains a large number of active researchers. Carson (2000) sums up the procedures, problems and status of the current research in the area.

2. The accounting framework for ecological and economic systems

A review of the current national accounting system used with slight variation throughout the industrial world is helpful. Here is a summary picture of that system.

The quest of this paper is to elaborate an analytical framework that can contain in a functional and meaningful way the economic and the ecological system. I begin with the accounting framework used for many years by economists, shown in Fig. 1, as a founding analogy.

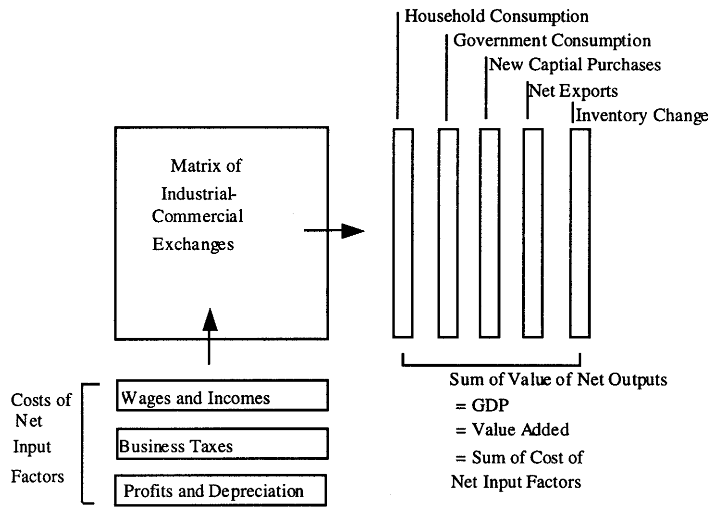

Fig. 1. The current economic national accounting system. The factors of labor and capital and indirect business and corporate profit taxes are (net) inputs to the economy as a whole. The inputs are needed in the production of the goods and services exchanged throughout industry and commerce and produced for the net output (shown here as five categories). All the flows are in monetary units. The net output sum is often called Final Demand or Gross Domestic Product (GDP) and the net input sum is called Value Added.

Three issues must be settled before modifying this framework to accommodate the ecosystem: the meaning or definition of net input and net output, the meaning of open versus closed system and the relative value of natural and manmade capital.

3. Definitions of net input and net output

The net input (valued added) of an economy contains the compensation value of employees and proprietors, profit taxes, dividends, rents and net interest payments, and indirect (non income corporate) taxes. All portions of the economic net input have only dollar measures: profits (thought of in economics as the cost of the factor input, capital), and the capital consumption allowances (estimates of the reduced dollar value of the capital stocks of the nation per year). These two categories amounted to ~10–11% of the constant dollar total net input for the US economy from 1948 to 1980 (Council of Economic Advisors, 1981). These latter measures are not especially accurate ones, particularly the capital consumption allowances. These values are compiled by the US Census Bureau as the depreciation reported by businesses and are more related to tax levels than to physical depreciation (Peterson, 1967). Sufficient wiggle-room can be found in these statistics to force a balance of net input and output in value terms.

The net output of an economy is defined as the value of consumption by households and government, all new capital formed, net exports and inventory changes, during the period of consideration. The sum of all five of these categories is called the gross domestic product (GDP). Economists measure the level and direction of economy activity by the level and changes of the GDP.

The idea of the services of a capital stock being an important determinant of the output of an economy suggests an analogy for the ecosystem: The services provided by the biocapital of an ecosystem are hypothesized to be important in the net output of that ecosystem. As we shall see below, the cost of providing biocapital to the ecosystem can be thought of as equivalent to the inclusion of the cost of man-made capital in the net input to the economic system. If the economic system and the ecological system were combined into a single input–output matrix, then the combined vector of net inputs would contain the usual mix of the economic values and the physical measures of the biological costs of provisioning the biocapital. If economic values for these biological costs could be somehow determined, the entire vector of net economic and ecological inputs would be cast in economic terms, and the way is clear for the calculation of the prices of ecosystem goods and services.

4. The relative value of natural and man-made capital

We can accept the economist's definition and evaluation of the net inputs, and then ask: What comparable costs exist in the ecosystem? This is a crucial accounting question if the economic and the ecological system are to be fruitfully combined. The net inputs to the ecological system must be clearly defined and converted to monetary units. The first step is relatively easy, if I analogize value-added as a measure of economic metabolism. After all, the value added are the factor costs of running the economic system and metabolism is the cost of running the ecosystem. I can then define the ecological net input as the metabolic costs of the natural or biological capital. In this way, metabolism and profits (and labor, taxes, depreciation, rents, and so forth) are seen as costs of production. Together they constitute the full set of net inputs to the combined system. In the ecosystem, the metabolism is the cost of operating, maintaining and replacing natural capital. This metabolism has a somewhat ambiguous physical measure. The metabolism could be thought of in the customary energy terms or in the carbon content of the standard metabolic measures. But there might be other forms of inputs to the metabolic process that originate in the environment. This means that the ecosystems' metabolic processes might not be wholly measured with a single input such as the metabolic energy of the living process in a particular sector. For example, the metabolic process of a tree involves the uptake of carbon, water, phosphorus (and more) and the expenditure of previously absorbed energy. The idea of multiple inputs in a given ecosystem sector can be handled in either of two ways. They may individually given relative values through experiments that measure the tradeoff between, say, carbon and water intake (see Klauer, 2000). When the relative values are determined, contingent value analysis is used to monetize one of these inputs, thereby, through the use of the identified relative values, monetizing the rest of the inputs. A more crude but simpler way to monetize the input is to monetize the biomass associated with the metabolic inputs through contingent value analysis, and then identify the best approximate relationship between the biomass and its metabolic flows, treated as a whole. This is the concept presented in the example found below.

Obviously, the process of contingent valuation is crucial in either monetizaton path. While fraught with technical difficulties, the profession of environmental economics seems to make significant strides with their research (Carson, 2000). The idea of asking people to value the biomass of trees may seem to the ecologist as silly; how could any person really understand and summarize such value? Two issues support this choice for valuation. The first is the idea that economic value is completely a human activity. We are routinely, indirectly and unconsciously setting such values on trees, for example, when we make real estate transactions and buy rain forest wood products. As our awareness of nature grows, these valuations will change, of course, so the analysis must be continually redone to capture these changes. The second supporting issue is that the activity focuses the research and individual consumer attention on these valuation questions. With time the accuracy of the technique should improve.

The exchange flows need only be measured consistently across the row of the exchange matrix and its portion in the net and total output. Each row of the input–output matrix may have a different flow measure. With the valuation of the ecosystem net inputs, we can combine the two systems in the same input–output accounting system, with commensurable flows. We can then measure the economic contribution of the ecosystem, and we can for the first time recognize that this combined system is an open one and estimate its technical efficiency.

5. Open and closed systems: a measure of technical system efficiency

The theoretical reason net economic input and output are equal is that the total output of each economic sector does not include the non-valued (zero-priced), physical exchanges between the environment and the economy. Since these flows are zero-priced by economic custom and since the flows in the economic accounting process are always measured in dollar terms, the total output (and net output) do not contain them. Thus, in spite of what is said about the constant dollar economic flows being proportional to the underlying physical flows, this claim is not strictly true. The value balancing process of national income accounting reveals an economy that is perfectly efficient in value terms: value of the total inputs equal the value of the total outputs.

The value of the factor inputs (the net inputs or value added) is equal to the total value of the net output, the GDP, by standard economic definition. Those things that physically joined or departed the economic system — sunlight, waste heat, solid waste, eroded soil, chemical emissions and so forth — are valueless, in the sense of the economic accounting system. We currently price them at zero. These items physically circulate in the economy and ecosystem (out, as noted above, but also into the economy in another place at another time) perhaps to unaccountably raise costs (pollution-related health loss, dredging of waterways, fishery loss and such) at the new location. Therefore, the economy is an open system in reality, even though it operates as if it were closed in the common valuation schema.

If pollution were to flow from a smokestack into the environment and be directly consumed by humans, the associated loss of health, though difficult to assign, is addressed by a number of suggested revisions to the GDP (see Daly and Cobb, 1989, for a definition of sustainable economic welfare). The indirect effects of such items as pollution on commercial animals or plants could also be addressed by revisions to the current input–output system flows.

The flows that I wish to especially address in this paper could be called irrecoverable stock or capital losses. They are not flows that disappear in one part of the economy only to reappear in another…these are true losses to the economic and ecological systems. They are flows like soil loss, the diffusion of chemicals and metals and the radiation of high temperature energy to such a low concentration that for all intents and purposes of any present or future system, they are lost. These lost flows include the flow of agricultural nutrients, such as nitrogen fertilizers, the heat in the exhaust of autos and electricity generators and the mingled materials waste in landfills.

To provide a reference for these flows in the economy, I will assume that the ecosystem sets the minimum rates for the loss of energy, chemical and material losses: the ecosystem has no irrecoverable losses by this definition (Hannon et al., 1993). Any soil, energy, chemical and material losses greater that those released by the ecosystem are deemed irrecoverable but economically valuable. We have the option not to lose them. If, for example, the process of agriculture converts the ecosystem for the production of food, only the associated increase in soil erosion and nutrient loss is considered unrecovered. I will classify these unrecovered flows as part of the total output of the economy, but not a part of the net output. This is the definition that allows the calculation of technical system efficiency. If we were able to cast the entire set of net inputs of the combined system into monetary terms, the economic value of the net output of the combined system could be calculated. We could then value the lost net outputs of the economic system and categorize such lost flows in the total system output measure, but not the net output of the system. Thus, the monetized value of the combined system net output would be less than the monetized value of the net inputs. A technical system efficiency could be defined as the ratio of the monetized value of the combined net input to the monetized value of the net outputs. This efficiency measure is not like the typical Pareto used in economics. This technical efficiency measures the avoidance of waste of the net input factors.

In summary, the efficiency of an economic system can be calculated using the natural ecosystem as a reference base. We will assume that the efficiency of the natural system is perfect; it has no losses. The increases in rates of high temperature heat loss (temperatures above the radiant temperatures of the least thermodynamically efficient member of system), of chemical and mineral diffusion are not compared to an absolute scale but to the scale that ecosystems provide. Heat energy is rejected from the ecosystem at temperatures in the range of 10–40°C, while heat exhaust temperatures from autos and from most of industry could range up ten times this level. Nitrogen and soil released from grassed areas are much lower than from agricultural areas in the same climate and topography (Mitchell et al., 1996; Ecological Society of America, 1997). Grasslands and forests are from 25 to 100 times as soil-retentive as typical soybean or cornfields, though careful farming can sometimes lower the relative rates to two (Wischmeier and Smith, 1978). Native tall grass prairie is very similar to forestland in soil retentiveness, even including the occasional burning (Koelliker and Duell, 1990). Thus, I move away from the abstraction of thermodynamics' absolute to the reference of the most efficient living system, the ecosystem.

I make the claim that the technical efficiency defined in this paper is useful from the standpoint of waste reduction and environmental impact for the economy. The measure is consistent and without double counting. Thus it is not possible for a firm to simply shift its waste generation to a supplier and claim a system-wide waste reduction. If improving this efficiency became a goal for the system, the procedure used here gives the framework for evaluating waste reduction policies. Furthermore, although the connection is tenuous, there exists argument for a connection between such wastes and what we define as a variety of environmental impacts. Improving this efficiency would mean a reduction in environmental impact, if the argument is true.

The three novel portions of the work are: the definition of metabolism as the net input of the ecosystem (similar in this respect to the costs of profits, labor and taxes in the economy); the use of economic techniques to evaluate these metabolic costs; and the addition of lost capital to the net output definition, allowing the formal computation of a combined technical system efficiency. The rest of this paper is a demonstration as to how this could be combined to yield meaningful measures of combined system activity.

6. Combining the systems: adding the ecosystem to the economic system

The next set of accounting decisions concerns the split between the purely economic part of the combined system and the purely ecological part. Arbitrarily placing all the inorganic natural resources in the economic portion leaves organic natural resources, those owned and marketed and those publicly owned and not directly marketed. Placing all of the agricultural processes, from fishing to crop raising, in the ecosystem portion of the exchange matrix allows for distinction between the natural and the agricultural portions of the ecosystem within the more general rubric of ecological exchange. With this greater definition, the accounting framework looks like this:

Many biological services do get monetized. The products of agriculture, fish, crops and livestock are stocks from which economic value is derived. Ocean and river fish are taken from the stock of reproductive fish, cattle from the reproducing herd, crops from the stock of farmland. The consequences of river, lake and ocean pollution, soil erosion, oxygen production, genetic diversity losses and the aesthetic changes are uncounted costs. The latter two, related to risk and to artistic opinion, are indirectly countable costs through such economic methods as willingness-to-pay (Freeman, 1979). The cost of economic risk is reflected in the discount rates

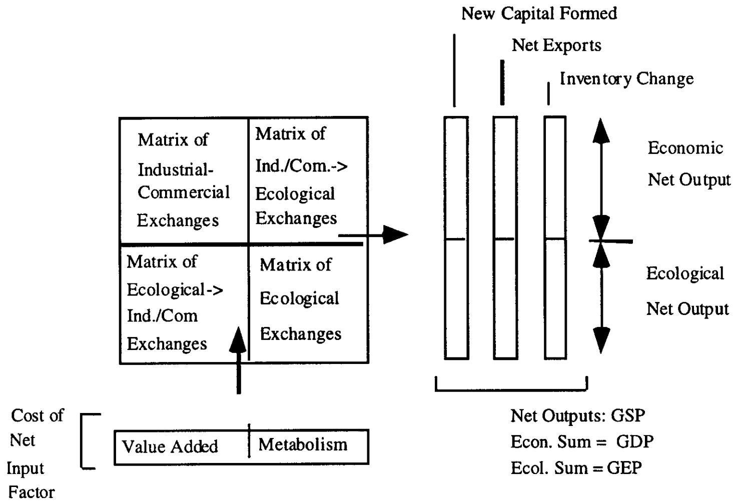

Fig. 2. The combined economic-ecological accounting framework.

embedded in the value of the rents, interest and profits within the economic value-added. I assume biological risk is represented in the metabolic costs of the natural stocks as well. Klauer (2000) demonstrates a more definitive discussion of the goods, services and sectors of an ecosystem.

I am struggling here to correctly evaluate the combined systems in a given time period, to create a complete accounting picture. Pollution is a physical flow and so is soil erosion. Consequently, they can become part of this accounting system. But pollution is handled within the exchange matrix. SO_2 pollution, for example, is absorbed by humans and by the ecosystem. With the combined matrix, such flows and their known consequences can be captured as many before me have discussed (Daly and Cobb, 1989). But the losses to the present and future counterparts of either system have to be specially accounted. A new column in the net output must be created to record the physical quantities irrecoverably lost to the combined system.

Technically, as long as the same units are used across a row of the system shown in Fig. 2, the accounting system is viable: each row can have a different unit of measure. This stipulation allows the purely economic transactions to be measured in monetary units and the ecological ones to be measured in physical terms, and yet combined in a common accounting set of matrices. It is also true that the exchange can be represented in the form of the more modern input–output accounting system using use/make matrices. I choose the simpler form only to keep this exposition simpler and allow the new principles to be shown more clearly.

7. The need for prices

It is clear that the net output of Fig. 2, with all its many units of physical and monetary measure, cannot be legitimately summed. Thus, no aggregate output for the combined system — no gross system product (GSP) nor system efficiency — is expressible. As a result, it is impossible to form a consistent set of prices through the usual economic equilibrium condition of price-marginal cost equality. With no single system of output measure, it is also impossible to calculate factor prices from the marginal physical product concept. These two very standard economic conditions are of no help in the combined system.

The exchange matrices outlined in Fig. 2 are in the economic system based on the receivers' willingness to pay for its inputs and the producers' willingness to accept that payment. In the ecosystem, the exchanges are based on a similar 'contractual' arrangement. While we do not see the vegetation as willingly giving its leaves to herbivores, the plants are in equilibrium with such exchanges. For example, they produce more leaves than are needed for its growth, they produce distasteful toxins, they time their leafing to avoid certain herbivores, they evolve seeding strategies to find places of low herbivore concentrations, etc. These physical exchanges can be viewed as flows in an agreed-upon contractual network. These ecosystem exchange flows are consistent among themselves in the same sense as the flows in the economic system. As can be seen in Appendix A, prices for such flows arise from the normalized exchange flows in combination with the net input. It is commonly assumed that these normalized exchange flows are fixed (for the short term, for small net output changes) and represent the 'technologies' of production. Thus these fixed ratios of the exchanges, some physically based, some economically based, are not part of the determination of the system prices. That job falls to the net inputs, but here we have the dilemma of noncommensurate measures.

Resolution of this dilemma begins with the realization that the net inputs to the combined system occur in only two types: the economic inputs and the metabolic inputs to the ecosystem. For the economic inputs, we already have the monetized value added. if we could monetize the metabolic flows of the ecosystem, we would have a consistently valuated net input vector. Thus, the problem lies in finding economic prices of the metabolic net inputs. How could this be done?

Begin with the argument that all prices are socially derived. Prices are measures that humans put on the stocks and flows that occur in our midst. The prices sought here do not exist outside the human social context. To derive such prices, I can only imagine that panels of people, representative of the entire society with an eye to the needs of future generations, could resolve this evaluation problem. It is possible that the rich literature of economic valuation[1] can provide a way to properly impanel a group to establish these relative prices (Freeman, 1979; Braden and Kolstad, 1991; Freeman, 1993). Ecologists, economists and experts in the methodology of economic valuation are needed to properly frame the panels and their questions. Contingent valuation is just one of the techniques that a panel could use to determine in effect the willingness to pay (or willingness-to-accept payment for) the services provided by the biocapital of the ecosystem. There are significant criticisms of these methods, but it is an area of intense economic research and the critical issues should be eventually resolved.

The crux of the measurement issue is that we need the economic value of the metabolism for each sector of the ecosystem. Through questioning of the especially empanelled citizens, we can expect to gain some evaluation of the stocks in these sectors but not of their metabolism. We need a means to convert the newly found valuation of the biological stocks into an evaluation of metabolism.

The key assumption employed is that the ratio for any particular stock of the amount of metabolism to the biological stock is a constant, independent of the unit of their measure. Ulanowicz and Hannon (1987), Hannon (1990)

[1] Professor John Loomis of Colorado State University suggests by private correspondence in 1998 the following reasonable approaches. The Capital Asset Pricing Model used in economics could be used to evaluate biocapital (factor income method). The value of a biocapital asset is the present value of the stream of its future net benefits, although this method requires knowledge of the dollar value of these costs and benefits. A second method is the replacement value method, where the cost of deployment of a known, least-cost technology achieving the same beneficial results as the biocapital asset, is the value of that asset (Letter of 6 January, 1997). Other techniques, such as the avoided cost method, the travel cost method, the hedonic pricing method and contingent valuation method, might also be called upon to evaluate the various stocks in the ecosystem. For example, large natural animals may be rather easy to evaluate, but soil bacteria might be given a very low, if not zero, value. By combining valuation of larger structures which contain bacteria, and by appropriate educational techniques, a combination of valuation techniques may produce a consistent price for bacteria.

showed that the metabolism to biomass ratio is the return rate for biological entities. The return rate follows the same definition as the capital return rate in economics. The assumption thus implies that the return rate for each biological sector is a constant, independent of its unit of measure. In our case we have the ratio in physical terms (e.g. joules of metabolism per joule of biomass) and from the panel we have the economic value of the biomass. This information and the assumption allow us to calculate the economic value of the metabolism for each biological sector.

At this point we have found the methods to express all of the net inputs in economic terms. Using the input–output theory outlined in Appendix A, economic prices can now be calculated for every sector of the combined ecological and economic system. Multiplying these prices by their associated net outputs and summing the results yields the GSP, the single total net output dollar value of the combined economic and ecological systems. This procedure avoids any double counting of value that might come from adding a large series of independent calculations.

The second important valuation issue is that of determining the appropriate monetary value of irrecoverable capital losses, such as eroded soil, waste energy and dispersed chemicals and metals. Much thought has gone into this question and the most appropriate summary is provided in the Survey of Current Business (1994). These authors note that the current economic accounts have no entry for the additions to natural resource stock, no explicit GDP entry for their contribution to production and no entry for resource depletion. While there are such accounts for capital items, there are none for natural resources. The Bureau of Economic Analysis suggests four ways in which the accounts could be amended to account for natural resources: estimates of current rents, presented discounted values, replacement costs and transactions-price. Each method has it own shortfall and advantages, and the Bureau gives tables of the estimates by each method for the years 1958–1991. They assessed these impacts on energy and metals. The inclusion of such values in national accounting reduced the rates of return in the mining industry from 23 to 4–5% and reduced the rate of return for all capital by 1–2%. The first three of these methods could be used to provide monetary estimates of irrecoverable lost capital for the proposed changes in national accounting.

8. An example

The theoretical development of the input–output relationships are simple ones and given in Appendix A. Here is an example of the combined system with arbitrary numbers.

The combined accounting framework shown in Table 1 has two novel features. First, the total sector output contains some flows that are lost to this and any future system. These flows appear under the column 'capital lost'. Energy waste, soil erosion and the dispersion of metals into landfills are examples. These flows represent the loss of a capital stock that cannot be replaced in the foreseeable future. Soil is eventually constructed to replace eroded soil, but the process is relatively slow and may not take place at all on heavily farmed lands. Much of the nation's steel food container output is landfilled today and there is no iron ore being produced by nature.

The net export column contains flows that are going (+) or coming into (−) this system. If they leave this system, they are to be used in some similar system. Consider a large mineral import of energy from another system. The new capital column contains the amounts of production of new capital, scheduled either for replacement of worn-out or obsolete equipment or buildings.

The second novel part of this accounting system is that the net input is composed of two or more types of system flows. These flows I have called the factor (man-made capital and biocapital) costs. They are the profits and capital depreciation for the first three columns, those representing the economy, and the metabolic energy flows of the (two) ecosystem sectors. One could even calculate a set of combined prices with this vector, but the economic prices would be in dollar terms while the ecosystem prices would appear as an energetic measure.

The net output r, evaluated by such a mixed

Table 1
The input–output accounting relationship for the combined economy and ecosystem[a]

		Production	Services	Minerals	Animal	Vegetative	Net output, r			Capital lost[b]	Total output[c], P (row sum)
							Net export	New capital	Total, r		
Economic sectors	Production[d]	15 000	900	700	500	500	1000	1000	2000	0	19 600
	Services[e]	8000	2000	100	200	500	50	0	50	100	10 950
	Minerals[f]	5000	0	0	0	1000	−1000	0	−1000	200	5200
Ecological sectors	Animal[g]	500	0	100	1000	0	−100	200	100	0	1700
	Vegetative[g]	1600	600	0	2000	0	50	1200	1250	0	5450
	Net input[h]	1000	300	400	18 000	20 000					
	Biocapital[i]				1800	2000					
	Panel values[j]				3.0	1.0	GSP: $\varepsilon * r$ = US$2371				
	Biocapital (US$)				540	200		97% Efficiency			
	Net input (US$)	1000	300	400	540	200	US$2440 = Total net input				
	Price[k], ε	1.083	0.156	0.267	2.159	0.199					

[a] 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 GSP, analogous to the GNP for the economy alone. Because some irreplaceable and irrecoverable flows occurred (open physical system) the GSP (2371) is less than the evaluated net input (2440).

[b] Capital stock not replaced (e.g. soil erosion).

[c] Row sum of all exchange flow + net output + capital lost.

[d] Measured in US$.

[e] Measured in person-hours.

[f] Measured in Mtons.

[g] Measured in ktons.

[h] Measured in US$ for the economy, quadjoules for the ecosystem.

[i] Quadcals of biocapital stock.

[j] Cents/quadjoule of biocapital. Determined by the consensus panel.

[k] US$/row measure.

units vector of prices could not be summed to form a single system measure. From the appropriate combination of economic valuation techniques, with a representative panel of knowledgeable citizens, the price of animal and vegetable capital was determined (imagined) to be 3 and 1 cent per quadrillion joules, respectively. With such figures, the dollar value of the animal and vegetable metabolism can be easily found at US$540 and 200 for this period, respectively. With this conversion, the net input is now cast into a common measure, a consistent set of prices can be calculated (see Appendix A) and multiplied times the net output, and then summed to find a consistent single measure of system performance.

This measure will always be less than the sum of the net inputs (both in dollar terms): US$2371 compared with US$2440. This inequality is an outgrowth of the presence of the lost capital flows, representing a kind of economic manifestation of the second law of thermodynamics. Because of these irreplaceable losses, value is not conserved in this system — the system operates with an efficiency measure. The total output column contains all the flows from all the sectors in the system; the difference here lies in the exclusion of the irreplaceable flows from the net output.

If this idea ever gains credence, the best accounting framework would be the dual exchange matrix approach now used by the US Bureau of Economic Analysis. This system is somewhat harder to explain, especially when I am trying to introduce several new concepts. However, it is more accurate as it involves more exchange data.

I believe the accounting procedure outlined in Table 1 is useful. It allows the unambiguous intermingling of the flows of the two systems most important to humans — the ecological and the economic. We can determine the direct and indirect effects of pollution-diminished crop growth, the true economic value of soil erosion and solid waste, and most important, the reflection of the ecosystem flows in the price of common economic goods and services. Surely the price of such economic products would rise as the natural subsidy drops due to a decline in natural stocks. We know there is a connection. This is a step in the direction of quantifying that knowledge.

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Appendix A. The calculation of prices based on the net input

Let the exchanges in the exchange matrix portion of the table shown in Fig. 2 have elements p_{ij}, with i the row designator and j the column designator. Let the row total output of each sector be p_j, the net output for that sector be r_j and the net input to that sector be E_j, and finally, let the price of the sector j output be ε_j. For balance of value across sector j, we must have the balance of evaluated flows across any sector as shown in Fig. A.1.

From this figure, we have the balance equation that can be solved for $\boldsymbol{\varepsilon}$, the vector of ecological prices:

$$\Sigma\ \varepsilon_i * p_{ij} + E_j = \varepsilon_j * p_j \qquad (1)$$

where E_i is the monetized net input for the ith sector, $\varepsilon_i * p_{ij}$ is the system price of the ith input times the quantity of the ith input, and $\varepsilon_j * p_j$ is the system price of the jth output times the quantity of the jth output. These system prices can be calculated from the vector equation using Eq. (1) as follows:

$$\boldsymbol{\varepsilon} = \boldsymbol{E} * \boldsymbol{p}^{-1} * (\mathbf{I} - \mathbf{G})^{-1} \qquad (2)$$

where $\boldsymbol{E} * \mathbf{p}^{-1}$ is the vector of net inputs[2], normalized by the total row sum output of each sector ($\boldsymbol{p}^{-1}$ is the inverse of the diagonalized total output

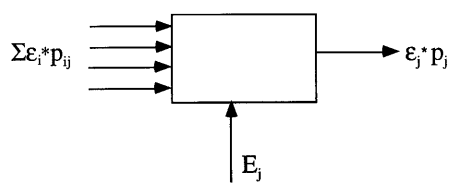

Fig. A.1. The ecological value balance for the jth sector of either the economic system or ecosystem. E_j is an element in the net input vector. p_{ij} is the product exchanged from sector i to sector j. p_j is an element in the total output vector for the product of sector j. ε_I is the price of input i.

[2] Bold letters indicate a vector or a matrix.

vector), **G** is the matrix of exchange elements, **P**, normalized down the column by each of the appropriate row sum of total output of each sector. **I** is a matrix of diagonal ones. The GSP, in value terms, is therefore:

$$\mathrm{GSP} = \varepsilon * \boldsymbol{r} = E \quad (3)$$

where E is the simple sum of the net inputs. Thus the system prices had to be calculated in order to convert the mixed units of the net output vector into the monetizing unit. The equality holds only when the system is closed; when the valued flows are conserved — that is, when there is no recognized dissipation flow. This equality represents a physically impossible situation. The real-world situation is represented by the inequality, indicating the effect of the second law of thermodynamics. So the valued net output of an open system always sums to less than the sum of the net inputs, and the definition of a technical system efficiency is possible. This efficiency is $(\varepsilon * \boldsymbol{r})/E'$ where E' is the total (scalar) value of the net input. It is always less than one.

Similar equations can be derived for the double matrix use–make form of input–output analysis.

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